Universidade do Minho
Escola de Engenharia

Miguel José Magalhães Lopes

A Mid-Level Framework for Independent Network Services Configuration Management

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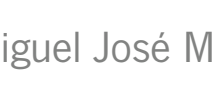
Programa Doutoral em Telecomunicaçãoes das Universidades do Minho, de Aveiro e do Porto



Universidade do Minho

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Abstract

Decades of evolution in communication network's resulted in a high diversity of solutions, not only in terms of network elements but also in terms of the way they are managed. From a management perspective, having heterogeneous elements was a feasible scenario over the last decades, where management activities were mostly considered as additional features. However, with the most recent advances on network technology, that includes proposals for future Internet as well as requirements for automation, scale and efficiency, new management methods are required and integrated network management became an essential issue.

Most recent solutions aiming to integrate the management of heterogeneous network elements, rely on the application of semantic data translations to obtain a common representation between heterogeneous managed elements, thus enabling their management integration. However, the realization of semantic translations is very complex to be effectively achieved, requiring extensive processing of data to find equivalent representation, besides requiring the administrator's intervention to create and validate conversions, since contemporary data models lack a formal semantic representation.

From these constrains a research question arose: *Is it possible to integrate the configuration management of heterogeneous network elements overcoming the use of management translations?* In this thesis the author uses a network service abstraction to propose a framework for network service management, which comprehends the two essential management operations: monitoring and configuring. This thesis focus on describing and experimenting the subsystem responsible for the network services configurations management, named Mid-level Network Service Configuration (MiNSC), being the thesis most important contribution.

The MiNSC subsystem proposes a new configuration management interface for integrated network service management based on standard technologies that includes an universal information model implemented on unique data models. This overcomes the use of management translations while providing advanced management functionalities, only available in more advanced research projects, that includes scalability and resilience improvement methods. Such functionalities are provided by using a two-layer distributed architecture, as well as over-provisioning of network elements. To demonstrate MiNSC's management capabilities, a group of experiments was conducted, that included, configuration deployment, instance migration and expansion using a DNS management system as test bed.

Since MiNSC represents a new architectural approach, with no direct reference for a quantitative evaluation, a theoretical analysis was conducted in order to evaluate it against important integrated network management perspectives. It was concluded that there is a tendency to apply management translations, being the most straightforward solution when integrating the management of heterogeneous management interfaces and/or data models. However, management translations are very complex to be realized, being its effectiveness questionable for highly heterogeneous environments. The implementation of MiNSC's standard configuration management interface provides a simplified perspective that, by using universal configurations, removes translations from the management system. Its distributed architecture uses independent/universal configurations and over-provisioning of network elements to improve the service's resilience and scalability, enabling as well a more efficient resource management by dynamically allocating resources as needed.

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Acronyms

4WARD	Architecture and Design for the Future Internet
6LoWPAN	IPv6 over Low Power Wireless Personal Area Network
ABE	Aggregate Business Entity
ACL	Access Control List
ACS	Active Configuration Server
ACSE	Association Control Service Element
AD	Active Decision
AE	Autonomic Element
AES	Advanced Encryption Standard
AMS	Active Monitoring Server
API	Application Programming Interface
ARP	Address Resolution Protocol
ASI	Active Service Instance
ASN.1	Abstract Syntax Notation One
ATM	Asynchronous Transfer Mode
AUTOI	Autonomic Internet
BEEP	Blocks Extensible Exchange Protocol
BER	Basic Encoding Rules

CCS	Candidate Configuration Server
CBC	Cipher Block Chaining
CIM	Common Information Model
CIMOM	Common Information Model Object Manager
CLI	Command Line Interface
CMIP	Common Management Information Protocol
CMIS	Common Management Information Services
COPS	Common Open Policy Service
COPS-PR	Common Open Policy Service - Policy Provisioning
CORBA	Common Object Request Broker Architecture
CPS	Configuration Pointing Server
CPU	Central Processing Unit
CSI	Candidate Service Instance
DEN	Directory Enabled Networks
DEN-ng	Directory Enabled Networks-next generation
DES	Data Encryption Standard
DHCP	Dynamic Host Configuration Protocol
DIFFSERV	Differentiated Services
DMTF	Desktop Management Task Force
DNS	Domain Name Service
DoS	Denial of Service
DTD	Document Type Definition
DTLS	Datagram Transport Layer Security
FCAPS	Fault, Configuration, Accounting, Performance and Security

FIND	Future Internet Design
FOCALE	Foundation, Observation,Comparison, Action and Learning Environment
FPGA	Field-Programmable Gate Array
GDMO	Guidelines for the Definition of Managed Objects
GIOP	General Inter-ORB Protocol
GSM	Global System for Mobile Communications
HMAC	Keyed Hashing for Message Authentication
HTTP	Hypertext Transfer Protocol
HTTPS	Hypertext Transfer Protocol over Secure Sockets Layer
ICMP	Internet Control Message Protocol
IDE	Integrated Development Environment
IDL	Interface Definition Language
IETF	Internet Engineering Task Force
IIOP	Internet Inter-ORB Protocol
INMF	Internet-standard Network Management Framework
INTSERV	Integrated Services
IOR	Interoperable Object Reference
IP	Internet Protocol
IPsec	Internet Protocol Security
ISDN	Integrated Services Digital Network
ISMS	Integrated Security Model for SNMP
ISO	International Organization for Standardization
ISP	Internet Service Provider
IT	Information Technology

ITU	International Telecommunication Union
JIDM	Joint Inter-Domain Management
JRMI	Java Remote Method Invocation
LDAP	Lightweight Directory Access Protocol
LPMS	Lightweight Policy Management Server
MAC	Message Authentication Code
MBTL	Model-Based Translation Layer
MD5	Message Digest 5
MIB	Management Information Base
MiNSC	Mid-level Network Service Configuration
MIT	Management Information Tree
MO	Management Object
MOC	Management Object Class
MOF	Managed Object Format
MSC	Monitoring Server Candidate
NACM	NETCONF Access Control Model
NETCONF	Network Configuration Protocol
NMRG	Network Management Research Group
NMS	Network Management System
OID	Object Identifier
OMA	Open Management Architecture
OMG	Object Management Group
OOD	Object Oriented Design
ORB	Object Request Broker

OSI	Open Systems Interconnection
OSI-NM	OSI Network Management
PBNM	Policy-Based Network Management
PCIM	Policy Core Information Model
PDP	Policy Decision Point
PDU	Protocol Data Unit
PEP	Policy Enforcement Point
PIB	Policy Information Base
QoS	Quality of Service
RADIUS	Remote Authentication Dial In User Service
RDN	Relative Distinguished Name
RFC	Request For Comment
ROSE	Remote Operation Service Element
RPC	Remote Procedure Call
SCTP	Stream Control Transmission Protocol
SFCB	Small Footprint CIM Broker
SHA-1	Secure Hash Algorithm 1
SID	Shared Information Data Model
SIP	Session Initiation Protocol
SLA	Service Level Agreement
SLP	Service Location Protocol
SMAE	Systems Management Application Entity
SMFA	Systems Management Functional Areas
SMI	Structure of Management Information

SMIng	Structure of Management Information Next Generation
SMIv1	Structure of Management Information Version 1
SMIv2	Structure of Management Information Version 2
SMON	Automated and Distributed Network Services Monitoring
SNMP	Simple Network Management Protocol
SNMPv1	Simple Network Management Protocol version 1
SNMPv2	Simple Network Management Protocol version 2
SNMPv2c	Simple Network Management Protocol version 2 with Community String
SNMPv3	Simple Network Management Protocol version 3
SOA	Service Oriented Architecture
SOAP	Simple Object Access Protocol
SSH	Secure Shell
SSL	Secure Sockets Layer
TCP	Transmission Control Protocol
TINA-C	Telecommunications Information Networking Architecture Consortium
TLS	Transport Layer Security
TMF	Tele-Management Forum
TMN	Telecommunication Management Network
TTL	Time-to-Live
UDP	User Datagram Protocol
UML	Unified Modeling Language
URI	Uniform Resource Identifier
USM	User-based Security Model
VACM	View-based Access Control Model

VoIP Voice over IP

WBEM Web-Based Enterprise Management

XML Extensible Markup Language

XSD XML Schema Definition

Chapter 1

Introduction

This chapter introduces the theme of network management. From early descriptions to the most recent proposals a short chronological overview is presented. With the growing complexity of network management environments, allied with a demand for cost reduction, new ways are being pursued to achieve higher levels of management automation. However, automating network management processes requires effective ways to deal with the network's heterogeneity. It is in this context that the thesis' objectives and contributions are built. This chapter also includes the document's organization.

1.1 Motivation

Means to control network devices have been pursued since the earliest days of communication networks. This is the principal purpose of network management activities. The main driving force behind the need for the implementation of network management is a financial one. The more important communication networks become the more relevant network management is. This is due to the fact that financial repercussions became potentially larger. Network management activities provide the means to detect, diagnose and correct erroneous states or performance degradation while minimizing the managed element's downtime. It also provides the means to actively change the managed element's state in response to business rules or operational context changes, facilitating the quick deployment of new administrative solutions, which is an important advantage in today's competitive and volatile markets. With the increasing complexity and heterogeneity of network management environments the search for effective automated network management methodologies become a central goal.

Historically speaking, network management presents a remarkable evolution and corresponds to the communication network's evolution. The initial references to network management appear during the mid to late 80s in a suite of standards known as the X.700 series that were jointly developed by the International Telecommunication Union (ITU) Study Group 7 (ITU SG 7) along with International Organization for Standardization (ISO). This resulted in the OSI Network Management (OSI-NM) [1] for the management of Open Systems Interconnection (OSI)-based systems [2]. This approach was adopted by ITU for the telecommunication network management which resulted in the ITU's Telecommunication Management Network (TMN) architecture [3]. However, with the exponential growth of Internet-based computer networks, and the corresponding decline of the OSI-based network systems, the OSI-NM was left mainly for the management of telecommunication networks, such as Integrated Services Digital Network (ISDN), Asynchronous Transfer Mode (ATM) and Global System for Mobile Communications (GSM), where it is still used. In parallel, the Internet community worked on a simpler proposal that could be easily implemented without imposing significant overhead to the managed devices. This resulted in the Internet Engineering Task Force (IETF)'s Internet-standard Network Management Framework (INMF) [4–6] based on the Simple Network Management Protocol (SNMP) [5] (also referred to as Internet Standard Management Framework [7], SNMP Framework [8, 9] or even SNMP). With the massification of Internet-based systems, the SNMP's based network management became widely used for the deployment of management tasks. However INMF did not defines a fully object-oriented management architecture and only provides a small set of management operations [10]. Allied to the network devices technological development as well as the demand for new management facilities, INMF began to lose effectiveness, thus other solutions were pursued, namely for configuration management [11].

In the early-mid 90s, the first Policy-Based Network Management (PBNM) proposals appeared [12–14]. With the increased complexity of the network systems as well as the services they provide, the means were required to formally describe the managed elements behavior (to be used for automation). The most popular propositions on the path to PBNM were defined in [15]. They include: management simplification for highly complex and heterogeneous network systems; service differentiation; reduction of the manpower required to administer the network; support for abstracted behavior description and a business driven management approach. The IETF's Common Open Policy Service (COPS) [16] is a PBNM protocol presented in the late 90s/early 2000s, supporting policy configuration between a Policy Decision Point (PDP) and Policy Enforcement Point (PEP) through a Transmission Control Protocol (TCP)-based transport

mechanism that includes security and atomic transactions. It's data model infrastructure, called Policy Information Base (PIB) [17], is quite similar to INMF's Management Information Bases (MIBs). PIBs contain policy objects to be manipulated by the COPS protocol. Initially, the COPS protocol was created to manipulate objects for the Integrated Services (INTSERV) framework [18]. However, it was later extended with policy provisioning with the Common Open Policy Service - Policy Provisioning (COPS-PR) standard [19], enabling its usage with Differentiated Services (DIFFSERV).

Also in the mid 90s, a new network management architecture followed the object-oriented programming trend for distributed applications. The Object Management Group (OMG) Common Object Request Broker Architecture (CORBA) [20] was one of the first distributed objects model providing support for network management while integrating existing heterogeneous network management solutions. However, the CORBA-based network management solutions did not receive wide support and failed to be deployed in a relevant scale due to the following reasons: CORBA-based management systems are complex and expensive to implement and operate in opposition to the SNMP's simplified management model [21]; it lacks a truly open and self-contained management information representation that could compete with the INMF's MIB concept [22]; it does not support efficient bulk data retrieval [10], essential for network management. Also, the Sun's Java Remote Method Invocation (JRMI) failed to gain wider acceptance in building management solutions related to the *Java* environment, not supporting legacy systems described in other languages such as *C++*. Other distributed object solutions were created but none of them gained enough significance to be considered as an alternative for INMF.

With the massification of the use of web technologies, web-based management gained increased recognition. A popular approach is the Desktop Management Task Force (DMTF)'s Web-Based Enterprise Management (WBEM) [23], presented in the late 90s. It implements request-response operations, emulating remote method calls with support for simultaneous requests, adequate for bulk management. The Common Information Model (CIM) [24] provides a group of generic classes from which among other *System*, *Network*, *Application* and *Service* information models are derived [10]. The CIM information models are specified using the Managed Object Format (MOF) language which is a standard way of describing object oriented classes and instance definitions in a textual form, thus improving human readability. The DMTF's WBEM also implements PBNM. The Policy Core Information Model (PCIM) [25] and its extensions [26] were defined to convey policy information. So, WBEM is an umbrella architecture which aims towards management integration of the heterogeneous network management interfaces.

With the intent of addressing the configuration management limitations found in SNMP [11], IETF recently proposed the Network Configuration Protocol (NETCONF) [27], which includes a complete and extensible set of operations permitting efficient and secure configuration provisioning using a document-oriented management approach. In order to improve the NETCONF management solutions interoperability, a vendor-independent data model definition language called YANG [28] was created.

More recently, several documents were published where present Internet limitations were identified [29–32]. Referred to as fundamental limitations, they include functional, structural and performance constraints that may not be addressed using current architectural paradigms. These limitations motivated new research works and the two main paths of development involve either the continuation of the present Internet evolutionary model or a disruption of the current paradigm creating clean-slate designs, also referred to as future Internet. Some of the projects dealing with the future Internet design and validation include FIA [33], NetSE [33] (both in USA), AKARI [34] in Japan, EIFFEL [35] initiative in Europe, among others. From a management perspective, new solutions have been proposed, which are not always solely aimed at future Internet management. Some also include support for the management of present Internet. Networks are increasing in size, functionalities, number of users, available services, vendors, expectations, etc. Management becomes a highly complex task which administrators must deal with. Therefore, automated management approaches are being pursued. The use of automated management processes will deal with highly complex management domains while reducing the operational cost because it reduces the need for human intervention. New solutions are being proposed, which include architectures, protocols and services, promoting self-management capabilities enhancing network management activities at several levels (economic, operational, strategic, etc). Autonomic network management is the most popular concept addressing automation of network management processes. Its application can be found in several research projects such as AutoI [36], 4WARD [37], ANA [38], FIND [39], AKARI [34], FOCALE [40] among others.

1.2 Objectives of this Thesis

Even though considerable advances have been made when it comes to network management domain, a few issues remain open. Today's most widely used network management frameworks (such as INMF for Internet or TMN for telecommunication networks) rely on the administrator's manual intervention. They are low-level applications that gather low-level management data and apply low-level management operations chosen using

empiric analysis. The management intelligence resides outside the network which makes them unable to deal with unforseen situations. Architectures such as these are limited to provide adequate management solutions that support new management challenges at an adequate scale [41]. On the other hand, early PBNM solutions tries to simplify network management procedures using automation. However, the level of automation provided is insufficient and hardly copes with the ever increasing complexity of heterogeneous elements of current and future networks [41]. Intent on providing a fully automated network management framework, the autonomic network management concept was proposed. Its main advantages are flexibility and adaptability for the implementation of self-management procedures, reducing administrator's dependency. The interaction between the administrator and the management system is provided through a goal oriented language [41] that is dynamically mapped into policies, later enforced without human intervention into autonomic elements across the network.

The most relevant approaches aimed towards management integration (such as autonomic network management, WBEM and others) are based on a model [42] where a group of independent network-wide configurations (policies) are translated to each managed device configuration using a configuration data translator entity. However, the implementation of such needed translation mechanisms, providing support for heterogeneous devices, introduces new constraints: the necessity to create and maintain syntactic translation mechanisms for each type of managed device (with low reuse of specifications) due to the heterogeneity of management interfaces and data models, which for large scale management domains, creates a complex task; semantic translations require the administrator intervention to validate/create semantic mappings due to the lack of formal semantic content on contemporary management data models. So, the mapping process can be very complex if dealing with large scale heterogeneous management domains. Furthermore, when performing a syntactical data translation the semantic of management data models is not consider which can result in data inconsistencies, errors or collisions when overlapped concepts exist between source and destination data models.

In order to overcome the implementation of management translations (and their inherent constraints) and still support the management of heterogeneous network services, a new framework is proposed: MiNSC. This framework relies on a distributed architecture and on the use of standard technologies (management interface and information models) to unify configuration management. It permits automation of some management tasks based on the representation of the managed service behavior. Furthermore it enables automatic deployment of service' instances configurations. These configura-

tions are generic and no complex translation mechanisms are needed as each vendor has the responsibility to create it's instrumentation in accordance to MiNSC's independent interface. Two different deployment modes are possible on the MiNSC architecture: used as a middleware for higher-level network management applications, integrating the management of heterogeneous network service implementations or; used in cooperation with a monitoring system to improve automation.

Throughout the thesis reference is made to information and data models. According to [43], information models (in network management) represent objects at a conceptual level, independent of any implementation detail or protocol used for transport data. They are also used to represent relationships between managed objects and a common way of describing information models is through a class diagram of the Unified Modeling Language (UML). On the other hand, data models represent a lower level of abstraction, including implementation and protocol specific details. Multiple data models may be derived from a single information model. Some standard data models include MIB and PIB.

The following objectives are pursued by this thesis:

- Propose an MiNSC framework for heterogeneous network service management overcoming the realization of intermediary one-to-many management translations. Since MiNSC is a middleware framework this should be realized using standard and independent management interfaces and information models, enabling management isolation from the network's service implementations heterogeneity. The proposed framework must be resilient and scalable (because it performs a highly sensible and important operation) and also improve resilience and scalability of the managed service itself;

- While MiNSC supports the integrated network service management without implementing a translation mechanism, the higher-level network management applications interoperability is assured by the usage of standard technologies. This promotes the competition among higher-level network management applications;

- Contextualize MiNSC framework in today's network management landscape. In order to accomplish this task, an exhaustive study must be performed to identify the limitations of current proposals addressing integrated management of heterogeneous network services and devices;

- Since MiNSC presents a new framework for integrated management, a study must be performed in order to demonstrate its validity. This conceptual study will consider a group of criteria including not only the requirements for contemporary network management but for future Internet management as well;

- Develop a MiNSC based prototype that demonstrates the proposed framework capabilities. For this to be accomplished experimentally, a standard-based service management information model must be designed and implemented using an SNMP-based solution. Several heterogeneous service implementations must be chosen and their corresponding configuration agents developed.

1.3 Contributions of this Thesis

This thesis aims to contribute to the increment of the current knowledge on network management by presenting:

- A study on the current state of knowledge regarding integration and automation of network management, including the most relevant academic proposals as well as the most important solutions commercially available. This study identifies current limitations and presented proposals to solve them;

- A definition of an MiNSC middleware management framework that enables integrated configuration management of heterogeneous network service implementations. MiNSC's management abstraction is provided through the implementation of independent data models based on network service standards descriptions and provide an abstracted view over all non-standard, implementation-specific details. An independent information model is designed for Domain Name Service (DNS) service management. Each model can be further divided into two hierarchical sub-models:

  - *Instance management information model* that corresponds to the lowest abstraction level where the service instance configuration is represented;
  - *Service management information model* that corresponds to the mid level abstraction, enabling the representation of the services behavior configuration. Instance configurations are automatically derived from service behavior configurations.

- An MiNSC based DNS management tool. This prototype is an important contribution because it provides a real implementation for management of heterogeneous DNS implementations, that is not reliant on intermediary translation mechanisms, and that is freely available to other researchers. An MIB was developed for configuration management of DNS implementations based on the Structure of Management Information Version 2 (SMIv2), implementing the information model proposed;

- An MIB providing a standardized representation for mid level network service configuration management. The data model provided eliminates the configuration management heterogeneity;

- An network service configuration deployment mechanism, as provided by MiNSC. With the independence provided by the implementation of the instance management information model and the service behavior representation maintained by the service management information model, the conditions are gathered to automatically calculate the managed service instance configuration;

- An service execution migration mechanism, as provided by MiNSC based on the realization of automatic and independent service instance configuration replication. When associated with the Automated and Distributed Network Services Monitoring (SMON) framework, MiNSC framework is able to replace a faulty instance without administrator intervention, improving service resilience. A similar approach can be used to improve service scalability. These are important contributions that are only contemplated in more advanced research projects using complex autonomic network management methodologies.

A group of technical documents were published as result of the research work developed for this thesis, namely:

- *Automated Network Services Configuration Management* [44] presented in the 1st IFIP/IEEE International Workshop on Management of the Future Internet (ManFI), June 2009;

- *Towards Automatic and Independent Internet Services Configuration* [45] presented in the 6th International Conference on Network and Service Management (CNSM), October 2010;

- *Automatic and Independent Domain Name Service Configuration Management* [46] presented in the 12th IFIP/IEEE International Symposium on Integrated Network Management (IM), May 2011;

- *A Two-Layer Architecture to Enhance Large Scale Heterogeneous Network Services Management* [47] presented in the 11th Conferencia de Redes e Computadores (CRC), November 2011;

- *Improving Network Services Resilience Through Automatic Service Node Configuration Generation* [48] presented in the IEEE/IFIP Network Operations and Management Symposium (NOMS), April 2012;

- *Improving Network Services' Resilience using Independent Configuration Replication* [49] presented in the Sixth IEEE/IFIP International Workshop on Distributed Autonomous Network Management Systems (DANMS), 31 May, 2013.

1.4 Document Organization

This thesis is extended over seven chapters. Each chapter content is summarized into the following subjects:

- The first chapter introduces network management theme and a short chronological overview is elaborated starting from the early days of network management up to the most recent proposals for future Internet management;

- Chapter two provides relevant background information, detailing all major standards as well as research and development projects in this field. A special emphasis is given to the solutions realizing integrated management of heterogeneous network services and devices;

- The limitations inherent to the realization of integrated management of heterogeneous network elements, based on management translations, are explored in chapter three. They served as the main motivation for the development of this research work. Also in this chapter an architecture for automatic, distributed and integrated network service management is presented, which includes a distributed framework for the network services monitoring (SMON); and another for configuration (MiNSC);

- The MiNSC framework is latter described in more detail in chapter four. Its architectural and functional design are explained in detail and how limitations of previous integrated network service management solutions, based on management translations, are overcome;
- Chapter five presents an MiNSC based prototype for mid-level DNS management. Architectural components are explained in detail, their interaction and its functional model is also described. Several advanced management functionalities were experimented using the prototype, including automatic DNS service deployment and instance configuration migration;
- Chapter six includes an evaluation of the proposed mid-level configuration management framework. Since MiNSC provides a new perspective for the integrated network service management, unable to be directly evaluated, a group of criteria were defined and their compliance was studied for reference tools and proposals with a similar scope;
- Conclusions end the thesis in chapter seven where a summary is made regarding the most important conclusions taken while also presenting a few tips for future work. The thesis contributions are also enumerated in this chapter.

Chapter 2

Network Management Landscape

This chapter provides the reader with an overview of the most relevant works within the field of network management. Following a chronological order, an overview is given placing special emphasis on current proposals for integrated network management, which are the main scope of this study. Over the last few decades, network management has become one of the most important research areas related to communication networks. Due to the fact that it is such a relevant research theme, important advances were made and several solutions were proposed in order to address numerous challenges. The following sections describe some of the most important proposals, discussing which challenges are addressed and which limitations still exist.

2.1 Open Systems Interconnection (OSI) - Network Management

The OSI-NM model contains the first reference to the subject of network management. Originally proposed for the management of OSI-based communication systems, the OSI-NM model never managed to gain wide acceptance because Internet-based communication systems prevail over OSI-based communication systems. Nevertheless, it became a reference for the following network management proposals, including the widely used INMF [5] and the TMN [22, 50] architectures, the later being an OSI-NM architecture for telecommunication networks. The OSI-NM model comprehends a suite of protocols, called the X.700 series, which were jointly developed by the ITU Study Group 7 as well as the ISO organization to manage end systems using OSI protocols. The model includes the specification for a management architecture described in the ITU Recommendation series X.700-X.703 [51], an information model that enables the managed objects' defini-

tion including their organization, a communication model which includes the protocols to be used for the object's remote management and a functional model that classifies all management functions which served as a reference for the following network management frameworks. The management functions as well as the corresponding information models that indirectly define message exchange are included in the X.730 [52], X.740 [53] and X.750 [54] document series (ISO 10164 Parts).

The OSI-NM model is based on the client-server architecture (also known as manager-agent). This role is assumed in the context of information exchange and may vary along time. Therefore, any OSI-NM system may perform both roles, even simultaneously, and both roles may change simultaneously. The management information may be exchanged not only between the Network Management System (NMS) and agents but between NMSs as well. In order to improve interoperability and obtain effective cooperation between NMS and agents *management knowledge* is exchanged taking into consideration the support for all relevant management functionalities (such as Management Objects (MOs) support, protocols, functions, etc).

The OSI-NM model is a very complete proposal which was considered as being ahead of its time [2], with a powerful object oriented modeling approach that was quite popular between software developers. However, its success was tied to the OSI's communication model. Due to the popularity of the Internet's communication model along its simplified management model based on SNMP, the OSI-based communication system declined including its management proposal. Even when using Internet's transport protocol, the OSI-NM was still referred as being too complex [10]. Nevertheless OSI-NM found its way in telecommunications networks as the basis for the TMN and served as a reference for the following network management frameworks. Due to its decline, there are no recent research works regarding OSI-NM evolution and applicability, although some important works can be found in [2,55–58]. In [59–63], a study on the cooperation between OSI-NM and SNMP to improve interoperability is presented. More recently, the application of OSI-NM concepts in the TMN architecture was addressed in [64–70].

2.1.1 Information Model

The OSI-NM information model [71–73] derives from object-oriented programming languages. Here MOs are used for representation of the managed resources containing properties that can be managed. The MO are instances from the Management Object Class (MOC) that defines properties which are common to all MOC instances. The MO properties are grouped into packages that can be defined as mandatory or conditional.

If defined as mandatory all properties defined in the corresponding package must be supported by all class instances. If, on the other hand they are defined as conditional, properties will be supported depending on the evaluation of certain conditions. The MO properties are modeled using the following dimensions: *attributes*, which characterize the properties and status of the MO; each attribute has specified its permissible values as well as operations; templates can be used to describe attributes and group templates might be used to combine attributes into groups that can be globally accessible; *actions*, that will affect an attribute or the MO as a whole; actions may be specific to an MO and are designed using a template; these are the means used to control MO by sending a message with the required parameters; *notifications*, for signaling asynchronous events initiated by an MO; the notification can be specific to an MO and are defined through a template; and *behavior*, used to record the semantics of attributes, actions, notifications and to represent relationships to other MO; it describes the MO's dynamic characteristics; in order to syntactically represent the resource information model, a Abstract Syntax Notation One (ASN.1) based notation referred to as Guidelines for the Definition of Managed Objects (GDMO) is used; the GDMO defines templates for the core MOC and templates for the other properties, namely attribute, action, notification and behavior.

Inheritance and Encapsulation were the two most important OSI-NM concepts, derived from the object-oriented programming languages. This means that an MOC may be defined as a subclass of one or more superclasses, inheriting all superclass properties (multiple inheritance) and refining or expanding the inherited properties. This enables a higher degree of the reuse of model specifications. Encapsulation is another important concept that provides the MO with the capability of guaranteeing its integrity. It hides its internal management operations and limits their access. One of the MO's most important attributes is its name definition. In the OSI-NM each MO is assigned a name that enables its unambiguous reference. Since each MO is incorporated into a containment hierarchy their identification's ambiguity is removed by uniquely naming the subordinate objects in relation to the containing object. The Relative Distinguished Name (RDN) refers to the unique name assignment relative to the containing node. This provides a globally unique naming method for MO identification. The concatenation of RDNs in the hierarchy creates the MO instance full identifier, enabling an unambiguous MO identification. The hierarchical structure of the MOs builds and important part of the system's information model referred to as MIB. The hierarchical name structure defined by the MO's unique name definition results in a tree referred to as the Management Information Tree (MIT), which is not static, growing with the MOs instantiation.

2.1.2 Communication Model

The OSI-NM communication model is implemented over the OSI's seven-layer reference model. At the Application layer, important elements are used, such as Common Management Information Services (CMIS), Remote Operation Service Element (ROSE), Association Control Service Element (ACSE), providing services that enable the MO's remote management. Among the elements listed above, only the CMIS were build for management tasks. The services and the management message structure used by the communication model can be found in the X.710, 711 e 712 standards [74–76].

The Systems Management Application Entity (SMAE), which is the communicating part of the OSI's management application is used to exchange information with other peer SMAE entities. The information exchange between management applications is based on specifically designed services called CMIS and are transported over the associated management protocol: Common Management Information Protocol (CMIP). CMIS provides a group of services (using service access points) that enable the execution of management operations over the entire remote MIT, which includes object instance access and manipulation. The ACSE is used by CMIS for the service's connection management and ROSE is used for the transmission of management operations. The services provided by CMIS may be classified into three groups [2], namely: *association management*, which includes the initialization, termination and abortion of CMIP connections provided by the ACSE services; *execution of operations*, that includes the service to perform the management operations over the MO (such as get, set, create, delete); and *event notifications*.

The CMIS provides an important group of features that includes scoping, filtering and synchronization [2]. The scoping feature enables the selection of a group of MO within the containment tree (as a subtree with a specified depth). Based on the scoping result set, certain objects may be selected through filtering. A filter provides the means to define one or more statements related to the existence of values of MO attributes. The synchronization feature may be used when accessing several MOs. It sets goals for service performance by enabling the manager to define a best effort (the request is performed in as many MOs as possible) or an atomic (the request is performed on all MOs or none) management service.

2.1.3 Functional Model

The OSI-NM model defines a group of management functions [2], including the object management function [77], state management function [78], alarm reporting function

[79], log control function [77] and workload monitoring function [80]. However, in order to clearly classify network management activities, five Systems Management Functional Areas (SMFA) were proposed. These areas are commonly known as Fault, Configuration, Accounting, Performance and Security (FCAPS) [51]. They serve as a reference for all younger management frameworks.

2.2 Internet-standard Network Management Framework (INMF)

The Internet-standard Network Management Framework (INMF) [5] is the most popular proposal for the management of Internet Protocol (IP) based networks. It provides a simplified view of the management concepts introduced by OSI-NM model, enabling a quicker adoption and easier understanding. Initially conceived as a short term solution, it quickly gained wider relevance with the popularity of Internet-based communication systems and became the standard for the management of the Internet. In order to promote simplicity, the INMF separated the managed variables (also known as objects) from the management protocol (used for transportation of the management information), so that each one could be developed independently. Instead of supporting a large amount of network management operations, the framework only supports a limited set of operations mainly oriented towards changing or retrieving the managed object values (they cannot be created or destroyed). The INMF framework is mainly composed by the following elements:

- An asynchronous management protocol, called Simple Network Management Protocol (SNMP), that was created to enable the exchange of information between the NMS and the managed device's agents. The protocol specification includes a small group of primitives for remote manipulation of object values, message exchange, message structure and encoding rules;
- In order to ensure higher levels of interoperability between managed devices and management applications, a consistent method is needed to describe the managed objects. The Structure of Management Information (SMI) is a standard language, based on ASN.1, created for this purpose. It enables the representation of the structure, syntax and characteristics of the management information to be used in the SNMP management framework;

- An MIB provides a standard structure to support the semantics of the managed element's objects. This structure supports the objects using a hierarchical representation containing the information used to manage the element's behavior. MIBs are defined in SMI and represent a very important management interface with interoperability concerns;

- Security considerations are also included in the framework. The User-based Security Model (USM) and the View-based Access Control Model (VACM) are the most relevant initiatives addressing security. This includes algorithms and mechanisms to ensure communication confidentiality, data integrity verification, entity authentication and access control;

- A management architecture that organizes the entities into manager and agent elements.

The framework has evolved over three versions and their main features are described next.

2.2.1 Architecture

It implements a client-server architecture where the server refers to the process performed at the managed resources (agent) and the client refers to the management application (manager). The management application gathers and processes data retrieved from the managed resource agent's that is only responsible for providing the required information through a standard interface. This means that all management effort is performed by the manager side, simplifying the agent operation (by the time this framework was proposed, managed resources had important performance constrains). On the other hand a significant amount of data has to be transferred to the manager, requiring several interactions and network traffic. This architecture focuses on simplifying the agents while pushing the management intelligence to the manager.

2.2.2 Information Model

In order to obtain higher levels of interoperability between the NMS and the managed element's agents, a common agreement is represented by the MOs, that in the INMF are organized in MIBs. The MIB is a conceptual repository that managed elements use to provide a standard view over their manageable resources abstracted by MOs. The NMS can use MOs to verify (and modify) the managed element state regardless any

implementation details. The MO represent a property of the managed element that must be treated as a data entity. Changes into the MO value induces changes to the managed element. The MOs are organized in a hierarchical tree structure, using a containment relation between the objects, which facilitates their naming and addressing. MOs are defined in MIB modules, where each managed property corresponds to a tree node and each node follows a hierarchical name identification, called Object Identifier (OID), relative to its containing node which may be registered as part of a global Internet object identifier tree. The SMI is the standard language for the MIB specification, that is, in order to describe INMF's management information model, SMI language was created as a subset of ASN.1. It provides a basic set of rules for specification of MOs, in a consistent manner that promotes the management interoperability, being available in two versions Structure of Management Information Version 1 (SMIv1) and SMIv2.

In an effort to create a unified modeling language, for several network management protocols, the IETF Network Management Research Group (NMRG) proposed the Structure of Management Information Next Generation (SMIng) [81]. It was created to address some of the SMIv2 limitations (such as expressiveness) and, more importantly, to be a independent model definition language, that could later be bound to multiple network management protocols. It was intended to take one step towards simplification and unification of network management protocols, aiming to avoid duplication efforts put forth when defining data models for several network management frameworks, while reducing the inconsistencies among them [82, 83]. So, one tool could be used to automatically generate the model implementation of several management interfaces through a single standard specification. However, an agreement on a common standard solution was never found. The mappings for SNMP were published in [84] and the work group came to an end. Their final conclusions were published in [81, 83, 84].

2.2.3 Communication Model

The initial version of the framework introduced the first version of the communication protocol, named Simple Network Management Protocol version 1 (SNMPv1) [4,5,85,86] and the first version of the model definition language SMIv1 [4, 6, 87]. The protocol was created to provide a simple way for the NMS to communicate with agents on the network elements. In this model, all the management complexity is pushed to the NMS that is expected to possess higher resource availability. This means that the agent's simplicity of operation was an important requirement. The SMIv1 language was used to define MIB modules and the managed element's corresponding MOs. Four protocol primitives were

included in SNMPv1, namely *Get-Request*, *Get-Next-Request*, *Set-Request* and *Trap*. However, the first version of the protocol has some functional limitations, namely the lack of support for the transfer of large amounts of data (since it does not provide the concept of bulk requests) and the lack of support for security mechanism, which prevented it from being actively used for configuration management. For this reason, SNMPv1 was mainly used for monitoring tasks. Also, SMIv1 presented a limited expressiveness for MOs definition.

A second version of the INMF was created and a new version of the Simple Network Management Protocol (Simple Network Management Protocol version 2 (SNMPv2)) [88, 89] and a second version of the model definition language, SMIv2 [90–92], were included aiming to resolve some the previous version's limitations. However, due to the lack of consensus between manufacturers and the standardization community about deployment of security mechanisms, they failed to gain wide acceptance. This caused the appearance of a protocol variation called Simple Network Management Protocol version 2 with Community String (SNMPv2c) [93], that included the same functional improvements of SNMPv2 except for the security capabilities, thus, using the same community string methodology from SNMPv1. The second version of INMF brought the capability of using new MO data types (using SMIv2), enabled message exchange between NMS (new primitive *Inform-Request*) and bulk data retrieval (using the primitive *Get-Bulk-Request*). With a new version of SNMP protocol the Protocol Data Unit (PDU) was redefined, enabling its use for all supported management operations.

A third version of the framework was created. It included a new version of the communication protocol (Simple Network Management Protocol version 3 (SNMPv3) [94–98]) that finally solved the security deficit that the previous versions presented. This version is commonly referred to as SNMPv2 with security mechanisms since it maintained the previous version management principles. It introduced the security model that ensured data integrity, entity authentication and communication confidentiality (using the USM model) as well as the access control mechanism (using the VACM model). The SNMPv3 now presents the security mechanism suited for performing configuration management even though infrequently used.

2.2.4 Terminology

The terminology used to refer about the framework that defines SNMP is ambiguous. In [4–6] it is referred to as Internet-standard Network Management Framework (INMF), more recently in [7] the framework is referred to as Internet-Standard Man-

agement Framework while its versions where shortly referred to as SNMPv1, SNMPv2 and SNMPv3. Reference to a SNMP Framework is made on [8, 9]. Due to the lack of consensus on a common reference for the framework, the author decided to use the term INMF when referring to the framework and SNMP when referring to the protocol. This way no confusion is made between both.

2.2.5 Additional Considerations

The INMF is a network management framework which is easily understood and implemented. This motivated its popularity and wide usage. As a result, most network equipment support an SNMP management interface either by implementing a proprietary or standard MIB. For this reason numerous research works have been published in a wide range of areas. The following paragraphs describe some recent works which focused on some of those areas.

The INMF framework is also gaining popularity for the management of wireless and sensor networks. In [99] the authors propose the implementation of SNMP and Session Initiation Protocol (SIP) protocols for the management of heterogeneous ZigBee and IPv6 over Low Power Wireless Personal Area Network (6LoWPAN) devices. To improve management performance Stream Control Transmission Protocol (SCTP) is used, since most common transport protocols do not consider the wireless links constraints. [100] and [101] include proposals to use SNMP in 6LoWPAN networks. [100] refers to the importance of using a management standard due to the large number of 6LoWPAN devices with limited computational, display and input capabilities. The authors propose a network management architecture of 6LoWPAN based on SNMP that takes advantage of using the existing network management tools, measuring the node's state and temperature. The authors conclude that a tradeoff between SNMP protocol parameters (such as timeouts, polling time and version) must exist in order to comply with the wireless link and 6LoWPAN device' limited capabilities. The authors also depict a scenario where a 6LoWPAN device temperature is retrieved using a traditional SNMP application. In [101] a 6LoWPAN-SNMP is proposed. This is a modified version of the SNMP to be used over the highly constrained 6LoWPAN devices. The 6LoWPAN-SNMP version uses header compression and extended protocol operations that reduce the number of SNMP messages, broadcasting a *Periodic-Get-Request* where each station automatically and periodically replies. A *Proxy Forwarder* entity is used as a 6LoWPAN gateway in order to enable interoperability. The authors conclude that, using 6LoWPAN-SNMP the total amount of network traffic is reduced approximately by half when being compared

to the traditional SNMP management scheme. The application of SNMP in wireless networks, namely in wireless sensors, has become very popular and more works can be found in [102, 103].

The INMF's security has also been actively researched. In [104], the authors study the impact of the security mechanisms on the SNMP protocol. The authors refer that one of the reasons that prevented the wide adoption of SNMPv3's USM was because the need to create another user and key management infrastructure not integrated into the existing ones. So, the authors study the impact of using different security solutions already integrated into existing key management infrastructures, such as Remote Authentication Dial In User Service (RADIUS). A detailed performance analysis was conducted including SNMPv3 over Secure Shell (SSH), Transport Layer Security (TLS), Datagram Transport Layer Security (DTLS) and USM. The secure transport protocols chosen follow previous work already published by the IETF's Integrated Security Model for SNMP (ISMS) where they were standardized in order to be used with SNMPv3 however, it lacked a detailed analysis over their performance. The authors conclude that SNMPv3, over SSH, enables a satisfactory integration with existing key management infrastructures. It is considered a good choice for networks with low packet loss rate and for applications able to maintain long SNMP sessions. SNMPv3 over TLS like the SSH, requires an underlying network which is reasonably reliable, provides a handshake process which is more efficient than SSH and requires a working X.509 public key infrastructure. The SNMPv3 over DTLS is very similar to the TLS however, as it provides the application with the retransmission capabilities, its usage is adequate for networks that experience high packet loss rates. The SNMPv3 using USM does not integrate well into the existing key management infrastructures and suffers from message overhead introduced by the security protocol. However, it is a good choice when retrieving/manipulating small volumes of SNMP data, when the group of users requiring SNMP access is limited and when the retransmission algorithms used are from the application. Following a similar perspective, [105] also evaluates the implementation of a secure alternative for the widely deployed SNMPv2 using Internet Protocol Security (IPsec). The authors compared the traditional implementation of SNMPv2c with and without IPsec (in *Transport Mode*) and obtained a 8.5% delay increase in request/response packets as well as an additional 1.2% to 1.4% extra overhead. The authors then concluded that using SNMPv2 with IPsec does not represent a significant performance decrease while ensuring confidentiality, data integrity, authentication and non-repudiation services. On the other hand, this solution requires the managed element support for the IPsec protocol.

From a slightly different perspective, [106] proposes an SNMPv3 architecture extension that implements a new type of access control, called Usage Control, to solve some of the VACM limitations, ensuring authentication and authorization through the establishment of sessions. The Usage Control Model includes a group of six components (*subjects*, *objects*, *rights*, *authorization*, *conditions* and *obligations*) used to assist the authorization process. To enforce the proposed model in an SNMP environment, the authors adapted the ISO's standard Reference Monitor composed by an Access Enforcement Facility where the SNMP objects are contained and an Access Decision Facility where access decisions are made using the Usage Control Model's core elements: *authorization*, *conditions* and *obligations*. The interaction between the proposed elements enables an increasingly flexible and detailed access control, using a periodic verification for session establishment.

SNMP has also been actively researched for network topology discovery methods such as the works presented in [107–109]. In all works, SNMP's wide availability and low overhead, combined with well known management objects (that includes the system description, interfaces address and routing table), are used to discover the network's topology. In [107] requiring only the support of Coaxial Line Terminals to derive the remaining elements topology (routers, switches, etc). In [108] the authors propose a method for topology visualization based on the SNMP protocol which involves two important techniques: automatic topology discovery and automatic topology drawing. In order to build the topology, the algorithm requires the network router support for SNMP to retrieve topological information (from MIB-II groups: *system*, *interfaces* and *ip*). Then, *Flash* technology was used to depict the network topology in a web page. In line with previous works, the work presented in [109] also uses SNMP to discover not only the existence of network elements but their connectivity as well. The algorithm implemented starts by discovering devices using a routing table, Address Resolution Protocol (ARP) cache or Internet Control Message Protocol (ICMP) requests. For each discovered device, the algorithm determines the SNMP support which will define the type of network device (router, switch, printer, or network terminal node). Specific information is retrieved from the MIB for each type of device. The algorithm uses this information to test the connectivity between network elements.

Some interesting works use SNMP in integrated management frameworks mainly through the use of a proxy, for two reasons: enable the integration of widely used SNMP-based managed elements in more advanced network management frameworks, commonly using Extensible Markup Language (XML) representations [110,111]; use the popular SNMP-based network management application for the integration of hetero-

geneous management interfaces, some of those proprietary [112]. In [110] the authors propose a template-based translation for an XML-SNMP management gateway defining, for each host, the data type support and management operations required to obtain and display the management information. This ultimately improves the management gateway performance. The authors propose the following templates: the *host template* which is used to characterize the managed host; the *graph template* which is used to display the managed data retrieved from the; *data query template* which is used to obtain managed data from the related OID values. The authors concluded that when compared to the traditional implementation of XML-SNMP management gateways, this has a significant improvement of performance, namely reducing usage of memory and Central Processing Unit (CPU), and network traffic. The work published in [111] proposes the creation of an XML-based network management system that has a universal gateway to support the management of SNMP and non-SNMP network elements. While the authors refer that XML-SNMP gateways are well defined in literature, they propose a five module architecture for XML-SNMP message conversion. In order to support the management of generic network elements, the authors propose a model based on the implementation of generic adapters and tables. The adapter is used for the communication of each particular managed element interface, converting from XML to the managed element's interface. The table stores each managed element details such as name, IP address, adapters used, managed objects, mapping between XML and managed element's specific attributes. With the referred architecture, the author aims to create a universal translation model. In [112] a SNMP proxy agent operates as a mediation device between a SNMPv3 management application and the device's proprietary management interface. It uses a combination of MIB trees and *contextNames* to map requests to the managed element proprietary management interface.

2.3 Common Object Request Broker Architecture (CORBA) - Network Management

CORBA is the core specification of the Open Management Architecture (OMA) which was designed to build distributed applications based on distributed objects in heterogeneous environments. This architecture promotes the transparent cooperation among objects regardless of their location and implementation details. CORBA enables the integrated development, use and management of distributed systems using the same architecture and development environment. This has a direct impact on the development

time and cost. The OMA architecture defines a group of models [22]: a *Communication Model* used to interconnect the distributed objects even in a heterogeneous environment; an *Information Model* used to define the object's interfaces using a Interface Definition Language (IDL); an *Organization Model* that defines the manner in which the distributed objects cooperate to build an interoperable system; a *Functional Model* which is a group of layered services available to all distributed applications (including management applications). One of CORBA's most important features is transparency: using the IDL specification the client application is unaware of the server objects physical or logical locations. Is also unaware of the object's implementation language and operation mode as well as the physical technology providing remote connectivity service and other physical details.

The objects defined in OMA are very general models for *things* and *concepts* [22]. Unlike the object definition used in OSI and in the INMF, in CORBA, only the object's fundamental properties are defined, such as the method to be remotely invoked, defining the object's interface. CORBA implements the Object Oriented Design (OOD) method for software design [113] where the modeling separates the object definition from its interaction with other objects. An independent IDL creates a uniform manner of representing the object's interfaces. CORBA then takes care of the low-level distribution details by creating a global distributing programming environment. Even though the CORBA specification was not specifically oriented towards network or system management tasks, any distributed application such as systems management can be deployed.

2.3.1 Architecture

CORBA also implements a client-server architecture. It's an open architecture composed by the submodules depicted in Figure 2.1[1] for the distributed object's remote methods invocation. The Object Request Broker (ORB) is the architecture's main component and enables a transparent interaction between client and server objects. When a request is submitted, the ORB is responsible for finding/locating the corresponding object, invoke the requested method, retrieve the results and send them to the client application (if any). The following submodules are included in the CORBA's specification:

- *Client IDL Stub* which represents a static invocation interface to the object's methods. One client stub must exist for each remote object management, so several stubs may exist simultaneously on the client's application. The client stubs are

[1] Figure inspired from [22]

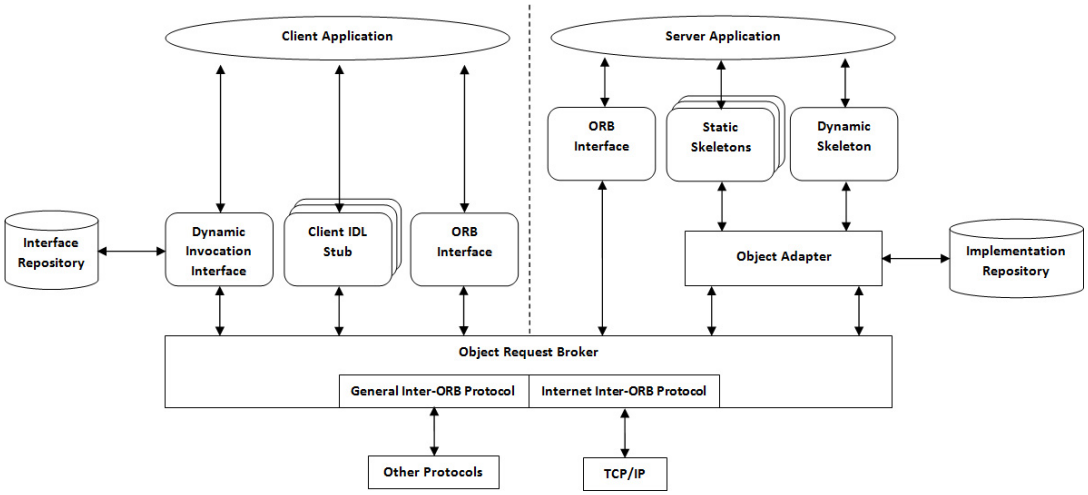

Figure 2.1: CORBA's submodules interaction

generated by IDL compilers based on the object's interface IDL notation. This creates an independent method invocation syntax suited for interoperability;

- *Dynamic Invocation Interface* is used when the remote object's methods and parameters are only determined in runtime. The object methods are extracted from the *Interface Repository*, isolating potential changes in the object's interfaces and increasing the system's flexibility. This means that client applications are not required to change with the object's interface. Such flexibility complicates client applications implementation, relying on a repository that must be used before each invocation;

- *ORB Interface* is a standard interface for both client and server objects. It enables the access to the core ORB operations which are mainly used for initialization functions. It provides the portable means for client application to access CORBA objects implementing services;

- *Static Skeleton* is the server's equivalent of the Client IDL Stub. Generated by an IDL compiler, the Static Skeleton provides a static interface to the server's implemented objects;

- *Dynamic Skeleton* provides the server with the capability of accepting methods' invocations even in the absence of an object's static description. This improves the server's flexibility by supporting new types of object classes and methods without having to be compiled. The relationship between the method invoked and the

object is dynamically created during runtime;

- *Object Adapter* mediates the client method's invocation to the skeletons connected to the server objects, mapping from a language independent representation to an implementation-specific representation. This passes the execution control on to the server application. The adapter also keeps track of the server object's life cycle. The Object Adapter also handles the object's references (since they are created in the server). It also deals with the method requests invoking the appropriate method at the Static Skeleton or Dynamic Skeleton. An *Implementation Repository* is used to store information regarding the server's objects classes, instances available and their reference;

- *Object Request Broker (ORB)* is one of the most important parts of the CORBA specification. It intermediates client and server requests, transparently selecting the server that is most suited to fill client requirements even through heterogeneous ORBs. The client application is unaware of the server's implementation such as the number of servers available, their versions, etc. So, the ORB is a distributed system which implements a procedure that communicates location transparent requests for methods between objects of the same or different systems.

OMA's organizational model implemented in CORBA enables a symmetrical approach implemented by objects where they can simultaneously assume the role of either client or server and where their cooperation is a requirement. This way, they enable a manager-agent, manager-manager and agent-agent relation. This is the most obvious advantage of enabling the cooperation between management systems besides the capability of building distributed management systems.

2.3.2 Information Model

CORBA is based on the interaction among distributed objects following a client-server architecture. The distributed objects do not follow the traditional object-oriented programming model. They are general concepts with a group of operations (methods) defined and are accessible over interfaces. The object's interface includes operation signatures identifying the operation, the return type and the list of required parameters. It is important to note that the interfaces support inheritance so, one interface may inherit operations from one (or more) interfaces. An IDL is used to define the object's interface. Grammatically similar to *C++*, this language only describes the object's interfaces, not

containing any type of procedural element. Since it is an independent notation, a compiler must be used to generate each implementation specific object interface (Client IDL Stub and Static Skeleton).

2.3.3 Communication Model

In the CORBA specification, the ORB is responsible for ensuring that the server object operations can be transparently invoked by client applications, creating a communication bus for the request transportation. The invocations to the object's operations are submitted to the ORB, routed to the corresponding server, executed and results sent back to the client application. In order for communication to occur the previous architectural elements are required for both client and server. Aiming to enhance the interoperability between heterogeneous ORBs, a protocol specification called Inter-ORB was created. The General Inter-ORB Protocol (GIOP) specifies the syntax and the semantics for the Inter-ORB message exchange, using any connection-oriented transport protocol. It defines the set of PDUs for message exchange, the transfer syntax for the method invocation, the byte ordering representation of IDL data types among others. The Internet Inter-ORB Protocol (IIOP) represents the GIOP implementation over the Internet's TCP/IP protocol stack (enabling the interconnection of ORB protocols over the Internet), describing how GIOP PDUs are framed into TCP PDUs. In order to universally identify the distributed objects, the CORBA specification uses a standard object reference called Interoperable Object Reference (IOR). This stores information to locate and communicate with an object.

2.3.4 Functional Model

The OMA's functional model defines a group of interfaces for high-level objects to be used by client applications. The functional model is organized into a layered structure where the higher layer objects inherit the functionalities provided by the lower layer objects [22]. The services provided can be classified into the following categories:

- *CORBA Services*, a set of basic functionalities for a transparent interaction in a distributed environment. These are a collection of system services that extend the ORB functionalities provided in the form of an IDL interface that all applications must implement. CORBA Services include object's instantiation, naming, event definition, sending and receiving messages;

- *CORBA Facilities*, a group of non-mandatory standard services that can be horizontally used in a wide range of applications;
- *Domain Interfaces*, these are the highest-level services to be applied in special domains such as health and finances. Such services are also optional.

The CORBA Services provide the basic functionalities that enable the distributed objects' operations in CORBA's environment. The CORBA Facilities extend the CORBA Service's properties and functionalities. This increases the range of applications where this framework can be used. CORBA's Domain Interfaces provide services for special areas based on CORBA Services and Facilities.

2.3.5 Additional Considerations

Even though CORBA's original vision would prevail as a distributed network management technology (supported by telecommunication vendors) it never gained significant scale on the network management domain, lacking fundamental management principles such as bulk data retrieval and resource consumption (creating management interface for thousands of managed objects that a network element might possess) besides the competition of emerging technologies such as Web Services [10]. Another limitation associated to CORBA is the lack of a self-contained and well defined management element that is capable of competing with OSI and INMF MIBs [22]. Nevertheless, CORBA network management gained popularity in the telecommunication industry where its complexity does not represent a significant drawback. The OMG Telecom Task Force addressed the definition of an Object Framework specification for the telecommunication domain. One of the most important initiatives is TINA-C [114], where telecommunication services used CORBA for the development and interoperation of management software. It aims towards an independence between the supporting network and the service they provide, enabling their parallel evolution [115]. As referred in [115], software for network and service management have common characteristics, so a common development platform would ease their development and maintenance. [115] also enhances CORBA's flexibility in the distribution and implementation of MOs when compared to more strict architectures such as INMF (service management may involve the cooperation among several managers and managed systems). Research works using CORBA for network management can be found in [116] where the authors propose a new Notification Service based on the *push model* associated with a filter mechanism which sends the events only to intended clients (this enables a more efficient event transmission within CORBA's Notifi-

cation Service). In [117], the authors linked intelligent agents and CORBA for telecommunication network management. Besides, each CORBA object is associated with a cache policy enabling intelligent agents to locally store the objects' value which in turn decreases the network management overhead. This is achieved because the intelligent agents relay requests between objects and the management application and cache some of those requests. The authors of [118] propose a Naming Service for CORBA's network management. Traditional CORBA Naming Service requires the objects' instantiation in order to obtain their identification which incurs into resource availability constraints. The authors propose a smarter naming service that does not require all object instantiation, using a garbage collector and a time stamp for each object creation. They conclude as to the improvement of resource availability. However, they obtained a longer response time when compared to the traditional CORBA Naming Service. Since CORBA is in direct competition with the widely used SNMP for management solutions, some research works propose their integration by either enabling SNMP-based management application support for CORBA elements or CORBA-based management applications support for SNMP elements. Some of those works can be found in [119–121], mainly using the Joint Inter-Domain Management (JIDM) specification translation algorithm [122] in order to enable the interoperability among the different domains (performing static translations).

2.4 Web-Based Enterprise Management (WBEM)

Founded in 1992, the DMTF initiative is a consortium for the development of management standards for enterprises and the Internet. The most relevant result of DMTF is a vendor-neutral management framework based on web technology called WBEM. During 1996, the initial specifications for the main components of WBEM were proposed as standards within the DMTF and IETF. So, WBEM is a set of management and Internet standard technologies that aim towards the unification of management systems by promoting the exchange of data between heterogeneous technologies and platforms. WBEM's management information model is defined by CIM [123], management messages are encoded in XML (XML-CIM) and transported over Hypertext Transfer Protocol (HTTP). Other technologies were defined such as CIM's Query Language [124] (providing the capability to select properties from sets of CIM instances), WBEM Discovery using the Service Location Protocol (SLP) [125] (provides the clients with the flexibility of accessing information regarding the existence, location and configuration WBEM servers services) and WBEM Uniform Resource Identifier (URI) [126] (which is a unique string of characters that identifies a CIM element). The CIM model is able

to express the structure and the semantics required for handling the management environment. The model follows an object-oriented structure supported by classes, objects, properties, methods, inheritance and associations for the representation of the managed elements oriented for enterprise desktop applications. WBEM aims to integrate different management approaches under one umbrella. This enables the technological separation of the management application and the heterogeneous management technologies of the underlying managed elements.

2.4.1 Architecture

WBEM implements a client-server architecture like most web applications. The architectural components included in WBEM are the following:

- The *WBEM Client* that is found in the management application and is responsible for issuing CIM Operation Messages Requests, encoded in XML, and receive the replies as CIM Operation Message Responses. The WBEM Client also receives asynchronous notifications from WBEM Servers;

- The *WBEM Server* is present in the managed elements and is in charge of receiving and processing CIM Operation Message Requests and issuing CIM Operation Message Responses. It also issues asynchronous notifications for WBEM Clients. One of the most important modules included in the WBEM Server is the Common Information Model Object Manager (CIMOM). It uses the information model stored within a repository (*CIM Repository*) to route requests between the management application and the *Providers* [127]. The Providers (also referred as Instrumentation Agents) interact directly with the actual hardware and software being managed, retrieving information from the managed resources and forwarding it to the CIMOM;

- The communication between the WBEM Client and Server is carried out using the HTTP protocol in turn, providing a reliable transport for CIM-based messages;

- The *network (or managed) element* is a manageable entity (such as a process, application, system, etc) including its instrumentation used by the Provider to execute its control.

2.4.2 Common Information Model (CIM)

The CIM is the most important component of the WBEM's specification and it defines an independent representation of management information, being mainly composed by two parts [24]: a *Specification* and a *Schema*. The Specification [123] describes an object-oriented meta-model, referred to as *Meta-Schema*, based on UML that includes expressions for common elements used for the representation of other models (such as classes, properties, methods, indications and associations). This enables the definition of syntax and rules of models. CIM's Specification also comprehends language and methodologies to describe the management data. This includes a syntax for the description of CIM's objects in the textual form (MOF) and their relations (using UML). The details for integration with other management models are also included in the Specification. CIM's Schemas [128] contain the common conceptual models in order to describe a managed environment thus, unifying the management data representation. It can be structured in the following layers:

- The *Core Schema* includes the management concepts applicable to all management domains. It contains a set of classes, associations, properties and methods that represent the basic vocabulary to describe the management system (such as *Product*, *ManagedSystemElement*, *SettingData*, *Location*, *StatisticalInformation*, *Configuration*, *Capabilities*, etc);

- The *Common Schema* expands the Core Schema with technologically independent, standard information models used in specific management areas. Some examples of common models include: *Applications*, *Database*, *Device*, *Event*, *Network*, *Systems*, *User*, *Physical*, *Policy*, etc. They are detailed enough for implementation or extended to support implementation-specific functionalities.;

- The *Extension Schema* represent technologically dependent extensions of the common models that the administrator can execute.

Final sections of CIM Specification [123] describe the numerous mapping alternatives available which enable the integration/interoperability of CIM-based management solutions with legacy management systems. This theme is also explored in [129]. The following forms of mappings are described in the specification:

- *Recast mapping*, where the meta-constructs of the source model are mapped into the meta-constructs of the destination model, so that a model represented in the

source can be represented in the destination. This mapping enables a syntactic interoperability [129];

- *Technique mapping*, where the meta-constructs of the destination model are used to describe the source model's constructs;

- *Domain mapping*, where the model instances from the source are mapped to the destination model thereby enabling a semantic interoperability [129]. As referred by the CIM specification, the domain mapping is a re-expression of content using a different model, also referred to as content-to-content mapping.

In order to reach full integration of management systems, a merely syntactic translation is not sufficient when source and destination domains represent the same concept in a different manner. This way a semantic conversion must be pursued, in [129] the authors use ontologies to provide additional semantics to the management information. However, performing the semantic mapping is not easy because it cannot be done fully automated [130].

2.4.3 Communication Model

The DMTF defined a CIM-XML protocol for message exchange between WBEM Clients and Servers. It uses the CIM's Specification and Schema for the representation of managed elements and a CIM-XML standard method to encode CIM data and operations in XML. The HTTP protocol ensures the CIM-XML encoded request and reply transportation in a reliable communication process between WBEM's Clients and Servers. The CIM Operation Message, defined in the CIM-XML protocol, has enhanced importance since it enables the invocation of operations on a target namespace. This definition includes messages that can be further divided into:

- *Intrinsic*, which is a group of methods defined by the CIM Operations over HTTP [127, 131] oriented towards the manipulation of the model itself. It includes methods for reading classes and instances, setting of classes properties, instances and classes manipulation (create, modify, delete), association and qualifier definition among others;

- *Extrinsic*, which is a method for remote invocation of functions defined on a instance of a class. When a CIM Server does not support the required method, a error message is sent back to the CIM Client.

2.4.4 Additional Considerations

Some recent projects use WBEM and CIM to create independent management solutions. In [132], the authors design and implement an embedded management solution, based on WBEM in order to assess its performance on a resource constrained managed device. The authors used an embedded Linux that runs on top of an Field-Programmable Gate Array (FPGA). IPsec was enabled to create a secure gateway whose policies are managed by WBEM. To evaluate resource consumption the authors compared three WBEM open source implementations, namely OpenWBEM [133], OpenPegasus [134] and SFCB [135]. It was concluded that since SFCB has been specially designed for resource constrained environments, it presents better performance for both static and run-time memory consumption. In order to enable the management application's independence regarding the managed element's implementation details, the authors used a CIM Schema composed by 59 classes located in six Provider libraries. Those Providers enable the management of networking, IPsec, keys, operating system and error messages. The authors concluded about the capability of WBEM to incur on a small footprint on embedded applications. In [136] a CIM extension model was developed in order to characterize and manage virtual network environments, regardless of the underlying virtualization platform. In [137], the authors propose a WBEM gateway for SNMP and CMIP integration, translating their details to WBEM CIM data types, services provided and protocols. In the proposed example, the authors used a CMIP-based management application and a group of SNMP-based agents. The gateway included a *system* object instance for each managed agent and was able to successfully route messages between heterogeneous elements. In all of the referred works syntactic translation is performed, converting from CIM's independent representations to other types of representations, based on Providers than must be customized. Some research works [129, 130] already address the addiction of semantic translation to CIM conversions, avoiding inconsistencies and collisions in syntactic conversions.

2.5 Network Configuration Protocol (NETCONF)

The NETCONF [27] protocol is the IETF's most recent initiative for network devices configuration management. Historically, the SNMP protocol has been used mainly for monitoring tasks, and there is a group of works referring about the SNMP's configuration management limitations [11, 138, 139]. Thus, a configuration management gap was created, commonly filled with proprietary solutions (with an important impact on

the management applications interoperability). To prevent the use of proprietary solutions, the NETCONF protocol was created. It implements a client-server management approach and uses XML for data encoding for both configuration data and protocol message exchange. NETCONF includes the mechanisms required to install, manipulate and delete configurations in network devices defined in *datastores*. Those datastores are defined by the managed device data model over which configuration management operations are realized.

2.5.1 Architecture

The NETCONF protocol is based on the client-server paradigm, like SNMP, with the client being a management application (manager) and the server being the agent placed on the managed element. Its organized on a layered architecture [27] which provides the protocol with the modularity that enables its evolution.

2.5.2 Information Model

The NETCONF protocol defines the notion of a datastore as the element over which the configuration management operations are performed to change the managed element state. The managed element's configurations are encoded in XML to promote the configurations independence and improve the management applications interoperability. The notion of datastore is similar to the INMF's MIB in the sense that both represent standard network management interface. However, they use different data representations languages and use different data model definition languages which provides them with different modeling capabilities. One managed element may possess several datastores simultaneously but the *running datastore* must always be present as it holds the configurations currently active in a managed element. With the datastore configurations defined in XML documents, the NETCONF protocol proposes the use of a subtree filtering mechanism to be used by NETCONF applications to efficiently navigate the document.

The datastore content is of the managed element proprietary nature, falling outside the NETCONF's scope. It specification refers that the datastore configurations are defined by each managed element information model, requiring a representation to verify the integrity of the datastore configuration and the validity of the messages exchanged. This enables each implementer/manufacturer to define proprietary management information models and validation mechanisms that might result in interoperability problems when integrating their management. To solve this problem the IETF proposed a stan-

dard data model definition language for NETCONF that enables the description of NETCONF's datastore structure, oriented for enhancing the protocol's functionalities. This language is called YANG [28]. Before YANG's standardization other languages were used, like XML Schema and RelaxNG. However, given the expressiveness of XML-based languages, with potential to rise interoperability problems [28], a language with a narrow scope was required, giving birth to YANG.

2.5.3 Communication Model

Based on a client-server architecture, the NETCONF communication model relies on a layered structure to fulfill the configuration management tasks [27]. The configuration management data is encapsulated at NETCONF's Operation layer where it has defined a group of configuration management operations available, namely *get-config*, *edit-config*, *copy-config*, *delete-config*, among others, to be applied over one datastore. The configuration management operations to be performed at the other communicating end are invoked using Remote Procedure Call (RPC). This provides a technologically independent communicating mechanism that, according to NETCONF's standard [27], can use the following configurations transport protocols (not limited to): SSH [140]; Simple Object Access Protocol (SOAP) [141]; TLS [142] and; Blocks Extensible Exchange Protocol (BEEP) [143]. The transport protocol establishes a communication channel between the client and the server. With NETCONF, any transport protocol can be used as long as it provides a well defined set of requirements: provide a connection-oriented transport operation ensuring reliability to the message exchange; data integrity must also be provided for error detection and correction for highly sensible configuration management operations; message confidentiality must be provided using an encryption algorithm; the transport protocol must ensure the communicating peers authentication since NETCONF does not provide other authentication verification mechanisms.

2.5.4 Additional Consideration

NETCONF is a recent protocol and, for this reason, some research studies describe its functionalities, while motivating its usage. The work published in [144] provides a general perspective of the NETCONF, providing some background and motivation, which can be summarized by the lack of a device-independent method that is able to efficiently manage the devices configurations. The authors also provide a very complete description of the NETCONF protocol, including its data model definition language. Furthermore, they present a YANG module to manage a DNS resolver, including a

configuration management message. A lot of other important documents describing NETCONF and YANG usage can be found in [145].

An empirical study of NETCONF is presented in [146] where the limitations of the traditional configuration management alternatives are explored (namely Command Line Interface (CLI), SNMP and CORBA), leading to the creation of a new protocol. The authors refer that CLI network management is limited due to the fact that it isn't standard so each vendor follows each own model. Regarding SNMP, the authors present a long list of limitations that include the lack of a complete configuration view, poor performance for bulk transfer and the lack of command aggregation capability, among others. CORBA lacks standard management objects. All these limitations lead to the creation of the NETCONF protocol. The authors compared the performance of NETCONF and SNMP for the management of a Voice over IP (VoIP) SIP server and concluded that NETCONF provides better performance in terms of number of transactions when retrieving a large number of objects because it uses a single transaction. On the other hand they concluded that, when retrieving a single object, NETCONF requires more bandwidth due to the XML verbosity, security and TCP session establishment. [147] demonstrates a practical integration of a YANG parser and semantic checker, called jYANG, for NETCONF protocol. A NETCONF client and server were developed extending a NETCONF-based Application Programming Interface (API). A YANG-based applet was created in accordance with the managed element data model defined in YANG, providing the administrator with a graphical interface for managing configurations, as well as their validation. The work published in [148] complement a NETCONF-based management solution with a framework that uses a domain specific language to represent network services configuration. The proposed management model divides the configuration management process into layers with a specific abstraction. First the concepts needed to specify configuration are defined and coded using the domain specific language, then configurations are codded and submitted to the proposed management system that uses NETCONF for their automatic deployment.

Since NETCONF is still not a widely used configuration management protocol, some works propose its integration on devices supporting the most popular network management protocol, SNMP. In [149] the authors focus on providing the NMS with the support for both SNMP and NETCONF devices. They use a NMS Drive that is responsible for the interface between the NMS Components and the manager parts responsible for issuing SNMP and NETCONF commands. The algorithm implemented by the NMS Drive starts by sending a NETCONF *hello* message to the managed device, if it receives a *hello-reply* then the NMS uses the NETCONF NMS part, otherwise it uses the SNMP

NMS part. Each NMS part was implemented based on a abstract interface composed by a group of methods. With the proposed strategy, traditional network management systems could support next generation network devices using an adequate configuration management protocol. Similar to this, the work on [150] enables the integrated management of CLI and SNMP network devices for NETCONF-based management system, using management gateways. Giving more emphasis to SNMP, the authors describe a gateway for the management translation that relies on a conversion algorithm that enable the syntactic translation from MIB to XML Schema Definition (XSD). The conversion mechanism uses the SMI MIB module, performs a lexical and syntax analysis to verify the module's textual description (removing unnecessary information like comments), perform data type translation (SMI to XSD) and performs the objects structure translation, which is then organized in four levels. Its also proposes a message mapping between NETCONF and SNMP.

Some studies were performed [151–155] to evaluate the capabilities of different languages for the data model definition to be used within NETCONF. The work published in [151] uses an extended version of the evaluation framework proposed in [153] to evaluate SMI, YANG and natural language (used in TR-069 [156]). The authors concluded that YANG represents the most balanced result, with relevant advantage in terms of security, data representation, interoperability, machine readability and conformance (namely versioning, error and event messages) when compared to SMI and natural language. Nevertheless, YANG is not protocol independent. Only natural language has fulfilled this criteria. In [152], the authors compared YANG to a XML-based data modeling language (XSD, Relax NG) for NETCONF protocol. The study was divided in two parts, theory and practice, and has considered important dimensions like: Expressiveness, Readability, Interoperability and Construction. The overall conclusions include: at the construction level, YANG has advantages because its not based on XML, which has limitations at the level of readability and terseness; regarding expressiveness, YANG includes the NETCONF's base elements (like *rpc*, *config*, *notification*), in opposition to XSD and Relax NG, hose element must be adapted; YANG was built with special concerns regarding readability, using a structure similar to programming languages like *C*, while defining *typedef* and *grouping* elements that may appear under many YANG statements, near of where its used (unlike XSD and Relax NG), improving its readability; interoperability of data types is ensured for YANG and XSD with the built-in and derived types. Giving the results of previous analysis, the authors concluded that YANG represent the best choice to be used in NETCONF. In [153] and [154], several data model definition languages were evaluated having NETCONF protocol in mind.

In [153] the authors establish a common framework for the evaluation of data modeling languages and concluded that the most popular modeling languages (GDMO, SMI, SMIng, MOF) have important limitations like the lack of protocol and naming independence, human readability, diversity of data types, specification of configuration and state data, extensibility, lock mechanisms and others. The authors also refer that these limitations should lead to the adoption of a more flexible language, like XSD, which has important advantages at the level of interoperability, data representation and extensibility. However, they also refer that XSD is too complicated and general for data model definition in network management. In [154] the authors compare XSD and YANG for NETCONF data modeling using the same criteria found in [153]. Again, they concluded about the XSD gains in terms of interoperability, data representation and extensibility. On the other hand it lacks semantic expressiveness, it is too complicated and excessively general as a data modeling language for network management. The authors also concluded that YANG is the best choice for NETCONF data modeling since it maps for its functionalities in a very straight-forward manner, while including the semantics required for the representation of NETCONF element's like notifications, error messages and lock mechanisms. However, YANG lacks protocol independence, being very tied to NETCONF. In [155] the authors referred that, in the long term, its better to use a domain specific language for NETCONF with enhanced stability, provided by IETF's control. Besides, such language can be optimized for NETCONF's features.

2.6 Future Internet Management

The Internet was so successful that it became a milestone of our society. However, along with its enormous success and wide deployment, it came to evidence its architectural limitations. Over the last few years, an important effort was made to clearly identify the Internet's main limitations so that future proposals would be able to overcome them while supporting the continuous growth in terms of users, devices, applications, heterogeneity, available services, mobility, manageability, etc. Some of the works published, regarding the identification of Internet limitations, can be found in [29,32,157–160] and it also provides important guidelines regarding the creation of next generation networks, mainly following two approaches: evolutionary or clean-slate. From a management perspective, several groups of requirements were defined. The most important goals were enumerated in order to create an effective system that would be able to support the management of future Internet. Depending on the type of approach followed, the requirements have some variations. Some of the following are commonly agreed upon [32, 160–164] and include:

automation of management procedures, based on high-level business goals represented as policies enforced through the implementation of autonomic principles; adaptability to the changing network conditions; scalability to accommodate an increasing number of user and connected devices (including sensor networks); management simplicity to minimize the operational cost and energy footprint; enhanced security; Quality of Service (QoS) insurance; management organization in planes to decompose complexity; support for generalized mobility; interoperability between management domains to promote cooperation and competition.

The most relevant concept on network management, in the context of contemporary and future Internet management, is autonomy [41, 165–167]. Autonomic network management aims to create new management solutions that cope with the increasing complexity and heterogeneity of today's and tomorrow's networks. The autonomic concepts provide the management system with the flexibility and adaptability to deal with unforseen situations, enabling self-governing (self-optimization, self-organization, self-configuration, self-adaptation, self-healing, self-protection) which provides higher levels of intelligence that enable its evolution along time to improve management efficiency. The interaction with the administrator must be limited to the definition of high-level management goals that the management system must follow after being translated into management policies. Several research projects implement autonomic network management using different architectures. Some of those projects are described in the following paragraphs.

Foundation, Observation,Comparison, Action and Learning Environment (FOCALE) [40, 168] is a research project for the integrated management of heterogeneous network elements supporting evolutionary and clean-slate designs. In this sense, it maintains support for the existing network management elements while proposing a new set of ideas for the management of the future Internet. FOCALE proposes the implementation of a hierarchical and distributed design based on the Autonomic Element (AE) which is responsible for the automation of the management process at the device or network level. The AE is composed by the Autonomic Manager which is responsible for retrieving monitoring information, verifying if the managed element's state is in accordance with the policies defined and generate technologically independent management data that drive the managed resource to the desired state. The AE is also composed by the managed resource and the Model-Based Translation Layer (MBTL) which is responsible for translating from the Autonomic Manager independent configurations and commands to the resource specific configurations and commands. The AE can then be hierarchically organized into the Autonomic Management Domain or the Autonomic

Management Environment according to a common set of rules. FOCALE's AE has defined two autonomic control loops to perform self-functions: a maintenance (for periodic state verification) and an adjustment (to apply state changes) control loop. To unify the management of heterogeneous data models, FOCALE proposes the use of a combination of independent information and data models (described by the Directory Enabled Networks-next generation (DEN-ng)), different levels of ontologies and finite state machines to add semantics to the facts represented in the managed element's data models, enabling the existence of semantic similarities among them [41]. The finite state machines are used to represent the managed element's behavior while policies are used to determine the state transitions. Machine reasoning algorithms are used to generate a hypothesis when errors occur, thereby enabling the management model automatic evolution. This project is still being developed [169] and the functionalities of the Autonomic Management Domain, Autonomic Management Environment, MBTL, the learning and reasoning elements are still missing or incomplete. Some works have been published using FOCALE.

The DEN-ng is the information/data model used by FOCALE to create a business oriented PBNM system. It evolved from Directory Enabled Networks (DEN) with three important enhancements [170]: representation of the policies as a continuum of related sub-policies; translation of the rules defined into configurations of the managed service and devices; use of policies to control the modifications of a managed entity according to a Finite State Machine model. Instead of defining a policy as a single entity, DEN-ng proposes that a policy has multiple constituencies with different views that may be organized as a continuum [170]. The proposed Policy Continuum creates five different views of the same policy representing different abstractions such as business, system, network, device and instance, reflecting the different people that work together to define and deploy policies to provide a Product or Service. Each constituent understands its domain and uses different terminologies to manipulate each set of management policies, performing the policy refinement (from business-level policies to device-instance policies), by adding or removing information. This simplifies the process of enforcing business-oriented management policies. In [166], the authors propose a semi-automated process based on human intervention in cooperation with ontological engineering techniques in order to perform the refinement process.

FOCALE's architectural proposal for the management of future Internet is based on the classification of its elements in planes, as referred in [171]. The *Data Plane* represent the network elements, the *Control Plane* includes the functionalities that govern the network's connectivity, the *Management Plane* includes the functionalities for governing

the deployment and operation of the network's resources and services, coordinating the behavior of several control loops. To conclude, the *Inference Plane* represents a coordinated set of decision-making components that represent the capabilities of the managed elements, the constraints placed upon (such as business policies) and context information [161], which enables the policies driven management.

In [172], the authors proposed an agent-based architecture to be used in FOCALE. This architecture simplifies the function of the MBTL. Translating from the Autonomic Manager independent language to all vendor-specific data commands may represent a management bottleneck when used in larger scale domains. The authors proposed the use of agents built with components, so the agent comprises the meta level that includes the basic functions that all agents must include and the advanced level which includes the vendor-specific components. Due to the fact that this agent is able to understand the MBTL common language as well as the vendor-specific language, the MBTL no longer requires support for all vendor-specific languages. In this case, conversion is made at the agent level.

In [173], the authors focused on distributing the autonomic components in order to achieve a higher scalability. The components are hierarchically organized to simplify their interaction, which reduces the management overhead, enabling a more efficient orchestration of the dissemination of context and management policies (with direct impact in the management system scalability). This is achieved by enabling only the child/parent communication. Using this hierarchical perspective, where the higher level AE has a broader view of the managed elements (but less detailed) and the lower level AE has more detailed information on a smaller scale, is a direct equivalence to FOCALE's inner and outer control loops. The authors presented an analytic comparison between a hierarchical and a flat management model considering the exchange of context data and concluded about a significant reduction on the management overhead when the number of managed resources increases. The advantages and drawbacks of using semantic mapping, based on ontologies, such as the one implemented in FOCALE, are also referred in [130], where the authors concluded that the reasoners incur into performance limitations when large ontologies are used. Besides, the mapping rules are not automatic and are based on heuristics since the data sources were defined syntactically and not semantically. On the other hand, they provide interoperability, higher design expressiveness and transfer of knowledge for the management application, which means higher degrees of automation, among other advantages. Other works using (or inspired by) FOCALE's AE may be found in [174–177].

Two important projects were created by the European Union in 2008 under the Seventh Framework Programme. Those projects were Architecture and Design for the Future Internet (4WARD) [37] and Autonomic Internet (AUTOI) [36]. The 4WARD project was completed in June 2010 and aimed to create a clean-slate architecture for the future Internet. The project was structured in six work packages where the most relevant project pertained to the network management defined the *In-Network Management*. The In-Network Management [178] appears in the context of the management decentralization requirement (also referred in [163]). The authors refer that the traditional development process, where the management capabilities are only considered at the end, is inadequate for the management of emerging network environments. Proposing a built-in, distributed management infra-structure, the In-Network Management aims to achieve a scalable, low complexity and robust management scheme for the management of future Internet. With the In-Network Management, the traditional (external) management entity does not interact individually with each managed device, instead a management plane is used to distribute management activities. Each device has embedded management capabilities and communicates with other network elements using a peer to peer paradigm. This way, embedded management functions may be coordinated to provide increasingly more complex functions [163]. The management plane used demonstrates autonomic behavior to ease manageability, reliability and lower management costs. Other works published regarding 4WARD's In-Network Management can be found in [179, 180].

The AUTOI project suggests the creation of a service- and self-aware Internet that manages resources using autonomic principles [181]. In order to reach these goals, AUTOI proposes the implementation of a self-managing virtual resource overlay network that can span across physical heterogeneous networks and support service mobility, security, quality of service and reliability. To this end, it uses the virtualization of network resources allied with autonomic network management and policy-based management techniques to describe and control the internal logic of the service [163]. The AUTOI structure is composed by five planes: *Orchestration*; *Service Enablers*; *Knowledge*; *Management* and; *Virtualization*. The Management Plane implements the autonomic control loops to manage the virtual resources on the Virtualization Plane on a management domain. Each Management Plane has knowledge base information defined as a Knowledge Plane. Each management domain also includes the management domain policy service, information and other supporting services. The Orchestration Plane deals with the interaction between different management domains.

As described in [157], the Future Internet Design (FIND) [39] project was created in 2006 to drive the research community to implement a future Internet based on the knowledge and experience of current networks using a clean-slate design. FIND's two most important projects include a management plane in the network design [182]. The first project was called *Design for manageability in the next-generation Internet* and defined the building blocks that can be combined to create the management plane and the second was called *Complexity-oblivious network management* and separated the data plane from the management plane in an attempt to reduce the complexity. Several other research projects addressing the management of future Internet such as the Autonomic Network Architecture [38], CASCADAS [183] and AKARI [184] exist.

2.7 Other Network Management Solutions

Several other network management solutions exist. CFengine [185] uses a declarative language to describe the low-level management policies expressed as *promises* (containing the domain's management intentions, highly dependent on the network resource's implementation detail). The promises defined are sent to management agents that extract their configuration management operations and ensure their automatic deployment. Some of the management activities performed include package installation verifications, configuration file generation, file protection and consistency checking. Puppet [186] is a similar management tool that also uses a declarative language to represent the desired state of the managed elements. PRESTO [187] is yet another network management system that uses templates (called *Configlets*) to generate device-native configuration files based on independent data sources. LCFG [188] and Smartfrog [189] represent two other relevant frameworks aiming towards the automation of management procedures.

2.8 Conclusion

This chapter presented some of the most important works within the area of network management by placing a special emphasis on the integrated management solutions. From the works presented, there is a group that focuses on the definition of management protocols in an effort to overcome the implementation of proprietary management mechanisms, commonly implemented by CLI while providing a group of functionalities that enable the network element's remote management. Some of those works are OSI, SNMP, CORBA and NETCONF. While providing a standard way of executing network management, these proposals do not aim to automate the management process nor do

they aim towards the integration with other management protocols. They simply focus on enabling the communication between a remote management application and a managed element regardless of its type, operating system, software version etc, using a standard protocol and interface.

Given the communication network popularity and the diversity that the network management interfaces has achieved (standard and non-standard), allied with an increasing necessity for more complex management functionalities deployed over larger scale domains, motivated the development of more complex management architectures that, while aiming towards the integrated management of heterogeneous management interfaces, provide some levels of management automation. It was in this context that WBEM and FOCALE were created even though WBEM does not directly provide automation. WBEM enables the integrated management of heterogeneous implementations using a group of common management models, later translated into the managed elements implementation details using recast mapping (syntactic translations) performed at the Provider level (even though domain mapping was also proposed adding semantic content to the models through the use of ontologies). In FOCALE, a semantic mapping is also proposed based on the application of different levels of ontologies that are used to enhance the management models with semantics in order to find similarity among the models that can be used to create a common representation among the heterogeneous models. According to the authors in [129, 130], the execution of only syntactic translations is insufficient, even though it is easily automated. It may cause inconsistencies when overlapped concepts exist between the source and destination models since their semantics is not considered or is limited. Semantic translations cannot be easily automated due to the lack of semantic content on existing management data models. Besides, performing semantic translation is complex and for large scale domains, the performance of the reasoning algorithms may compromise the performance of the management system. The limitations inherent to the application of translation methods on integrated network management solutions serve as a motivation for the work presented in this thesis.

Chapter 3

Automated, Distributed and Integrated Network Services Management

The most relevant network management frameworks of the state of the art were considered in the previous chapter. The existence of such wide range of solutions raises an important challenge when creating an automated network management solution that must integrate management. This chapter describes the most common alternative when creating an integrated network management framework, highlighting its most relevant limitations. In an effort to overcome those limitations a new proposal is presented that aims to create a unified management service composed by two clearly separated processes: monitoring and configuration.

3.1 Motivation

The heterogeneity in network management is present at different levels and it has been solved by the application of different methods. The most popular network management frameworks (such as OSI and INMF) deal with the heterogeneity of data representations by creating a uniform representation for the management data while defining a group of management operations as well as a management protocol for the provisioning of the management operations. In the same sense, CORBA also provides uniform access to management objects through the object's interface. Even though the object definition has a specific programming language, the definition of the object interfaces through IDL, later compiled into different programming languages, associated with the ORB,

enables the transparent invocation of the object's methods as well as the retrieval of data regardless of the object's implementation details.

On a different level, WBEM enables the technological independence between the management application and heterogeneous network elements by creating a common interface integrating all existing network management interfaces. CIM's independent management representations and protocol operations are mapped into each network element management interface (or implementation) through the use of Providers. So, WBEM deals with management heterogeneity providing information models whose representations are mapped into several target network elements based on web technology. As such, some works address the use of WBEM as an integration tool [129,130,190,191], to refer the need to include extra-semantic representations to obtain an adequate mapping translation and consistent integration among the heterogeneous network management frameworks available.

There is also the aim towards the creation of an integrated network management framework with automation concerns in order to deal with management complexity. Autonomic network management is a recent research area providing important contributions. Among the several proposals, the FOCALE project aims to permit management of legacy devices (non autonomic elements) using traditional management schemes. In FOCALE's project, high-level business-oriented policies generate independent configurations continuously enforced to each network element management interface (and data model) through the use of an MBTL. This creates an automated network management framework supporting the integrated management of heterogeneous network services and devices. The translation process includes not only syntactic conversion of management representations but also semantics through the use of different levels of ontologies, finding semantic similarities between heterogeneous representations. However, the implementation of semantic translations embraces relevant difficulties. Most implemented network management data models have implicit semantics (being often agreed between administrators) without a standard representation [130, 192]. Such empirical semantic representations require manual intervention from the administrator to create and/or validate the mappings which, for large scale environments, can be very complex (the same can be said for debugging tasks) [130, 193].

Previous frameworks depict that the heterogeneity in network management may be solved at different levels. The integrated management of heterogeneous network elements is gaining enhanced relevance due to the requirements for higher levels of automation in network management. In this sense, translation mechanisms have been proposed supporting one-to-many conversion either using a syntactic or semantic trans-

lation. However, the realization of these translations inherit important limitations. So, new solutions are necessary in order to deal with management heterogeneity, mainly on large scale system.

3.2 Integrated Network Management

Communication networks evolve not only in size but also in terms of complexity. New network management solutions were proposed to effectively cope with this evolution, as described in the previous chapter. But, this resulted in an increasing heterogeneity in terms of network management solutions. An important approach that deals with management heterogeneity is presented in Request For Comment (RFC) 3139 [42] and depicted in Figure 3.1 creating an integrated network management framework. Here, the *Configuration Management Data* represents high-level policies embedding the business goals describing the behavior pretended for the management domain. Then, in conjunction with the *Network Topological Information* (containing the management domain elements details) as well as the *Network Status Information* (containing monitoring information), the *Network-Wide Configuration Data* is generated. This data represents mid-level independent policies from which the *Device Local Configurations* are derived. The *Network-Wide Configuration Data* mid-level policies provide a network-oriented view of the management goals in opposition to the business oriented policies seen in the *Configuration Management Data*. This makes mid-level policies much easier to implement and to manage because they do not contain device-specific data and neither provide a high-level view of the management. It provides an independent representation for the expected behavior of the managed elements, used to generate each device specific configuration. In order to enforce the *Network-Wide Configuration Data*, a *Configuration Data Translator* is used to translate from the mid-level independent policies to the *Device Local Configurations*, according to each device management interface language and data model.

3.3 Management Translations' Taxonomy

Contemporary translation mechanisms implement different strategies in order to deal with management diversity, however, they can be classified according to the entity where they are performed. Three main approaches should be considered as in [22]:

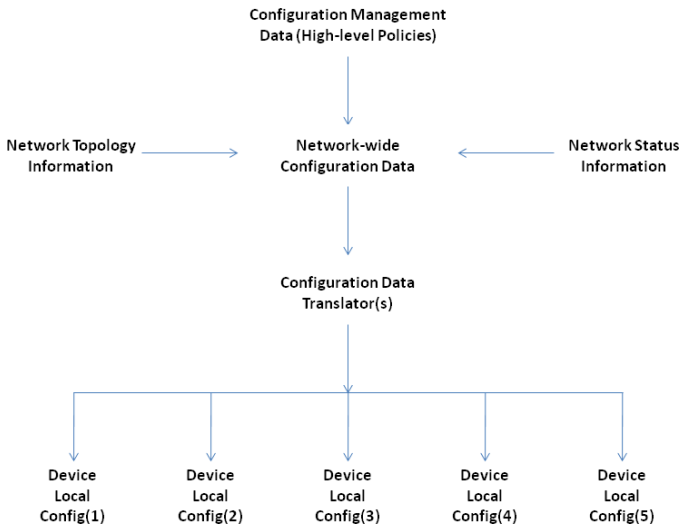

Figure 3.1: RFC 3139 integrated network management model

- *Multi-architectural management application*: in this architecture, management diversity is solved using applications that support heterogeneous protocols. The translation of the information is performed within the management application. Implementing such an architecture complicates the development of management applications because the addition of a new network element requires extensive administrator labor to evolve the management application while ensure that all networked elements are managed;

- *Multi-architectural agent*: in this case, the managed element's agents are responsible for accepting all protocol requests, converting them into local representations. Inverse translations are required for adequately replying. If different management applications are supported, the agent is responsible for dealing with the resulting concurrency to ensure data consistency. If management applications are required to deploy high-level management tasks, the complexity is pushed to all agents and resource consumption becomes an issue, as is software complexity;

- *Management gateway (intermediary management translation)*: this strategy isolates the management application from the managed element's diversity enabling each one to construct its best management implementation. Then, the management gateway is responsible for management application and managed element's protocol and data model adaptation, while enabling each one to adequately focus on supporting one management interface. However, implementing an intermediary

translation mechanism introduces new difficulties which will be latter explored in this chapter.

3.4 Intermediary Network Management Translation

This methodology is gaining increased recognition. It promotes a technological independence between management application development and the diversity of network elements, enabling the addition/deletion/edition of mappings while keeping both management application and network elements operational. In order to build a true interoperable management gateway, both management information and communication protocol must be converted.

3.4.1 Management Information Translation

When considering the translation of management information, two different types of conversions may be performed as referred in [22]:

- *Syntactical translation* represents the simplest conversion. In a syntactical translation, the description on the source data model is converted to the destination data model. Therefore, in the case of well defined representations, this type of translation can be adequate for automation;

- *Semantic translation* is much more complex. In a semantic translation, the semantics of source and destination data models must be precisely analyzed in order to obtain high levels of data integration.

3.4.2 Management Protocol Translation

Performing a protocol translation implies that several features provided by a source protocol must be translated into another. According to [22], the features to be mapped include control, query, response and asynchronous event notification messages. In order to perform an adequate translation between protocols, a name mapping between properties in the source request and the corresponding properties in the destination must also be defined.

3.4.3 Implications

The underlying implications of using intermediary management translation mechanisms, mapping from one independent management representation to many implementation-specific management representations, must be considered.

Management representations tend to be static, described in well known languages and the resulting data from a syntactic translation, even though in accordance with the destination data model, does not take into account the semantics of both source and destination management data [22]. This might create data inconsistencies or collisions with management domains maintaining overlapped concepts with different representations [129]. This type of translation is deterministic, that is, the result is always the same [22], not allowing dynamic evolution in the mapping models. This makes syntactic management information translations suited for automation.

On the other hand, when implementing a semantic translation, the content of the information defined in the source representation must be analyzed and an attempt is made to map the source content into semantically equivalent content in the destination representation. This usage of semantic representations implies that network administrators could reason an abstracted view of the management information, regardless of the management models specificities, to create an interoperable semantic management environment. That is, creating an integrated management framework from both source and destination representations [22]. The disadvantage of such an integration is that translations cannot be executed automatically because there is not a formal specification, commonly agreed, of the model's semantics and an in-depth analysis would be required from both source and destination information models semantics [22]. Current data models are syntactically defined with precision, not semantically, so the rules of mapping to ontologies are based on heuristics. Thus, this process is not suited for automation [130]. Human intervention is still used for the creation/validation of semantic mappings [130] and to support their evolution. Ontologies play an important role in the unification of management models by providing the means to include semantic-awareness into the information/data models [130], enabling the creation of a common language to be mapped into the implementation-specific data models. Besides, ontologies permit the use of inference and learning techniques which enables dynamic evolution of mappings. In this case, current reasoners would introduce important performance constrains to the management effectiveness [130]. Further discussion on the usage of semantic models to ease the interoperability between different management domains and applications, enabling different administrators or software components to clearly understand the definitions

and management rules and goals defined by other administrators, is done on [191].

The configuration translation mechanisms are highly dependent on the managed element's functionalities. Since they are subject to frequent updates, their management data model is likely to evolve. This will force an evolution into the translation process which may result in a high administrative effort (mostly manual) in maintaining the translation mechanisms up-to-date regardless of whatever translation model is used. Different translation mechanisms must be created for different devices or service implementations because there is a low re-use of specifications even though they perform similar tasks. Also, management protocol translations must be developed and maintained for all management protocols that are involved in an interoperable management environment.

The existence of errors is inherent to any translation mechanism based on human intervention. Furthermore, the implementation of a semantic translation mechanism increases debugging difficulty, which makes it hard to implement for a larger scale network management domain.

Limitations may also be found depending on the location of the translation element. If it is deployed in a central entity, it will support limitations on its resilience, scalability and performance, since it is dependent on a single point of failure and creates a bottleneck for some management tasks. If pushed into the managed element, it will decrease resources availability and increase their implementation complexity.

Based on the previous considerations, it seemed relevant to find a valid alternative that could provide an integrated network management infrastructure while overcoming the need for intermediary translation mechanisms that rely on complex information and protocol translations.

3.5 Integrated Network Service Management Requirements

Building an intermediary entity to deal with network management heterogeneity must be carefully planned in order to comply with network management evolution. The following list of items, compiled based on the future Internet management requirements referred in [160, 161, 163], present some important functionalities that should be addressed:

- The automation of management procedures is one of the most important goals in contemporary network management frameworks. Networks are increasing in size, complexity and diversity. At the same time, improved efficiency is being demanded. The response to this demand is the current diversity of management solutions which, in turn, creates highly complex management problems to solve. The automation of management procedures is a key concept to tackle such complexity. This presents the advantage of reducing the errors inherent to manual operation. Besides, the intervention time is reduced when failures are detected and new management decisions are deployed automatically. This enables the administrator to focus on more important planning and optimization tasks that will improve the network's overall performance. In this context, an intermediary management entity can contribute to the automation of management procedures enabling the higher-level management processes to focus on strategic and administrative operations oriented for the automation of complex management decisions, abstracting the management infrastructure deployment details;

- NMSs can belong to different administrative domains implementing different management goals. They can also be contained within the same administrative domain being subject to different constraints. Regardless of the NMSs deployment characteristics, it might be required to exchange management data among them (for resolution of conflicts, inconsistencies and others). Therefore, its important to promote interoperability between NMSs. An intermediary entity may provide such interoperability through the use of a standard network management interface that creates a uniform representation understood between all NMSs. This enables the dissemination of information between different NMSs, promoting their cooperation or competition for a given management role in a domain;

- Networked elements are subject to periodic updates and new elements are introduced on a daily basis. This dynamism must be absorbed by the NMS intelligence. Since high-level management applications implement highly complex integration models, representations, relations and algorithms, the network elements' evolution incurs in important modifications to the management representations which may imply a complex, long and expensive (and mostly manual) task. An intermediary management entity based on standard definitions could be used to isolate NMS software from the network elements' evolution;

- As networks are growing in size and complexity, an increased number of interactions between NMSs and managed elements is required. It is important to guarantee that the management systems cope with the network's growth, so the intermediary entity should provide good scalability, distributing the management effort through a group of hierarchically organized management servers;
- The management of the network is driven towards the definition of business goals or objectives mainly represented by policies. These high-level representations must be translated into heterogeneous, lower-level configurations of managed elements through intermediary alternative management mechanisms, not prone to the same limitations of the referred translation mechanisms;
- Communication networks evolved from an architecture which was centered on the technologies implemented by the constituent network devices to an architecture that is based on the services it provides called Service Oriented Architecture (SOA). In this context, the management functionalities must also be provided as services. However, the management of network services creates complex challenges because they implement distributed architectures, maintain complex management models, have a large number of users and are made available by a large number of heterogeneous vendors. Keeping this in mind, the intermediary entity must aim for implementation of a service management, being itself a service, following the trend of SOA architectures.

3.5.1 Network Service Definition

Enterprises Information Technology (IT) infrastructures have evolved over several dimensions. Such evolution resulted in an exponential growth in terms of complexity which was reflected in the diversity of platforms, protocols, development environments available, among others [194]. The need to cope with the increasing size, complexity and heterogeneity of IT systems as well as their geographical distribution motivated the implementation of distributed computed systems realizing well defined functions to other network elements or users, abstracting unnecessary implementation details. Addressing this requirement for abstraction gave birth to the *Network Service* concept. Some of the features common for the network service definition found in [194] include: *modularity* (performing a well defined group of operations); *loosely coupled* (hiding the implementation details from the user); *technology neutral* (accessible through well defined interfaces) and; *location transparent* (identified by a well defined URI). An SOA architecture facilitates the interactions and communications between services by grouping the services into

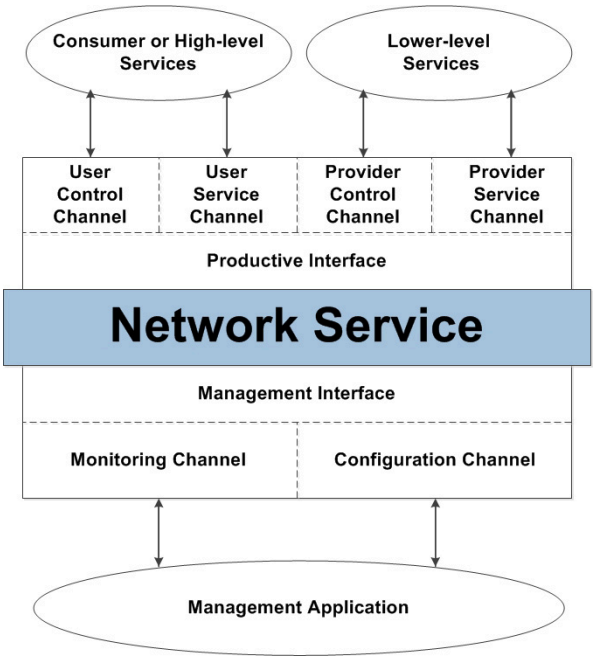

Figure 3.2: Conceptualization of a *Network Service*

a framework where service providers can advertise their services in registries where they can be discovered, accessed, and used while enabling the establishment of adequate Service Level Agreements (SLAs) [194]. This view changed the initial network management paradigm oriented for the management of network devices to a new paradigm oriented towards the services that a network is able to provide. The implementation of SOA architectures is gaining increased recognition [195] addressing the management of future Internet where the management activities are also available as network service [160].

The network service reference used throughout this thesis was introduced in [196] and it's conceptualization is depicted in Figure 3.2. According to this definition, the network service contains two main interfaces: *Productive* and *Management*. The Productive interface contains two channels: one enabling the service to be consumed (*User Channel*) and the other to consume lower-level services (*Provider Channel*). Each channel is further divided into *Control* and *Service* sub-channels: the *User Control Channel* of the Productive Interface controls the User Service Channel (which is used to exchange data for the execution of service procedures). The Provider Channel has analogous utilizations for the interaction with low-level network services. The Management interface also contains two channels, *Monitoring* and *Configuration*, to request the execution and collect the results of management activities. Figure 3.2 is the network service represen-

tation modeling as a *black box* which implements a given set of functionalities regardless of the underlying technological details. A network service becomes completely defined through its interfaces that implementers and users must comply to. This definition may contain a set of activities that can be performed individually or collectively, pursuing the same goal, like the network's productive services (like DNS, Email, DHCP, etc.), applications, protocols, mechanisms (such as IP, routing, etc.) or devices. With this approach, the networked functions, objects, and processes from heterogeneous sources are exposed as hierarchical services embedding management functionalities, creating a dependency graph decoupled of the underlying implementation details where the management functionalities are also represented as network services. An example of such an hierarchical network service domain is depicted in Figure 3.3.

Figure 3.3 depicts two types of services: one group of services performing productive operations and a group of services executing the management tasks. A *DNS Client* uses the service provided by *DNS Service* which on the other hand consumes the services provided by the *DNS Protocol* and *IP Protocol* to exchange messages. From the management perspective, the service provided by *Network Service Management* enables an independent access to the management functionalities by any network management application. The Network Service Management consumes a group of lower-level management services responsible for the management of each productive network service such as *DNS Service Management*, *DNS Protocol Management* and *IP Protocol Management*. A clear hierarchy is demonstrated for both service types.

3.5.2 Network Management Activities

Network management activities were introduced in the OSI's FCAPS classification. Even though these classifications were presented in the early days of network management, they are still considered a reference for the operational network management including for future Internet management [160]. However, the most recent requirements for the automation of management activities, new network management activities must be considered [196].

The *operational management* activities are represented using traditional FCAPS classification. It includes the procedures that deal with the functional aspects of network management such as: *fault management* involving the detection, recovery and documentation of anomalies and failures through the examination of alarms, statistics or reports; *configuration management* ensuring the network's desired operation by recording, maintaining and updating network configurations. It involves tasks such as defining

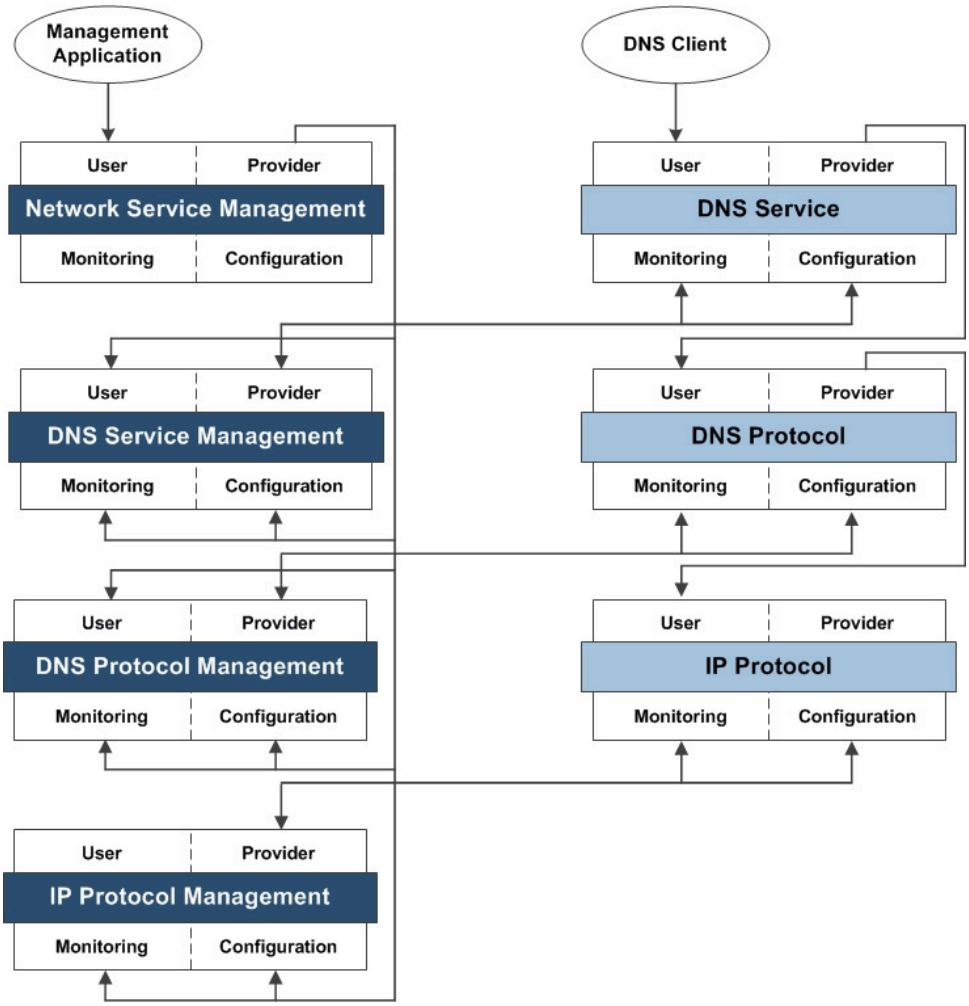

Figure 3.3: Network services domain including management

threshold values and names, setting filters, configuration changes and corresponding historic documentation, software installation, etc; *accounting management* that provides user management for billing in accordance with network resource usage. Some of the defined functions include tariff administration, charge generation, bill production, payment processing, usage reports generation, distribution and surveillance, etc; *performance management* that ensures a reliable and high quality network operation, therefore, it encompasses all the measures required for ensuring that QoS parameters conforms to the service level agreement. Some of these relate to resource monitoring for performance bottlenecks, log evaluation and regulation of crucial performance parameters such as throughput, delay, packet loss, congestion level, etc; *security management* refers to the

management activities related to the network's security threats while ensuring user privacy and controlling user access rights. These include the definition of security policies, threat analysis, user access control enforcement, definition of confidentiality and privacy schemes, security report generation, etc. It is important to refer that all operational activities rely on the two most basic network management interfaces: monitoring and configuration.

Automation of network management procedures require high-level independent management information representations. One of the most common forms of these representations are the network management policies which are used to describe the pretended behavior of the managed services. The definition and implementation of these policies requires a new group of activities that are not contemplated on the operational network management activities. This new group of management activities are referred to as *strategic management* [196] and includes the definition of the global security policies to be enforced in the management domain (containing the different security solutions depending in the service offered and who is consuming it), definition of the network service access policies (for the service consumption), definition of the high-level network management policies (that embed the business goals) and from which the service behavior is derived. At this level, the global naming and addressing strategies are also defined for all the managed services. Monitoring information is taken (in the form of technical reports) regarding the operational management deployment and user satisfaction levels that might lead to changes in the business-oriented service management policies.

In order to ease the deployment of some of the high-level network management policies into the corresponding operational activities, a new intermediary group of activities is introduced. These are referred to as *administrative management* activities [196], and are responsible for ensuring that all administrative requisites are met according to strategic requirements. Some of the activities include the enforcement of naming and addressing schemes defined in the strategic management, generation of technical documents to be used as input for the operational and strategic management (like service consumption and accounting reports), monitoring of the operational network management activities and generation of the adequate procedures to guarantee the operational network management is in accordance with strategic management definitions.

3.5.3 Automation and Distribution

The most common solutions for the automation and distribution of network services management use independent representations later mapped into heterogeneous man-

aged element interfaces, be it through a syntactic or semantic management translation, or both. However, the implementation of management translations is far from ideal, potentiating content loss or requiring intensive administrator manual intervention due to the lack of automatic processes that map the semantics inherent to all the heterogeneity available in contemporary networks. These limitations are further amplified when considering the management of large scale domains. There is also a trend that uses network services provided by SOA architectures to hide the complexity of the network's distributed processes. This implies that the management activities also become available as network services to manage the network's productive services.

A new mid-level architecture addressing the heterogeneous network service management, while promoting the automation of some management procedures, is being proposed. It uses the network service definition presented in the previous section where all network services include two basic network management interfaces for the monitoring and configurations tasks. Depicted in Figure 3.4, the new *Automated, Distributed and Integrated Network Service Management* framework is composed of two peer subsystems. One deals with the monitoring tasks (*Automated and Distributed Network Service Monitoring (SMON)*) and the other with the configuration tasks (*Mid-level Network Service Configuration (MiNSC)*). Both subsystems provide two independent services that high-level network management applications might use to manage the network's productive services regardless of their underlying technological details. Both subsystems are able to cooperate in the augmentation of the network's productive service resilience to node's failures or performance degradation, automatically migrating a service instance. In order to perform the migration procedure, each subsystem has the following responsibilities:

- The monitoring subsystem (SMON) is responsible for the calculation of the network service's QoS levels and comparing them to the pretended values, defined administratively, as well as the calculation of the corresponding configuration management operation which brings the monitored service to the pretended state;
- The configuration subsystem (MiNSC) is responsible for effectively deploying configuration management operations triggered by the monitoring service or high-level management applications, abstracting the network's productive services heterogeneous implementation details creating a uniform management view.

These are the most important goals aimed by the Automated, Distributed and Integrated Network Services Management framework:

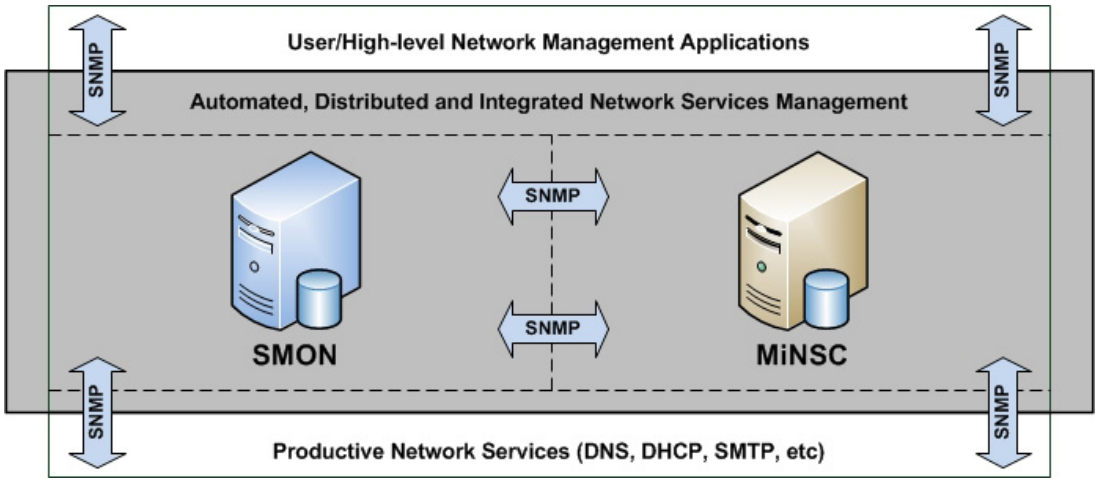

Figure 3.4: Automated, Distributed and Integrated Network Services Management

- Present a mid-level service, based on a distributed architecture, for network services management. Operational management is realized through two basic management interfaces, monitoring and configuration;
- Automation of some management tasks at the intermediary level, such as the network service resilience improvement. This simplifies the high-level network management applications. Simplification of the high-level network management applications is also obtained by not requiring the implementation of translation mechanisms to support management heterogeneity.
- Improve the network's productive services resilience by migrating the instances's execution when needed. With the monitoring service measuring the service QoS levels and automatically triggering reconfiguration procedures (that are able to spam from a single configuration parameter fine tuning to the complete or partial service replication procedure) the network service resilience is improved in terms of instance's failure or performance degradation.

The SNMP protocol can provide a reliable and secure management data transport between the framework elements. The implications of using SNMP is studied later in this thesis. The proposed subsystems are tightly related and their presence is essential to provide the network services operational management. The next sections present the two main building blocks of the proposed framework. However, only the configuration management subsystem is explored in detail in the following chapters, as is the focus of this thesis.

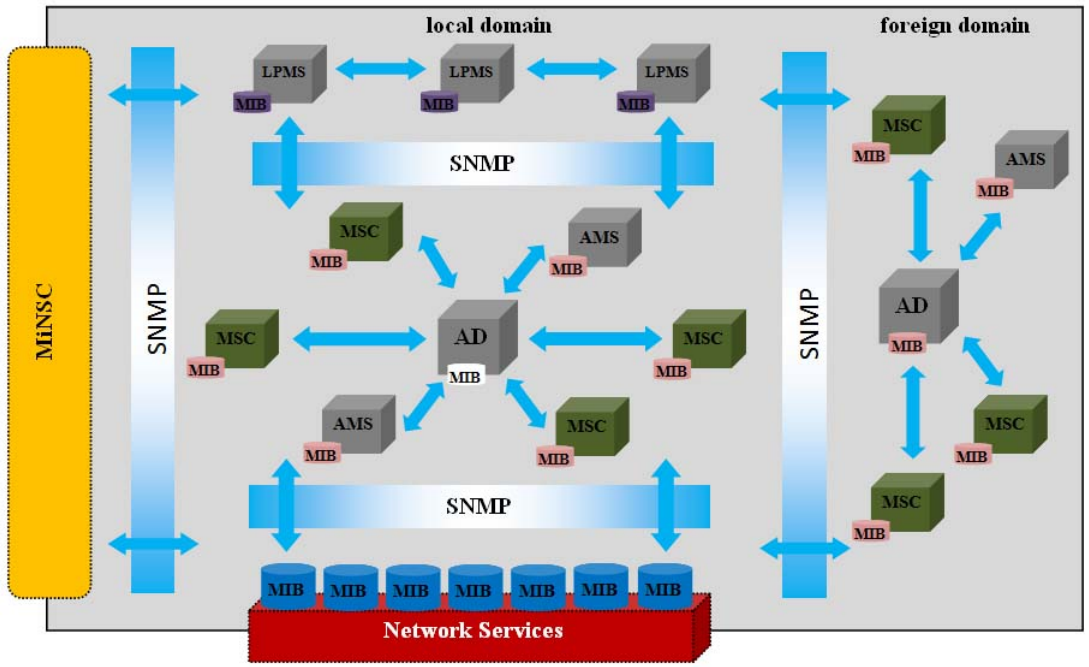

Figure 3.5: Automated and Distributed Network Service Monitoring

3.5.4 Automated and Distributed Network Service Monitoring (SMON)

The deployment scenario provided by the Automated and Distributed Network Service Monitoring subsystem is depicted in Figure 3.5 and published in [197]. The monitoring process is distributed using a set of monitoring modules. These modules are classified into Active Monitoring Server (AMS) and Monitoring Server Candidate (MSC), with AMS actively performing monitoring tasks and MSC in stand-by mode, not actively performing any type of monitoring task. However, MSC modules are prepared to become AMS when decided by the decision module. The decision module implements the concept of policy management server that derives management decisions from operational management policies applied to a set of QoS values calculated by the monitoring modules.

The distribution of the monitoring modules as well as the decision to make them AMS or MSC is yet to be studied. However, this process may be achieved with the aid of human intervention thus, Active Decision (AD) modules must support an interface to an administrator or higher-level management servers like generic Lightweight Policy Management Servers (LPMSs). The AMS modules are mid-level management servers acting simultaneously as managers and agents. This creates a hierarchical monitoring

system with several functional management levels, each one with filtering and processing capabilities of the monitored data. This mechanism provides scalability, maintaining the higher flows of management data contained on the leaves of the monitoring service hierarchy. On the other hand, in higher-level monitoring modules, closer to the top of the functional hierarchy, that is, close to the AD modules, subsystem reliability and resilience will be much more important than performance. This can be attained by carefully calculating AMSs and MSCs quantities and location.

3.5.5 Mid-Level Network Service Configuration Management (MiNSC)

This thesis focus on the Automated, Distributed and Integrated Network Service Management framework's second component: the Mid-level Network Service Configuration subsystem. It has the responsibility of deploying configurations simplifying management of heterogeneous network services. This subsystem is extensively explained and evaluated in the following chapters.

3.6 Conclusion

Currently, there is a tendency to use high-level network management representations to describe the goals pretended for a management domain. Those high-level representations are later translated into each management interface of the elements being managed through a translation mechanism using two different strategies. They either implement a syntactical or semantical translation. However, the implementation of management translation mechanisms incurs in well identified limitations that include content loss and extensive administrator intervention dependency, which, for large scale heterogeneous environments may be unfeasible. With the adoption of a SOA architecture the problem remains and solutions that deal with heterogeneous network service management are required. With this in mind, an Automated, Distributed and Integrated Network Service Management framework is proposed. This solution not only supports management of heterogeneous network services, simplifying NMS, but also provides additional functionalities improving service resilience.

Chapter 4

MiNSC: Mid-level Network Services Configuration Management

This chapter describes the Mid-level Network Service Configuration (MiNSC) subsystem introduced in previous chapter. It summarizes the motivations leading to the development of this new configuration management framework. The MiNSC's architectural details and its functional model are also explained. This chapter ends with usage considerations for MiNSC based solutions, including its inherent limitations.

4.1 Motivation

Heterogeneous network management problem is far from being solved and networks are evolving towards a service oriented paradigm which needs a network management evolution. The implementation of high-level network management applications, aiming to simplify and automate management procedures, make use of syntactic and semantic translations to enforce high-level management representation into the low-level network element's management interface and data model. Regardless of whatever management translation alternative is used, it incurs into important limitations such as management data loss or inconsistencies, as well as dependency on manual intervention by the administrator. Furthermore, when speaking of larger scale management domains, these strategies are complex to implement. It is also important to notice recent trends towards the implementation of service oriented architectures. This hides the networks complex implementation details using an abstracted view of the network and it's com-

ponents, enabling the establishment of adequate SLA that users and service providers must comply to. These conclusions motivate the development of the MiNSC framework, a configuration management service, based on standard technologies, that overcomes the implementation of management translation mechanisms while promoting management simplification.

4.2 Integrated Network Service Management

Network services tend to be well described in international standards, management information models can be derived from those descriptions and all network service implementations, in agreement with the standards, should be manageable using only standard technologies (information and data models), creating a network service management abstraction. The implementation of such standard-based management abstraction unifies the network service management regardless of the underlying implementation details. This is the basis for the MiNSC's proposal and represents MiNSC's alternative for heterogeneous network service management which is divided into two sub-layers. The first (and lower) management abstraction layer unifies the management of specific network services through the implementation of standard-based service management information models (referred to as instance management information model) on a standard interface. The second (and higher) management abstraction layer, takes advantage of the unification provided by the lower layer to enable an additional and independent set of meta-configurations defining the overall service behavior which promotes automation of the service management. Those meta-configurations are defined by the service management information model and are directly used in the automatic service configuration deployment (service instance configuration generation) and automated service instance execution migration, which improves the managed service's resilience and scalability. On the top of MiNSC, high-level network management applications use its management abstraction for simplification.

The MiNSC's two layer management model is depicted in Figure 4.1, which is an evolution of the previous proposal presented in Figure 3.1. As stated previously, the *Configuration Management Data* represents the high-level (business oriented) policies while the *Network-Wide Configuration Data* represents the mid-level, independent network service meta-configurations following the service management information model. Such configurations result from the combination of the business-oriented management policies and the performance of the managed service. The MiNSC framework is responsible for the automatic deployment of the network service configuration, based on

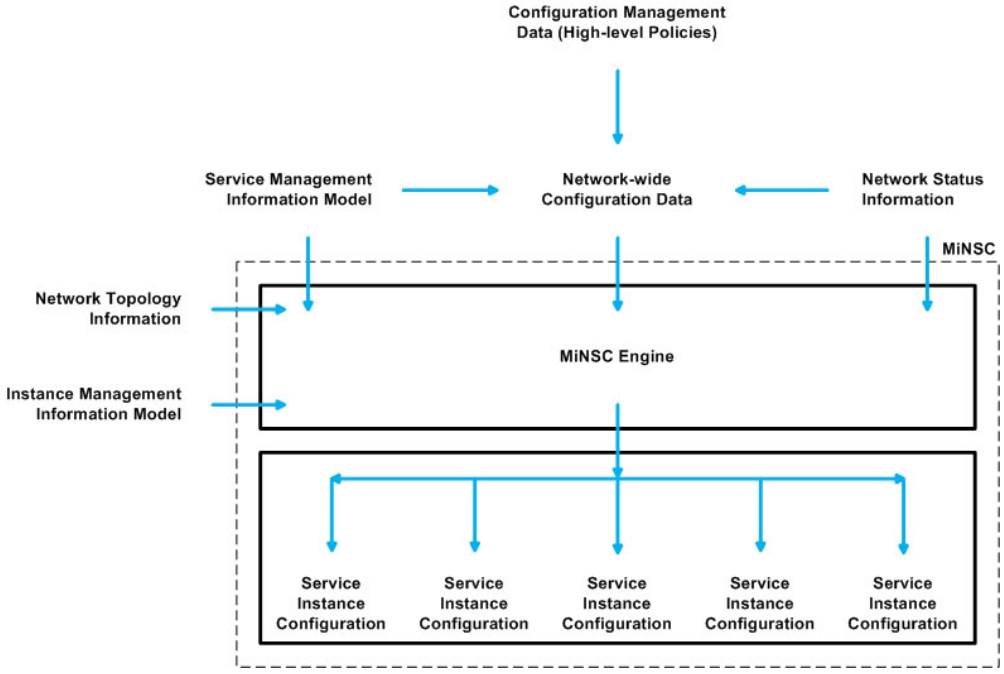

Figure 4.1: MiNSC's network service management model

the meta-configurations defined, calculating the quantity of network service instances required and automatically deriving an independent configuration for each one. In order to execute the service configuration deployment, MiNSC's higher management abstraction layer uses the instance management information model as well as the instance's topological information, concerning the management domain, in order to acknowledge their availability. This layer also requires the monitoring information to initiate some management procedures, namely to execute the automatic migration of the service instance execution and service physical expansion process. MiNSC's objectives are summarized as follows:

- As mentioned in the previous section, the current trend on management of network heterogeneity is through the implementation of intermediary translation mechanisms either through a syntactical or semantic approach. MiNSC overcomes the need for intermediary network management translations by using standard-based service management information models, to abstract the heterogeneous management representations, associated with a standard network management interface able to effectively support configuration management operations. This ensures management applications interoperability, eliminating the need for translations.

Thus, MiNSC creates a new service configuration management interface unifying network service management. Network service vendors are then responsible for supporting the proposed interface, developing its instrumentation, in order to adequately manage their heterogeneous implementations;

- Automation of management procedures is one of the most important goals pursued by contemporary network management proposals. In this sense, MiNSC takes advantage of the management abstraction implemented in two layers to provide some automation, namely for the service configuration deployment and instance execution migration, which improves the service's resilience and scalability;
- Provide a scalable and resilient architecture to address scale requirements of contemporary and future networks by using a distributed management framework over both abstraction layers. As such, scalability and resilience improvement methods for both network and management services can be futher achieved through replications of the service instance's independent configurations, enabling a migration of the service execution.

4.3 Architecture

MiNSC is part of the Automated, Distributed and Integrated Network Services Management framework responsible for the enforcement of configuration management operations. It's logical deployment scenario is depicted in Figure 4.2 and most of its details can be found in the following papers [44, 45]. It is clearly similar to the SMON subsystem and they may even share the same physical infrastructure. MiNSC relies on a two layered architecture (one layer for each abstraction level) composed by a distributed group of configuration servers and managed service instances. Figure 4.3 provides details regarding MiNSC's layered architecture which is explored thoroughly in the following sections.

4.3.1 Network Service Instance Management Layer

Following a bottom-up approach, the first management layer is composed by service instances executing the network's productive services (such as DNS, Dynamic Host Configuration Protocol (DHCP), etc.). The execution of a service instance can be classified as *active* (when actively executing a network service) or *candidate* (not actively executing a network service but in stand-by mode ready to execute a service in the future). Therefore, a network service instance may be classified as an Active Service Instance (ASI) or

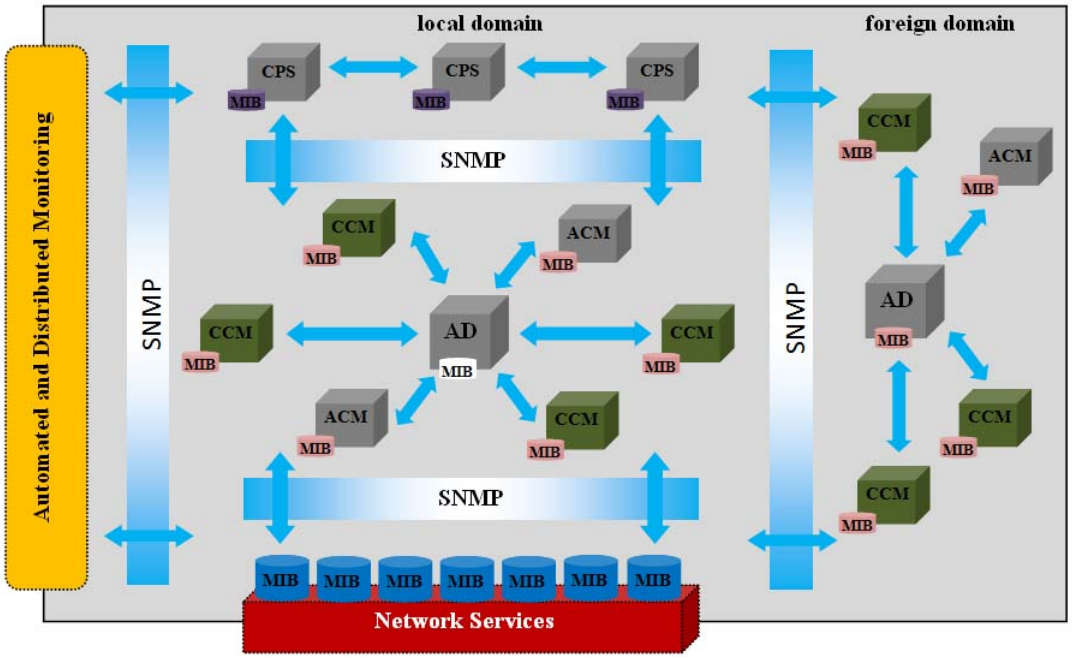

Figure 4.2: MiNSC's deployment scenario

Candidate Service Instance (CSI), depending on the execution state, and a network node may possess several classifications (one for each type of service). Active and candidate instance classification (or state) is temporary, depending on the configurations assigned. However, special attention is required when assigning their classification. Candidate instances should be placed in distinct administrative domains, use different operating systems or software implementations/versions to avoid active instance' security vulnerabilities, be connected using different Internet Service Providers (ISPs), etc. This makes active and candidate instance the most heterogeneous possible, reducing their probability of simultaneous failures, consequently improving resilience. It is also important to note that for a instance to be classified as candidate no configurations are required, the absence of configurations places the instance execution in stand-by.

The process of defining the service instance classification depends on the administrative requirements as well as the number of service instances available. Two distinct instance classification alternatives can be used:

- The administrator provides a graduated list of service instances available. Based on the service redundancy redistribution defined (service meta-configurations) the number of active and candidate instances is calculated. The list provided is used to assign classifications;

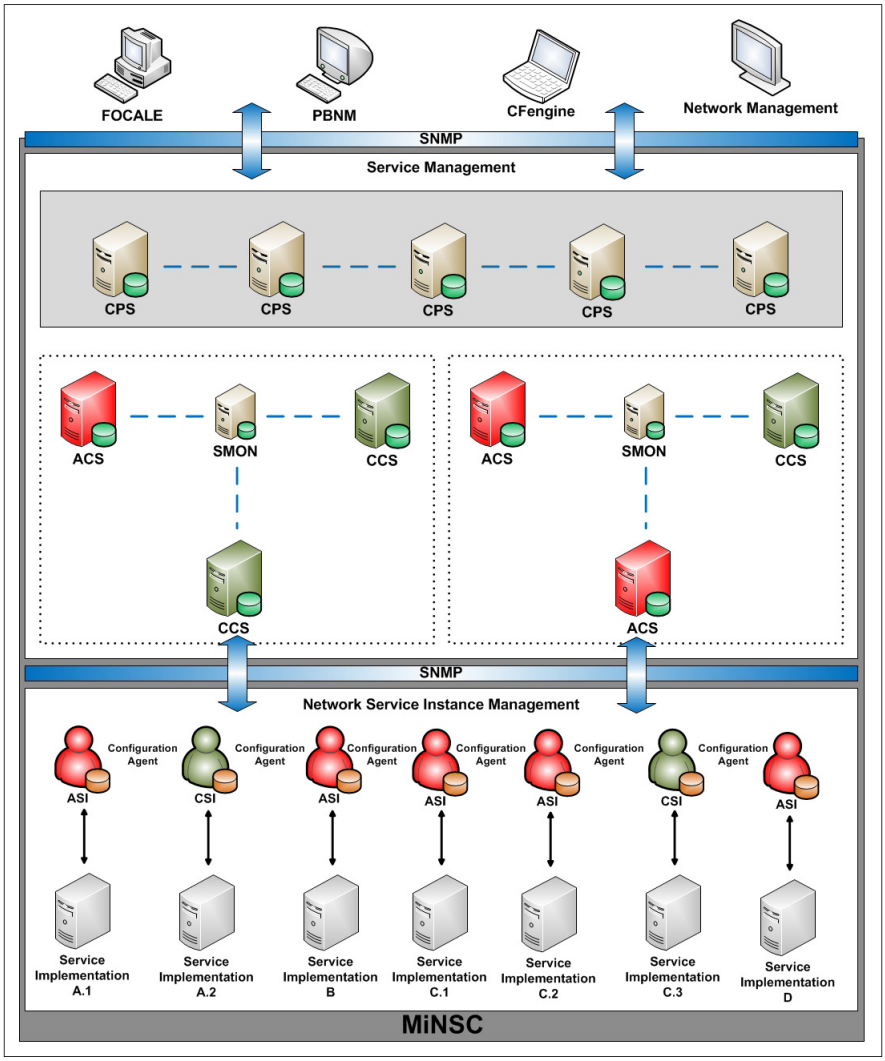

Figure 4.3: MiNSC' service management architecture

- Implementation of a serialization algorithm that by taking the number of service instances available, the service redundancy distribution defined in addition to the costs associated to each service instance, applies a cost minimization algorithm to find the best network service deployment pattern and corresponding ASI and CSI classification.

Regardless of the alternative implemented, it solely provides an initial service deployment pattern. However, this process represents a very important mechanism as it directly impacts the MiNSC's capability of improving the network service resilience and scalability. Then MiNSC may modify the service instance classification according to the monitoring

information, reflecting the instance's performance and fulfillment to the administrative goals. Dynamically varying the service instance classification/state (according to the monitoring information) enables service execution tuning beyond the traditional network service configuration parameters, providing additional management flexibility. The main advantages are:

- In case of a faulty service instance, service execution can be transferred to a different instance maintaining the service's intended performance. This is achieved by automatically replicating the ASI configurations to a CSI (changing it's classification to ASI), thus transferring execution from the faulty ASI. The decision to perform the migration operation is taken by the administrator (through the inspection of monitoring data) or by an automated monitoring system (like SMON), acknowledging the need to perform a migration procedure based on the values of QoS obtained. This mechanism improves resilience to service instance failures or performance degradation;

- MiNSC's capability to dynamically add new service instances acting over their classification improves network service scalability. Once a scalability problem is detected within a network service, SMON triggers a network service expansion procedure to increment the number of ASI instances, reducing the number of CSI instances available. A similar procedure can be implemented to reduce the amount of ASI instances used, thus enabling an efficient allocation of network resources;

- Economical advantages are also inherent to MiNSC's dynamic classification management. Performing a more efficient resource management and resilience improvement methods promotes the maintenance of established SLA.

At this level, the first management abstraction is implemented, providing a unification layer over the service implementation's specificities. This means that, for a given service (let's say service *A*) all the heterogeneous implementations (*A.1*, *A.2*, *A.3*, etc) are equally managed based on a unique instance management information model for service *A*. All management tasks are deployed through a standard network management interface (MIB) implemented by the configuration management agent present in all network nodes. This agent, besides implementing the management interface, also manages the node's service instance classification and supports the creation of their instrumentation. The use of standard-based service management information models implemented on a standard service management interface overcomes the need for network management translations, which is one of the MiNSC's primary goals. It is important to notice that all service

instance configurations at this level are calculated at the *Service Management* layer. The creation of a new configuration management interface unifying management, makes all service implementers responsible for the creation of the adequate instrumentation for management of their products, avoiding disclosure of implementation details.

4.3.2 Service Management Layer

Based on the service management information model, the MiNSC's higher management abstraction layer defines service management meta-configurations embedding the behavior desired for the network service. These meta-configurations are used, among others, to automatically generate each network service instance configuration at *Network Service Instance Management* layer. The following objectives are pretended for this layer:

- Implement a distributed architecture supporting high levels of scalability and resilience for the configuration management service;
- Use the configuration independence, provided by the *Network Service Instance Management* layer, to support automated service management procedures like the automatic generation of service instance configuration, service instance migration and service expansion/redution (automatic addition or removal of network service instances);
- Use of a standard network management interface that, besides enabling the management of the network service meta-configurations (defined by the service management information model), promotes the interoperability of higher-level network management applications;
- Support for a standard interface to be used with the monitoring subsystem. This monitoring subsystem should be able to detect functional or scalability problems at both layers and trigger the realization of configuration management operations at this layer;
- Enable the implementation of a service instance serialization algorithm to determine the classification of service instances according to administrative management goals.

Figure 4.3 depicts the elements presents at the *Service Management* layer. Much as the *Network Service Instance Management* layer, the configuration management servers support simultaneous management instances with classifications such as Active Configuration Server (ACS) or Candidate Configuration Server (CCS). The interface with the monitoring system is represented by a connection with the SMON server. The ACS classification refers to servers actively managing a network service. They maintain the network service meta-configurations in addition to a graduated list of the service instances used for service deployment. On the other hand, the CCS classification refers to a management server that is in a stand-by mode to be used in case of an ACS failure or service expansion. Figure 4.3 represents two logical groups of configuration management servers for the management of two network services. The *Service Management* layer also includes the Configuration Pointing Server (CPS), which plays a fundamental role within the layered architecture to enable a scalable and resilient management operation, by aggregating the configuration servers classification.

An MIB is implemented by the *Service Management* layer elements to promote higher-level management application interoperability. This same type of interface is used for interaction with the monitoring system, providing software independence, used to inform the management servers as to the need to deploy a configuration management procedure. CPS servers use the monitoring interface to manage the classification of management servers thus migrating and extending servers to improve the management framework's overall scalability and resilience. It is important to note that, at this layer, the network service management procedures are divided into server's associations. Here, ACS and CCS servers are grouped and perform management tasks for a given network service. Their task is complemented by the CPS servers which are shared by the management domain to identify, at any given time, ACS servers responsible for the management of a given network service. As network management is a fundamental part of communication network's operations, it is very important to ensure its availability even when in the presence of management server failures. In this sense, and in order to improve the management framework's resilience to server failures, the following considerations should be taken:

- The CPS servers define the ACS and CCS servers classification to perform management tasks for each network service. They also define the periodicity by which ACS server configurations are replicated to CCS. This ensures that network service management execution is quickly migrated to a different server in the event of ACS failures (by promoting a CCS server to ACS);

- In case of an ACS failure, detected by the monitoring system, the CPS is responsible for the election of a CCS (using a graduated list of servers) to continue the configuration management task (replacing the faulty ACS);
- Failures at the CCS servers should not lead to any resilience problem because they are not actively performing any service management procedure;
- The CPS servers do not introduce resilience constrains within the *Service Management* layer. Their database is shared among all of the domain's CPS servers. This means that, as long as there are CPS servers available within the domain, management servers are still able to be assisted.

The *Service Management* layer also takes into consideration scalability concerns, as it also relies on the monitoring information to act accordingly. In this sense, in order to improve the management framework's scalability, the following considerations should be taken:

- When the monitoring system informs the CPS as to the existence of performance degradation due to scalability problems, a service expansion procedure should be executed to distribute the load;
- A CPS server deactivates part of a faulty ACS configuration, activating the same part on a CCS using the configurations previously replicated;
- This increases the number of management servers available thus improving the management service scalability.

Server Referencing

The CPS servers perform an important task within the *Service Management* layer. Due to the dynamism of management servers, the CPS servers maintain updated information regarding which network service is being managed by which ACS servers, while making this information available to external management applications. The CPS server main tasks are summarized in the following items:

- As referred previously, the main objective of the CPS is to register and maintain configuration management servers classification information. This information is made available to external management applications through a standard management interface enabling a simple and fast way to find which servers are responsible for the management of a given network service;

- The CPS also assists the *Service Management* layer initial classification of management servers. This is performed using the implementation of a serialization algorithm such as the one used for the classification of network service instances. This should take into account the desired redundancy distribution level for the configuration management service, the number of management servers available as well as their location;

- The registration database is shared by all CPS servers available at the management domain. This ensures information availability while eliminating the single point of failure and improves scalability;

- The CPS servers are also responsible for setting the configuration replication mechanism on the CCS, used to automatically and periodically replicate the ACS server configurations. These configurations are used for execution migration in case of failures;

- The configurations replicated in CCS are also used by the CPS servers to deploy a load-balancing mechanism, increasing the number of ACS servers performing a network service management, when required.

4.3.3 Configuration Agent

The configuration agents are present in all framework elements, therefore, they play a fundamental role within the architecture. Their responsibilities include the following:

- Implementation of a standard network management interface, MIB, that ensures a uniform data representation and management at any layer, thus, promoting interoperability. This interface in conjunction with standard-based service management information models unifies the management of heterogeneous implementations of network services;

- The management interface implemented support the service instances configurations management, including their classification and replication mechanism;

- Support the development of management interface instrumentation for heterogeneous service implementations. Such instrumentation must be developed by the implementation vendors to avoid disclosure of the service's implementation details and improve management efficiency;

- Present the lowest footprint possible into the network node performance. In order for this to be performed, the agent should be kept simple and efficient.

4.3.4 Configuration Management Protocol

The specification of a configuration management protocol is vital to the efficient enforcement of the MiNSC's management operations to the configuration agents. The requirements for an efficient configuration management protocol have been studied for a long time [11, 42]. However, given MiNSC's management specificities (namely for a standard configuration management interface, efficient and secure protocol operation) the previous requirements were redefined [44] to effectively deploy MiNSC's configuration management operations. The following list summarizes the most important requirements for the use of a configuration management protocol within the MiNSC's framework:

- It must support a standard configuration management interface. Given the mid-level purpose of MiNSC's architecture, a standard configuration management interface would promote high-level management applications' interoperability and wide use of the MiNSC framework;
- The configuration management protocol must provide an efficient (with the smallest impact possible for the networks operation), secure (providing user access control, authentication and message encryption) and reliable operation (error free and message delivery assurance);
- Management data may have a large volume at times. In this case, the configuration management protocol must provide an efficient method to transport management data by using, for example, data compression mechanisms;
- A basic set of configuration management operations must be supported such as *Get*, *Set*, *Delete*, *Modify* and *Notification* which will serve as a basis for the development of advanced operations such as *Backup*, *Restore* and *Replicate*;
- The management interface must provide a data model definition language with a balanced compromise between its expressiveness and flexibility, enabling the strict representation of data models that ensures management applications interoperability.

Even though there exist several configuration management protocols that are able to accommodate the previous requirements, some were developed (or are commonly applied) in network management contexts such as SNMP, NETCONF or HTTP-based transport protocols. SNMP is the most popular network management protocol mainly due to its simplicity in terms of use and implementation as well as the interoperability provided through a well known management interface. It is used mainly for monitoring applications due to its initial security limitations. This historically deviated the SNMP's usage from configuration management operations. The MIB implementers also fail to develop useful objects for configuration management [11] relying on proprietary implementations to ensure the device configuration management. The NETCONF protocol was developed to address the configuration management limitations of SNMP. It possesses a group of advanced functionalities developed especially for the configuration management of IP devices. However, due to the fact that it is a recent protocol, it is not as widely used as SNMP. Finally, HTTP is a generic application data transport protocol that can also be used for network management operations. HTTP has the advantage of possessing several development tools and of being a highly flexible protocol due to the use of XML-related languages. On the other hand, it is not widely used within network management contexts and its extreme flexibility may impose interoperability problems which can be a detrimental factor [28]. Taking into consideration the identified set of requirements for configuration management operations, their deployment as MiNSC's configuration management protocol was evaluated, and the results are depicted in Table 4.1.

SNMP

The second and third versions of the SNMP protocol are no longer insecure and unreliable network management protocols, implementing a USM [198] and VACM [199] security models. The security model defined in USM is responsible for the algorithms that ensure user authentication and message encryption/decryption mechanisms. Secrets keys are shared by managers and agents for authentication and encryption. For example, the HMAC-MD5 and HMAC-SHA algorithms are available for authentication and CBC-DES algorithm for message encryption. VACM is responsible for the administration of the access rights to MIB objects. This restriction is performed in two dimensions: providing access to selected parts of the MIB or restriction to specific operations. The reliability of SNMP's data transport operations depends on the transport protocol used: the User Datagram Protocol (UDP) or TCP [200], depending on the management requirements.

Table 4.1: Configuration management protocols evaluation

Features	SNMP	NETCONF	HTTP
Authentication	✓	✓	✓
Access Control	✓	✓	✗
Confidentiality	✓	✓	✓
Reliability	✓	✓	✓
Data Compression Optimization	✗	✗	✓
Scalability	✗	✓	✓
Basic Operations	✓	✓	✓
Advanced Operations	✗	✓	✗
Interoperability	✓	✓	✗
Data Model Definition Language	✓	✓	✗
Data Model Definition Expressiveness	✗	✓	✗
Processing Requirements	✓	✗	✗
Available Implementations	✓	✗	✓
Wide Usage	✗	✗	✗

Scalability is one of the INMF's most referred limitations. When considering the traditional use of SNMP, having a central manager station performing monitoring tasks, periodically polling management agents, a large amount of agents (or when the number of objects to be pooled is very large) makes the polling period too large and in this situation, important monitoring information may be lost [11]. This scalability limitation is inherent to the manner in which SNMP is used regardless of the transport protocol. SNMP further amplifies this limitation (when using UDP data transport protocol) by requiring a larger amount of transactions between manager and agents to deploy management data. Other network management protocols (such as NETCONF) enable the realization of several management procedures in a single transaction. SNMP used in a distributed configuration management context, where there is no need for periodic pooling, makes it a valid alternative.

From the perspective of configuration management operations, SNMP only provides basic functionalities such as *Get*, *Set*, *Get-Bulk* and *Notification*, missing several advanced configuration management operations including support to rollback on configurations as well as configuration history representation. It is important to note SNMP's *Get-Bulk* operation. This operation enables the manager application to retrieve a large

portion of the agent's MIB with a single request. However, SNMP's Basic Encoding Rules (BER) are not space efficient (presenting an high degree of redundancy in the payload), allied with the non-use of data compression techniques, makes SNMP less efficient for large data transfers (even though a draft exists [201] for SNMP's payload compression).

MIBs represent an important element for the promotion of management application interoperability. It is a self-contained, well described and well identified hierarchical structure of management objects which are easily accessible through SNMP. When speaking in terms of the definition of data models, the SMI is extensively refereed as being highly limited in its expressiveness because it misses a lot of object-oriented programming concepts and rules [153]. However, such a constrained set of management data definition rules makes the MIB a highly interpretable interface reducing management application interoperability issues. From MiNSC's early information model implementation perspective, since they are initially constituted by a small group of classes containing solely attributes (and not methods), associated trough a UML *Composition* relation, SMI language representation based on tables and table pointers is sufficient. Besides, SNMP is a very mature technology, with several tools available for the development of SNMP-based management solutions, also including the development, validation and implementation of MIBs.

NETCONF

NETCONF is an ambitious project which tries to solve some of the most relevant SNMP's configuration management limitations. The IETF's NETCONF protocol provides an advanced set of features which accommodate the configuration management requirements of current and future networks. It is a recent proposal whose standardization occurred in September of 2006 [27] and it's data model definition language occurred in October of 2010 [28]. NETCONF provides a reliable and secure provisioning of configuration management operations which can be elaborated using the following data transport protocols: SSH, TLS, BEEP and SOAP. However, NETCONF is not confined to the previously mentioned data transport protocols and many others may be used as long as they are connection-oriented, providing a reliable and sequenced data delivery, and include support for authentication, message integrity and confidentiality. Access Control was not addressed in NETCONF's initial specification. However, a recent proposal already addresses the issues associated with NETCONF's lack of access control (NETCONF Access Control Model (NACM) [202]) by creating a standard mechanism which

will restrict operations and contents for each authorized user. NETCONF implements a document oriented configuration management approach with data being encoded in XML. XML's excessive verbosity represents a considerable limitation for a NETCONF operation incurring into high overhead in the communication when a small number of objects is being managed. The initial specification does not address data compression mechanisms even though some work is done to address this problem [203, 204].

NETCONF is still a recent configuration management protocol and extensive evaluation is required to access its capabilities. It is based on the client-server paradigm but improved scalability is obtained by requiring a single client-server transaction to deploy a large number of management operations. Such capability is frequently compared to SNMP over UDP which requires a larger number of transactions specially when managing a large number objects [205]. However, the XML data encoding, processing and manipulation is not trivial and when it is performed at managed elements containing limited resources, some performance limitations may be introduced. This is further enhanced with the use of compression and encryption algorithms that incur in further processing requirements, so it is important to maximize the efficiency of auxiliary tools, like XML processors and encryption tools [206]. NETCONF defines, just as does SNMP, a management interface called *datastore*. This datastore works as a database by storing the managed element's XML configuration (including the state information). The datastore structure is defined by the NETCONF's data model definition language, YANG, which provides a standard way to define NETCONF's management data models. The specification of a standard management interface (including the standard data model definition language) and a standard configuration management protocol ensures the NETCONF based management applications interoperability.

Considering the configuration management operations provided by NETCONF, only the basic set of operations are available by default. However, an advanced set of operations may be provided as *Capabilities* to complement the basic operations, resulting from the capabilities negotiated between the manager and the agent. This maximizes the operational capabilities of both ends. The basic operations defined for the management of configurations defined in datastores include: *get*, to retrieve the managed element running configuration and state information; *get-config*, to retrieve a specific part of a datastore configuration; *edit-config*, to modify all or a specific part of a datastore configuration; *copy-config*, to create or replace a datastore configuration with the contents or another datastore; *delete-config*, to delete configurations belonging to a specific datastore; *lock*, to lock a datastore configuration for concurrency purposes; *unlock*, to release a previous lock. The advanced operations include, among others, the following

capabilities: *writable-running capability*, to refer to the capability of the agent to write on the running configuration datastore; *candidate configuration capability*, to refer to the agent's support for candidate datastore; *confirmed commit capability*, to request the response, in a given time period, as to the execution of a configuration management operation. In case of timeout the manager and agent configurations revert to the previous sate; *rollback on error capability*, to refer to the capability of the agent to rollback to a previous stable state; *validate capability*, to refer to the capability that performs content verification in a datastore; *distinct startup capability*, to refer to the capability that defines a managed element startup configuration datastore.

NETCONF standards were defined during the last years including its data modeling language. Initial experimental implementations are being developed and tested. A long path is expected for NETCONF when it comes to wide usage. However, it provides the means to cope with today's configuration management requirements while having space to evolve and reach for new functionalities.

HTTP

HTTP [207] is an important data transport protocol for general use being very popular for the retrieval of web pages. Due to its vast popularity, it has a wide community of developers with several tools and APIs supporting the development of HTTP-based solutions. HTTP provides a generic and simple data transport operation supporting several types of payload data through a reliable and secure data transport operation using TCP and TLS [208, 209]. For data compression HTTP specification [207] has defined *GZIP* [210], *Compress*, *Deflate* [211] and *Identity* even though others could be used. It has implemented a basic access control mechanism based on user authentication. The two standard user authentication methods available for HTTP are found in [212] and include:

- The most conventional form of authentication is the *Basic Authentication*, where the user sends its authentication credentials within a *base64* encoded string to the server which can easily be intercepted and decoded. This authentication method is not considered a secure procedure;

- The HTTP's *Digest Authentication* employs increasingly sophisticated security mechanisms based on hashes to ensure the users's authentication. This scheme does not encrypt the message, rather it creates an authentication method which avoids sending the user's credentials in clear. When a client requests a resource

using a Digest Authentication, the server replies with a nonce (a unique server-specified data string), then the client executes an MD5 hash of the username, password, the URI of the desired resource and the nonce sending it back to the server. The server verifies the hash sent with its own calculation of the same elements and in the case of a match, the user authentication is performed.

In order to identify the resources present on the server HTTP defines URIs. Allied to this identification is a group of methods which provides a basic set of actions to be performed on server resources. Some of those methods defined by the HTTP specification include:

- *Get* method that is issued by the client to obtain a server's resource representation;
- *Post* method that is issued by the client to send an entity containing arbitrary data to the server for processing. The URI sent in the message identifies the processing application;
- *Put* method that is issued by the client to command the server to store a resource representation on the URI sent in the message. For security reasons, the use of this method may be prohibited;
- *Delete* method enables the client to erase a resource representation (identified by an URI) present on the server. However, just as the *Put* method, it is subject to security restrictions.

From the network management perspective, this set of methods provides the basic set of functionalities required with the exception for the support of notifications. HTTP implements a client-server architecture with one manager station managing several network elements. Due to the fact that HTTP is a generic data transport protocol, it does not contain a self-contained management interface and data model definition language. However, since HTTP is commonly used to transport XML data, the XSD document definition language can be used to define management data models. According to [28], the use of such a generic language for a data model definition may introduce interoperability limitations due to the language's extreme flexibility, enabling multiple forms of model definition. In order to be applied in the context of network management, tight data model definition languages are preferred because they reduce the definition ambiguities that may result. The use of XML also contains advantages when representing management data based on complex data models. Using XML over HTTP protocol provides a document-oriented management approach by using a single transaction between

manager and agent to perform several management operations over a large set of management objects. This improves scalability, however it is also important to ensure that the XML processing tools present at agents perform efficiently when manipulating large files to avoid performance degradation. The HTTP protocol gained visibility in network management for its flexibility, carrying management data encoded in XML, which can be easily visualized in any traditional web-browser. However it never gain wide usage as other network management protocols.

Configuration Management Protocol Evaluation

Table 4.1 depicts the evaluation of the previous configuration management protocols according to a group of functionalities considered relevant for the provisioning of configuration management operations in MiNSC framework. Table 4.1 indicates a clear difference between the HTTP protocol and the other two in terms of the management functionalities provided. Such differences demonstrate HTTP's inability to be used in MiNSC's architecture since it does not provide important functionalities that would be decisive for its usage. The HTTP's main limitations are inherent to the protocol's generic purpose which, when associated to a general purpose data model definition language, may incur in interoperability's limitations in the context of configuration management. The HTTP protocol is not widely used for management tasks, which represents an important factor as an easy integration with existing management solutions is an important requirement. In addition to this, the HTTP protocol does not provide an advanced group of configuration management operations, being limited to a group of methods built to enable an efficient operation in the web environment lacking, for example, the notification definition. Besides, HTTP lacks a well defined and self-contained interface for the managed resources description and identification (such as a MIB).

SNMP and NETCONF represent the strongest candidates that can be used within MiNSC's distributed framework. Regardless of their considerable differences (SNMP has been historically used for monitoring purposes while NETCONF was born from INMF's configuration management limitations), they present important similarities considering their usage in MiNSC's framework:

- Both protocols provide a reliable and secure configuration management operation with authentication, confidentiality and access control. Even though the access control is not part of NETCONF's initial specification, a draft has been proposed;

- Both protocols promote management application interoperability through the implementations of standard languages to define the management interfaces. However, NETCONF's data model definition language (YANG) was standardized recently and extensive study, development, implementation and deployment is yet to occur before it reaches the INMF's SMI maturity. For this reason, the implementation of NETCONF might still incur into some interoperability limitations;

- A considerable amount of implementations and development tools are available for both protocols. However, due to the fact that NETCONF is still a recent protocol, many of the implementations available are still being developed. On the other hand, SNMP provides a stable set of implementations and APIs for the development of SNMP-based applications with a large number of tools, including for the specification and validation of MIBs;

- The basic set of configuration management operations is provided by both protocols enabling the retrieval, update and deletion of managed object's values as well as notification support;

- Both protocols are still not widely used for configuration management operations. SNMP is mostly applied for monitoring tasks and NETCONF has not gained wide acceptance yet. However, the use of the SNMP protocol for configuration tasks involves a small effort since the protocol has defined methods to change the object's state by requiring only the provisioning of configuration management objects in the MIBs.

On the other hand, some relevant differences must also be considered:

- SNMP lacks the advanced set of configuration management operations provided by NETCONF that includes the locking of configurations (for concurrency support), rollback on errors, configurations with time validation, negotiation of features with agent capabilities, configuration validation, atomic configuration operations, history, among others;

- The design simplicity of SNMP makes it much simpler to implement (at the agent level) and use by pushing the management complexity towards the management application. In this sense, lightweight agents are the only requirements. On the other hand, NETCONF requires advanced (and intelligent) agents with increased

resource consumption. NETCONF agent design and implementation must be carefully performed due to the fact that processing large XML files may reduce performance;

- SNMP is a widely used network management protocol while NETCONF is taking the first steps in the network management world. Thus, in the perspective of enabling integration with contemporary network management applications the use of SNMP has considerable advantages: the same protocol and agents are used requiring only support for the proposed standard-based models. Furthermore, NETCONF is not used for monitoring management, so a management domain would have to use different technologies for monitoring and configuration;

- SNMP and NETCONF performance has been studied in several works [146, 205]. Their main conclusion refers to an enhanced performance of NETCONF when the number of managed objects is considerably large. When the number of objects is lower, NETCONF's excessive overhead (due to XML data coding) leads to performance degradation. In opposition, SNMP provides an improved performance when the number of managed objects is lower due to its low overhead. With an increased number of managed objects, SNMP requires a higher number of transaction which may result in a scalability issue. However, this analysis takes into account the usage of SNMP over UDP protocol which should not be directly compared to NETCONF's usage of the TCP protocol;

- NETCONF's data model definition language supports a higher degree of expressiveness enabling the application of object-based oriented concepts such as inheritance or hierarchy. This enables the representation of much more complex data models than INMF's SMI.

Considering the evaluation of both protocols, the author decided to use SNMP as MiNSC's configuration management protocol due to the following reasons:

- SNMP seems to be the best alternative to promote a smooth integration with contemporary network management applications. The success of NETCONF is still unknown. There is no way to predict if it is ever going to be widely used or not. On the other hand, SNMP is already widely deployed and if it is used in MiNSC, it will facilitate integration with existing management solutions;

- MiNSC is independent regarding the configuration management protocol used. It merely uses the protocol to provide a reliable and secure channel for the provisioning of the framework's element configurations. The protocol implemented can change in time, along with the configuration management requirements;

- Future transition from the use of SNMP to NETCONF is possible and simple. In the case of more complex management data models or requirements for more advanced configuration management functionalities, it is easier to migrate from SNMP to NETCONF than the other way around;

- MIBs and SMI provide a well known and mature technology with a lot of development and validation tools. Those tools are extensively experimented and tested providing a smooth path for implementation of a real prototype;

- Most of INMF's scalability evaluations use its traditional implementation through a centralized architecture which results in a low scalable operation. When used in a distributed management architecture INMF's (potential) scalability limitations should be mitigated. In MiNSC, the configuration management process is distributed by a group of ACS servers. Besides, the use of the TCP transport protocol adds the capability to send in a single transaction an unlimited amount of Get/Set operations, addressing the scalability issues for the management of a large number of objects. From an empirical point of view, even though a network element may contain a large number of managed objects, not all objects are managed at the same time, or all the time;

- In order to maintain management application simple (within a management domain), and since SNMP is already widely used for monitoring a SNMP-based configuration management solution must be pursued to avoid duplication of technologies.

SNMP and NETCONF provide valid alternatives for MiNSC's overall configuration management technology. According to the previous analysis, SNMP seems to have advantage at this moment so it was the one selected, however thanks to MiNSC's independence (from the configuration management protocol), the use of SNMP is not definitive and can naturally evolve towards the use of a more advanced solution, such as NETCONF.

4.3.5 Security

The security of distributed systems assumes a greater importance with direct repercussions on their performance, reliability, availability and others. From a distributed system perspective, security must be provided by two main parts [213], one that deals with the security of the communication between remote processes (or users), using a secure channel that ensures authentication, message integrity and confidentiality. The other part deals with the management of authorization, ensuring that a process (or user) is only granted access rights to perform the operations that it is entitled to.

The implementation of a secure channel, between remote processes, is required in order to avoid the most common forms of security threats such as unauthorized access to data (solved through confidentiality), unauthorized modification of data (solved through the implementation of mechanisms that ensure message integrity) and unauthorized activities (solved through authentication). So, the most common way of providing a secure communication channel requires the authentication of all communication parties, verification of the message integrity and encryption of the message content.

It is important to note that authentication and message integrity cannot be dissociated. In order to verify a communication party authentication, the message integrity must also be ensured. Even though the message integrity is ensured, its origination must be verified. Some of the security mechanisms used for authentication include: the *authentication based on a shared key*, where the sender and the receiver share the same authentication key (without message encryption this mechanism can be easily defeated through a reflection attack). The scalability of this method is also questionable due to the fact that in a network with N hosts, each host must share the keys of N-*1* hosts (assuming the communication among them) which, in case of a large N, can lead to a scalability problem; the *authentication using a key distribution system*, which implements a centralized alternative through the implementation of a *key distribution center* managing the N system's keys. Scalability and reliability problems are also introduced by this centralized mechanism. Once compromised, the key server enables the unauthorized access to all systems; the *authentication using public-key cryptography* which is the most popular way to perform authentication relying on the distribution of public keys to elaborate authentication.

Message integrity is another important security mechanism which ensures that the message content was not changed during the communication channel transport, or if content was changed this can be verified by the receiver. There are several alternatives to perform message integrity verification, *digital signatures* is the most obvious option. It

can be used with public key encryption to verify message integrity (with some processing costs). A message digest of fixed length is created, resulting from a cryptographic hash function computed from the message. The message digest is sent along with the message to the receiver and is used to verify whether or not the content was changed.

Confidentiality ensures that the message content is hidden from unauthorized parties and is performed through message content encryption. Such encryption can be performed using shared keys or the receivers' public key.

When requiring the remote invocation of an operation over someone's objects within a client-server architecture, the verification of the requester rights to perform such operation by means of an access control is involved. Controlling the access to someone's objects involves enabling their invocation (to access their state), their management (such as creation, deletion, renaming, etc) and their methods invocation. Three similar methods can be used in order to perform access control [213]: i) implementing *access control matrix* where each row represent a user and columns represent objects. The access control is defined by a matrix *M[u,o]* listing the operations that each user(u) can perform on the objects(o). However, if a large number of users and millions of objects are in place, the matrix implementation is not the most efficient method; ii) associating *Access Control List (ACL)* to objects listing the operations that each user is able to perform; iii) associating each user with a list of operations that can be performed on each object.

SNMP's Security Model

The second and third versions of INMF introduces important security measures to the most widely used network management framework. The security mechanisms implemented are well described in the USM [198] model, which is responsible for authentication, encryption and integrity of the SNMP message and the VACM [199] model, which is responsible for the MIB objects access control functions.

The USM provides important security mechanism related to the communication channel. When performing authentication procedures, each communicating participant must share a secret authentication key. The sending entity includes a Message Authentication Code (MAC) in the SNMP message whose generation is based on message content, sender identification, transmission time and the secret authentication key shared between sender and receiver (the initial definition of secret keys is outside of the SNMP scope). The receiving entity uses the same shared authentication key to calculate the authentication code again. If the code sent in the message matches with the one calculated at the receiver, the sender entity is authenticated and message integrity is verified. The

USM specification recommends Message Digest 5 (MD5) and Secure Hash Algorithm 1 (SHA-1) algorithms in collaboration with the Keyed Hashing for Message Authentication (HMAC) algorithm to compute a message digest to be placed in the SNMP message. The HMAC algorithm uses a secure hash function (MD5 or SHA-1) to produce the MAC. The USM specification has defined two alternatives for authentication protocols:

- HMAC-MD5-96 that uses the MD5 security hash function and a 128 bits authentication key to generate a 128 bits MAC truncated to 96 bits;
- HMAC-SHA-96 which uses the SHA-1 security hash function and a 160 bits authentication key to generate a 160 bits MAC truncated to 96 bits.

In order to guarantee communication confidentiality, an encryption method is applied. Just as for the authentication method, a secret encryption key is shared between sender and receiver. When required, all sent traffic is encrypted by Data Encryption Standard (DES) using the secret encryption key and the reverse operation is performed at the receiver using the same key [214] and encryption algorithm. For the realization of the encryption operation, USM recommends the Cipher Block Chaining (CBC) mode of the DES algorithm and a 128 bits privacy key. The model uses two cryptographic functions: one for privacy and the other for authentication. They require two separate secret keys to be shared between the communicating parties which are not accessible with SNMP's interface.

The USM specification also defines a *timeline* mechanism to guard against message delay or replay (which consists in a type of flow manipulation attack), requiring a message to be delivered within a reasonable time window. Using a synchronization mechanism, the SNMP's sending engine estimates the time for the remote engine (at the message receiver) and this value is placed in the outgoing message. If the time of the incoming message is greater than the receiver engine's local time (within a differential of 150s), the message is considered authentic. If not, it is considered not authentic and the indication *notInTimeWindow* is returned to the calling method.

The VACM model is responsible for the verification of whether or not a requested operation to a specific part of an MIB is permitted or not. Such access control is performed by the SNMP agents processing requests from managers and verified at a PDU level. The goal of the VACM model is to enable SNMP agents to implement differentiated access levels (to its MIB) to different managers. The access restriction is performed in two different ways: it restricts the access to certain parts of the MIB or restricts the operations a manager is able to perform over a certain part of the MIB [214].

The VACM model specifies the MIB's access rights based on groups, where each user is included in a group. Different groups may have different security levels. The VACM model enables separate definitions of the sender identity, authentication information, access control, MIB view and others. Security in SNMPv1 relied solely in the *community* concept. SNMPv2 and SNMPv3 include substantial improvements in terms of flexibility and functionality (at the security level) when compared to SNMPv1.

MiNSC's Security Model

MiNSC's security model is tied to the security model provided by its configuration management protocol. In this sense, MiNSC implements the SNMP's USM model to ensure the communication security between framework elements and the VACM model for access control. It is important to note that INMF does not define any sort of standard method for the configuration of its security mechanisms (USM, VACM). Since their configuration is not accessible through the SNMP protocol, the setup must be included in MiNSC's configuration interface. This means that MiNSC also shares the same security limitations as SNMP. The following lists some of the most popular security attacks and how they are resolved by SNMP based on the description presented in [215]:

- The use of shared keys makes SNMP prone to brute-force attacks in an attempt to find SNMP's authorization and encryption keys. However, [97] defines an algorithm for mapping from the user's password to the authorization and encryption keys that besides enabling a simple definition and use of keys slows brute-force attacks. Two different passwords can be defined in order to generate authentication and encryption keys. The *localized key* process is described in [97] where different keys are used for different agents related to the same manager. The most important implication of this process is that if an agent's key becomes compromised, the remaining keys does not;

- Message stream modification is an important security problem. Since SNMP is most commonly designed to operate over a connectionless transport protocol, messages can be recorded, reordered, delayed or replayed to perform unauthorized management operations. This security limitation is resolved by using a connection-oriented transport protocol. Timeline verification of messages can also be used to mitigate this problem;

- The masquerading attack refers to the request of operations in someone else's role. This occurs when the attacker succeeds at acting as an authorized manager. One

way to perform a masquerade attack is by using spoofed addresses. This can be resolved by using USM's authentication mechanism;

- Modification of information is performed when a third party is able to intercept the message transmission and modify its content. This way, the attacker can use messages from an authorized entity to perform unauthorized management operations. This type of attack is performed by modifying the management PDU while maintaining the authentication information. In order to deal with this security threat, the USM's message integrity must be implemented;

- A disclosure attack refers to the access of confidential information by sniffing non-encrypted network traffic. An attacker can observe the message exchange between manager and agent to learn the values of managed objects or notifications to be used in other attacks much like masquerading. Message encryption is one way to mitigate this problem;

- A Denial of Service (DoS) attack in SNMP refers to the blocking of message flow between manager and agent. Commonly a DoS attack is a result of other security threats and so preventing this type of attack is complicated;

- Traffic analysis refers to a situation where an attacker observes the general traffic pattern in order to be able to derive future attacks. Due to the periodicity of management procedures, the prevention of this type of attack is also very difficult.

4.4 Functional Model

In this section MiNSC's functional model is presented in order to better understand its functionalities. In this sense, the individual functionalities enabled by both management layers are described followed by the functionalities obtained when integrated into a single framework.

From the *Service Management* layer perspective, the following list of activities comprehend MiNSC's most important functionalities that can support a scalable, resilient and independent network service configuration management framework. However, these sets of activities are not final and further functionalities may be introduced to evolve MiNSC's capabilities.

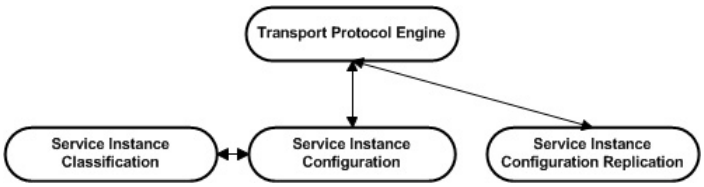

Figure 4.4: Network Service Instance Management layer functionalities graph

4.4.1 Network Service Instance Management Layer

The *Network Service Instance Management* layer realizes the activities related to the management of heterogeneous network service instances, unified through the implementation of standard-based information models on a standard interface. This creates a unique management data model. Therefore, the following activities are performed at this level:

- *Service Instance Classification*, the configuration agents present in the network service instances enable the management of their classification by activating and deactivating the service execution in accordance with the configurations assigned by the ACS servers;
- *Service Instance Configuration*, the configuration agent's MIB enables the network service configuration management by implementing a unique data model. Enabled activities include the modification, addition and deletion of configuration data elements;
- *Service Instance Configuration Replication*, is used by CSI servers to automatically replicate the ASI independent configurations. Adaptation of configurations is also performed.

The graph depicted in Figure 4.4 provides a simplified view of the *Network Service Instance Management* layer functional dependency.

4.4.2 Service Management Layer

The *Service Management* layer supports a group of functionalities based on the configurations universality provided by the *Network Service Instance Management* layer:

- *Server and Instance Serialization*, this functionality is responsible for the calculation and registration of service instance classification considering the service in-

stances available, their weights (administratively defined) and the service redundancy distribution level pretended. This functionality is performed by the CPS servers, to distribute configuration servers, and by the ACS servers, to distribute network service instances;

- *Network Service Deployment*, uses service meta-configurations to perform the automatic calculation of each service instance configuration (at the *Network Service Instance Management* layer). In order to perform this task, *Server and Instance Serialization* is used to compute the service deployment pattern, graduating the service instances available;

- *Instance Expansion*, uses the configurations replicated to physically extend network service instances, transforming candidate instances into active. This is performed by load-balancing of configurations and is used to improve the managed service scalability;

- *Server Expansion*, used to improve a configuration service scalability following the same foundation as instance expansion functionality;

- *Instance Migration*, performed by the ACS servers to migrate a faulty ASI service execution to a CSI using replicated configurations. This functionality improves the managed service resilience, mitigating any instance failure identified by the monitoring system;

- *Server Migration*, performed by CPS servers to migrate a faulty ACS service execution to a CCS using replicated configurations. This activity improves the configuration management service resilience;

- *Service Management*, this activity is performed when the service meta-configurations are changed and a new *Network Service Deployment* must be executed to compute new service instance configurations;

- *Server Configuration Replication*, this mechanism is used by CCS to automatically replicate (and adapt) the ACS independent configurations. This enables the migration of configuration management activities between servers;

- *Server Classification*, the configuration agents present in the configuration servers enable server classification management, activating and deactivating the management activities based on the configurations assigned;

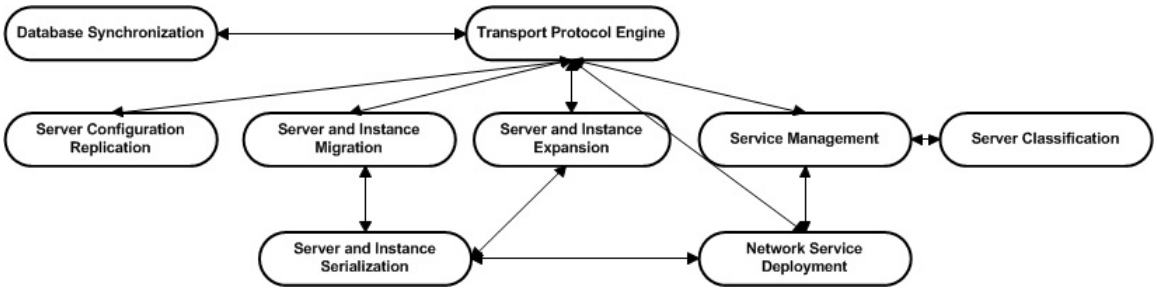

Figure 4.5: Service Management layer functionalities graph

- *Database Synchronization*, used by CPS servers to improve their scalability and resilience. The database, storing the configuration server's registration, is shared among all servers available within a domain. In case of failures, any CPS can be used as interface with management applications.

The functional model implemented by the *Service Management* layer is depicted in Figure 4.5. The model includes four main functionalities under which the execution of all the others depend on:

- *Server and Instance Migration*, this functionality uses the configurations previously replicated to migrate the service execution from an active to a candidate element. The *Server and Instance Serialization* functionality is used to obtain the graduated list of servers/instances available for migration;

- *Service Management*, this functionality is responsible for the service meta-configuration management. When new meta-configuration are defined this functionality is responsible for making them effective in network service instances. Changes to the service meta-configuration commonly involve changes the managed service behavior, not directly related to its resilience and scalability improvement methods;

- *Service Expansion*, this functionality is responsible for increasing the number of active elements supporting a service, improving its scalability. The *Service and Instance Serialization* activity is used to obtain the graduated list of servers/instances available for expansion. This functionality uses the configurations replicated to perform load-balancing;

- *Network Service Deployment*, this functionality performs the automatic computation of each network service instance configuration, according to the defined service meta-configurations. To implement this functionality, the *Server and Instance Serialization* is used to compute the service deployment pattern. Then, *Service Management* functionality will deploy each instance configuration.

Given their importance, some functionalities shall be further discussed in the context of each layer.

4.4.3 Server and Instance Configuration Replication

The configuration replication procedure (performed at both layers) takes advantage of the configuration universality supported by MiNSC. Its usage should take into account the following considerations:

- This procedure automatically and periodically copies the framework's active element configurations to a candidate element. Given the independence provided by MiNSC's abstracted configurations, no configuration translation is required, even if source and destination elements use different implementations of software or hardware;

- This procedure aims to be a preventive measure for the eventuality of existing failures in MiNSC framework elements. In case of an active element failure, if its configurations can be localized within a candidate element, the service execution can proceed by replacing the faulty element. This operation is only possible due to the abstraction provided by MiNSC's configurations and it's distributed architecture with over-provisioning of network elements. This improves the framework's element resilience to failures;

- The configuration replication procedure also enables the realization of a load-balancing mechanism between active and candidate elements. This is performed by deactivating part of the active element's independent configurations while activating the same part at the candidate. This improves the service's scalability;

- The replication procedure can be realized using two different alternatives: one that includes only the active element's static configurations, which is referred as a *lossy* replication procedure, since the element's dynamic configurations are not considered; the other alternative includes the active element's static and dynamic

configurations, which is referred to as a *lossless* replication procedure. The framework element's static configurations do not change during service operation and defines its behavior, while dynamic configurations result from the service execution, complementing static configurations (such as a cache);

- Changing the active and candidate classification (or state) at the *Network Service Instance Management* layer (changing the managed service physical location) has important implications from the network service's client perspective. Therefore, two different methods can be used to migrate network service instance execution:
  - **Changing the service instance's physical and logical location**, means that the instance execution is migrated to a new physical location (new network service instance). This also means that all remaining instances that were not involved in the migration process, but have a configuration dependence, must be updated to ensure the service configuration consistency. This task is carried out by the ACS server responsible for the service configuration management. Migrating a service instance (to a new location) means that the service' clients must also be updated. In order to perform this task, the ACS server can use the client's DHCP, updating the reference for a new service instance instance. Then, a DHCP Server-Initiated Configuration Exchange [216] can be used to update the clients. If name to address translation is required, Dynamic DNS [217–220] can be used to update the instance's new address;
  - **Changing the service instance's physical location while keeping it's logical location** means that the service instance execution is migrated to a new physical location (new network service instance) however, the previous instance's logical location is kept. From the replication process perspective not only are the service instance configurations replicated, but also the source instance's logical configurations (such as the network address, network mask, gateway, among others) is as well. This means that, new logical configurations must be assigned to the faulty node. From the replicated service instance perspective, since its logical address is maintained, service clients and peer service instances do not have to be updated.

Its important to note that the configuration replication procedure works in thigh relation with the monitoring subsystem, which is responsible for the detection of service failures (or performance degradation), to improve services resilience. A serialization algorithm

that, in accordance with the management domain goals, performs the service instance classifications is also fundamental for the elaboration of the replication process.

Lossy Configuration Replication

A lossy configuration replication procedure uses MiNSC two layer infrastructure to replicate a service instance static configurations (at the *Network Service Instance Management* layer). In order for this to be performed, the service deployment procedure is repeated using a modified set of service instances. When a service is deployed, the service instances are classified as ASI or CSI. If failures are detected on a ASI and a lossy configuration replication is requested, the service deployment is repeated, excluding the faulty instance hose configurations are deactivated. This way, the faulty instance's static configurations are replicated to a different instance that will continue the execution of the managed service. For the execution of service deployment the service meta-configurations, defined on MiNSC's *Service Management* layer, are used.

Lossless Configuration Replication

The realization of a lossless configuration replication procedure means that the static and dynamic configurations of framework elements are considered. In order for this to happen, the element's configurations are automatically and periodically replicated from active to candidate. To promote a quicker migration of service execution, the replicated configurations are also adapted to include the destination element's details (such as IP address, domain name, etc). Since the replication process includes the framework element's static and dynamic configurations, data losses are mitigated, which promotes a smoother migration process.

4.4.4 Database Synchronization

MiNSC framework is based on the elaboration of configuration replication procedures to improve service resilience and scalability at both management layers. In order for this to be fulfilled, a synchronization mechanism must be used to ensure the integrity of configuration data between active and candidate elements. At the CPS server level, a synchronization mechanism is also used to disseminate the registration database among all available CPS servers. As the management data to be synchronized is present in MIBs, different alternatives can be used:

- At the configuration management agent level, the creation of a daemon, implementing an SNMP server that automatically and periodically copies the active element's configurations, storing the replicated configurations locally;

- Create a special instrumentation, for the configuration agent's MIB, that would store service configuration in a database. Then any standard database replication mechanism is used to synchronize active and candidate elements.

As previously referred, the first alternative was implemented for ASI and ACS configuration replication. This simplifies configuration agent's implementation by using the same configuration management protocol. However, this process gains higher complexity when considering the synchronization of CPS, where any server can be the source or destination of a synchronization procedure. On the other hand, this synchronization is expected to be infrequent, occurring only when the configuration management servers classification changes. So, the first alternative is costly and complex to implement because it requires periodic polling of all CPS server databases to search for updates. The second alternative requires a conversion to a database technology, for the replication and merge of different database versions, making the synchronization process also complex. One variation of the first alternative is possible, through the use of notifications and lock mechanisms:

1. When one of the CPS MIB is updated (adding, modifying or removing a reference), it goes into a *lock* state (using VACM) and a notification is sent to the remaining CPS informing about the existence of updates;

2. When the remaining CPS receive the notification they also *lock* their MIBs for updates. Then they perform an update of their references;

3. When all CPS MIBs are updated, the source CPS update is made effective, and the *lock* is released.

4.4.5 Network Service Deployment

The network service deployment is an important functionality supported by the management unification provided by the *Network Service Instance Management* layer and the service oriented management approach provided by the *Service Management* layer. This functionality uses the service meta-configurations (embedding the service behavior pretended) to calculate and deploy each service instance configuration (including

the configurations dependencies when several servers cooperate in a distributed fashion). MiNSC abandons the traditional server-oriented configuration management, using a two-layer configuration representation, which enables a service oriented configuration management approach. From a practical perspective, this means that a service is no longer managed by individually controlling its supporting servers. In MiNSC, a service is managed based on the overall behavior pretended which is latter translated into the servers configuration. The network service deployment functionality is implemented by ACS servers where the service meta-configurations are defined. The service management information models implemented include:

- Support for the configuration of standard functionalities and other configurations administratively required for service operation. This ensures homogeneous operation. When generating each service instance configuration their dependencies are also ensured;
- Support the definition of service redundancy distribution level, that is used in combination with a serialization algorithm, to physically distribute the network service execution between the service instance available. This means that the service redundancy distribution level is translated to the number of instances used and their classification.

The network service deployment functionality ends with the configuration enforcement into the corresponding network service instances, using a standard configuration management protocol.

4.4.6 Service Expansion

Service expansion is, such as the migration procedure, one of MiNSC's most important functionalities aiming to improve network and management service's support for larger scale domains. This functionality takes place at both management layers:

- At the *Network Service Instance Management* layer, the service expansion functionality increases the number of network service instances used for a service deployment, having direct influence on the service scalability. This activity increases the number of ASI instances, load-balancing part of their independent configurations replicated on CSI thus, extending the managed service physical support;

- At the *Service Management* layer, the service expansion functionality increases the number of configuration management servers used for management tasks, having direct implications on MiNSC's scalability. This activity, carried out by the CPS servers, increases the number of ACS servers activating part of their independent configuration replicated on CCS.

It's important to note that, regardless of the layer where it is implemented, service expansion is capable of improving a service scalability by increasing the number of elements. This is executed using the interface for the monitoring service, that, besides referring the existence of scalability problems, also identifies faulty elements. Once the problem is detected, MiNSC's ACS and CPS server's are responsible for acting accordingly and perform the load-balancing process to try to mitigate the scalability limitation. The load-balancing process deactivates part of the faulty element's configuration while activates the same part at a candidate element (using the independent configurations previously replicated), which increases the number of active elements available. This algorithm takes advantage of the configuration independence and can be applied regardless of specific service implementations. Besides enabling service extension (by dividing the framework elements configurations), it is also possible to do the reverse operation, concentrating configurations on a smaller number of active elements (and consequently increasing the number of candidate nodes). This enables an efficient resource management, using only active elements when they are required.

4.4.7 Server and Instance Serialization

To execute the framework element's classification (as active or candidate) a serialization algorithm is used. This thesis does not propose a final method to solve this problem, as it depends on the specificities of the management domain where it is used. The serialization algorithm is implemented with different goals, that are summarized by:

- Obtain a graduated list of network service instances used for the realization of service deployment, based on the domain's management goals. From the graduated list of network service instances and the service redundancy distribution level defined, instances become classified as ASI or CSI. Such classification contains important implications at the level of the network service' scalability, resilience and consumption of resources;

- The same process is used to classify the configurations management servers as ACS and CCS. This procedure has a direct impact on MiNSC's resilience, scalability and resource consumption;

As referred, the implementation of this algorithm depends on the domain's management goals and possesses important implications at both the network and management services. A few hints are provided as to the different strategies that may be followed when addressing this problem:

- *Manual* serialization, where the administrator manually graduates MiNSC's elements at both layers. While this is a viable alternative for small management domains, where it is easy to keep track of the network elements classification, this will not be adequate for large domains, where the implementation of manual procedures is a complex task;
- *Random* serialization is a viable alternative to the manual classification by performing an automatic graduation. However, since this procedure depends on a random process, the unreliability of classifications can incur into instability and unpredictability, which results in loss of control;
- *Dynamic* serialization is another automatic process, based on the definition of weights, to create a more flexible graduation. In this process, costs are assigned to instances and a cost minimization (or maximization) algorithm is used to choose a minimum number of elements that is in accordance with the administrative needs. This process possesses the advantage of benefitting from the fact that costs associated to instances can be dynamically updated (using, for example, a monitoring system), which means that the classification can change accordingly to their performance, creating a dynamic instance serialization process taking into consideration monitoring information.

The serialization of MiNSC's elements is not limited to the previous methods. Any method can be used as long as a graduated list is obtained. Each administrator should be able to use the method that is most adequate to its management domain and know how.

4.5 Resilience Improvement Method

The term resilience, applied to networks and services, was described [221, 222] as the ability of a network to provide and maintain an acceptable level of service in the eventu-

ality of failures or constraints to a normal operation. For this to be fulfilled, the authors add that network systems should include resilience provisioning methods. Besides, networked systems should be continuously measured to find failures (or constraints), verify service's operational state and performance degradation. An acceptable level of service is commonly described using SLA contracts, established between clients and service providers using quantitative parameters such as service availability, throughput, latency, packet loss, jitter, etc.

One way of improving the network service's resilience is by ensuring a normal execution in all instances. A normal execution is defined by the SLA contract established and verified by a monitoring system. The aim of MiNSC's resilience improvement method is to lower the impact of instance failure or performance degradation, that will impact the final service level obtained. The resilience improvement method proposed is based on the over-provisioning of network service instance and the periodic replication of independent configurations. This enables the framework elements execution migration in case of failure or performance degradation.

4.5.1 Over-provisioning

MiNSC's resilience improvement method is based on the over-provisioning of elements classified as active or candidate. A network service is deployed according to the SLA established which, among others, defines the number of elements physically supporting the service (classified as active). Beyond this group of elements another group is defined, classified as candidate, that periodically replicate active element's configuration. When failures (or performance degradation) is detected, candidate elements continue service execution with minimum data losses.

4.5.2 Cost-aware Management

The over-provisioning of framework elements implies additional resources, which has a financial repercussion. Nevertheless, candidate elements are expected to be shared with other network elements, thus mitigating the cost. Also, the use virtualized elements can reduce the total cost of ownership. The dynamic classification of active and candidate elements represent a dynamic allocation of resources. This enables a more efficient resource management, optimizing the cost involved.

4.6 Final Remarks

While simplifying the management of heterogeneous network service implementations, MiNSC also improves management functionality. However, important implications are also inherent to the application of this model. This will be identified and evaluated through a perspective of future evolution.

4.6.1 Standard Management Information Models

The implementation of standard management information models has been extensively used by several organizations such as:

- The IETF has defined several objects with different aims like:
  - The RFCs 2819 [223], 3014 [224], 3413 [225], 3418 [226] mainly used for fault management activities;
  - The RFCs 3165 [227], 3413 [225], 3418 [226], 4133 [228] mainly used for configuration management;
  - The RFCs 2819 [223], 4502 [229], 4711 [230] mainly used for device performance management;
  - The RFCs 4668 [231], 4669 [232], 4670 [233] mainly used for security management.
- The DMTF, through the definition of CIM [234], provides standard definitions for network management. Some of the concepts referenced by CIM include:
  - *Application*, that represents the information required to deploy and manage software products and applications;
  - *Database*, that defines the management components for a database environment;
  - *Device*, that manages the functionalities provided by hardware, including the management of their configurations and state;
  - *Network*, to manage the network's communication connectivity, services and protocol.
- The Tele-Management Forum (TMF) defined the Shared Information Data Model (SID) [235] to build an information reference model and common vocabulary with

business concerns for the telecommunication industry. The SID information framework is divided into eight layered domains, each one containing several business entities called Aggregate Business Entity (ABE) such as *Product*, *Service* and *Resource*.

The implementation of standard management models aims to create a well defined group of management references to be widely used and deployed, enabling the interoperability and integration of heterogeneous management solutions, and the dissemination of information between heterogeneous elements. This prevents the proliferations of non-interoperable and proprietary network management frameworks and defines a common group of functionalities that enables the creation of more efficient integrated management applications. While the implementation of standard management models represents an adequate method to integrate the management of heterogeneous elements, some problems are also found, which stem mainly from the standardization process, including the ones referred in [236] and that include:

- The standardization processes takes a long time to be completed. The standardization work groups are mainly composed by vendors and an agreement must be reached among their requirements. So, standardization is a complex and long process. Furthermore, the commercial pressure to introduce new functionalities (representing a commercial leverage) incurs into the implementation of proprietary management functionalities, unlikely to be widely used, thus creating management interoperability problems;
- Finding the right level of abstraction in standard management models is a complex task. A model cannot be too generic, since the definition of highly generic concepts leads to many different interpretations, which may incur into interoperability problems. On the other hand, the model cannot be too low-level because their applicability is lost (losing their integration purpose). A trade-off must be reached for model abstraction;
- The quality of the standard management models produced can be, at times, questionable for several reasons:
  - As previously referred, finding the right level of abstraction is a complex task;
  - The commercial pressure is a key reason to develop low-quality models;
  - The technological experts are not interested in participating in the standardization process due to commercial pressure.

From the previous reasons, and others identified in [236, 237], the implementation of standard network management models can be problematic. The implementation of such models is, historically, the most common way to avoid the proliferation of proprietary management solutions. However, in order to be fulfilled, the standardization process should be altered and made more expedite. In this sense, [236] proposes an approach that simplifies standardization process relying on an iterative, multi-layer management model. The proposed process can be summarized as follows:

1. A small team of experts in a given technology is gathered to build an initial conceptual model known as the *Lightweight Universal Information Model*. This model contains the core classes to manage a given technology including annotations that capture the rational of the expert's choices;

2. Then, management specialists derive management data models from the previous information model;

3. Vendors implement the proposed data models and create management applications to manage their products as soon as possible. Beta-test costumers are used to experiment the management functionalities, reporting bugs or provide comments that will help improve functionalities;

4. Further iterations improve the model specification based on the feedback provided by the beta-testers. So, based on the feedback, the final *Universal Information Model* is proposed;

5. New data models are specified for the diverse network management languages;

6. New implementations of the management data models are created by the vendors, including their management applications to be later sold to a large customer base.

MiNSC and the Standard-based Service Management Models

One of the consequences inherent from the implementation of standard management information models is the framework's inability to manage the service's non-standard functionalities. Even though those do not represent the most important ones, they commonly provide added-value features, that, associated with the standard functionalities can differentiate offers from several vendors. Therefore, two important conclusions should be taken: first, the software producers and device manufacturers will refrain from creating advanced vendor-specific (non-standard) features because they will become non-interoperable, and; if they really intend to implement their functionalities, this will push

them to work harder and faster to evolve the standards to include those functionalities. These problems affect all frameworks implementing standard models, such as WBEM, however, they enable the specification of non-standard extension models to support particular management needs. Obviously, this eliminates a sense of competition between software implementers. On the other hand, the competition is gained at different dimensions:

- From the perspective of the service provider, they become less limited to the group of service implementations available, being able to select the most adequate with the certainty that their management is ensured by means of standard models. This makes network service implementers compete in terms of the performance of their implementations and not in terms of number of extra functionalities;
- Most importantly, a new competition level is obtained at the management application level. While, currently, the network service vendors commonly provide service implementations and their correspondent management application, with MiNSC, such dependency is not necessary. So, service implementations and management applications are autonomous, enabling an important competition at the management application level and the functionalities they provide.

MiNSC uses minimalist standard-based service management information models, considering only the standard requirements for the service management and not vendor-specific requirements. This simplifies the standardization process while enabling the specification of service management models much quicker than finding an overall agreement on complex models.

4.6.2 Integrated Network Management

It is important to note that MiNSC is not an integrated network management framework as is FOCALE or WBEM, enabling the management of network elements implementing heterogeneous management interfaces or data models. Such type of integration must be necessarily conducted through the implementation of management translations. A different level of integration is proposed in MiNSC. That is, heterogeneous network service implementation can be effectively managed based on the association of standard-based service management information models and a standard management interface (representing unique data models), thus creating a new configuration management interface. This eliminated management translations from the management system. MiNSC's new integrated management perspective includes important concerns related to the service

scalability and resilience, besides simplifying and potentiating automation of service management tasks.

4.6.3 Confidentiality

Within MiNSC, a configuration management interface is used to provide the management independence to support the heterogeneity of service implementations. However, in order to make the management operations effective, access to important parts of the service implementation is required. For this to occur, high levels of integration is required between the management interface and the heterogeneous implementations, this provided through the interface's instrumentation. On the other hand, service implementers are not willing to disclose their implementation details to third party implementers, which endangers the effectiveness of the new configuration management interface.

In order to maintain service implementer confidentiality and still obtain high levels of integration, the development of a management interface instrumentation must be the service implementer's responsibility. The network service implementers are in the best position to achieve the best integration, between the configuration management interface and the heterogeneous service implementations, without disclose the implementation details.

4.6.4 Service Mobility

MiNSC's distributed architecture introduces an important concept: the service's physical mobility. Its capability to dynamically change the number of supporting instances has important implications, apart from those already referred (the service resilience and scalability improvement) that includes:

- Service expansion can be used to improve the resource allocation, increasing the number of elements when the number of requests increases and reducing their number when they are no longer needed (supporting effective resource management);
- The service's physical mobility can also be used to improve the network's efficiency and performance. In large networks, the service can be moved closer to the place where a high number of requests originate avoiding congesting the network and performance degradation.

To effectively implement service mobility a serialization algorithm is required, that dynamically computes instance classification in thigh relation with a monitoring system.

4.7 Conclusion

In this chapter, MiNSC framework is completely described. It considers a new integrated network service management perspective that does not rely on intermediary translation mechanisms to manage heterogeneous network service implementations. MiNSC framework is based on the implementation of standard-based service management information models, enforced through a standard management interface, that creates a unique data model eliminating the necessity of using management translations. The proposed framework is built over two layers that also simplifies network service management, by automating some management procedures and by enabling a more efficient resource management. However, MiNSC's proposal also includes some limitations, namely the dependency on standardization processes and the required support of service vendors to create adequate instrumentations for their products, according to MiNSC's configuration management interface.

Chapter 5

Implementation and Results

In this chapter a MiNSC based prototype is described and experimental results are discussed as a mean to demonstrate the framework's capabilities. The chapter also includes the standard-based information models for DNS service management, sub-divided by MiNSC's management abstraction layers, including their MIB implementations. The development tools used for the prototype implementation are presented in the following sections, along with the description of the main modules developed and algorithms applied by the framework elements. A set of experiments using the developed prototype is also described and discussed. The results will vouch for the prototype usefulness and MiNSC validity.

5.1 Motivation

The prototype was created to provide a deeper understanding as to the effectiveness of the framework's most important features, besides evaluating the feasibility of its management model. The prototype implements the management of DNS service. This chapter specifies the corresponding management information models used. Two main components were developed for the experiments: a configuration server (ACS) and a configuration agent to manage heterogeneous DNS server instances. With both elements, features such as independence, resilience and scalability improvement methods were experimented. The algorithms applied are also explained here. The developed prototype represents an important contribution for the validation of the proposed network service management model, serving as an initial reference for latter improvements.

5.2 Architecture

As previously mentioned, the MiNSC's layered architecture relies on network service instances (at the *Network Service Instance Management* layer) and configuration management servers (at the *Service Management* layer). In order to fulfill the tasks assigned to each component, the architecture comprehends two fundamental elements: a **configuration management server** that includes the required modules to support the server's classification (ACS, CCS, and CPS), mechanisms to improve network and management services resilience and scalability, a standard network management interface to improve management application interoperability and a module to manage the lower-layer service instance's configurations; a **configuration management agent** that includes the required modules to support the service instance classification (ASI and CSI), mechanisms to improve network services resilience and scalability and a standard network management interface that unifies the heterogeneous network service implementations management based on a unique data model.

5.2.1 Configuration Management Server

The configuration management server is one of MiNSC's key components for building a distributed service configuration management framework. It is responsible for orchestrating the network service instance configuration, at the lower layer, ensuring that they comply with behavior administratively defined. The configuration management servers are implemented at the *Service Management* layer, through a distributed architecture, that uses the management independence provided by the *Network Service Instance Management* layer to simplify the management of heterogeneous network service implementations. Figure 5.1 depicts the structure of a configuration management server which is comprised by two parts:

- The *SNMP Engine* which enables communication between peer servers or service instances, in the MiNSC prototype. The SNMP's USM and VACM security models use TCP transport mapping, thus providing a secure and reliable message exchange;

- The *MiNSC Engine* is responsible for the execution of the advanced management operations such as service instance configuration management, server classification, instance serialization, service deployment, configuration replication procedure, execution migration, among others.

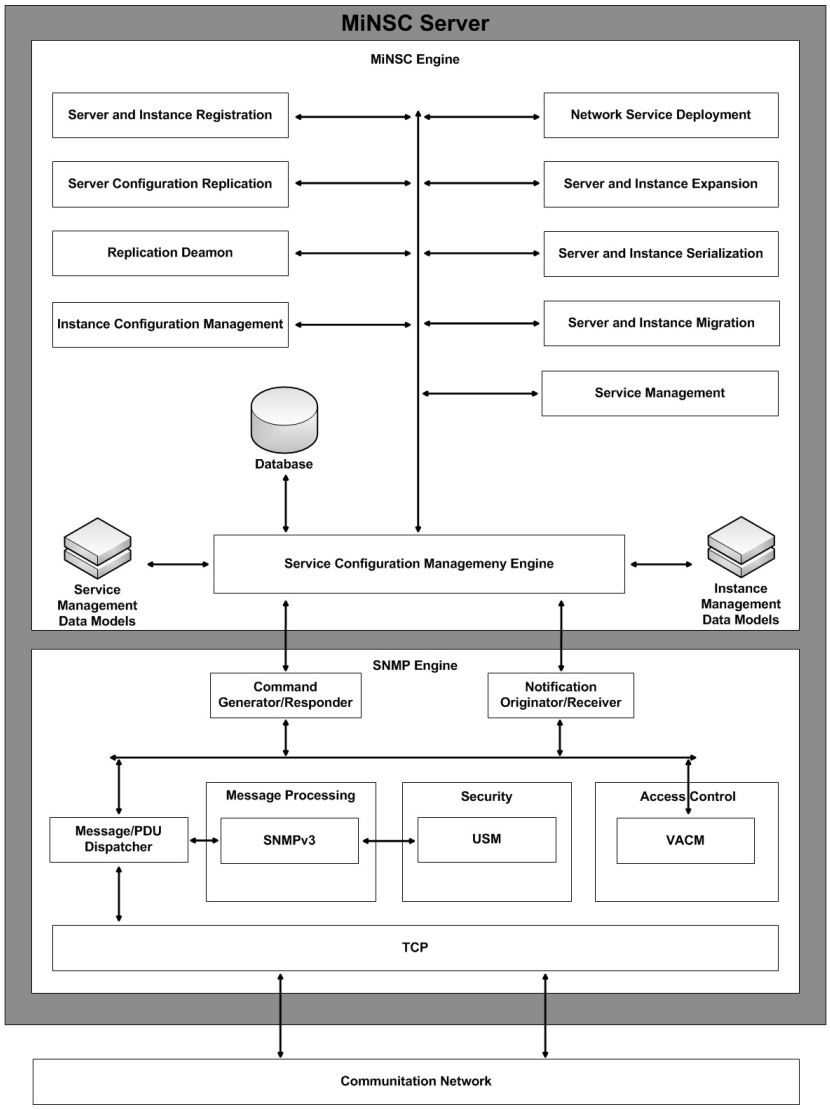

Figure 5.1: MiNSC's configuration management server structure

SNMP Engine

The SNMP Engine uses the manager's traditional structure with a few simplifications. Only SNMPv3 messages are supported (to ensure the message privacy, integrity and communicating parties authentication) and only TCP transport mapping is enabled (to ensure the reliability for the message exchange). Since the configuration management servers are intended for mid-level operation, they include a *Command Generator/Responder* module to generate and respond to requests as well as a *Notification*

Generator/Receiver module to send and receive notifications. Depending on the origin of the message, the *Message/PDU Dispatcher* module performs one of the following operations:

- When a message is generated at the MiNSC Engine, it is transferred to the SNMP Engine becoming an SNMP message PDU. The *Message/PDU Dispatcher* receives the PDU and uses the *Message Processing* subsystem to create an SNMPv3 compliant message where the PDU is encrypted (using DES algorithm) and the authentication and integrity codes are added (using MD5 algorithm) to the message headers. The SNMP message is then sent to the destination in an TCP segment;

- When the configuration management server receives a request message, the reverse procedure is performed. The *Message/PDU Dispatcher* retrieves the SNMP message from the TCP segment, sending it to the *Message Processing* subsystem to process in accordance with the protocol version. The *Security* subsystem is then used to decrypt the message, verify the sender's authenticity and message integrity. If the security verification is successfully completed, the message is returned to the *Message/PDU Dispatcher* to be redirected to the *Command Generator/Responder* module where the sender's access permission is verified (using the VACM model). If the permission is granted, the PDU is sent to the MiNSC Engine.

MiNSC Engine

The MiNSC Engine is responsible for performing the service management tasks at the configuration server level. Some of its responsibilities include: deployment of network service instance configurations, the orchestration of their behavior based on the service meta-configuration administratively defined, support for a higher service management abstraction to simplify the network service management activity, realization of a mechanisms that uses the distributed architecture and configuration independence to improve the configuration management service resilience and scalability. The MiNSC Engine uses the SNMP Engine to exchange reliable and secure messages with remaining elements, including the network service instances, management applications, peer configuration servers and monitoring systems. At the MiNSC Engine, MIBs provide a standard interface for the network service management and a database that is used to provide a non-volatile storage (for configuration operations history, network service configuration, instances and server classification, etc). The service management data models implemented at both layers must be included in the MiNSC Engine, in order to enable

configuration management operations at both layers. The varied modules used by the MiNSC Engine include:

- The *Replication Daemon* which is used when the server is classified as CCS and has to periodically replicate the ACS server's configuration. This daemon periodically synchronizes the CCS MIB with the ACS configuration either be replicating configurations to replace a faulty ACS server or to implement load balancing;

- When new service configurations must be deployed the *Server and Instance Serialization* module is used to find the best service deployment pattern according to the available instances and the service redundancy distribution level defined on the meta-configurations. This model applies an algorithm that, in accordance with the administrative goals, provides a graduated list of service instances available;

- The *Network Service Deployment* module is responsible for taking the service meta-configurations, and use the graduated list of service instances provided by the *Server and Instance Serialization* to calculate each service instance configuration. When performing the service deployment, the instance's *Replication Daemons* are also configured to activate the instance's configuration replication procedures;

- The *Server and Instance Expansion* module is responsible for the configuration management service and managed service physical extension. It performs a load-balancing procedure between active and candidate elements using previously replicated configurations. Upon receiving the indication for an expansion process (from the monitoring system or management application), a given percentage of the active element's configuration is deactivated while activating the same part at the candidate. This extends the amount of service resources by increasing the number of active elements;

- The *Server Configuration Replication* module is responsible for managing the execution of configuration replication procedures at the configuration server level. When the server is classified as CCS this module controls the *Replication Daemon* to automatically and periodically replicate the ACS configuration. Configuration adaptation is also done, to include the CCS details;

- The *Server and Instance Registration* module is used for referencing the classification of service instance and configuration management servers. It stores references (for a domain) as to which instances and servers were used for service deployment;

- The *Server and Instance Migration* module uses the configurations replicated to migrate the service execution from a faulty ACS to a CCS. This module is also used to orchestrate the migration process at the managed service instance level. Depending on the notification provided (by the monitoring system) this module deactivates the service execution on the ASI while activating on the CSI using the configuration previously replicated (when performing a *lossless* replication process). The module also supports the *lossy* replication process by repeating the service deployment with a different deployment pattern;

- The *Instance Configuration Management* module defines a generic interface for the network service instance configuration management. This modules is used when changes must be executed and is protocol independent;

- The *Service Management* module includes the managed objects instrumentation, defined by the service management information model. When new meta-configurations are defined, *Network Service Deployment* module is used to perform their deployment.

5.2.2 Configuration Management Agent

The configuration management agent is another relevant part of MiNSC's framework. It complements the framework elements by supporting the management unification of heterogeneous network service implementations, based on the association of standard technologies. The agent's structure, depicted in Figure 5.2, is composed by three parts, SNMP and MiNSC Engine and a group of heterogeneous network services instrumentations.

SNMP Engine

The SNMP Engine follows the agent's traditional structure [215] implemented with two important requisits: the agent only supports SNMPv3 messages (to ensure the authenticity, confidentiality and message integrity of communicating parties) and only TCP transport mapping is supported to ensure communication reliability. These impositions are shared with the Configuration Management Server. So, SNMP messages are received by the *Message/PDU Dispatcher* module using the TCP transport mapping. Those messages are then routed to the *Message Processing* subsystem for security verification in accordance to the included message headers. Since the agent only supports SNMPv3 security mechanisms, the USM subsystem is used to verify message security dimensions.

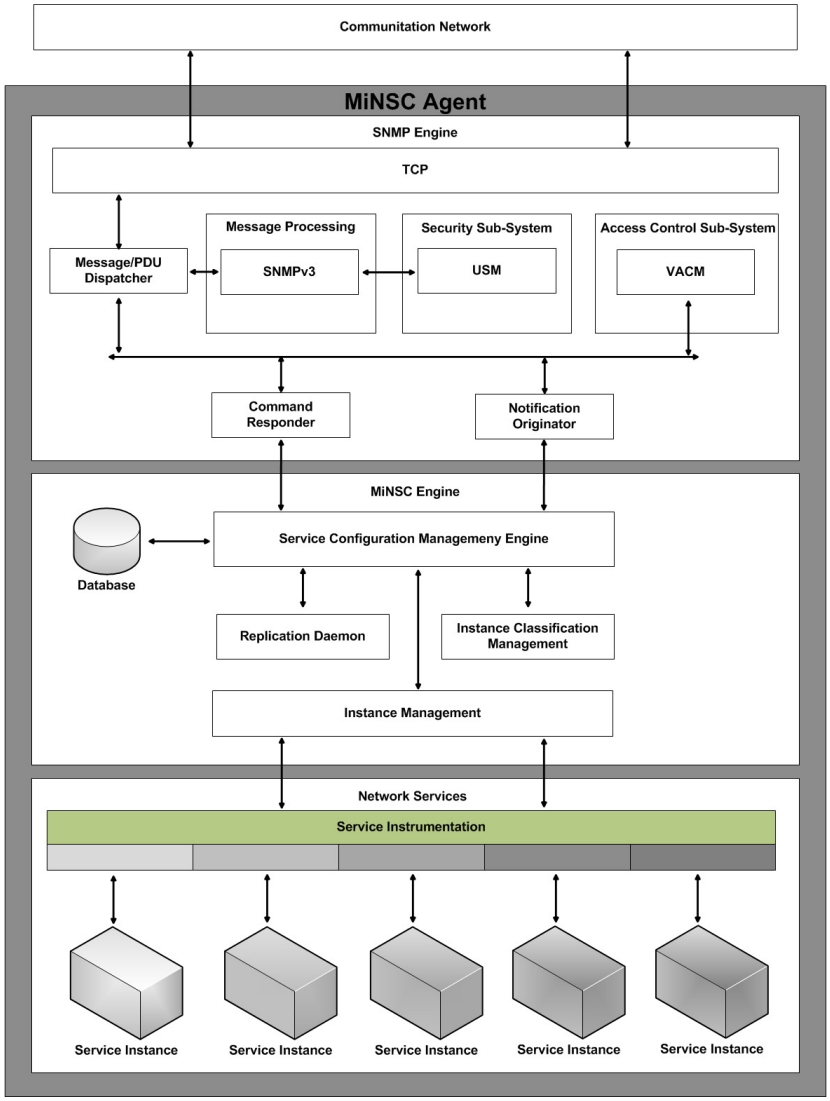

Figure 5.2: MiNSC's configuration management agent structure

The *Message Processing* subsystem returns the message to the *Dispatcher* module which then routes the message to the *MiNSC Engine* after verifying the sender's permission (at the *Command Responder* module) by using the *Access Control* (VACM) subsystem.

MiNSC Engine

The MiNSC Engine realizes the configuration management operations on network service instances based on independent representations. The following modules comprehend this part of the agent:

- The *Service Configuration Management Engine* is responsible for receiving the service configuration management PDUs and deployment of the effective management of network service and replication daemon configurations;
- The *Replication Daemon* performs instance configuration replications by periodically copying the ASI configurations, adapting their content to the new instance details while storing them in MIB tables for a quick service execution migration;
- The *Instance Classification Management* module manages the node's instance classifications by locally starting, stopping or restarting the service execution according to the defined configurations;
- The *Instance Management* is the first part of the Agent's instrumentation which contains the objects defined by the instance management information model to be remotely managed using SNMP commands. The managed objets are organized in MIBs.
- The *Database* is used to store important information in a non-volatile memory. The database is used to store information as to the node's instance classification, configuration management history, service instances logs, configurations and other relevant control information.

Network Services

The Network Services represents the part of the agent where the service's instrumentation is specified for universal implementations. The instrumentation supported was divided into two parts: the first part, referred as **Service Instrumentation**, represents a group of methods and representations commonly applied to all implementations. The second part includes the implementation-specific representation of the Service Instrumentation.

5.3 Development Tools

MiNSC defines a new architecture to be implemented from scratch. From the group of elements and functionalities defined, only an essential set was implemented to experiment and validate the framework's most relevant mechanisms. The prototype modules were developed in Java Standard Edition (SE) version 1.7.0 using the NetBeans 6.9 Integrated Development Environment (IDE). MiNSC uses SNMP as the network management protocol and the SNMP4j API was used to implement the configuration agent

(and corresponding MIB) as well as the configuration servers. In order to specify the configuration agent's MIB, the *MIB Designer* application was used enabling a faster definition of a syntactically correct MIB, described in SMI. To facilitate the configuration agent's MIB implementation based on the SNMP4j API, the AgenPro application was used.

5.3.1 MIB Designer

The MIB Designer is a visual tool used for the creation and edition of MIB modules in accordance with the SMI rules. Using a drag-and-drop interface, the MIB objects type and structure are quickly defined without direct contact with SMI notation, associated with an error checking tool thus ensuring a fast development of syntactically correct MIB modules. The syntactical verification eliminates the most common mistakes inherent to the language's low-level definitions, which for larger projects can be highly complex to manually debug. So, the MIB Designer IDE simplifies the MIB specification activity providing varied functionalities that facilitate development tasks. The defined MIB modules can be later exported in text, XML, XSD, SMIv1 or SMIv2 language. Some of the features enabled by MIB Designer include the following:

- MIB modules created automatically in SMIv2;
- Conversion between SMIv1 and SMIv2;
- Flexible search options;
- Syntax verification at the level of MIB modules and objects;
- Flexibility edition including support for copy, cut, paste, spell checking, etc.

5.3.2 AgenPro

The AgenPro fills the gap between the MIB specification and the agent implementation environment by generating the MIB implementation code (in *Java* or *C++*). So, the AgenPro uses the MIB specification, provided by the MIB Designer (defined in SMI), and a group of Code Generation Templates to define the output code which is compliant with SNMP4j API, automatically generating the MIB's basic instrumentation. This tool enables a quick development of the agent following the MIB specification provided. Some of the features provided by AgenPro include the following:

- Automatic generation of a MIB structure and objects code, simplifying the development of a MIB's instrumentation;
- Ensures the correct definition of the OID structure, table and object type definition, methods for table row management, definition of object value constraints, notification and object instances value initialization;
- Enables the integration between MIBs and the configuration agent. MIBs can be updated, added or removed with minimal changes to the agent. The agent can also be changed without changing the MIB's support;
- The code generation is based on the standard SMI specification, there's no use of specific conversion tags.

5.3.3 SNMP4j

The SNMP4j is an open source API for the development of the two basic SNMP elements in *Java*: the *Manager* and the *Agent*. Some of the features provided by this API include:

- Two different APIs for building SNMP-based applications, one basic API supporting the basic *Manager* functionalities and an extended API for the development of *Agent* specific functionalities;
- A *Command Originator* and *Notification Originators/Receiver* were defined specifically for the creation of *Manager* applications while *Notification Originator*, *Proxy Forwarder* and *Command Responder* functionalities were defined for the *Agent* application;
- Both SNMP4j APIs support any of the three types of Message Processing subsystems (MPv1, MPv2c and MPv3) for the processing messages of the three versions of SNMP;
- The standard security subsystem, USM and VACM, are supported by both APIs;
- Support for MD5 and SHA-1 authentication algorithms as well as Advanced Encryption Standard (AES) 128, 192 and 256 privacy algorithms;
- Support for UDP, TCP and TLS transport mappings.

The code generated by AgenPro is based on SNMP4j API. This API was chosen because it supports the SNMPv3 over TCP protocol, which was an important requirement of the security and reliability of MiNSC's configuration management protocol.

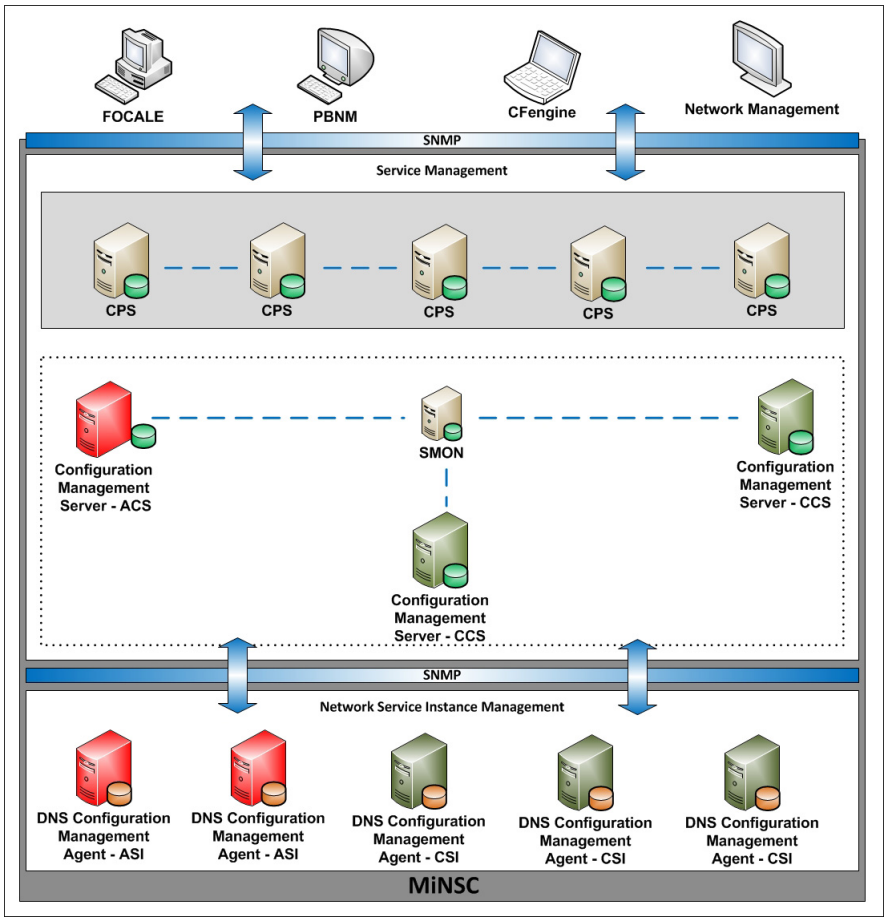

Figure 5.3: MiNSC's DNS management architecture

5.4 Prototype Development

In this section, the implementation details of an MiNSC based prototype for DNS service management are explored, revealing how the most important functionalities are performed. The framework components organization is depicted in Figure 5.3. This section further explains each element, including the implemented modules and algorithms.

5.4.1 DNS Management Information Models

MiNSC's management functionalities rely on the implementation of standard-based information models, their implementation provides the management unification required for the integration of heterogeneous network service implementations. Since all network services must comply with international standards, one valid alternative is to derive

management information models from those standard definitions. Their implementation on a standard management interface creates a management unification based on a unique data model. Such models enable the management of any service implementation that works in accordance to the standards, supporting the management of their standard functionalities and ignoring all the vendor-specific functionalities provided. The management information models based on the service's standard parameters creates minimalist models that focus on the essential part of service management. This perspective goes against the traditional method of building standard management models, which commonly create a complete set of features to support most of the vendor's specific functionalities. The application of such models increases their implementation complexity besides resulting in a slower standardization process, (since an agreement must be achieved among all vendor requirements as explained in [236]). The implementation of MiNSC's simple service management information models has important advantages, simplifying the creation of the models and their implementation.

Two DNS management information sub-models are described in the following sections. These models are based on the study of DNS service standard descriptions and aims to support essential DNS management functionalities. It enables independent DNS management and serves as a starting point for the development of more advanced models, requiring further development in order to support advanced functionalities.

DNS Instance Management Information Model

The DNS instance management information model is used in MiNSC's *Network Service Instance Management* layer, enabling the management of the service's standard functionalities in terms of universal implementations. The deployment of this model provides a semantic unification that overcomes the need to implement semantic or syntactic mappings when creating integrated management applications. The proposed model is represented in Figure 5.4 and enables the management of the most essential functionalities of DNS instances such as standard resource records, caching, recursion and notification support. The model is built around the definition of DNS *Zones* to organize the instance's configurations.

The DNS instance management information model is depicted in Figure 5.4, using a UML class diagram, where each class represents a well defined group of DNS instance configuration parameters. These classes are related to each other through *composition* relations, meaning that the child class life cycle is limited to the parent life cycle. This property is also true for configuration management, where some configurations only make

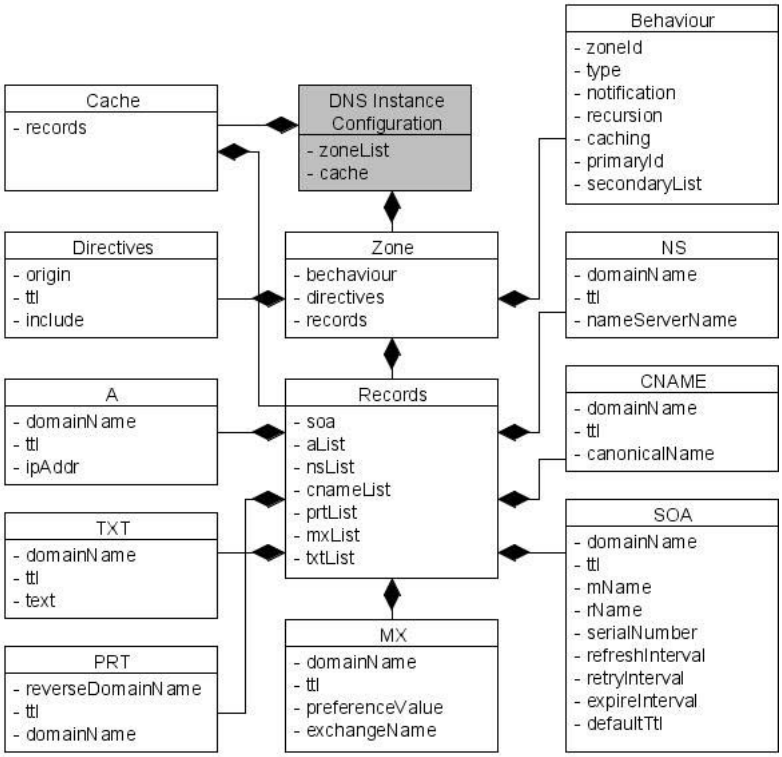

Figure 5.4: DNS instance management information model

sense in the presence of others (for example the relation between DNS resource records and the *Zone* configuration).
Globally, the proposed model is composed by the following parts:

- The DNS instance management information model supports the configuration of the instance's static and dynamic configurations. The static configurations are represented by the *Zone* that characterize the DNS service being provided. These configurations do not change during the regular service operation (or have infrequent changes). The service instance's dynamic configurations are represented by the *Cache*, and include standard resource records gathered from the server's operation;

- The entire model is built around the *Zone* class definition. It includes the attributes to characterize the domain name server behavior as well as the elements requiring name to address translation, represented through the standard DNS resource records;

- The DNS resource records are the basic data elements used in the naming system. Some of the most common resource records (defined in [238]) are included in the model, such as *A*, *CNAME*, *MX*, *NS*, *PTR* and *SOA*. This model also represents the DNS standard directives defined in [238, 239];
- The *Behavior* class enables the definition of the DNS instance behavior for a DNS *Zone*. Among the several attributes presented, the following have enhanced responsibility for the behavior definition:
  - The **Type** attribute defines the instance behavior for a DNS *Zone* in accordance with the primary or secondary classification [238];
  - The **Notification** attribute enables the usage of the notification mechanism [240]. When DNS *Zone* configurations are updated the notification mechanism is used to inform secondary name servers about the necessity to execute a *Zone* transfer;
  - The **Recursion** attribute describes whether or not the name server accepts recursive queries [238] or not;
  - The **Caching** attribute enables the realization of caching [239, 241] at the name server level. If so, it also defines the type of caching (positive or negative);
  - The **PrimaryID** and **SecondaryList** attributes identifies the primary and secondary name servers respectively.

The DNS instance management information model was implemented in a MIB, being decomposed into SMI tables and table row pointers. The MIB structure defined is only partially depicted in Figure 5.5 due to space constraints, complete representation can be found in [242]. The object's tree was built under the *Experimental* object (OID 1.3.6.1.3) and it clearly separates the objects for the MiNSC's network service instance configuration management operations (OID 1.3.6.1.3.1) and the SMON network instance monitoring objects (OID 1.3.6.1.3.2). In this manner, the MIB supports the objects for the two most basic instance management operations. The objects defined for the instance configuration management include, namely the DNS (OID 1.3.6.1.3.1.1), DHCP (OID 1.3.6.1.3.1.2) and E-mail (OID 1.3.6.1.3.1.3) defining the root for their corresponding instances management information models. The DNS node management information model (previously depicted in Figure 5.4) was placed under the DNS object, being decomposed into tables and table row pointers to model the *composition* relation of the classes. The model decomposition showed that a table was created for each class defined:

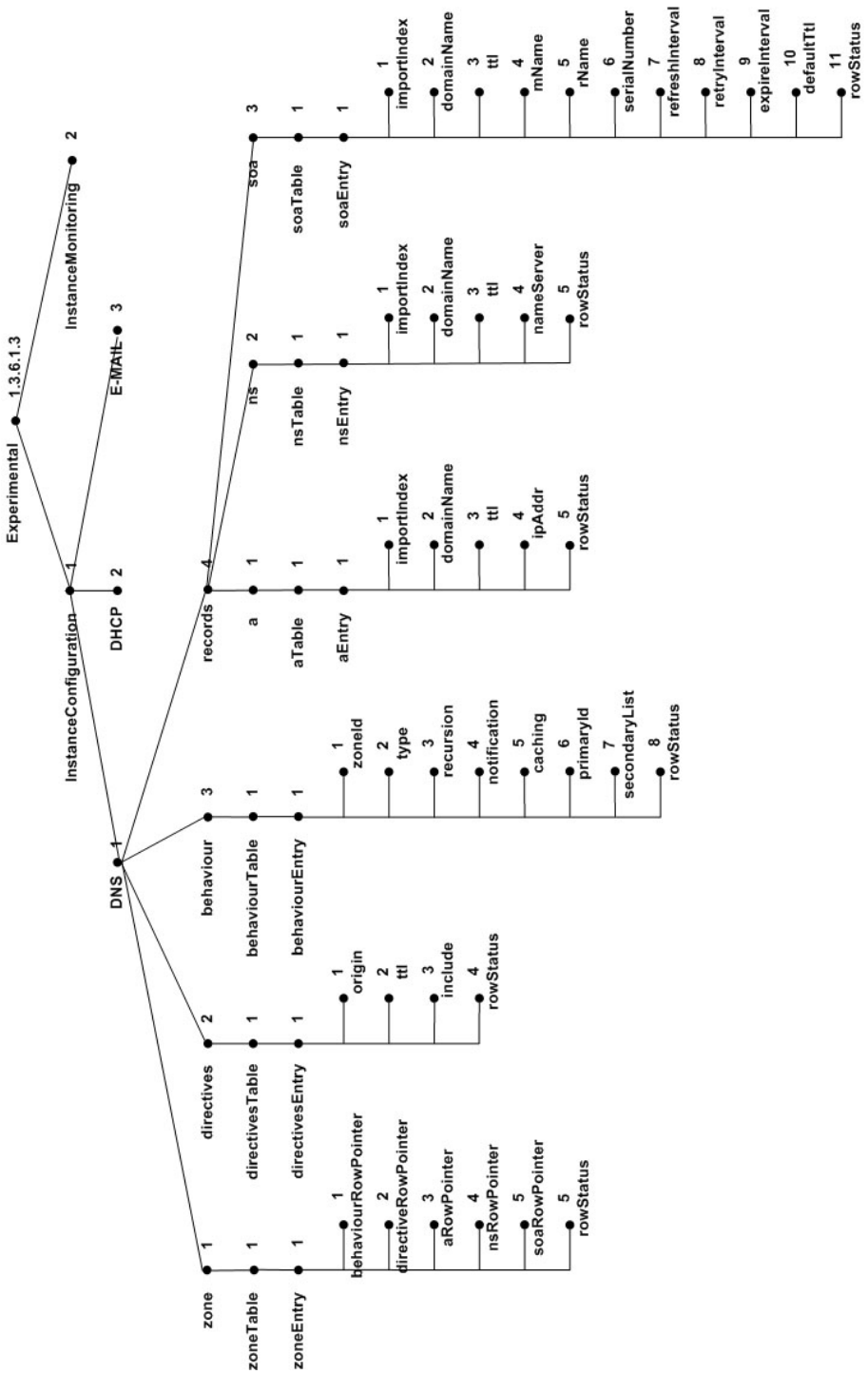

Figure 5.5: DNS instance management MIB

- *zoneTable* represents the *Zone* class MIB implementation, defined through a table that contains table row pointers for the model's remaining tables (like *behaviorTable*, *directivesTable*, *behaviorTable*, *aTable*, *nsTable* and *soaTable*);
- *directivesTable* represents the *Directives* class MIB implementation, defined through a table that contains the DNS directives' standard parameters like *origin*, *include* and *ttl*;
- *behaviorTable* (OID 1.3.6.1.3.1.1.3.1) represents the *Behavior* class MIB implementation, defined through a table containing the *Zone*'s behavior definition parameters like the *zoneId*, *type*, *recursion*, *notification*, *primaryId* and *secondaryList*;
- The *records* (OID 1.3.6.1.3.1.1.4) represents the *Records* class MIB implementation, defined through an object that is the root for a MIB tree containing the standard DNS resource records representations:
  - **aTable** represents the *A* class MIB implementation, defined through a table that contains the *A* resource record standard parameters like *domainName*, *ttl* and *ipAddr*. It's important to notice that the *importIndex* (OID 1.3.6.1.3.1.1.4.1.1.1.1) enables the association of several *A* resource record representations to a DNS *Zone*, containing a unique identifier;
  - **nsTable** represents the *NS* class MIB implementation, defined through a table containing the *NS* resource record standard parameters like *domainName*, *ttl* and *nameServer*;
  - **soaTable** represents the *SOA* class MIB implementation, defined through a table that contains the *SOA* resource record standard parameters like *domainName*, *ttl*, *mName*, *rName*, *serialNumber*, *refreshInterval*, *retryInterval*, *expireInterval* and *defaultTtl*;

An additional parameter called *rowStatus* was included in all tables in order to perform table's row management.

DNS Service Management Information Model

The DNS service management information model is used in MiNSC's *Service Management* layer, enabling the automation of some configuration management tasks, as well as, management simplification provided through a service-oriented management approach. The proposed model is depicted in Figure 5.6, using a class diagram, being composed of the following classes:

- The *Domain* class defines the DNS service authority domain. The *authority* attribute represents the DNS service domain's identification while the *parent* attribute represents the domain's parent name identification;
- The *Operation* class describes service behavior. The following attributes are included:
  - The **Redundancy-Distribution** attribute is used for the calculation of the service deployment pattern. Its value is used to calculate the DNS instances classification (the number of ASI and CSI) as well as their distribution;
  - The **Notification** attribute enables the usage of the notification mechanism on primary name servers. The notification attribute is either defined with a *true* or *false* value;
  - The **Caching** attribute enables the DNS instance's caching mechanisms. It's defined with *none*, *positive*, *negative* or *both* values, referring to the types of caching supported;
  - The **Volatility** attribute refers to the expected variation for the primary name server *Zone* configuration. A *high* volatility translates into a lower refresh interval value, meaning that the secondary name servers must update their configurations more frequently;
  - The **Persistence** value refers to the persistence that secondary name servers present when failing to update the *Zone* configuration. A *high* persistence value defines a lower retry interval, meaning that the secondary name server waits less time to contact the primary name server;
  - The **Validity** attribute refers to the duration of the *Zone* configurations transferred to a secondary name server. A *high* validity value defines a large expiry value, which corresponds to the time elapsed of the last successful *Zone* configuration transfer;

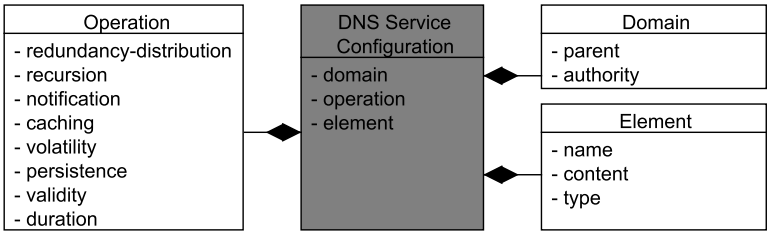

Figure 5.6: DNS service management information model

  - The **Duration** attribute refers to the duration desired for the DNS resource records when cached. A *high* duration means that they are maintained in cache for a larger period of time.

- The *Elements* class enables the representation of network elements requiring name to address translation such as a web-server, e-mail server, printer and others. The following attributes are defined for this class:

  - The **Type** attribute identifies the type of network element requiring name to address translation such as *Printer*, *WebServer*, *EmailServer*, etc;
  - The **Name** attribute refers to the network element's domain name;
  - The **Content** attribute refers to the network element's address.

More trees were defined under the Experimental object (OID 1.3.6.1.3). One identifying the root of the objects for the network service configuration management operations (OID 1.3.6.1.3.3) and the other to include the objects for the network service's monitoring operations (OID 1.3.6.1.3.4) as depicted in Figure 5.7. To support the configuration management of several network services, a tree was defined for some services: DNS (OID 1.3.6.1.3.3.1), DHCP (OID 1.3.6.1.3.3.2) and E-mail (OID 1.3.6.1.3.3.3). The DNS service management information model was represented under the DNS management object by using tables and table row pointers, including the following:

- *serviceTable* represents the DNS *Service* class MIB implementation, containing the table row pointers for the remaining tables, namely *doaminTable*, *operationsTable* and *elementTable*;

- *domainTable* represents the *Domain* class MIB implementation, including objets supporting values for the *parent* and *authority* attributes;

- *operationsTable* represents the *Operation* class MIB implementation, including objets supporting values for the *redundancy-distribution*, *notification*, *caching*, *volatility*, *persistence*, *validity* and *duration* attributes;

- *elementsTable* represents the *Elements* class MIB implementation, including objets supporting values for the *name*, *content* and *type* attributes. Due to the fact that one service may contain several elements, the *importIndex* identifies the corresponding *serviceTable* row;

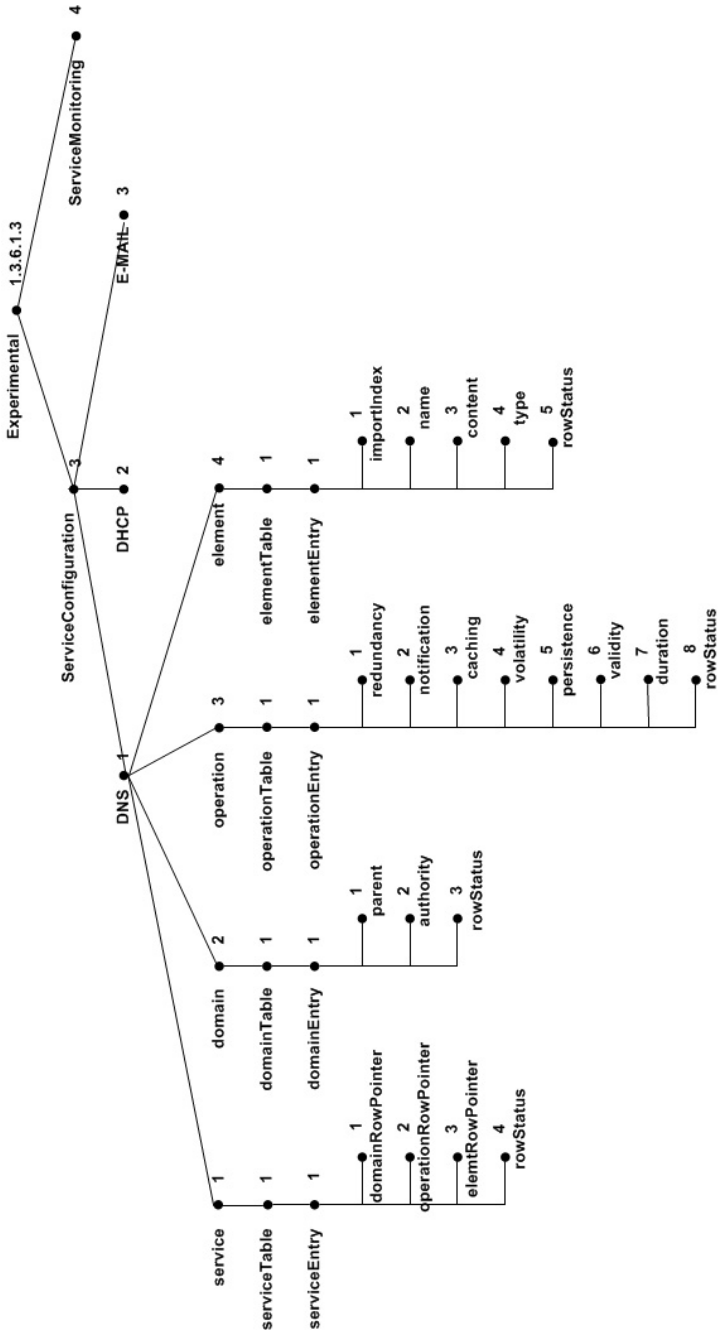

Figure 5.7: DNS service management MIB

5.4.2 Configuration Management Server

The MiNSC's configuration management server architecture is depicted in Figure 5.1 and is globally composed by two parts: the SNMP Engine that provides a reliable and secure

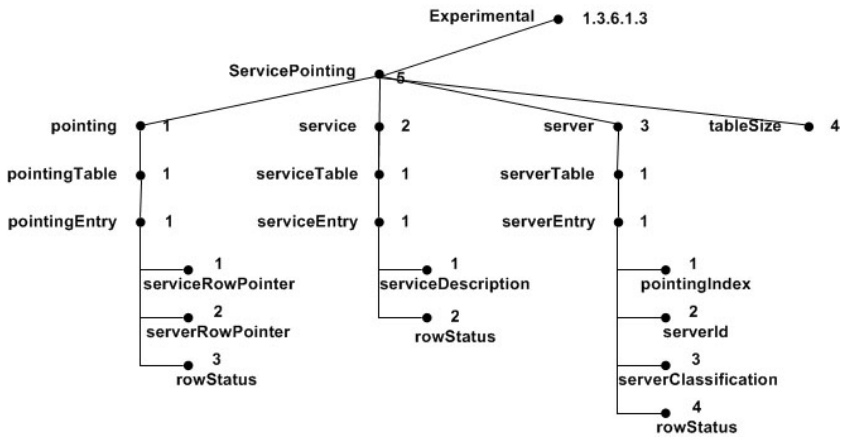

Figure 5.8: Server and Instance Registration MIB

management of network service instance configurations through the exchange of SNMPv3 messages; the MiNSC Engine, that was built on top of the SNMP Engine, provides a group of management functionalities that includes management simplification, resilience and scalability improvement methods. The functionalities provided are brought by a group of modules already referred in this chapter. The following sections focus on the exploration of the MiNSC Engine details. The SNMP Engine functionalities, which are well known and described in international standards, were implemented using the SNMP4j API. The protocol used for authentication was HMAC-MD5-96 and the CBC-DES protocol was used for privacy. The VACM access control mechanism was not implemented for the prototype since it is irrelevant in terms of proof of concept.

Server and Instance Registration

The Server and Instance Registration module provides an important functionality, maintaining references about the configuration servers classification (ACS and CCS) in an MIB. The MIB structure used by this module is depicted in Figure 5.8 and includes the following tables:

- The *pointingTable*, references rows in other tables, namely the *serviceTable* and *serverTable*. This enables the association of services to server/instance's classification;
- The *serviceTable*, enables identification of a service;
- The *serverTable*, lists classifications of server/instances.

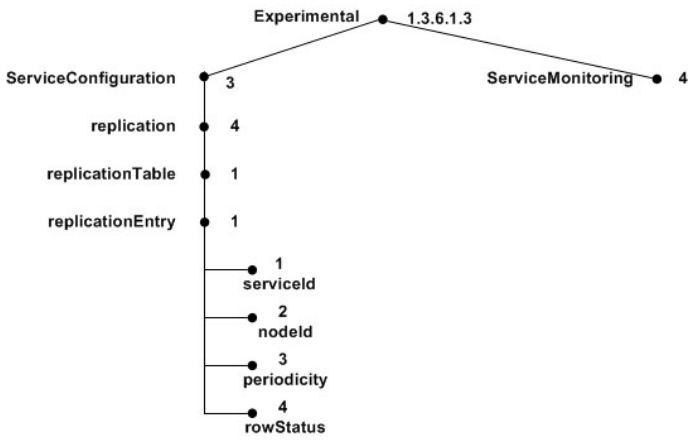

Figure 5.9: Service Replication MIB

On CPS servers, the Server and Instance Registration module works in cooperation with a Database Synchronization module, ensuring the reference data consistency by propagating the information among all servers. This synchronization mechanism may be implemented using locks to CPS's MIB. However, for this prototype the Database Synchronization module was not developed, being addressed in future work.

Replication Daemon

The Replication Daemon module represents a process being performed by CCS servers, responsible for periodically replicating the ACS server configurations, with the purpose of improving the configuration management service resilience and scalability. The CPS servers are responsible for setup the Replication Daemon operation, using the Service Replication MIB with the structure depicted in Figure 5.9 composed by the following objects:

- The *serviceId* identifies the network service to be replicated (such as DNS, DHCP, E-MAIL), which refers to specific MIB tree;
- The *nodeId* identifies the configuration server to be the source of the replicated meta-configurations;
- The *periodicity* defines the time period in which the CCS server retrieves the ACS service meta-configurations.

The *replicationTable* defines a list of ACS servers whose service meta-configurations are periodically replicated to the CCS Service Management MIB. However, not only the service meta-configurations are replicated, the service instance's classification stored in the ACS's Server and Instance Registration MIB (1.3.6.1.3.5) are also replicated, enabling the configuration management execution migration.

DNS Parameters

When deploying a DNS service, the conversion of some high-level meta-configuration parameters is required for the instances low-level configurations, in accordance with administratively defined requirements. Values defined for the service redundancy distribution level, volatility, persistence, validity and duration (defined as *high*, *medium* and *low*) must generate numeric values corresponding to the number of active and candidate instances, their distribution and other DNS standard configurations such as refresh, retry, expire and Time-to-Live (TTL) values. To enable a more flexible definition, a DNS Parameters MIB (depicted in Figure 5.10) was created, being composed by the following tables:

- *distributionTable* that maps from the redundancy distribution level (DNS service meta-configurations) to the percentage of active instances required and their distribution pattern (such as *static*, *random*, *minimization-cost* or *maximization-cost* for example). In this prototype the following configurations were used:
  - level: **High**, activePercentage: **30**, distribution: **static**;
  - level: **Medium**, activePercentage: **50**, distribution: **static**;
  - level: **Low**, activePercentage: **90**, distribution: **static**.
- *volatilityTable* that maps from the volatility level (DNS service meta-configurations) to the value used for the DNS SOA refresh:
  - level: **High**, value: **3400**;
  - level: **Medium**, value: **3600**;
  - level: **Low**, value: **3800**.
- *persistenceTable* that maps from the persistence level (DNS service meta-configurations) to the value used for the DNS SOA retry:
  - level: **High**, value: **400**;

  - level: **Medium**, value: **600**;
  - level: **Low**, value: **800**.

- *validityTable* that maps from the validity level (DNS service meta-configurations) to the value used for the DNS SOA expire:

  - level: **High**, value: **86000**;
  - level: **Medium**, value: **86400**;
  - level: **Low**, value: **86800**.

- *durationTable* that maps from the duration level (DNS service meta-configurations) to the value used for the DNS TTL:

  - level: **High**, value: **3400**;
  - level: **Medium**, value: **3600**;
  - level: **Low**, value: **3800**.

Monitoring

MiNSC's configuration management servers include a interface to the monitoring system. This interface is used to informe as to the need to execute a configuration management operation. In this sense, a MIB table was created (Monitoring MIB (1.3.6.1.3.4.1.1.1)) to define such interface, describing a configuration management operation to be performed on a instance/server. The table structure of the Monitoring MIB is depicted in Figure 5.11 and is composed by the following objects:

- The *serviceId* identifies the network service (such as DNS, DHCP, E-MAIL);
- The *instanceId* identifies the network service instance or configuration management server requiring a configuration management operation;
- The *operation* identifies the configuration management operation to be performed. Such operation might be the execution migration, service expansion, deactivation of configurations or other to be added in the future.

It is important to note that this interface was created with the purpose of experimenting some of MiNSC's management functionalities. It should be refined when the specification of the monitoring system is completed.

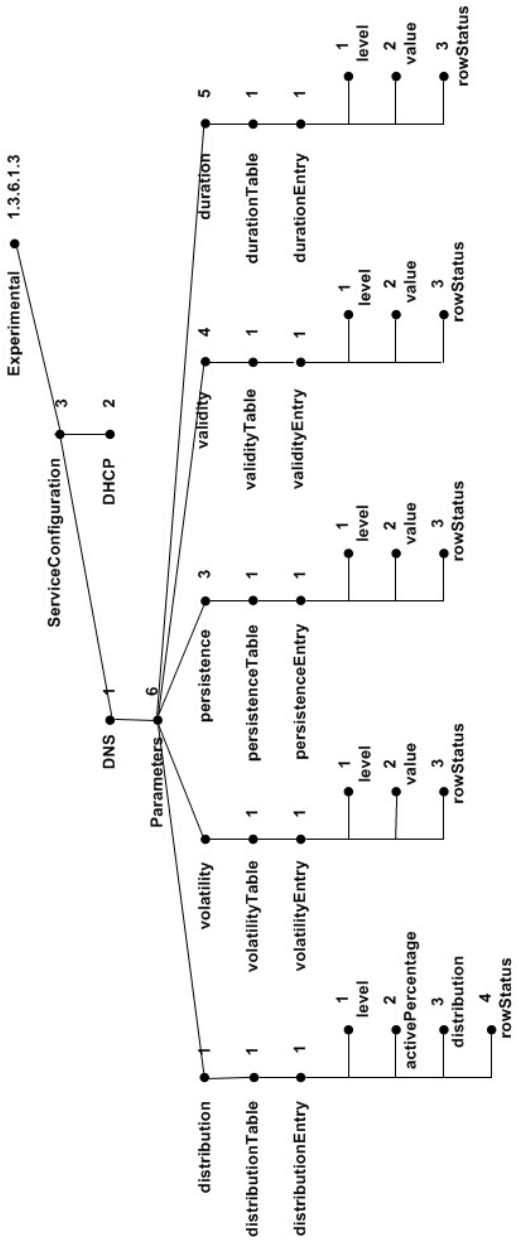

Figure 5.10: DNS Parameters MIB

Network Service Deployment

The Network Service Deployment module is responsible for taking the DNS meta-configurations (defined by the DNS service management information model) and automatically calculating the DNS instance configurations (defined by the DNS instance

management information model) including their configuration dependencies. For the developed prototype, deployment was performed using the procedure represented in Algorithm 1. This algorithm receives an index (i) identifying the corresponding meta-configurations in *serviceTable* (DNS Service Management MIB (1.3.6.1.3.3.1)), and executes the following procedure:

1. Using the *GetDNSInstancesRegistered* method, the list of DNS instances available is retrieved from the ACS's *Server and Instance Registration MIB* (1.3.6.1.3.5);

2. If at least one DNS instance is available, the service deployment is executed;

3. The DNS service meta-configuration is retrieved (from *DNS Service Management MIB* (1.3.6.1.3.3.1)) using the *GetDNSServiceConfiguration* method;

4. The DNS service administrative parameters defined are retrieved from the *DNS Parameter MIB* (1.3.6.1.3.3.1.6) using the *GetDNSServiceParameters* method;

5. The service instance serialization algorithm is applied using the *ApplyInstancesSerialization* method. It computes the DNS instances classification in accordance with the service redundancy distribution level desired, the DNS parameters defined and the number of DNS instances available;

6. The *AssignRedundancyClassification* method uses the DNS instances classified as active to define their role, one as primary and the remaining as secondary name servers;

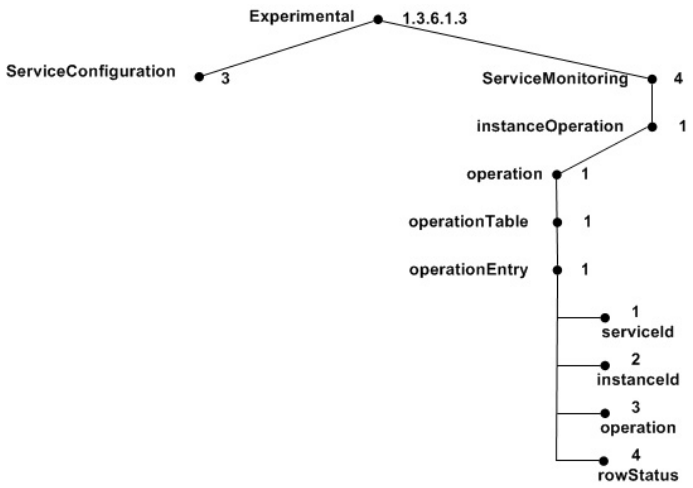

Figure 5.11: Monitoring MIB

7. The *RegisterInstancesClassification* method is used to store the instance classification at the *Server and Instance Registration MIB* (1.3.6.1.3.5). The maintenance of the instance's registration in an MIB enables the complete ACS service configuration replication;

8. The *GenerateActiveDNSInstancesConfigurations* method takes the DNS service meta-configuration, the DNS parameters defined and the instances classified as active to automatically calculate the ASI configurations, including their configuration dependencies;

9. The *GenerateCandidateDNSInstancesConfigurations* method takes the DNS service meta-configuration and the instances classified as active and candidate to calculate instance configuration replication procedures;

10. For each active instance configuration generated, the *DeployDNSInstanceConfiguration* method is used to securely deploy the DNS instance configurations into the *DNS Instance Management MIB* (1.3.6.1.3.1.1). The *ListenNotification* method is used to ensure that the DNS instance configurations were effectively applied while waiting for instance notification;

Algorithm 1 DNS service deployment

$n \Leftarrow GetDNSInstancesRegistered()$
if $n > 0$ **then**
  $service \Leftarrow GetDNSServiceConfiguration(i)$
  $parameters \Leftarrow GetDNSServiceParameters()$
  $n \Leftarrow ApplyInstancesSerialization(service, parameters, n)$
  $n \Leftarrow AssignRedundancyClassification(n)$
  $RegisterInstancesClassification(n)$
  $activezoneList \Leftarrow GenerateActiveDNSInstancesConfigurations(service, parameters, n)$
  $replicationTable \Leftarrow GenerateCandidateDNSInstancesConfigurations(service, n)$
  for $zone \in activezoneList$ **do**
    $DeployDNSInstanceConfiguration(zone, n)$
    $ListenNotification(zone)$
  end for
  for $row \in replicationTable$ **do**
    $SetCandidateReplicationTable(row, n)$
    $ListenNotification(row)$
  end for
end if

11. For each candidate instance configuration generated, the *DeployCandidateReplicationTable* method is used to securely deploy the replication table content into the *Instance Replication MIB* (1.3.6.1.3.1.4.1). The *ListenNotification* method was used to ensure that the DNS instance configurations were effectively applied while waiting for instance notification.

Instance Migration

The Instance Migration module was implemented in the prototype to improve the managed service resilience to instance failure. This module uses the network service instance independent configurations, periodically replicated in candidate, and the Network Service Deployment module to enable the service execution migration in case of failure. Regarding the maintenance (or not) of the service instance dynamic configurations two types of procedures might be performed: lossy or lossless.

In a lossy DNS instance execution migration procedure only the service instance's static configurations are considered, dynamic configurations are lost. To perform this procedure, the steps described in Algorithm 2 are executed. The algorithm input parameters required include the service index (i) in the *DNS Service Management MIB* (1.3.6.1.3.3.1) and the IP address of the faulty instance (*instanceId*):

1. The DNS service meta-configuration (defined at the *DNS Service Management MIB* (1.3.6.1.3.3.1)) is retrieved using the *GetDNSServiceConfiguration* method;

2. Using the *GetDNSInstancesRegistered* method, the DNS instances used for the service deployment are retrieved from the *Server and Instance Registration MIB* (1.3.6.1.3.5);

3. The periodic instance configuration replication procedure, defined by the service deployment, is suspended at the CSI using the *StopCandidateReplication* method. This method sets *Instance Replication MIB* (1.3.6.1.3.1.4.1) rows for deletion;

4. The instances classification registered by the service deployment, at the *Server and Instance Registration MIB* (1.3.6.1.3.5), are erased using the *DeleteInstancesRegistration* method;

5. The service execution, at the faulty instance (*instanceId*), is suspended using the *UndeployDNSInstanceConfiguration* method. This methods erases configurations by setting *DNS Instance Management MIB* (1.3.6.1.3.1.1) rows for deletions;

Algorithm 2 Lossy DNS instance execution migration

```
service ⇐ GetDNSServiceConfiguration(i)
n ⇐ GetDNSInstancesRegistered(i)
StopCandidateReplication(n)
DeleteInstancesRegistration(i)
UndeployDNSInstanceConfiguration(service, instanceId)
n ⇐ RemoveDNSInstance(n, instanceId)
if n > 0 then
  parameters ⇐ GetDNSServiceParameters()
  n ⇐ ApplyInstancesDistribution(service, parameters, n)
  n ⇐ AssignRedundancyClassification(n)
  RegisterInstancesClassification(n)
  activezonelist ⇐ GenerateActiveDNSInstancesConfigurations(service,
  parameters, n)
  replicationTable ⇐ GenerateCandidateDNSInstancesConfigurations(service, n)
  for zone ∈ activezonelist do
    DeployDNSInstanceConfiguration(zone, n)
    ListenNotification(zone)
  end for
  for row ∈ replicationTable do
    DeployCandidateReplicationTable(row, n)
    ListenNotification(row)
  end for
end if
```

6. From the group of instances previously used for service deployment, the faulty instance (*instanceId*) is removed using the *RemoveDNSInstance* method;

7. If at least one service instance is still available, a new service deployment is executed;

8. The DNS service parameters administratively defined were retrieved from the *DNS Parameter MIB* (1.3.6.1.3.3.1.6) using the *GetDNSServiceParameters* method;

9. For the remaining available instances, the service instance serialization algorithm is applied using the *ApplyInstancesSerialization* method. It computes the DNS instances classification in accordance with the service redundancy distribution level desired, the DNS parameters defined and the number of DNS instances available;

10. The *AssignRedundancyClassification* method uses the active instance classification to define the primary and secondary name servers roles;

11. The *RegisterInstancesClassification* method stores the instances classification at the *Server and Instance Registration MIB* (1.3.6.1.3.5);

12. The *GenerateActiveDNSInstancesConfigurations* method takes the DNS service meta-configuration, the DNS parameters defined and the active instances to automatically calculate the ASI configurations, including their configuration dependency;

13. The *GenerateCandidateDNSInstancesConfigurations* method takes the DNS service meta-configuration and the active and candidate instances to calculate instance configuration replication procedures;

14. For each active instance configuration generated, the *DeployDNSInstanceConfiguration* method was used to securely deploy the DNS configurations into the *DNS Instance Management MIB* (1.3.6.1.3.1.1). The *ListenNotification* method is used to ensure that the DNS instance configurations were effectively applied, waiting for instance notification;

15. For each candidate instance configuration generated, the *DeployCandidateReplicationTable* method was used to securely deploy the replication table contents into the *Instance Replication MIB* (1.3.6.1.3.1.4.1). The *ListenNotification* method is used to ensure that the replication table configurations were effectively applied.

When performing a lossless DNS instance execution migration procedure, both static and dynamic configurations of DNS instances are considered. For this to be fulfilled, Algorithm 3 is implemented, requiring the identification of the service index (i) in the *DNS Service Management MIB* (1.3.6.1.3.3.1) and the IP address of the faulty instance (*instanceId*):

1. The DNS service meta-configuration (defined at the *DNS Service Management MIB* (1.3.6.1.3.3.1)) is retrieved using the *GetDNSServiceConfiguration* method;

2. Using the *GetDNSInstancesRegistered* method, the DNS instances used for the service deployment are retrieved from the *Server and Instances Registration MIB* (1.3.6.1.3.5);

3. The periodic instance configuration replication procedure, defined by the service deployment, is suspended at the CSI using the *StopCandidateReplication* method. This method sets *Instance Replication MIB* (1.3.6.1.3.1.4.1) rows for deletion;

Algorithm 3 Lossless DNS instance execution migration

$service \Leftarrow GetDNSServiceConfiguration(i)$
$n \Leftarrow GetDNSInstancesRegistered(i)$
$StopCandidateReplication(n)$
$UndeployDNSInstanceConfiguration(service, instanceId)$
$n \Leftarrow RemoveDNSInstance(n, instanceId)$
$n \Leftarrow ActivateCandidateDNSInstanceConfiguration(service, n)$
$replicationTable \Leftarrow GenerateCandidateDNSInstancesConfigurations(service, n)$
for $row \in replicationTable$ **do**
  $DeployCandidateReplicationTable(row, n)$
  $ListenNotification(row)$
end for
$UpdateDependencies(n, service)$
$UpdateRegisterInstancesClassification(n, service)$

4. The service execution, at the faulty instance (*instanceId*), is suspended using the *UndeployDNSInstanceConfiguration* method. This methods erases configurations by setting *DNS Instance Management MIB* (1.3.6.1.3.1.1) rows for deletion;

5. From the group of instances registered for the service deployment, the faulty instance (*instanceId*) is removed using the *RemoveDNSInstance* method;

6. The *ActivateCandidateDNSInstanceConfiguration* method is used to migrate the service execution to a candidate instance using the configurations previously replicated. The DNS instances classification is updated;

7. The *GenerateCandidateDNSInstancesConfigurations* method takes the DNS service meta-configuration and the instances classified as active and candidate to define new instance configuration replication procedures;

8. For each candidate instance configuration generated, the *DeployCandidateReplicationTable* method was used to securely deploy the replication table contents into the *Instance Replication MIB* (1.3.6.1.3.1.4.1). The *ListenNotification* method is used to ensure that the replication table configurations were effectively applied.

9. The *UpdateDependencies* method is used to update the unchanged ASI configuration to include the new DNS instance;

10. The *UpdateRegisterInstancesClassification* method updates the instance classification of the service deployment in the *Server and Instance Registration MIB* (1.3.6.1.3.5.1.1.1).

Instance Management

The Instance Management module provides a generic interface for the network service instance configuration management. This interface is independent of the underlying management protocol and includes the following attributes:

- *InstanceId*, identifying the network service instance to be managed;
- *ObjectOID*, identifying the object to be managed according to the instance management information model;
- *Operation*, identifying the management operation to be performed: ADD, SET, GET, DELETE;
- *Value*, is an optional attribute used to change the object's value.

Server and Instance Expansion

The Server and Instance Expansion module is used to increase the number of elements supporting the network or management service. This process uses the independent configurations replicated at both layers to divide the service execution between active and candidate elements. For the expansion process, a percentage of the active element's configurations are migrated, suspended in the active element and activated in the candidate element. This creates a new active element extending the network or management service resource support. The reverse operation can also be created, concentrating the active elements configurations thus reducing their number. The procedure which enables a DNS instance expansion is described in Algorithm 4 and includes the following steps:

1. The DNS service meta-configuration (defined at the *DNS Service Management MIB* (1.3.6.1.3.3.1)) is retrieved using the *GetDNSServiceConfiguration* method;
2. Using the *GetDNSInstancesRegistered* method, the DNS instances used for the service deployment are retrieved from the *Server and Instances Registration MIB* (1.3.6.1.3.5);
3. The periodic instance configuration replication procedure, defined by the service deployment, is suspended at the CSI using the *StopCandidateReplication* method. This method sets *Instance Replication MIB* (1.3.6.1.3.1.4.1) rows for deletion;
4. The service execution, at the active instance to be extended, is modified using the *UndeployDNSInstanceConfiguration* method that erases a percentage of DNS *Zone* configurations (*DNS Instance Management MIB* (1.3.6.1.3.1.1));

Algorithm 4 DNS instance expansion

$service \Leftarrow GetDNSServiceConfiguration(i)$
$n \Leftarrow GetDNSInstancesRegistered(i)$
$StopCandidateReplication(n)$
$configuration \Leftarrow UndeployPartDNSInstanceConfiguration(service, instanceId, percentage)$
$n \Leftarrow ActivateCandidateDNSInstanceConfiguration(configuration, n)$
$replicationTable \Leftarrow GenerateCandidateDNSInstancesConfigurations(n)$
for $row \in replicationTable$ **do**
  $DeployCandidateReplicationTable(row, n)$
  $ListenNotification(row)$
end for
$UpdateDependencies(n, service)$
$UpdateRegisterInstancesClassification(n, service)$

5. The previously erased configurations, at the active instance to be extended, are activated in one of the candidate instances using the *ActivateCandidateDNSInstanceConfiguration* method. This creates a new active instance;

6. The *GenerateCandidateDNSInstancesConfigurations* method takes the instances classified as active and candidate to calculate new instance configuration replication procedures;

7. For each candidate instance configuration generated, the *DeployCandidateReplicationTable* method was used to securely deploy the replication table contents into the *Instance Replication MIB* (1.3.6.1.3.1.4.1). The *ListenNotification* method is used to ensure that the replication table configurations were effectively applied;

8. The *UpdateDependencies* method is used to update the unchanged ASI configuration to include the new DNS instance;

9. The *UpdateRegisterInstancesClassification* method updates the instance classification of the service deployment in the *Server and Instance Registration MIB* (1.3.6.1.3.5).

Server and Instance Serialization

The Server and Instance Serialization module enables the calculation of the framework element's most adequate distribution according to their number and the defined level of redundancy distribution. It outputs a graduated list of classified elements to be used

Algorithm 5 Instances serialization

$activePercentage \Leftarrow GetActivePercentage(service)$
$n \Leftarrow SetActivePercentage(n, activePercentage)$
$n \Leftarrow SetCandidatePercentage(n, activePercentage)$

for service deployment. Several alternatives could be used to implement this module however, for the purpose of simplification, a *static* alternative was created within this prototype, not considering the element's physical/logical location, instead it ordered by the element's domain name. This module is executed when the *ApplyInstancesSerialization* method is used for the Service Deployment and the implemented algorithm (depicted in Algorithm 5) includes the following steps:

1. The *GetActivePercentage* method uses the redundancy distribution level (DNS meta-configuration) to retrieve from the *DNS Parameter MIB* (1.3.6.1.3.3.1.6) the percentage of active and candidate instances required;

2. The *SetActivePercentage* method uses the percentage of active elements required and the number of DNS instances available to assign active instance classification;

3. The *SetCandidatePercentage* method uses the percentage of active elements required and the number of DNS instances available to assign candidate instance classification.

Instance Configuration Calculation

When executing service deployment a method is required that, based on the DNS meta-configuration and the group of instances available, computes each instance configuration. The method responsible for this task is the *GenerateActiveDNSInstancesConfigurations* which, for this prototype, realizes the activities depicted in Algorithm 6 and includes the following steps:

1. The *GetActiveDNSInstances* method receives the graduated list of DNS instances classification (n) and retrieves the details of the ones classified as active (ASI);

2. For each active instance, a *Zone* configuration is generated (DNS instance management information model). The *Zone*'s *Behavior* configuration is assigned using the *SetDNSInstanceBehavior* method. To execute this task, it uses the DNS *Operation* and *Domain* meta-configuration as well as the details of the active instances. The *parent* and *authority* attributes build the *Behavior*'s *zoneid* while the attributes

Algorithm 6 Generation of active DNS instance configuration

```
active ⇐ GetActiveDNSInstances(n)
for instance ∈ active do
  zone.Behavior ⇐ SetDNSInstanceBehavior(service.Domain, service.Operation,
  active)
  if zone.Behavior.type = primary then
    zone.Records ⇐ SetDNSInstanceRecords(service.Domain, service.Elements,
    parameters)
  end if
  activezonelist = activezonelist + zone
end for
```

of the DNS *Operation* class enable the direct configuration of the *Behavior* attributes, namely *notification* (for primary name servers), *recursion* and *caching*. To the *Behavior*'s *type* attribute is assigned primary or secondary. Depending on the *type* assigned is filled the *Behavior*'s *primaryid* with the primary name server IP identification or *secondarylist* with the IP addresses of secondary name servers. The process of assigning *type* roles, in this prototype, is random (one primary and the remaining secondary);

3. For a primary DNS instance the *Zone*'s *Records* must be configured. The *SetDNSInstanceRecords* method is used to convert from the DNS *Elements* defined, requiring name to address translation, to the instance *Records* such as *SOA*, *A*, *NS*, *MX*. The *DNS Parameter MIB* (1.3.6.1.3.3.1.6) is used to assign from DNS *Operation* meta-configuration to SOA configurations (such as *refresh*, *retry*, *expire*, *ttl*, etc).

The Service Deployment module uses a complementary algorithm for the calculation of the candidate DNS instance configurations. This algorithm is implemented by the *GenerateCandidateDNSInstancesConfigurations* method being depicted in Algorithm 7 and includes the following steps:

1. The *GetActiveDNSInstances* method receives the graduated list of DNS instances classification (n) and retrieves the details of the ones classified as active (ASI);

Algorithm 7 Generation of candidate DNS instance configuration

```
activelist ⇐ GetActiveDNSInstances(n)
for active ∈ activelist do
  replicationTable = replicationTable + CreateReplicationRow(service, active,
  parameters)
end for
```

2. The *CreateReplicationRow* method is used to create a table compatible with the *Instance Replication MIB* (1.3.6.1.3.1.4.1) with a list of all active instances. This table is sent to all candidate instances. It includes the identification of network service instance as well as service type and replication period. One replication row is defined for each active instance.

Database

The Database module was developed for a persistent storage of service instance's registration. It stores the instances IP address, network service instances supported as well as their classification.

Service Management

The Service Management module was implemented using SNMP4j API, it includes the implementation of the management objects, defined by the DNS service management information model, that enabled integrated DNS management.

5.4.3 Configuration Management Agent

As stated before, MiNSC's configuration management agent architecture was depicted in Figure 5.2 and was globally defined by three parts: the SNMP Engine which provides a reliable and secure management of network service instance configurations through the exchange of SNMPv3 messages; the MiNSC Engine that receives the SNMP messages and ensures the effectiveness of the configuration management operations, on heterogeneous implementations, based on standard object representations. The MiNSC Engine also implements the modules required to perform periodic instance configuration replication procedures; the third part of the agent, referred to as Network Services, contains the heterogeneous network service instances and their corresponding instrumentation.

Like the configuration management server, the configuration management agent is composed by a group of modules which provide the service management functionalities. Their implementation details are explored in the following sections, more specifically for the DNS service management. The SNMP Engine was implemented using the SNMP4j API, supporting the SNMPv3 Message Processing subsystem and TCP transport mapping. The protocol used for authentication was HMAC-MD5-96 and the CBC-DES protocol for privacy. No access control mechanisms were implemented.

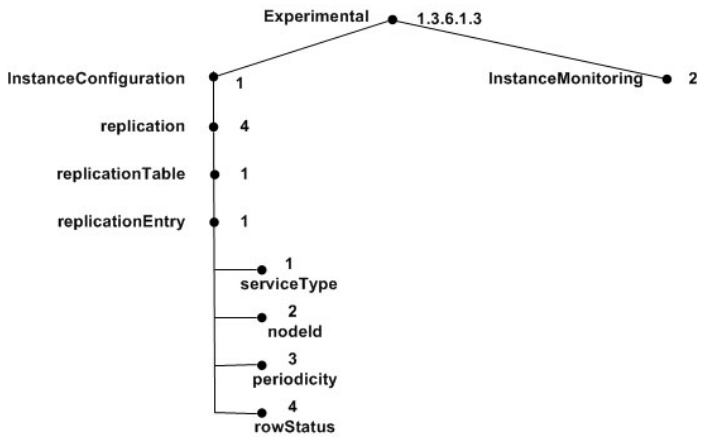

Figure 5.12: Instance replication MIB

Replication Daemon

The Replication Daemon module is a process performed by CSI instances responsible for periodically replicating the ASI instance configurations with the purpose of improving the managed service resilience and scalability. The configuration of the replication process is the responsibility of ACS servers, using the Instance Replication MIB whose structure is depicted in Figure 5.12, being composed by the following objects:

- The *serviceId* identifies the network service to be replicated (such as DNS, DHCP, E-MAIL), which refers to specific MIB tree;
- The *nodeId* identifies the network node to be the source of the replicated configurations;
- The *periodicity* defines the time period in which CSI server retrieves the ASI configurations.

During the replication process ASI configurations are adapted to includes the CSI details (IP address, domain name, etc.), promoting a quicker migration of service execution. The following adaptations were performed when replicating a DNS instance configuration: if classified as primary name server, the attribute *mName* (from SOA resource record) must be updated to include the new node's domain name. Besides, two resource records (*NS* and *A*) must also be updated to support its name to address translation; no adaptation were performed for a secondary name server.

Instance Management

The Instance Management module was implemented using SNMP4j API, it includes the implementation of the management objects defined by the DNS instance management information model.

Instance Classification Management

The Instance Classification Management module works in cooperation with the Instance Management module to enable the management of instance classification: initiating the service execution when new instance configurations are defined; stoping the service execution when all instance configurations are erased; and restarting the service execution when configurations are changes. When no instance configurations are defined, the Instance Classification Management module enables the replication procedure by activating the corresponding Replication Daemon.

Service Instrumentation

The Service Instrumentation module is divided into two parts: the first part that includes a interface common to heterogeneous service instance implementations; the second part that includes the instrumentation required for the management effectiveness of first part. The first part includes the following group of independent configuration management methods:

- *Get*, to retrieve all or a part of the service instance configurations;
- *Set*, to define new service instance configurations;
- *Add*, to add a new configuration element to an already existing service instance configuration;
- *Put*, to update an existing configuration element;
- *Delete* to delete all or part of the service instance configurations.

The implementation of the previous methods for different implementations represents the second part of the module. In this prototype they were implemented for three vendor specific DNS implementations.

5.5 Experiments

In this section the author demonstrates MiNSC's most important functionalities through the presentation of the results of a small set of experiments for the DNS service configuration management. The most important goals of this section include the demonstration of:

- MiNSC's capability to overcome the use of management translations when supporting the integrated management of heterogeneous DNS implementations;
- MiNSC's management simplification supported by universal configurations deployed on heterogeneous DNS implementations;
- MiNSC's capability to perform an automatic (and secure) deployment of a DNS domain configuration based on the meta-configurations administratively defined;
- MiNSC's capability to enhance resilience and scalability of the managed DNS service.

SMON plays a key role by notifying the configuration management server as to the need to enact configuration management procedures. However, this enaction of SMON falls out of the scope of this thesis, so the notification interaction was manually triggered.

5.5.1 DNS Instance Configuration

The number of DNS instances used depends on the redundancy distribution level pretended for the management context. Based on the DNS meta-configurations defined, the administrator is able to distribute instance classification as required. Using three DNS implementations and three levels of redundancy distribution, the following deployment patterns may be found:

- When the DNS service is deployed with a *high-level* of redundancy distribution only one DNS instance is classified as ASI (the remaining two are classified as CSI). The following configurations are deployed for the primary name server and include: the definition of a DNS *Zone* identified as *scm.di.uminho.pt*; a SOA resource record; disabled *caching*, *notification* and *recursion* mechanisms.

```
- Zone(Directives(origin=scm.zone.com),
          Behavior(type:Primary, zoneId=scm.di.uminho.pt,
          notification:no, recursion:no, caching:no),
          Records(SOA(domainName=scm.di.uminho.pt,
          ttl=3600, mName=ns1.scm.di.uminho.pt, rName=root.di.uminho.pt,
          serialNumber=20100101, refreshInterval=3600,
          retryInterval=3600, expireInterval=604800, defaultTtl=3600)
          NS(domain_name=scm.di.uminho.pt,
          name_server_name=ns1.scm.di.uminho.pt),
          A(domain_name=ns1.scm.di.uminho.pt, ip_addr=192.168.10.10)))
```

- When the DNS service is deployed with a *medium-level* of redundancy distribution two DNS instances are classified as ASI (one primary and one secondary name servers) and one is classified as CSI. The primary name server includes now the configurations for the secondary name server. The secondary name server includes the DNS *Zone* configuration with the pretended behavior. The configurations deployed for the primary name server are the following:

```
- Zone(Directives(origin=scm.zone.com),
          Behavior(type:Primary, zoneId=scm.di.uminho.pt,
          notification:no, recursion:no, caching:no,
          secondaryList(192.168.10.11)),
          Records(SOA(domainName=scm.di.uminho.pt,
          ttl=3600, mName=ns1.scm.di.uminho.pt, rName=root.di.uminho.pt,
          serialNumber=20100101, refreshInterval=3600,
          retryInterval=3600, expireInterval=604800, defaultTtl=3600)
          NS(domain_name=scm.di.uminho.pt,
          name_server_name=ns1.scm.di.uminho.pt),
          NS(domain_name=scm.di.uminho.pt,
          name_server_name=ns2.scm.di.uminho.pt),
          A(domain_name=ns1.scm.di.uminho.pt, ip_addr=192.168.10.10)
          A(domain_name=ns2.scm.di.uminho.pt, ip_addr=192.168.10.11)))
```

The secondary name server configuration includes the DNS *Zone* identification, the server behavior definition and the primary name server identification:

```
- Zone(Behavior(type:Secondary, zoneId=scm.di.uminho.pt,recursion:no,
          caching:no, master=192.168.10.10))
```

- When the DNS service is deployed with a *low-level* of redundancy distribution three DNS instances are classified as ASI (one primary and two secondary name servers). The primary name server includes now the configurations for the secondary name servers. The secondary name servers includes the DNS *Zone* configuration with the pretended behavior. The configurations deployed for the primary name server are the following:

```
- Zone(Directives(origin=scm.zone.com),
          Behavior(type:Primary, zoneId=scm.di.uminho.pt,
          notification:no, recursion:no, caching:no,
          secondaryList(192.168.10.11, 192.168.10.12)),
          Records(SOA(domainName=scm.di.uminho.pt,
          ttl=3600, mName=ns1.scm.di.uminho.pt,
          rName=root.di.uminho.pt,
          serialNumber=20100101, refreshInterval=3600,
          retryInterval=3600, expireInterval=604800, defaultTtl=3600)
          NS(domain_name=scm.di.uminho.pt,
          name_server_name=ns1.scm.di.uminho.pt),
          NS(domain_name=scm.di.uminho.pt,
          name_server_name=ns2.scm.di.uminho.pt),
          NS(domain_name=scm.di.uminho.pt,
          name_server_name=ns3.scm.di.uminho.pt),
          A(domain_name=ns1.scm.di.uminho.pt, ip_addr=192.168.10.10),
          A(domain_name=ns2.scm.di.uminho.pt, ip_addr=192.168.10.11),
          A(domain_name=ns3.scm.di.uminho.pt, ip_addr=192.168.10.12)))
```

The secondary name server configuration includes the DNS *Zone* identification, the server behavior definition and the primary name server identification:

```
- Zone(Behavior(type:Secondary, zoneId=scm.di.uminho.pt,recursion:no,
          caching:no, master=192.168.10.10))
```

5.5.2 DNS Management Evaluation

A complementary analysis was conducted as to evaluate MiNSC's effectiveness for DNS management compared to popular DNS management tools such as Probind [243], unxsBind [244] and Roster [245]. This study was divided into three parts: the first part evaluated the DNS management from the network operation perspective; the second part evaluated the provisioning of most basic DNS management functionalities; the third part evaluated the provisioning of advanced management functionalities. These results are depicted in Table 5.1 and the most important conclusions drawn from them include:

- From the *network operation* perspective, all DNS management framework's perform similarly. MiNSC supports communication reliability, communicating parties authentication and privacy through the implementation of SNMPv3 over TCP, using CBC-DES Symmetric Encryption Protocol for confidentiality and HMAC-MD5-96 for authentication. Probind uses the reliability of the *Rsync* mechanism over secure SSH to synchronize server files and manage DNS server configurations. UnxsBind uses the MySQL database replication mechanism to synchronize the DNS server configurations, thus supporting communication reliability, privacy and user authentication. Roster uses a Secure Sockets Layer (SSL) enabled XML-RPC protocol for the distributed DNS servers configuration, also supporting client authentication based on Lightweight Directory Access Protocol (LDAP) and others;

- From the *simple functionalities* perspective, all framework's provide similar capabilities even though there exists MiNSC's inability to manage non-standard functionalities (such as Bind's *serial-query-rate*). So, all frameworks enable the management of most basic functionalities. These includes multi-server management, server role management (primary/secondary), resource records and options management, including the definition of caching type, notifications, recursion, among other mechanism;

Table 5.1: DNS management tools features evaluation

Functionality	MiNSC	Probind	unxsBind	Roster
Network Operation				
Privacy	✓	✓	✓	✓
Authentication	✓	✓	✓	✓
Reliability	✓	✓	✓	✓
Simple Functionalities				
Configuration Validation	✗	✗	✗	✓
Master/Slave Management	✓	✓	✓	✓
Multi-Server Management	✓	✓	✓	✓
Options Management	✓	✓	✓	✓
Resource Record Management	✓	✓	✓	✓
Zone Management	✓	✓	✓	✓
Proprietary Functionalities	✗	✓	✓	✓
Advanced Functionalities				
Interoperability	✓	✗	✗	✗
Scalability	✓	✗	✗	✗
Resilience	✓	✗	✗	✗
Heterogeneity	✓	✗	✗	✗
Automation	✗	✗	✗	✗

- *Advanced functionalities* are necessary for a management framework's capability to support a larger scale, heterogeneous DNS management environment where concepts such as automation, interoperability, scalability and resilience are fundamental to the effectiveness of DNS management applications. With the exception of MiNSC, all frameworks fail to provide an adequate response to these advanced requirements due to the following reasons: most frameworks do not improve scalability or resilience, because they are mostly dependent on centralized entities; they do not support integrated DNS management, supporting only the most popular implementations; they do not support the automation due to the fact that they are based on low-level mechanisms, dependent on the administrator's manual intervention to derive and enforce management decisions; do not promote interoperability, using proprietary interfaces. At this level, MiNSC also does not implement a highly automated DNS management solution (even though it provides some

degree of management automation), but it supports the integrated DNS management (without applying intermediary management translations). Furthermore it is based on a distributed, two-layer architecture, improving the DNS management scalability, resilience and maintaining high-level of interoperability (to higher level management applications), through the implementation of a standard interface;

- Based on this evaluation its clear that most common DNS management applications, commercially available, provide similar alternatives at the level of network operation and most simple functionalities. They support secure and reliable configuration management of multiple servers, DNS zones and other basic functionalities. On the other hand, they fail to include advanced management functionalities, such as, integrated management, automation and resilience improvement methods.

5.5.3 DNS Instance Configuration Replication

The DNS instance configuration replication was the first experimental procedure performed with MiNSC's prototype whose results were published in [46]. In this experiment, a configuration management server was used to replicate the DNS instance static configurations between heterogeneous implementations. The main goals were to:

- Demonstrate the effectiveness of the DNS instance management information model by enabling the management of standard DNS functionalities;
- Demonstrate MiNSC's *Network Service Instance Management* layer unification by enforcing independent configurations on heterogeneous DNS implementations, without using management translation mechanisms.

The experimental scenario is depicted in Figure 5.13 where two DNS instances were used, one serving as the source of configurations and the other as destination. For this experiment three DNS implementations were used, namely Bind9 for Linux (Ubuntu) and MS Windows and Posadis also for MS Windows. It is important to note that only the instance's static configurations were replicated.

The source DNS instance was configured with two DNS *Zones*: *abc.zone.com*, where the instance behaves as a primary name sever; and *xyz.zone.com*, where the instance behaves as a secondary name server. The complete set of configurations used for the DNS instance includes the following:

```
- Zone(Directives(origin=abc.zone.com), Behavior(type:Primary,
          zoneId=abc.zone.com, notification:no, recursion:no, caching:no,
          secondaryList(192.168.10.9; 192.168.10.10)),
          Records(SOA(domainName=abc.zone.com, ttl=3600,
          mName=ns.abc.zone.com, rName=root.abc.zone.com,
          serialNumber=20100101, refreshInterval=3600, retryInterval=3600,
          expireInterval=604800, defaultTtl=3600),
          NS(domainName=abc.zone.com, nameServerName=ns.abc.zone.com),
          NS(domainName=abc.zone.com, nameServerName=ns0.abc.zone.com),
          NS(domainName=abc.zone.com, nameServerName=ns1.abc.zone.com),
          A(domainName=ns.abc.zone.com, ipAddr=192.168.10.8),
          A(domainName=ns0.abc.zone.com, ipAddr=192.168.10.9),
          A(domainName=ns1.abc.zone.com, ipAddr=192.168.10.10)))

- Zone(Behavior(type:Secondary, zoneId=xyz.zone.com, recursion:no,
          caching:no, master=192.168.10.11))
```

The first *Zone*, identified as *abc.zone.com*, includes the definition of the standard directives, the *Zone*'s behavior (defining the name server role as well as other standard DNS mechanisms) and seven resource records identifying the *Zone*'s name servers (not included in the presented excerpt). The second *Zone*, identified as *xyz.zone.com*, includes

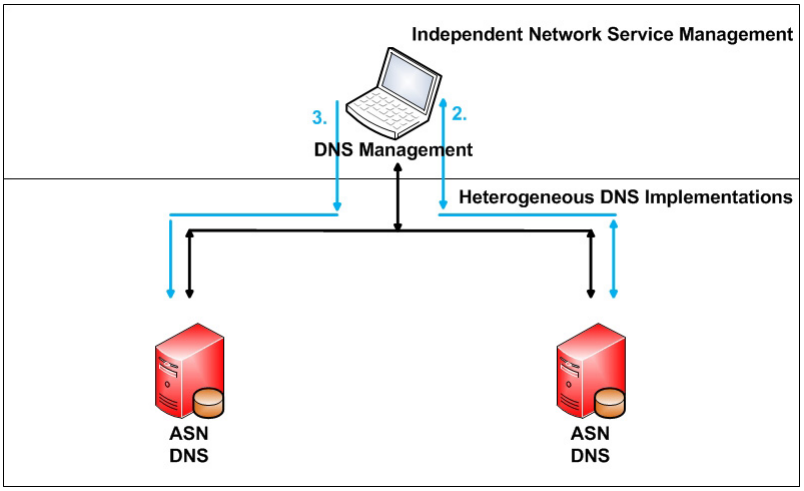

Figure 5.13: DNS instance configuration replication

Table 5.2: DNS instance configuration replication

Replication combination	Duration (seconds)
Bind9(Lnx) - Bind9(Win)	5.435
Bind9(Lnx) - Bind9(Lnx)	5.791
Bind9(Lnx) - Posadis(Win)	5.213

the definition of its behavior (defining the name server role as well as the identification of the corresponding primary name server, not included in the presented excerpt). The replication procedure was executed with the following sequence:

1. The administrator initiates the replication procedure defining the replication instance source and destination;
2. The replication procedure retrieves the independent configurations from the source DNS instance. These configurations are adapted to include the destination instance details (namely at the *mName* attribute as well as the corresponding *NS* and *A* resource records);
3. The replication procedure deploys the replicated configurations to the destination instance, activating its execution.

The configuration replication experiment was performed using different combinations of two DNS instances, being repeated several times for each combination, in order to compute an average procedure duration. For each combination, the configuration replication procedure duration is depicted in Table 5.2.

The following results may be observed:

- In the first combination, the DNS instance configurations were replicated between a Bind9 (Linux) and a Bind9 (MS Windows) DNS instance. It took, on average, 5.4 seconds to be completed;
- In the second combination, the DNS instance configurations were replicated between a Bind9 (Linux) and a Bind9 (Linux) DNS instance. It took, on average, 5.8 seconds to be completed;
- In the third combination, the DNS instance configurations were replicated between a Bind9 (Linux) and a Posadis (MS Windows) DNS instance. It took, on average, 5.2 seconds to be completed.

The most important conclusions taken from this experiment can be summarized as follows:

- The DNS instance management information model proposed, enables the configuration management of standard DNS functionalities (such as DNS *Zones*, as well as caching, recursion and notification mechanisms), on heterogeneous implementations, only requiring the development of an MIB instrumentation;
- The DNS instance configuration replication procedure took, on average, 5.5 seconds to retrieve the static configurations from a source DNS instance, deactivate its service execution, modify the configuration to include the destination instance details, deploy and activate those configurations at the destination DNS instance. This process was completed regardless of the instances implementations, without using management translation mechanisms. This demonstrates the management unification provided by MiNSC's *Network Service Instance Management* layer.

5.5.4 DNS Service Deployment

In this experiment, both MiNSC's management layers were used to perform the automatic setup of a DNS domain. The DNS service meta-configurations were administratively defined at the *Service Management* layer, enabling the automatic generation of the DNS instances configurations at the *Network Service Instance Management* layer. The DNS service deployment scenario is depicted in Figure 5.14, being composed by three DNS instances, where the configurations are deployed, and one configuration server (ACS) where the DNS meta-configurations are defined. With this experiment the following objectives were persued:

- To create a mid-level mechanism that simplifies the DNS service management, namely supporting the automatic setup of a DNS domain, referred to as DNS service deployment;
- To demonstrate the effectiveness of MiNSC's *Service Management* layer by automatically computing the DNS instance configurations based on the DNS meta-configurations;
- To demonstrate the framework's autonomy by modifying the DNS service deployment resource support (using various DNS instances implementation).

The following DNS service meta-configurations were used:

```
- Domain(parent:di.uminho.pt, authority:scm)

- Operation(redundancy-distribution:low, recursion=no, notification:no,
  caching:no, volatility:low, persistence:low, validity:low, duration:low)
```

A DNS domain called *scm.di.uminho.pt* was created with no *Elements* defined. The service behavior, defined by the *Operation* meta-configuration, included: a *low-level* of redundancy distribution, ensuring that all DNS instances available were classified as ASI (one primary and two secondary name servers); a *low* value for *volatility*, *persistence*, *validity* and *duration* that were mapped into DNS instance configurations like TTL, Refresh, Retry and Expire (using DNS Parameters MIB); *no* value for deactivation of standard DNS functionalities namely *notification*, *caching* and *recursion*. The DNS service deployment was performed with the following sequence:

1. The administrator submitted the DNS service meta-configurations to the ACS server using the MIB interface;

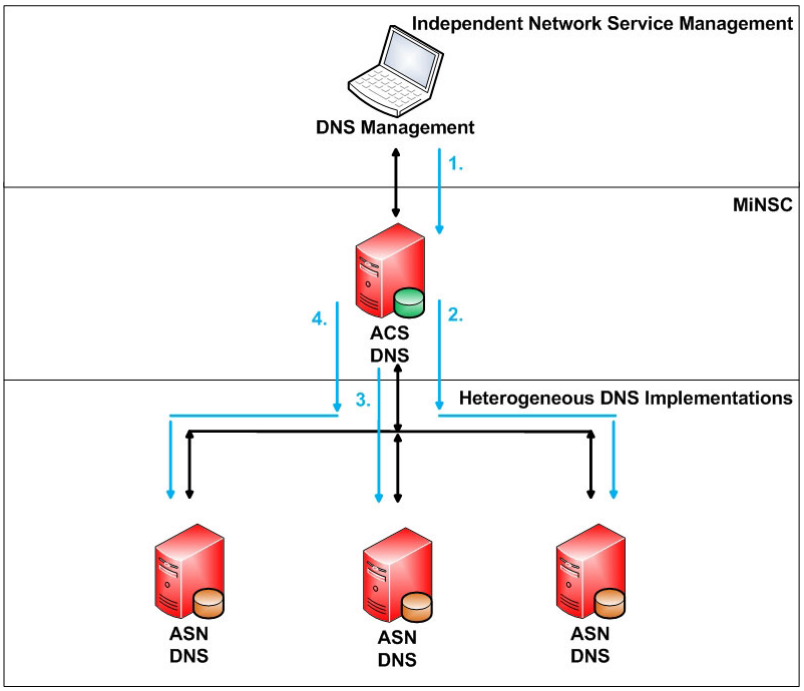

Figure 5.14: DNS service deployment

Table 5.3: DNS service deployment

Deployment Pattern	Duration (seconds)
A-A-A	4.035
A-A-B	3.919
A-B-B	3.469
A-B-C	3.558
A-A-C	3.908
A-C-C	3.471
B-B-B	3.017
B-B-C	3.005
B-C-C	3.340
C-C-C	3.154

2. The ACS server used the DNS service meta-configuration to derive the DNS instance configurations. The primary name server configuration was deployed using the ASI's MIB;

3. The configurations for the first secondary name server instance were deployed using the CSI's MIB;

4. The configurations for the second secondary name server were also deployed using the CSI's MIB.

The configurations deployed for the primary and secondary name servers can be found in the previous section, when the DNS service is deployed with a *low-level* of redundancy distribution. To demonstrate MiNSC's management independence three different DNS implementations were used, creating different deployment patterns: a Bind9 implementation for Linux (refereed to as A) and MS Windows (referred to as B) and a Posadis implementation for MS Windows (referred to as C). The DNS service was deployed using different combinations of three implementations and the average procedure duration (each deployment procedure was repeated several times) is depicted in Table 5.3. The most important conclusions taken from this experiment can be summarized as follows:

- The deployment procedure demonstrates MiNSC's capability to automatically setup a DNS domain based on a group of meta-configurations. This procedure simplifies the administrator's task by automating a traditionally manual operation, improves

management efficiency by reducing typographic errors and enables quick (and secure) setup of a network service;

- The deployment process is almost completely autonomous in terms of instance heterogeneity, which demonstrates the framework's independence regarding service implementations. This is important because management translations aren't used and the administrator doesn't need to understand all the implementations detail;
- The DNS service deployment process took, on average, 3.5 seconds to be completed. The time taken includes the configuration calculation and their secure and reliable deployment, using SNMPv3 with notification confirmation, for three servers (one primary and two secondary). So, this prototype takes, on average, a little more than 1 second to deploy a *Zone* configuration in a DNS instance.

5.5.5 DNS Instance Execution Migration

MiNSC's *Network Service Instance Management* layer provides the management universality, which enables the management of heterogeneous network service instances regardless of their implementations details. Such unification provides simplicity by overcoming the use of management translations. The realization of more advanced operations is also enabled, such as the migration of a network service instance execution, based on the automatic replication of configurations with the following purpose:

- To improve service scalability by increasing the number of network service instances defined for a service deployment. With the ASI instance configurations automatically and periodically replicated to CSI instances, a new ASI is created by activating part of those configurations at the CSI. So, this procedure increases the number of ASI instances defined by a service deployment through the load-balancing of configurations replicated from a ASI to a CSI, which extends the network service resource support. This procedure is referred to as a service instance expansion;
- To improve the service resilience (to instance failures or performance degradation), migrating the service execution from a faulty ASI instance to a CSI instance using the ASI instance configurations previously replicated. When an ASI instance fails (detected by the monitoring system), the ACS server deactivates the service execution at the faulty instance (if possible) and activates the service execution at the CSI instance using the replicated configurations, automatically replacing the faulty instance with minimum data losses.

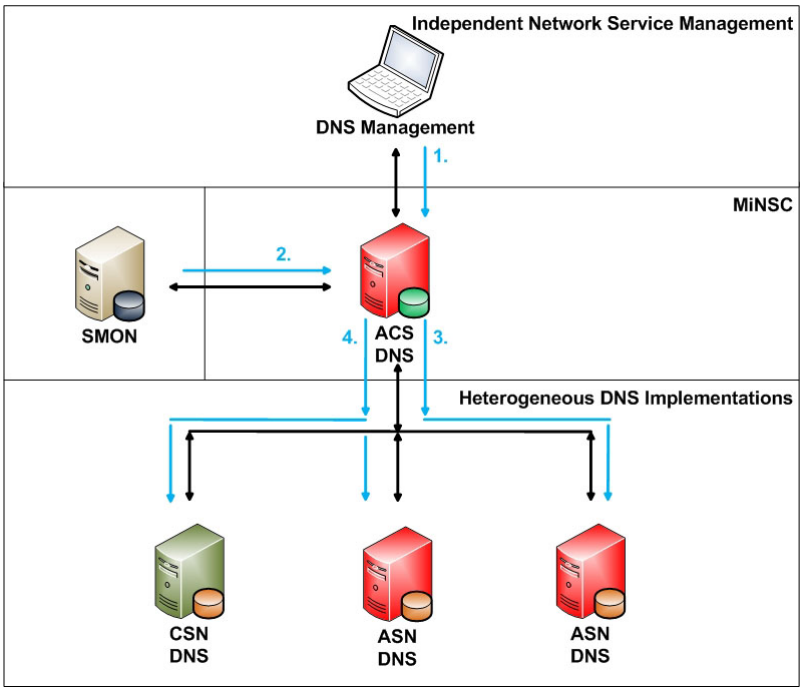

Figure 5.15: Lossy DNS instance execution migration

Considering the realization of the instance execution migration procedure, it's important to evaluate the maintenance (or not) of the instance's dynamic configurations (to minimize migration data losses). This procedure is obtained by means of two different processes: the first is based on the repetition of the service deployment, referred to as the *lossy instance execution migration* procedure, where the instance's dynamic configurations are not considered; the second is based on the execution of automatic and periodic configuration replications, referred to as the *lossless instance execution migration* procedure, where the instance's dynamic configurations are also included.

Lossy DNS Instance Migration

In a lossy DNS instance execution migration procedure only the instance's static configurations are replicated (the dynamic configurations are not included). In MiNSC, such a procedure is performed using the repetition of the service deployment procedure with a different pattern that excludes the instance referred to as faulty. So, the static configurations of the faulty instance are copied to a different location, where service execution is activated. Figure 5.15 depicts the procedure sequence for a lossy DNS instance execution migration:

Table 5.4: Lossy DNS instance execution migration

Deployment (seconds)	Fault	Migration (seconds)		
		Undeploy	Deployment	Total
Low Redundancy Distribution				
2.884	P	4.775	1.724	6.515
2.882	S	5.174	1.835	7.016
3.220	S	4.841	1.919	6.787
Medium Redundancy Distribution				
2.205	P	3.346	1.689	5.041
2.090	S	3.590	1.851	5.448
High Redundancy Distribution				
1.213	P	1.533	0.970	2.515

1. The DNS service is deployed over three DNS implementations using different redundancy distribution levels based on administratively defined DNS meta-configurations;

2. The monitoring system (SMON) notifies the configuration server (ACS) about the need to perform a lossy instance execution migration due to a faulty DNS instance;

3. The configuration server deactivates the service execution at the faulty DNS instance, which is proceeded by the realization of a new DNS deployment (considering the remaining instances) based on the DNS meta-configurations previously defined;

4. The service instance configurations are generated and deployed, embedding the configurations of the faulty instance.

The MiNSC based prototype was used to test a lossy DNS instance execution migration and the results are depicted in Table 5.4. It's important to note that the monitoring information was manually generated, simulating a DNS instance failure. Three different service deployments were used to experiment this procedure, corresponding to the levels of redundancy distribution defined.

When the DNS service was deployed with a *low-level* of redundancy distribution, all instances were classified as ASI (one primary and two secondary name servers). After the migration procedures, only two ASI instances remain active (one primary and one secondary name servers). From Table 5.4, it can be verified that the DNS service deployment over three DNS instances took, on average, 3 seconds to be completed;

when an error occurred in a DNS instance it took, on average, 4.9 seconds to undeploy the previously deployed configurations (involving the deactivation of three instance configurations); then, it required, on average, 1.8 seconds to redeploy the DNS service configurations for the two remaining nodes. On average it took 6.8 seconds to migrate a DNS instance configuration, applying a lossy procedure, after receiving the monitoring notification. The same procedure was repeated for *medium* and *high-level* of redundancy distribution and obtained, on average, a duration of 5.3 and 2.5 seconds respectively.

Some important conclusions could be taken from this experiment:

- Using a lossy DNS instance execution migration procedure is possible to improve DNS resilience by transferring the service execution, when a failure is detected, based on the instance's static configurations. This is performed by redeploying the DNS configurations, excluding the faulty instance, automatically re-distributing the configurations for the remaining instances. The monitoring system contribution is essential for this procedure;

- Since the lossy DNS instance execution migration procedure does not considers the instance's dynamic configurations, data losses are found which may cause disruptions in the service execution;

- The migration process is highly dependent on the number of ASI instances available. As the number of instances increases, the longer time it takes to migrate a service instance since the service must be undeployed and redeployed for a larger number of instances;

- For this prototype the procedure of migrating a faulty instance took, on average, approximately double of the time taken to initially deploy DNS instance's configurations. This is explained by the necessity of undeploy previously deployed configurations (which takes approximately the same time as their deployment) and redeploy new configurations on a lower number of instances;

- Such migration procedure is performed automatically, regardless of the instances details, without using management translations. This proposal represents an important gain to DNS resilience, not found in any other management framework, that commonly implement manual-based procedures for a limited set of instance implementations.

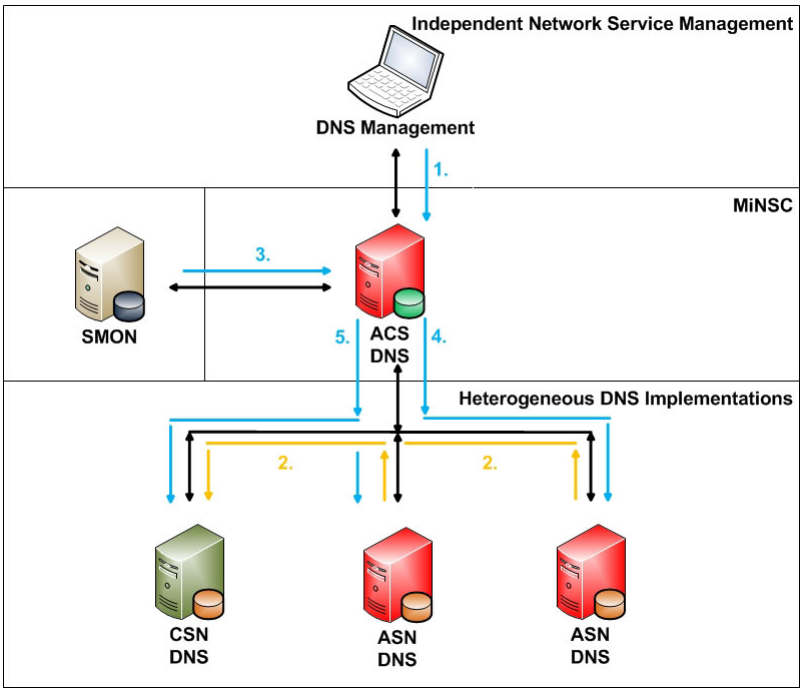

Figure 5.16: Lossless DNS instance execution migration

Lossless DNS Instance Migration

Also with the purpose of improving the DNS resilience to instance failures, a lossless DNS instance execution migration procedure was specified aiming to preserve the instance's static and dynamic configurations, in opposition to the previous proposal. To this matter the lossless migration procedure ensures that, in the event of service instance failure, configurations are previously replicated in a redundant element, thus enabling a seamless service execution transfer without effective data losses. Such a functionality was implemented in the MiNSC prototype and experimented for the DNS management test bed.

The sequence for the realization of the lossless DNS instance execution migration procedure is depicted in Figure 5.16 and includes the following steps:

1. The DNS service is deployed over three DNS implementations using different redundancy distribution levels based on administratively defined DNS meta-configurations;
2. When the DNS service configuration is deployed, the CSI nodes are configured to automatically and periodically replicate the ASI static and dynamic configurations.

It's important to note that during this process configurations are adapted to include the CSI details and promote a quicker migration process, as previously described;

3. The monitoring system notifies the configuration server (ACS) to perform a lossless DNS instance migration, identifying the corresponding faulty instance;

4. The ACS server deactivates the service execution at the faulty DNS instance;

5. The ACS server activates at one of the CSI instances available, the faulty instance's configurations previously replicated. This migrates DNS execution minimizing data losses. The ACS server also updates the remaining DNS instances configurations, maintaining their integrity. New replication procedures are also defined for remaining CSI.

The MiNSC based prototype was used to perform the lossless DNS instance execution migration. The results are depicted in Table 5.5 and the activities included refer to:

- Act. 1: The replication procedure, defined by the DNS service deployment, is stopped at the CSI by setting the state rows of *Instance Replication MIB*. The service execution at the faulty DNS instance is deactivated through the deletion of its DNS *Zone* configuration at the *DNS Instance Management MIB*;

- Act. 2: Activation of the faulty instance's configurations on a CSI.

- Act. 3: Deletion of the CSI's *Instance Replication MIB* table. New table configurations are deployed for the remaining CSI instances (if any), defining new replication procedures;

- Act. 4: Instance configuration dependencies are updated to maintain the integrity of the DNS configuration.

To experiment this procedure, at least one instance must be classified CSI. In this sense, the DNS service was deployed with *medium* and *high-level* of redundancy distribution. When the DNS service was deployed with a *medium-level* of redundancy distribution, two DNS instances were classified as ASI (one primary and one secondary name servers) and the other was classified as CSI. The DNS deployment took, on average, 2.7 seconds to be completed. The migration process took, on average, 7.4 seconds to be completed ending also with two ASI.

Table 5.5: Lossless DNS instance execution migration

Deployment (seconds)	Fault	Migration (seconds)				
		Act. 1	Act. 2	Act. 3	Act. 4	Duration
Medium Redundancy Distribution						
2.827	P	2.028	1.502	2.663	1.210	7.407
2.657	S	1.733	1.533	2.628	1.494	7.392
High Redundancy Distribution						
1.660	P	2.009	1.438	2.979	0	6.431

When the DNS service was deployed with a *high-level* of redundancy distribution, one DNS instance was classified as ASI (primary name server) while the remaining two instances were classified as CSI. The DNS deployment took, on average, 1.7 seconds to be completed. The migration process tool, on average, 6.4 seconds to be completed ending also with one ASI. Since the primary name server has no dependencies no time was required to update dependencies.

It was concluded that:

- When the DNS was deployed with a *medium-level* of redundancy distribution it took, on average, approximately three times the DNS deployment duration to migrate a instance execution. When the DNS was deployed with a *high-level* of redundancy distribution it took, on average, approximately four times the DNS deployment duration to migrate a instance execution.

  This difference is mainly found due to the short deployment duration taken for a *high-level* of redundancy distribution, while most remaining migration activities duration were maintained for both levels. This results in a higher time relation for a *high-level* of redundancy distribution;

- To perform a lossless DNS instance execution migration at least one candidate instance must exist to execute the configuration's replication;

- Based on the CSI configuration replication procedure, it was possible to transfer the DNS service execution to a different instance without data losses, regardless of implementations details. This procedure improves DNS resilience to instance failures;

- In this experiment only the DNS instance's static configurations were migrated. To avoid *cache poisoning* attack, DNS instances commonly block external updates to their cache, so dynamic configuration were not replicated.

Comparing the realization of a lossy and a lossless DNS instance execution migration procedure the following conclusion were taken:

- The lossless DNS instance execution migration procedure can only be performed when candidate instances are defined. The lossy DNS instance execution migration procedure can be performed regardless of existence of candidate instances, in their absence it reduces the number of active instances;
- Both procedures improve the DNS resilience to instance failures. For the lossless DNS instance migration procedure a candidate instance is used to directly replace a faulty instance while in the lossy DNS instance migration procedure the service deployment is repeated to change the deployment pattern (replacing the faulty instance by a candidate or by concentrating in a lower number of instances);
- The redeployment of DNS configuration requires temporary service suspension while the lossless DNS instance migration procedure only individual instance temporary suspension is required;
- For the presented prototype the lossless DNS instance migration procedure takes more time to be completed than the lossy DNS instance migration procedure. The additional time took by the lossless DNS instance migration procedure was due to the additional procedures performed such as the management of replication tables and configuration dependencies update;
- The procedure duration difference for both alternatives is not significative for an automated process that overcome the limitation inherent of a manual procedure;
- The realization of both procedures duration depend on the number of network service instances, their classification and configurations defined.

5.5.6 DNS Instance Expansion

The DNS instance expansion is a complementary functionality that increases the number of ASI instances in response to scalability limitations (due to resource constraint). Based on the execution of periodic instance configuration replication procedures DNS instances

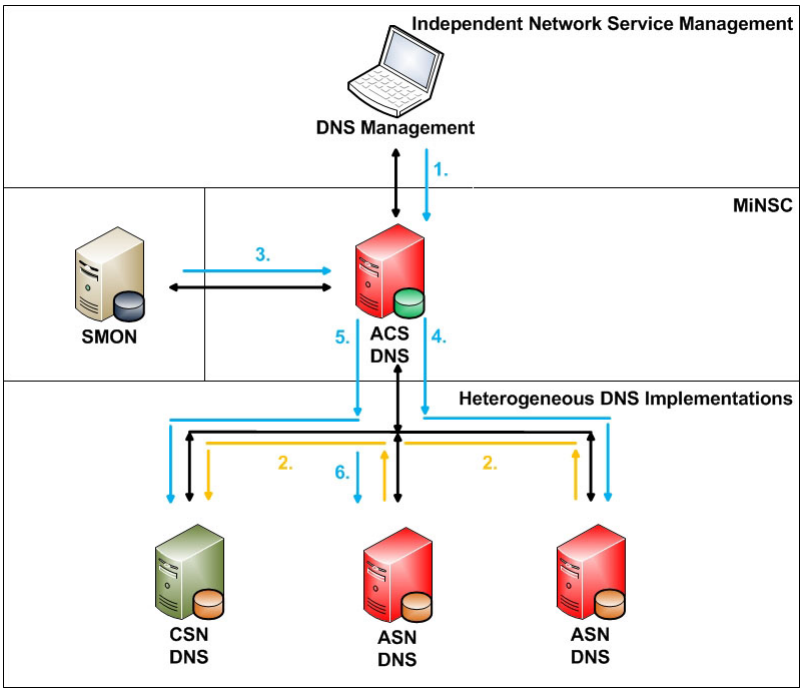

Figure 5.17: DNS instance expansion

may be extended, transforming CSI into ASI instances. The DNS instance expansion procedure is depicted in Figure 5.17 and includes the following steps:

1. Two DNS *Zones* are deployed (*scm.di.uminho.pt* and *scm1.di.uminho.pt*) over three DNS instances using *high* and *medium-levels* of redundancy distribution;

2. The instances classified as CSI are responsible for the periodic replication of ASI configurations;

3. The monitoring system notifies the ACS server about the need to perform a DNS instance expansion, identifying the instance to perform load-balancing;

4. The ACS server deactivates part of the faulty ASI's configurations. In this experiment, 50% of the ASI's configurations were deactivated, which means that the *Zone* identified by *scm1.di.uminho.pt* was suspended;

5. The DNS *Zone* suspended at the ASI is activated at the CSI, using the previously replicated configurations. This extends the DNS service resources to include a new ASI;

Table 5.6: DNS instance expansion

Fault	Expansion (seconds)				
	Act. 1	Act. 2	Act. 3	Act. 4	Duration
Medium Redundancy Distribution					
P	2.613	1.842	5.660	2.240	12.359
S	1.903	1.714	5.388	3.267	12.278
High Redundancy Distribution					
P	2.553	1.644	5.992	0.934	11.125

6. Unchanged instance configurations are updated to include the new ASI. Remaining CSI replication tables are updated.

Using MiNSC's prototype, the DNS instance expansion procedure was experimented and the results obtained are summarized in Table 5.6. The activities referred in the table are the same as those from the previous experiment. At least one DNS instance must be classified as CSI, so DNS service was deployed with *medium* and *high-level* of redundancy distribution. When the DNS service was deployed with a *medium-level* of redundancy distribution, the procedure to expand a DNS instance took, on average, 12.4 seconds (considering a primary name server for load-balancing) and 12.3 seconds (considering a secondary name sever for load-balancing) to be completed. The difference between procedures duration is considered irrelevant and happened due to the fact that primary name servers have a larger amount of configurations to be managed. When the DNS service was deployed with a *high-level* of redundancy distribution, the procedure to expand a DNS instance took, on average, 11.1 seconds to be completed.

The following conclusions were taken from the experiments:

- With MiNSC's instance expansion mechanism the ASI's configurations can be balanced (for a given percentage) to a CSI, creating a new ASI. This improves DNS scalability by increasing the number of resources available;
- The DNS service was securely and automatically extended in a few tenths of seconds. If it were to be performed manually, would take several minutes and would be prone to manual errors;
- The implementation of such a mechanism promotes a more efficient resource management, increasing the number of service instances as required;

- Future developments include the realization of a complementary mechanism aiming to concentrate configurations, decreasing the number of resources used.

5.6 Conclusion

This chapter explores the practical details associated with the implementation of a MiNSC based prototype for DNS management. In the beginning of the chapter, the structure of the prototype elements was described including the modules implemented and algorithms applied. Then, the two-layer DNS management information model was described, including their formal representation in a MIB tree. The final part of the chapter was used to describe the experiments made, focusing on demonstrating feasibility and effectiveness of MiNSC capabilities for DNS management. The experiments involved the cooperation of the *Service Management* and *Network Service Instance Management* layers to enable the integrated DNS management.

From the group of experiments made it was possible to confirm the universality of the DNS management data model proposed, enabling the management of heterogeneous implementations with negligible differences. The *DNS deployment* was experimented for the automatic setup of a DNS domain. In a few seconds, a DNS domain composed by three servers was automatically and securely created. The *DNS instance expansion* increased the number of DNS instances based on load-balancing of configurations, using candidate instances, to improve DNS service performance and scalability. Even though this procedure requires the over-provisioning of DNS instances, it enables a more efficient resource management, assigning instances as their are required.

The *DNS instance execution migration* used candidate instances to improve DNS resilience to instance failures. Whatever the migration alternative used, a faulty (active) instance is automatically replaced by a candidate (which becomes active) is a few tens of seconds. The most important differences between the alternatives presented are the maintenance of the faulty instance's dynamic configurations and the necessity of candidate instances, which incurs into additional resources. To conclude, the results clearly demonstrate the effectiveness of MiNSC's service management functionalities when applied to a practical management example.

Chapter 6

Evaluation

After exploring MiNSC's details, including results from a prototype experiment, it is important that its contribution within the context of contemporary network management frameworks be evaluated. As such, this section provides a theoretical evaluation comparing relevant integrated network management frameworks with MiNSC's proposal. From the evaluation results, the author concludes that MiNSC does not aim to replace any of the evaluated frameworks. Instead, it can be used as a alternative for the implementation of management translations, whose limitations were previously identified, while potentiating resilience, scalability and interoperability of the network management service and of the managed services.

6.1 Motivation

Contemporary network management frameworks which aim to support heterogeneous network elements use management translations [42] to effectively enforce independent management representations (such as policies) into management interfaces and data models. However, the implementation of management translations represents a complex task, hard to be fulfilled in large scale heterogeneous networks, which, when allied to other limitations, make the availability of such proposals very scarce. MiNSC creates a complementary alternative for the configuration management unification of heterogeneous network service implementations. These not only overcome the limitations inherent to the management translations but contain additional concerns regarding service resilience, scalability, interoperability and management simplification as well. This chapter evaluates MiNSC's contribution in comparison to well known integrated network management frameworks such as FOCALE and WBEM.

FOCALE is a distributed architecture for orchestrating the behavior of heterogeneous network elements based on semantically rich representations with a high orientation towards business goals. FOCALE implements the autonomic network management control loop by automatically adjusting the network element's behavior in accordance with administratively defined business policies. Those policies are refined by autonomic managers and applied to autonomic network elements that ensure their effectiveness. In case of non-autonomic network elements (also refereed to as legacy), FOCALE proposes the use of an MBTL which semantically translates from the autonomic manager's independent configurations to the network device's specific management interface and data model. However, such semantic mapping may be too complex to be implemented in highly heterogeneous environments.

WBEM is another important network management framework aiming at the integration of heterogeneous desktop applications, latter extended to the management of networked elements. It defines a group of standard information models hiding the heterogeneity of network elements from the management applications. However, in order to enforce independent configurations into the network element's heterogeneous data models, Providers must be created and maintained. This requires the administrator manual effort that besides being complex is error prone.

The following evaluation considers a group of criteria and evaluates their fulfillment in each of the referred frameworks. The evaluation criteria were compiled keeping in mind the most important requirements oriented towards the realization of a mid-level operation supporting the heterogeneous network management, further complemented with some lower-level requirements for the management of IP-based networks [42]. The evaluation results are depicted in Table 6.1, including the corresponding evaluation criteria, which are explained thoroughly in the following sections.

6.2 Automation

The automation of network management procedures is gaining recognition which is mainly motivated by the increasing complexity of networked systems and increased requirements for enhanced management efficiency. Since this is an important requirement for contemporary network management systems, it is important to highlight the manner in which the evaluated frameworks address this requirement. The following items summarize the most important motivations for automating the network management process based on [246, 247]:

Table 6.1: Integrated network management evaluation

	MiNSC	WBEM	FOCALE
Automation	-	-	+
Configuration Management Provisioning	+	+	*
Heterogeneity	+	-	+
Interoperability	+	-	*
Management Information & Data Models	+	+	+
Resilience	+	-	*
Scalability	+	-	*

- Automation provides better control of the network element's most advanced functionalities, ensuring support for their ever increasing complexity, while decreasing dependency for manual intervention by the administrator;

- Reducing the administrator's dependency, through automation, has imposed important consequences for the network's operational state. It improves network efficiency by decreasing the errors inherent to a manual-based process, reduces network element's down-time (by decreasing the intervention duration), consequently improving profits as a result of the network's stability, maximizing the investment and reducing the number of specialized professionals required to operate the network. Furthermore, the deployment for new management solutions becomes easier and faster;

- One important consequence from the implementation of automatic network management procedures is the promotion of the deployment of more complex functionalities (at the network device's level) which ensures their management aside from enabling their integration in increasingly complete (and complex) network management models;

- The capability to manage proactively is another important inherent functionality which stems as a result of the application of automatic network management, in opposition to the contemporary reactive network management frameworks. This means that the management system may use third party data (such as context) to distinguish the network element's tendency to be in a erroneous state, automatically taking the necessary measures;

- Network management simplification is also achieved with the implementation of automatic network management. This is most commonly achieved using management policies which the management system must automatically enforce. This ensures the automatic control of network element's state by automatically generating configurations and converting them from independent representations to device-specific configurations;
- State of the art network management frameworks commonly rely on the implementation of management translations, between the independent representations maintained by the management application and the network element's data model. Given the management translations intermediary position, automation may be added to simplify the management applications operations. This requires the introduction of an abstraction level, delegating some automated management tasks at the intermediary level, that transparently deals with network elements low-level details;
- Network security may also be improved using automatic network management. Global security policies can be defined administratively, which are quickly and automatically deployed to the network element's configurations. This enables an expedite deployment of security measures using a flexible method in response to security threats.

WBEM

No particular implementation from WBEM's specification is known (at the moment of this writing) to create an automatic network management solution. It could though be used as part of a automated network management infrastructure, providing the management abstraction that is capable of isolating the management applications from the network element's heterogeneous implementations and management interfaces. So, as described in Chapter 2, WBEM focus on the implementation of management independence rather on automation.

The lack of automated management functionalities is clearly demonstrated in the most popular WBEM implementations such as OpenPegasus [134] and WBEMServices [248] where they mainly propose the implementation of WBEM divided into three components: the CIM Client that is responsible for issuing CIM Operation requests and receive/process responses; CIM Server that receives and processes CIM Operation requests and issues responses; CIM Provider responsible for processing CIM Operation requests mapping to the resource-specific configuration and commands using the

adequate instrumentation. It is not the WBEM implementation's responsibility to automatically orchestrate the managed resources overall behavior, instead they are only responsible for enforcing the defined individual management requests.

To support integration, WBEM relies on the implementation of Providers at the managed element level that translate from CIM independent representations into specific implementations and data models. However, the management abstraction level provided is only adequate for the mapping process without further automation concerns, even though a WBEM Server can be used in a hierarchical structure implementing the models with Proxy Providers to manage distributed elements. In this sense, WBEM does not include the capability to perform more than the translation process, not supporting the simplification (through automation) of management procedures at the intermediary level.

FOCALE

FOCALE is a PBNM framework that, by implementing the autonomic control loop, creates an automated management framework to simplify the ever increasing management complexity of network element functionalities, besides supporting an adequate business driven management model. To support automation of integrated network management, FOCALE is based on the following principles, as explained in [41]:

- Use a combination of information and data models (DEN-ng) to establish a common model, with a technological and platform independent representation, that can be mapped into technological-specific functionalities;
- Ontologies are used to add semantics, augmenting the facts represented in the management model;
- The combination of models and two layers of ontologies are used to discover and program semantically similar concepts in managed elements, independently on their languages and data models;
- The facts represented in management models are used to construct finite state machines to represent the management system behavior;
- Context-aware policies are used to govern the managed element's behavior, determining the set of state transitions required when the system is not in a optimal state. This is performed based on the implementation of multiple control loops;

- Machine reasoning algorithms are used to generate a solution hypothesis in the presence of problems;

- Machine learning algorithm are used to reinforce actions that lead the managed system to the desired state.

This enables the creation of self-governing systems, that based on the business-oriented policies, support the management of more complex managed elements, but, at the same time reduces human dependency. FOCALE's control loop is composed by the management system and the managed elements whose state and operational context is retrieved and normalized. If they are not at the desired level, new configurations are generated in order to drive the managed element to the desired state. State verification and configuration generation is based on the defined management policies, which are business oriented in FOCALE's architecture.

A Policy Continuum [15] is used in the transition from a business perspective into a technological perspective. The implementation of the Policy Continuum [249] into different constituents of the continuum (using different concepts and terminologies) defines and develops shared policies. The Policy Continuum constituents include a Business, System, Administrator, Device and Instance views, each one to use its own set of concepts and terminologies defined through an information model (DEN-ng), optimized for their specific needs. In DEN-ng each view is strongly related with the other which enables different constituents to be associated with each other. The policies are treated as a continuum and their different views are related to each other through model mappings (translations). These mappings may change the policy abstraction level, enabling the application of business oriented policies to device configurations.

FOCALE provides a complete management architecture, ranging from the management application interface with the administrator down to the network element's configuration and control. High levels of automation is achieved using business-oriented policies to automatically derive the network elements behavior at the AE level, and using the Policy Continuum to refine the management policies and autonomic control loops to ensure their automatic enforcement. To semantically integrate heterogeneous network elements the MBTL is used, translating from a common representation to several implementation-specific representations. Even though the MBTL implements an intermediary operation, it does not includes any management abstraction able to at the intermediary level automate management tasks. Such automation is performed at the application level (AE).

MiNSC

As explained in previous chapters, MiNSC is part of an Automated, Distributed and Integrated Network Services Management framework composed by two subsystems: SMON [197] and MiNSC. To obtain higher levels of automation for network service management, both subsystems are required. SMON is used to retrieve the network service state, interfacing with higher-level network management applications to verify whether or not the present state is the desired one. If this is not the case, it then informs MiNSC to perform a configuration management operation that might comprehend a new network service deployment, based on the network service meta-configuration, service instance execution migration, service expansion and others. Configuration management operations can also be of human initiative. MiNSC's automated management functionalities were explained in previous chapters. The most relevant include:

- *Service Configuration Management* refers to the activities that are performed whenever the service meta-configurations are administratively changed or when some configuration management operation is requested through the monitoring interface. When the network service meta-configurations are changed, a new network service deployment must be performed which might result in changes to the service deployment pattern and/or service instance configurations. When requested by the monitoring system, other types of configuration management operations may be performed such as the service instance migration (which means the automatic migration of the service instance execution from active to candidate), the service expansion (to increase the network service physical support) and others to be defined in the future (such as instance configuration parameter tuning);

- *Network Service Deployment* uses the two-layer management abstraction to integrate the management of heterogeneous network service implementations and simplify the network service instance configuration setup, based on the service meta-configuration defined. The network service deployment uses the meta-configuration to automatically compute the number and distribution of network service instances as well as their configurations, including their dependencies and their effective enforcement;

- *Service Instance Migration* uses the configuration independence, provided by MiNSC's management layers, and the replication process, performed by candidate instances, to automatically migrate the network and management service instance execution with the purpose of increasing service resilience to instance failures;

- *Service Expansion* aims to improve resource consumption and scalability at both layers, by increasing (or decreasing in the future) the number of instances used by the management or network service. This functionality is performed using load-balancing of replicated configurations.

Its important to note that previous automated management functionalities are possible due to the management abstraction implemented at MiNSC's *Service Management* layer. The representation of the service meta-configuration, embedding the behavior pretended, provides a service-oriented management perspective in opposition to the common server-oriented management approach. This potentiates the realization of automation at the intermediary level.

Despite the increased recognition that automatic network management procedures gained, they are differently supported by the evaluated frameworks. From WBEM's perspective, no specific automated network management method was proposed in its specification. WBEM aims to fill the gap between the network management applications and the heterogeneous managed resources, which are specially oriented for desktop applications. WBEM's management abstraction is based on standard information models, called CIM, uses a standard protocol for client-server message exchange and defines an encoding method to represent the CIM and management operations into the transport protocol supported representation. WBEM uses Providers to syntactically map from CIM's abstracted representation into implementation-specific representations. While integrating the management of heterogeneous managed elements, it does not specify any method to promote the automation of management procedures or any management abstraction suited for automation. However, WBEM could be used as part of an automatic network management framework, providing the mid/low-level operation, responsible for management abstraction and integration.

MiNSC provides an additional level of automation for the network service configuration management, based on a new perspective that does not rely on management translations. Instead, MiNSC provides additional management abstraction implemented in two layers. The *Network Service Instance Management* layer aims at the management unification of network servers through the implementation, for each service, of a single data model derived from a standard-based service management information model. The *Service Management* layer provides an additional level of abstraction that aims to automate the configuration management procedures of underlying network servers, dealing with lower-level configuration details. At this layer, a service oriented management ap-

proach is supported, defining the managed service behavior. However, MiNSC has a tight relation with SMON to achieve some degree of network management automation, which means that on its own, MiNSC only provides a limited set of automated configuration management operations. Besides, MiNSC and SMON do not aim to create the ultimate automated management framework, they provide a mid/low level operation to be used by higher-level network management applications, that by integrating their functionalities, enable simplification. Some of MiNSC automatic configuration management functionalities include service deployment, service expansion and service instance migration.

At a different level, FOCALE proposes a fully automated network management framework. The realization of a high degree of automation is motivated by the increasing complexity, heterogeneity and number of network elements, as well as enhanced efficiency for management systems. The first part of FOCALE's automated network management framework is the Policy Continuum. The continuum enables the representation of the policies defined for a constituent using different abstraction levels, ranging from business terms until technological specific terms. The second part of FOCALE's automated network management framework is the autonomic control loop that is used to ensure the policies effectiveness. The autonomic control loop starts by capturing monitoring data from the network elements. Then this data is analyzed, by the autonomic manager, to identify the network elements state. If the network element's state is not in accordance to the pretended state, described by the policies, the autonomic manager automatically computes the optimal state transition. In each state, new configuration commands are automatically generated using vendor-specific command templates. Context-aware management policies verify the enforcement of the configurations generated, closing the autonomic control loop.

6.3 Configuration Management Provisioning

In this section, the author compares different configuration provisioning methods implemented by the referred frameworks. The following evaluation is based on the configuration management requirements defined in [42]. However, due to the lack of FOCALE's practical details, a proper comparison between the three frameworks could not be performed.

The following dimensions must be considered in configuration management provisioning:

- The provisioning functionalities include the most basic elements used for the remote management of configurations, such as: addition, deletion and update of parts or complete configurations sets; definition of notifications or confirmations to acknowledge the occurrence of asynchronous events; instantiation or deletion of objects; execution of managed object's methods; maintenance of the configuration history (for debugging and roll-back on operations in case of failure); etc;

- Given the importance that configuration management possesses, other functionalities must be ensured: *security* to hide the configuration management activities from unauthorized access, using the implementation of encryption methods allied with an authentication method, to ensure the communicating entities' authenticity and access control; *reliability* is another important characteristic of the configuration provisioning which tries to ensure a reliable operation where the configuration management message lost is mitigated; in order to improve the integrity and stability of managed elements, *configuration validation* and *error detection* mechanisms must be implemented thus, verifying the configurations prior their deployment as well as roll-back in case of failures.

WBEM

WBEM uses an evolved mechanism for configuration management provisioning, based on the invocation of object's methods, instead of directly changing the object's value and relying on their underlying management functionalities (as in MIBs). This can cause a few problems when several objects need to be atomically updated [250]. Two types of methods may be invoked by WBEM Clients for configuration provisioning: *intrinsic* and *extrinsic*. Intrinsic methods are used for the management model's manipulation and includes methods to retrieve, delete, create, list the model's classes, instance associations and qualifiers as referred in WBEM Operation specification [125]. The extrinsic methods are CIM class (or instance) methods that may be invoked by WBEM Clients to perform a function (at the Provider level) defined in the Schema. The result of the method invocation is then redirected to the corresponding client for acknowledgment. WBEM supports an interface that receives asynchronous information regarding events and alarms (called Indications) that have occurred in the managed device and in which an operator has expressed interest. This interface is present at the WBEM Client and is referred to as Listener Interface. However, other equally important elements are present at the WBEM Server: the Indication filters are used to determine whether or not an Indication satisfies a predefined pattern; the Subscriptions are consulted to determine whether any

operation is interested in being notified as to the Indication; the Handlers which are responsible for sending the Indication to the Listener Interface; the Indication Providers are used to physically detect the events/alarms, creating Indication instances and pass them on to the WBEM Server. So, when an event occurs the Indication Provider creates an Indication instance passing it to the WBEM Server, the filters are then examined to determine whether or not that Indication can pass through. If this is the case, it moves on to the associated Indication Handlers interested in this type of event. The corresponding Indication Handlers pass the Indication to the Listener Interface. CIM's Event model enables the representation of several types of events: the CIM_ClassIndication enables the definition of events arising from the manipulation of model classes (creation, deletion, modification); the CIM_InstIndication enables the representation of events related to the manipulation of classes (like the previous CIM_ClassIndication), also including the invocation of a method on them; CIM_ProcessIndication is used to model external events (unrelated to the model manipulation).

From a security perspective, WBEM's specification uses the services provided by the Hypertext Transfer Protocol over Secure Sockets Layer (HTTPS) protocol to ensure the communication's reliability and confidentiality. By default, WBEM's specification supports two types of client authentication methods: Basic Authentication over SSL and Digest Authentication. However, the WBEM Server includes a Security interface for an external authentication mechanism such as LDAP. Based on the authentication mechanisms, ACLs may be used to limit the access to specific name spaces (as in OpenPegasus [134]).

From a configuration validation perspective, WBEM does not implement any specific method because it does not deals directly with configurations. In WBEM, the management application's requests are mapped into CIM's methods, generating CIM commands at the WBEM Client. From the WBEM Server's side, the method implementation is supported at the Provider level. In this sense, there is no need to use configuration validation mechanisms as long as the methods are correctly mapped at the Client level and well implemented at the Provider level.

FOCALE

Conclusions regarding FOCALE configuration management provisioning cannot be easily executed since there are no implementation details at the time of this writing. However, since it is based on the MBTL intermediary translation, two levels of configuration management provisioning could be inferred (depending on the location of the MBTL):

one used to exchange independent configurations between the autonomic server and the MBTL; the other for the exchange of implementation-specific configurations and commands between the MBTL and the heterogeneous management interfaces. In this sense the provisioning of configurations will always depend of the technologies used at both levels.

MiNSC

Such as FOCALE, MiNSC configuration management provisioning is dependent on the underlying network management interfaces used (even though it includes definitions for the most basic configuration management operations, such as, *Get*, *Set*, *Delete*, *Modify* and *Notification*). This enables its configuration management provisioning capabilities to be extended as required. In MiNSC's specification, a well known network management interface was proposed (MIB) which enables the use of SNMP primitives for the network service configuration management provisioning. With the service instance's management information models implemented in MIBs, the instance's configurations may be partially or completely retrieved, updated and deleted using SNMP's primitives, accessing values of MIB object instances. SNMP also enables the transmission of asynchronous notifications that, in the case of MiNSC, gains higher relevance because they are associated to the completion of configuration management operations (used to ensure their effectiveness). When a new configuration element is added/removed, from the instance's configuration, the agent is responsible for sending to the configuration server a notification informing as to its successful execution.

On the other hand, SNMP do not provide any configuration verification mechanism and this is not relevant at this level. This is explained by two reasons: first, MiNSC does not enable a concurrent access to the managed instance configuration because only one ACS server is enabled for each service instance. This means that concurrent data integrity is ensured; the service management information model implemented in SMI provides a narrow scope for eventual configuration (syntactical) errors. However, it lacks a semantic verification engine to ensure the overall configuration consistency in relation to the behavior pretended. Other configuration management functionalities, such as the configuration's history, may be performed at the ACS server, enabling the execution of rollback on errors, if required. This requires ACS further development. From a security perspective, MiNSC implements the security measures defined in SNMPv3, providing configuration management data confidentiality, manager and agent authentication, message exchange integrity and access control.

In terms of the configurations provisioning, both MiNSC and WBEM frameworks provide the identified requirements using different perspectives. While in WBEM configurations are managed mainly through the methods invocation, either applied to the management model or at the managed object defined on the Schema, in MiNSC configurations are directly managed using MIB object values. They both support the implementation of asynchronous notifications. However, WBEM's notifications support a more complete mechanism with filtering and handling.

On the other hand, MiNSC and WBEM do not support the implementation of configuration validation and error detection mechanisms. From a security perspective, both ensure the management data confidentiality, client authentication, message integrity and access control mechanisms.

6.4 Heterogeneity

With the ever increasing heterogeneity of network elements (including services), effective ways of promoting integrated management, automation and efficiency in management systems is required. However, the management of heterogeneous network elements is commonly based on the implementation of management translations, that can be performed either using static or semantic approach, incurring into important limitations. When referring to the network elements, two different levels must be considered: when the heterogeneity is present at the management interface and data model level; or when the heterogeneity is present at the implementation level. In general, in order to support the heterogeneity of management interfaces (and data models), management translations are required. The management of heterogeneous implementations is commonly solved through the implementation of standard interfaces, providing a standard representation for the management data. A complementary alternative is proposed by MiNSC based on unifying standard technologies to overcome the limitations inherent to complex translation mechanisms for the management of heterogeneous implementations.

WBEM

WBEM's management framework supports both types of heterogeneity, at the management interface and at the implementation level. It proposes standard information models, representing abstract concepts, to be latter mapped into the network elements heterogeneous interface and implementation (based on a web interface). To effectively enforce abstracted representations, Providers are implemented performing one of the

following types of translations: *technique*, *recast* or *domain* as described in CIM's Interoperability model [250]. So, WBEM enables different mappings using syntactic (or semantic more recently) approach with different levels of complexity. According to [250], the Providers that must be commonly supported by WBEM Servers include: the *Method Provider* to handle calls made to extrinsic methods; the *Instance Provider* to handle the management of instances of particular classes (creation, enumeration, deletion, etc); the *Property Provider* to handle requests for gets and set on instance's properties; the *Association Provider* to handle association between classes or instances; the *Indication Provider* to handle notifications; and the *Query Provider* to handle queries. Each *Provider* function is converted into low-level, implementation-specific or management interface.

FOCALE

The FOCALE project aims to reduce the administrator's dependency by automating network management tasks. This important requirement is motivated by the increasing number and complexity of network elements, the increasing number of networked users, their heterogeneous requirements, solutions diversity, functionalities, capabilities, etc. It is obvious that the implementation of manual-based management systems does not copes with such complexity, resulting in management applications with low flexibility and efficiency. FOCALE's integrated network management is oriented towards the management of heterogeneous interfaces, rather than implementations, since it does not defines a management interface as WBEM does.

In order to integrate such heterogeneity ontologies are used at two different levels, enabling network elements (performing similar operations) to be correlated and managed through a common vocabulary. To fulfil this task, the MBTL was created in an attempt to support the management of non-autonomic network elements (also referred as legacy elements), translating from an independent representation (coded in XML) to vendor-specific configurations and commands. For the mapping process, a domain-specific ontology (called lower ontology) is used to add semantics to the facts represented in the network element's management models. This provides a formal definition for each fact, as well as, linguistic relationships. In a management domain, several domain-specific ontologies may exist, each on representing terms for a domain. With the purpose of define common terms to be used as basis for integrating multiple domain-specific ontologies, a generic ontology was created (called upper ontology). This ontology was defined to augment the facts represented in DEN-ng, facilitating the fusion of knowledge between the

models, using semantic relations [41]. DEN-ng information and data models constitute the basis for the common language that are latter associated with semantic content.

Using this common vocabulary, management data from heterogeneous elements may be compared and their state easily verified. This mapping process should enables the execution of management functionalities with similar semantics on heterogeneous devices regardless of the data model and language implemented.

MiNSC

MiNSC employs a simpler alternative for the management of heterogeneous network service implementations. The association of standard technologies, such as a standard-based service management information model and a standard network management interface produces, for each network service, a unified data model that eliminates the management heterogeneity, the realization of management translations and their inherent limitations. This creates a new configuration management interface, that pushes any type of translation into the instrumentation layer, inside the implementation of the network service element. So no translations between different models are realized inside the management system. MiNSC does not support integrated management of heterogeneous management interfaces, which can only be performed using management translations. Instead, it includes a unifying configuration management interface able to efficiently deploy configuration management of heterogeneous network service implementations.

WBEM, FOCALE and MiNSC implement three different alternatives regarding the management of the network's heterogeneity. WBEM defines a group of standard information models intended to manage heterogeneous implementations or interfaces. WBEM's CIM contain a group of management concepts which, can be used in several management domains, abstracting the network element's implementations details. However, in order to be used they require the implementation of Providers, that acting as middleware elements, translate from the CIM-based representation to implementation-specific configurations and commands performing the management operations. As referred in [129], syntactic management conversion (*recast*) is the most common form of translation found in WBEM to integrated the management of heterogeneous network elements. As previously referred, this introduces a group of well identified limitations and some works already address semantic translation (*domain*) [130]. The realization of a semantic translation enables higher levels of integration, specially when integrating overlapped representations. However, it also incurs into important limitations which makes is ques-

tionable when considering the integrated management of larger scale domains.

FOCALE implements a more advanced mapping scheme, based on the semantic translation between DEN-ng independent representation and the device-specific configurations and commands, performed at the MBTL level. However, as previously mentioned, real data models lack formal semantic representations, depending on the administrator's manual intervention to create or validate the semantic contend and its mappings. For heterogeneous environments, this mapping process is to complex to be efficiently performed and maintained.

MiNSC proposes a complementary alternative that, like WBEM, is based on standard definitions. On the other hand, unlike WBEM (and FOCALE), MiNSC does not aim to integrate the management of heterogeneous network management interfaces. Instead, it does propose a new configurations management interface implementing a unified data model that eliminates the management heterogeneity and the need to implement management translations inside the management framework. This new management perspective overcomes the limitations imposed by the translation process. MiNSC implements a mid-level management abstraction which makes it suited to be directly implemented on the network elements without translation. This only requires the vendor's support to the proposed interface by developing the corresponding instrumentations to their products. A management process based on standards represents potential gains when applied in highly heterogeneous environments.

6.5 Interoperability

Achieving the maximum level of interoperability is the goal of any middleware system. However, higher levels of interoperability can only be achieved when standard interfaces are used thus, leaving no doubts as to how middleware is used by higher-level applications or how it uses lower-level elements. In network management, this problem is further enhanced due to the availability of management interfaces, some of them promoting interoperability more efficiently than others, depending on the flexibility of the management data models' definition language. In addition to this, it is important to note that one of the requirements for future Internet management [160] is the implementation of interoperable systems. They promote the competition between high-level network management applications that, even when in different domains, may compete for a management role. Obviously, this can only be achieved using interoperable middleware systems.

WBEM

WBEM standards include two important elements that must be considered when referring to its interoperability within higher-level network management applications. In this sense, in addition to the CIM models, WBEM specification includes the xmlCIM Transport Encoding and HTTP Access. The xmlCIM encoding specification provides a standard way to represent CIM's data using XML language that will be transported over the HTTP protocol. A Document Type Definition (DTD) is used to map CIM objects to XML elements. In this situation, the commands and responses to be applied to CIM elements are also encoded. HTTP Access refers to the transport mechanism for CIM message encapsulation into HTTP request and response messages using XML. In order to attain interoperability, both the XML representation and the HTTP encapsulation were standardized.

While this represents an adequate interface for higher-level network management applications, the management model definition in DTD, which is an XML-based language, represents an important limitation when referring to the management systems interoperability. The first drafts of YANG [28] refer that the extreme flexibility of XML-based languages (like XSD, DTD, RelaxNG, etc) and their excessive expressiveness provides XML data with too much freedom. If the management model is defined in a not so strict language, it may rise interoperability issues at the management application level. Besides, WBEM implements a general purpose transport protocol which lacks several fundamental management concepts (such as a management interface) with a well defined structure of objects or data. This includes their universal identification, type definition, operations support (with scoping and filtering) and support for notification definition.

FOCALE

Conclusions regarding FOCALE's interoperability are difficult to draw due to its lack of implementation details, preventing an adequate evaluation. Nevertheless, since FOCALE implements an hierarchical architecture, the interoperability of its constituent element interfaces can be studied. As such, the following conclusions can be summed up:

- The non-autonomic network elements possess several types of management interfaces (some of them proprietary) that must be supported by the autonomic server. In this sense, achieving high-levels of interoperability at the network element level is a difficult task;

- The MBTL aims to provide the first level of management integration within the AE, semantically translating from the DEN-ng independent representation, maintained by the autonomic manager, to the device-dependent configurations and commands. Given the lack of implementation details, further conclusions regarding the MBTL interoperability cannot be drawn. However, its interface with the autonomic server should be performed using standard management interfaces to promote the server's interoperability;

- The autonomic manager receives the management policies that will be enforced at the AE level. This can also be considered as an interface point to higher level management planes (like the inference plane) where the AE policies are negotiated. Therefore, interoperability must also be ensured at the AE level, to promote the competition of systems at the inference plane level.

So, FOCALE's interoperability requirements may be considered at several levels. On the other hand, regardless of the location of the interface points, they must be based on standard management interfaces instead of generic or proprietary. This promotes the interoperability between autonomic elements.

MiNSC

Achieving high levels of interoperability was one of the most important reasons why a MIB interface was chosen for MiNSC's framework. MIBs represent a widely used and standard network management interface whose objects are defined using a well known data model definition language (SMI). SMI language is referred to as being to strict and limited in its expressiveness, however, such limitations provide a tight representation of management data models which mitigates interoperability problems.

In order to promote MiNSC's management interoperability, MIBs are used in all interfaces: at the *Network Services Instance Management* layer provides a unified management data model, for the implementation of instance management information model. This interface promotes interoperability with MiNSC's configuration management servers (*Services Management* layer); at the *Services Management* layer provides a unified management data model, for the implementation of service management information model. This interface promotes interoperability with higher-level (external) management applications; present in all framework elements, a MIB promotes an important technological isolation between MiNSC and SMON.

Regarding WBEM's and MiNSC's interoperability evaluation, similarities can be found as both propose the use of well known and standard transport protocols in order to enforce management operations. However, they rely on completely different interfaces with important implications. WBEM uses HTTP protocol, which is a general purpose protocol with a large number of functionalities. It also uses DTD as management data model definition language and a web server, as interface, to receive the requests and issue responses. Managed resources are globally identified using generic URIs. On the other hand, MiNSC uses the SNMP protocol, which is a standard protocol for the management of Internet systems. SMI is a standard language for definition of data models implemented in MIBs. An MIB represents the management interface, supporting the managed objects structure and identification. This means that from WBEM perspective, we gain flexibility but such flexibility might expose some interoperability limitations. On the other hand, MiNSC has a rigid interface expressly dedicated to network management with lower flexibility, however, maintaining high interoperability capability.

6.6 Management Information & Data Models

To enable the integrated management of heterogeneous network elements, management frameworks commonly use independent representations latter translated to specific management interfaces and data models. The most common way of supporting the management of technological specific parameters, is to enable the inclusion of additional representations to the technologically independent model, either through the augmentation using semantic concepts or by model extension. However, a new alternative is proposed with MiNSC, hose information model focus on the service standard parameters, overcoming the need for model extension. In this section, the author considers network management from the models perspective, comparing the most representative alternatives with the MiNSC proposal.

WBEM

As previously referred, WBEM's specification includes the CIM's *Meta-Schema*, which includes the terms used to express information models, their usage and semantics. This model is described in UML [251] and includes the following elements (not limited to): *Schema* is used for administration and class naming; *Class* defines the managed element properties (that represents the class data) and methods(that represents the class behavior); *Property* is unique to a class and is used to denote a class characteristic; *Method* is

an operation that may be invoked and it must also be unique for a class.

WBEM's schema includes three different types of management information models: the *Core Schema* which includes the basic concepts applicable in any management domain, which in turn creates a basic vocabulary for describing managed systems comprehended by a small set of classes, associations and properties; the *Common Schema* includes the models that will be used in specific management domains such as *Applications*, *Database*, *Device*, *Event*, *Interop*, etc. Other *Common Schemas* can be found in [123]; the *Extension Schemas* that companies use to extend these *Common Schemas* and encompass features unique to their products [250].

Extension Schemas enables administrators to leverage CIM's basic model classes and associations addressing their management needs. This extension is obtained by adding new properties to an existing class or sub-class, addition of new classes or definition of new namespaces in CIM or in proprietary schemas. This extension enables the management of implementation-specific functionalities of network elements while complying with the WBEM architecture, even though non-standard information models extensions are used. This method, although complex, is implemented to integrate the management of heterogeneous network elements.

FOCALE

DEN-ng models are used for modeling telecommunication information from business concepts down to the managed element's low-level functionalities. Its highly flexible and extensible modeling capabilities can be augmented with technologically dependent information and data models. As referred in [166], the combination of DEN-ng information and data models with domain specific ontologies enable the use of state information to verify if the models accurately reflect the element's current operational status, while creating a common vocabulary that enables heterogeneous data models to be semantically related. Theoretically, using a semantic representation, based on ontologies, enables the management application to learn and reason, dynamically evolving even in the presence of unforseen situations, while ensuring the automation of management tasks. In FOCALE, the definition of a single universal language that has no underlying business reason is avoided [41]. Instead, knowledge interoperability is obtained implementing a set of ontologies which will identify syntactic and semantic elements of interoperability between vendor-specific languages and independent information/data models.

The facts represented in DEN-ng information/data models are augmented with semantic concepts using ontologies. These ontologies are composed by different building blocks, creating an upper level ontology that includes the common terms for integrating multiple lower-level domain-specific ontologies. The upper ontology corresponds to a set of common concepts and terminologies that all users and applications agree on. This terms are then used to create Finite State Machines that represent management system behavior. Policies are used to determine the state transitions required when the system is not in the desired state. As referred in [41], a reasoning algorithm is used to generate a hypothesis, in the presence of unforseen impairments, while the learning algorithm is used to reinforce actions that restore the system to an acceptable behavior. Domain specific ontologies are used for multiple management domains, where the facts represented in the managed element's data model are augmented with semantic information. The managed elements represented in the lower ontology are then semantically related to the upper ontology.

MiNSC

From MiNSC's configuration management perspective, independent service management information models are implemented in both layers, providing different abstraction levels at each layer. Those models focus on the service's standard descriptions without, further developments and extensions (so, they exclude support for any implementation-specific, non-standard, functionality). At the lower management abstraction layer, all service's non-standard functionalities are abstracted using a group of independent (standard-based) configurations. At the higher management abstraction layer some management tasks are automated, ensuring the service overall behavior based on the meta-configurations defined. Both service management information models focus on the service management efficiency, rather then supporting the integration of a large amount of specific, low-level functionalities (as commonly found).

Management data models also play a vital role within MiNSC framework. One of MiNSC's most important goals is to overcome the implementation of management translations. This is achieved based on the association of a standard-based service management information model (at each layer) and a standard network management interface. This means that a single data model is implemented at each layer (for each network service), providing a uniform data representation. This eliminates management heterogeneity and the necessity to implement conversions.

Two different lines of though can be found from the management models perspective. The first alternative includes a technological independent base extended or complemented with the managed elements implementation details (either using a syntactic or semantic mapping). Theoretically, this enables the management of all network elements implementations/vendor specific functionalities. However, it also incurs into the translation limitations previously identified. This solution is implemented in WBEM, where CIM *Common Schemas* may be extended using *Extension Schemas*, enabling the technologically-independent models to be extended and manage technological-specific parameters. In FOCALE, a similar alternative is implemented where different levels of ontologies are used to unify the management of heterogeneous data models. Domain-specific ontologies enhance the facts represented in the managed element's data models with adequate semantics. A higher level ontology provides additional semantics to DEN-ng independent representations, supporting a semantic integration of domain-specific ontologies.

MiNSC proposes a second alternative, based on the implementation of a standard-based service management information model, that cannot be extended. This model is implemented on a standard management interface, resulting on unique data model. Such unification, means that there is no necessity to implement management translations inside the management system. However, this alternative requires vendor's compliance to standard information models, developing the interface instrumentation. The author believes this approach is simpler and fast to implement, potentiating interoperability, since it does not aims to integrate management requirements of heterogeneous functionalities.

6.7 Resilience

Given the importance that networked systems have acquired, the maximization of their availability even in the presence of an error is of total relevance. So, it is important evaluate the existence of methods that promote their availability, commonly referred to as resilience improvement methods, and they can be implemented at distinct levels: at the networked elements level enabling, for example, the distribution of data or the existence of redundant elements to be used as recoveries from failures; at the management framework level where it could improve the network element's resilience, by using their state information to act pro-actively or in reaction to specific events, avoiding erroneous states or tendencies. It can also be used to improve the framework's own resilience, ensuring the availability of the management operations applying, for example, the distribution of data or redundant elements. This ensures that the network element's state

is kept under control under all conditions. Obviously, since the resilience improvement methods implemented at the network element level are not always present, the methods implemented at the management framework level gain enhanced relevance.

WBEM

WBEM implements a traditional client-server architecture relying on a centralized entity, the WBEM Client, which issues management commands to the WBEM Servers, present at the network element level, or in a hierarchical structure where the WBEM Servers enable the centralized management of distributed Providers using Proxy Providers. Regardless of the management structure implemented, WBEM does not specify any explicit or implicit resilience improvement method defined in its standard specifications. It commonly depends on a central entity, that creates a single point of failure, without any fault compensation mechanism thus, from the management framework's perspective, no resilience improvement methods are provided. Following the same perspective, WBEM also does not specify any implicit or explicit resilience improvement method at the network element level. This means that no redundancy or other measures are provided to overcome the existence of network element's failures. WBEM is referred to as having low resilience for both levels, management infrastructure and network elements, for these reasons.

FOCALE

Considerations regarding FOCALE's resilience improvement methods cannot be easily elaborated as a result of lack of real implementation details. However, since its management architecture is based on the policy enforcement at the AE level, the presence of failures in the management infrastructure, external to the AE (namely in another AE, Autonomic Environment/Domain or even at the Orchestration Plane), do not influence the enforcement of policies locally, even though their incapacity to be updated. This isolation represents an important implicit resilience improvement method.

When unforseen events occur within the AE, the Autonomic Server is able to dynamically evolve the management model, using learning and reasoning capabilities. Actions are automatically calculated, based on management policies, to restore the management domain to the pretended state. Then, such event is placed in the Autonomic Server knowledge domain, as well as the action taken. This represents an explicit resilience improvement method because some element's failures may be addressed using this process. However, it is important to consider the role of the MBTL within the AE, whose imple-

mentations details are also lacking. While performing a semantic translation, the MBTL location is vital for the AE resilience. If implemented on a centralized entity, the MBTL creates a single point of failure with undesired performance limitations. Considerations regarding the Autonomic Server resilience improvement methods, within the AE, where not taken since its structure is not detailed in the model's description. FOCALE has the potential of creating a highly resilient network management infrastructure, however, it is still under development and lacks implementation details to conduct a thorough evaluation.

MiNSC

Resilience improvement methods represent one of MiNSC's most important features, based on the configuration independence provided and a distributed two-layer architecture, improving resilience at both levels. MiNSC's resilience improvement method relies on the over-provisioning of elements (classified as candidates) at both layers: i) at the *Service Management* layer this method protects the configuration management servers against failures. This way, management service resilience is ensured; ii) at the *Network Service Instance Management* layer this method protects against the network service instance failures. This way, managed service resilience is also ensured. At both layers, MiNSC uses active and candidate elements, independent configurations and configuration replication procedures. As described in previous chapters, the active elements actively perform a service execution (configuration management service or network service depending on the layer) while the candidate elements automatically and periodically replicate the active element's independent configurations. When failures occur in active elements, the independent configurations replicated enable the service execution to proceed (migrating its execution) with minimum data losses. It is obvious that this requires a tight integration with a monitoring system, notifying as to the active element's failures, thus initiating the service execution migration process. This monitoring system must, in cooperation with the management application, define what's *failure* and what's accepted degradation on the QoS of each management context.

In this section, the author considered the implementation of resilience improvement methods at two distinct levels: at the lower level of network elements and; at the higher level of management framework. WBEM's specification excludes any implicit or explicit resilience improvement method, for any of the referred levels, implementing a centralized architecture with management resilience constraints. On the other hand, FOCALE is

a network management architecture with a potentially high degree of resilience due to the isolation provided by the autonomic control loop. However, since it lacks implementation details, its adequate evaluation is not possible. The autonomic control loop provides FOCALE with the flexibility that might enable an adequate reaction to failures. However, the implementation of FOCALE's MBTL must be carefully planned as, if it is supported by a central entity, it may incur into important management resilience and performance limitations. MiNSC's two-layer, distributed network service configuration management framework provides an explicit resilience improvement method, based on the distributed classification of elements and the execution of automatic (and periodic) independent configuration replication procedures, which are stored in candidate elements. This improves the managed service's and management framework resilience to failures, migrating the execution of faulty elements.

6.8 Scalability

Communication networks evolve, not only in size (increasing the number o elements) but also in the number of functionalities provided and their complexity. The capability to support this evolution without losing management effectiveness is a requirement for network management systems. This requirement is further enhanced by the necessity to create integrated network management frameworks that, while aiming to increase efficiency, also require wide support for the increasing domain's heterogeneity. The implementation of a scalable network management system is essential for its long-term success, overcoming performance limitations, duplication of systems and re-engineering as referred in [252]. Given the scalability requirements for the management of current and future networks, a scalable network management system must be able to accommodate the ever increasing number of managed elements, management objects and efficient retrieval of large volumes of management data without incurring into significative performance losses. If it does not scale well, the management framework will have a decreased life span, present performance degradation and will require re-engineering or management systems duplication.

WBEM

WBEM specification refers that a WBEM-based network management solution can be built using two different architectures [250]: one that is implemented using a traditional centralized architecture where the management application, implementing a WBEM

Client, manages a group of WBEM Servers implemented at the network element level. This type of architecture is not very scalable, its performance is tied to the number of network elements and the amount of managed data exchanged; the other type of management architecture implements a hierarchy, where a WBEM Server is placed in a central entity, using an inter-device model to manage lower-level WBEM Servers implementing intra-device model, at the network element level. This type of architecture is used when services are defined across several devices. However, even in this type of architecture, the management tasks continue to be centralized, incurring into scalability and performance limitations. The author concludes that both architectures use a centralized organization with important scalability implications, even though the implementation of a hierarchical architecture enables integration of the management of a group of network elements.

FOCALE

The FOCALE project was created with the specific purpose of creating a highly scalable and distributed network management framework, based on the implementation of autonomic control loops and distributed planes. FOCALE proposes the use of AE at the lower level to automatically enforce the business oriented management policies at the network element level. FOCALE's management architectural proposal is based on the classification of its elements in planes (Data, Control, Management, Inference), as described in previous chapters. Those elements are theoretically described in [171], lacking important implementation details for a deeper scalability evaluation.

FOCALE's scalability can be evaluated from the management planes perspective. The network elements represent the *Data Plane* and no scalability improvement method is referred at this level. The *Control* and *Management* planes have enhanced importance, namely for the implementation and coordination of the control loops (management elements state verification, calculation and deployment of new configurations using the MBTL). Among those, the MBTL has enhanced importance for the AE scalability because, if implemented by a central entity, introduces performance constraints which degrades scalability. The implementation of autonomic control loops, at this level, provides an important isolation regards other scalability limitations that may be found in external loops. However, the plane's elements must be planed in order to overcome performance limitations. The *Inference Plane* doesn't have direct influence in FOCALE's scalability, its just used for the dissemination of management policies and policy conflict resolution, even though it is intended to be implemented as a distributed process.

MiNSC

To improve service scalability, MiNSC uses the following elements: a two-layer distributed architecture with over-provisioning of elements (active and candidate); the independence of service configurations enabled by the implementation of a standard-based service management information model on a standard interface; the execution of configuration replication procedures at both layers; a load-balancing process that uses the configurations replicated to divide the service execution between several elements. MiNSC's scalability improvement methods are applied at both layers. Each have a different purpose: at the *Service Management* layer it aims to improve MiNSC's configuration management service scalability; at the *Network Service Instance Management* layer where it aims to improve the managed service scalability. When the monitoring system identifies a performance degradation within an active element, it starts a load-balancing process that deactivates a percentage of the element's configurations, while activating the same percentage at the corresponding candidate instance, using the previously replicated configurations. This may extend the service's physical dimension or overall resource availability, consequently improving the service scalability.

This method can be used on a similar process to reduce the service's physical size or resource consumption, concentrating service execution in a lower number of elements or less resources. So, aside from improving scalability, this method also enables a more efficient resource consumption, dynamically allocating resources as needed. It is also important to highlight the importance of the monitoring system to detect, evaluate and inform as to the element's state, enabling MiNSC to issue a reactive measure.

The implementation of methods for scalability improvement is essential for long term success of a network management framework. From this study, the author concluded that WBEM excludes considerations regarding this criteria, implementing a centralized architecture with scalability constraints. In contrast, FOCALE aims to be a highly distributed network management framework, based on the application of autonomic control loops and distributed management planes with theoretical scalability gains. However, within the Management Plane, the MBTL presents a potential scalability limitation if implemented in a centralized entity, therefore, distributed solutions must be pursued. For now, FOCALE is mainly composed by a group of guidelines with low implementation details and further developments are required in order to conduct a proper evaluation. On a different perspective, MiNSC uses a two-layer distributed architecture, independent configurations and over-provisioning of instances to dynamically increase (or reduce) re-

sources for the deployment of a service at both layers. This enables a more efficient resource management with important scalability consequences.

6.9 Summary of Comparative Analysis

A summary of the previous evaluations can be found in Table 6.1 where the effectiveness of each item is considered for WBEM, FOCALE and MiNSC. A "+" sign identifies a high level of support while a "-" identifies no support or low level of support. A "*" means that no clear consideration could be concluded. Some conclusions should be taken from these evaluations:

- Today's most popular way to support the integration of heterogeneous network elements management, follows the RFC 3139 [42] guidelines, where syntactic or semantic translations are used to map from independent representations to implementation specific information models and interfaces. However, this strategy incurs into well identified limitations referred in previous chapters which result in a large complexity at the application level. This strategy is followed not only by WBEM and FOCALE but also by most frameworks integrating heterogeneous network elements, representing the most expedite method to integrate heterogeneous management interfaces and data models. MiNSC's strategy to support heterogeneity is achieved by proposing a new configuration interface based on the association of standard interface technologies and universal information models;

- From the perspective of management models, the evaluated frameworks propose different alternatives depending on whether or not they implement management translations. The frameworks that implement translations, namely FOCALE and WBEM, enable their standard management information model's extension to support the network element's heterogeneous data model. This is an expedite method, however, it is important to note that, when a high degree of heterogeneity is found, the management application's complexity may be overwhelming. MiNSC provides a simpler alternative based on standard (and static) information models, implemented on unique data models, that do not aim towards the support for the network element's heterogeneous functionalities. Instead, it only supports the management of standard functionalities that vendors must comply with. This enables management application simplification and efficiency. Even at the network elements level, it permits a better implementation of standard functionalities, because these are done on the element's software and hardware directly;

- From the management automation perspective, MiNSC does not aim to be a fully automated network management framework, such as FOCALE. Given its mid-level operation, MiNSC enables some degree of automation using a two-layer distributed architecture and configuration universality, such as configuration deployment, instance execution migration and service expansion. This has important implications regarding service's resilience and scalability, only found in advanced research project like FOCALE. This mid-level automation is a consequence of its level of abstraction, enabling the orchestration of the network service instances behavior, feature not available in WBEM's specifications;

- Management translations, such as the ones implemented in FOCALE, are performed preferably at the management application level. Its performance can seriously influence the framework's overall performance and depending on its location, resilience and scalability limitations may exist. On the other hand, FOCALE provides a distributed architecture but it lacks the implementation details (namely of its MBTL) to conclude about its resilience and scalability capabilities. The author concluded that in WBEM the translations are performed by the Provider at the managed element level. This means that the management applications performance is not excessively influenced by the translator. However, some scalability and resilience limitations are found due to the framework's centralized architecture. Aiming to dynamically improve the network and management service resilience and scalability, MiNSC proposes the use of a two-layer distributed architecture that uses the configuration's universality to dynamically allocate network service instances, as required, extending or replacing a faulty one;

- It can be concluded that MiNSC does aim to replace any of the existing integrated management frameworks. Instead, MiNSC defines a new configuration management interface, based on standards, that overcomes the realization of translations. Because it uses universal/independent configurations and over-provisioning of elements, additional management functionalities are enabled, available only in more advanced research projects, besides the management simplification provided.

6.10 Limitations

Even though MiNSC provides important management gains as identified in the previous chapter, some limitations are also present, mainly as a consequence to the implementation of standard-based technologies:

- The implementation of standard-based service management information models have important implications inherent to the underlying standardization process. Those implications are extensively described in [236] and they include: a long time to be concluded, which means that management models may not be available when they are required, promoting the implementation of proprietary technologies; reduced quality of the models proposed, being mainly motivated by commercial reasons, failing to attract the technology specialist and; an agreement is hard to achieve among all companies. This creates models which are either too generic and as a consequence are complex to implement (and can incur into interoperability problems) or too low-level, losing the integration perspective of the models. So, in order to make MiNSC rapidly available, the standardization process should be more expedite;

- Another obvious consequence of using standard-based service management information models is that non-standard parameters and functionalities become unmanaged. This retracts the implementers from creating value-added functionalities for their solutions. This obviously eliminates some competition between service implementers. In order to overcome this limitation, the implementers must try to standardize their innovations which in turn guarantees that they are widely accepted to be included in the management standards. Again, this requires an expedite standardization process for a quick introduction of innovation. On the other hand, competition is gained at the management application level. With the implementation of standard-based service management models on a standard network management interface, any management application can be used. This promotes the competition among them.

6.11 Conclusion

In this chapter, the author clarified MiNSC's proposal and demonstrated its usefulness compared to other proposals when addressing network management integration. A clear distinction is made between the proposals based on management translations and MiNSC. As long as heterogeneous management interfaces and data models are available, management translations must be applied. However, this generates high degrees of complexity for management applications that beside supporting a wide spectrum of functionalities must take management efficiency as a concern. In this sense, MiNSC contributes with a new configuration management interface for network services. The fact

that is based on standard technologies narrows the management applications scope to the essential part of the network service management which is the management of their standard functionalities. Besides, MiNSC provides a group of mid-level functionalities, important for contemporary management frameworks, only included in more advanced frameworks.

Chapter 7

Conclusion

MiNSC's configuration management framework was described, evaluated and its rationale to support integrated network service management was discussed. Apart from overcoming the limitations inherent to traditional management translation mechanisms, MiNSC provides important operational gains that are not always available on traditional mid-level integrated network management solutions. This chapter concludes this thesis by summarizing the most important contributions and conclusions taken from previous chapters.

7.1 Motivation

As referred previously, there is a tendency to use integrated network management solutions mainly motivated by the necessity for the automation of management processes to deal with the ever increasing complexity of communication networks. However, the formulation of integrated network management is highly complex and commonly implemented using an independent management representation latter mapped into heterogeneous management interfaces and data models, either by a syntactic or a semantic mapping. Obviously, this enforces an important level of management independence between the high-level management applications and the diversity of managed elements supported by the independent representations. The execution of semantic translations is gaining increased recognition as it tries to prevent data from being lost while promising seamless mapping even when overlapped representations exist. However, due to the lack of standard semantic content on contemporary data models, the semantic mapping between heterogeneous data and information models becomes highly complex, thus requiring the administrator's manual intervention to create, evaluate, maintain and evolve

the mappings. This problem retains enhanced importance when considering highly heterogeneous domains with an elevated number of elements. This solution provides vendors with the freedom to decide on the type of functionalities provided on their implementations and the way they are managed, promoting competition among them without much concern as to how the management is integrated with other elements on the management domain, using proprietary solutions frequently.

MiNSC defines a complementary approach. Instead of supporting all network element management interfaces and data models, a new service configuration management interface was proposed to unify the management of heterogeneous implementations allied with a standard-based service management information model. The use of this interface ensures that all service implementations are equally managed (using the same interface technology), overcoming management heterogeneity as well as the necessity to implement management translations inside the management system. It is obvious that this approach limits competition at the network service implementation level thus restraining vendors from the development of value added functionalities. On the other hand, competition is gained at the management applications level. Vendors can still propose value added functionalities, although they must first be approved and adapted in a standardization process. MiNSC is a two-layer distributed architecture, that, by using universal configurations, improves resilience and scalability. It is based on an abstracted group of service configuration parameters (defining the service behavior) so management automation, when used in cooperation with SMON, can be achieved. The remaining sections of this chapter restate the most relevant contributions and include a summary of the most important conclusions taken from this work. The final section discusses future work to add further functionalities or dimensions that complement or extend MiNSC's mid-level operation.

7.2 Main Contributions

The most important contributions were already listed in chapter one however, those contributions can now be further detailed based on MiNSC's implementation and evaluation:

- Chapter two introduces some of the most important research works of the last decade on network management, like WBEM, FOCALE and future Internet management. Fundamental technologies and concepts like SNMP and PBNM are also presented. A special emphasis is given on integrated network management, its

open issues and challenges were discussed as motivation for the development of a new standard-based network management middleware;

- Proposition of a new middleware architecture (MiNSC), that, by implementing a two-layer operation based on standard information and data models, enables the integrated management of heterogeneous network service implementations. The new configuration management interface proposed overcomes the one-to-many management translations that uses syntactic or semantic mappings. Other operational gains are obtained when using MiNSC's distributed architecture, such as the improvement of the service's resilience and scalability, as well as the promotion of management automation;

- Chapter five includes a standard-based DNS management information model, that, even though it is not extensively detailed, it is well suited for the purpose of demonstration and prove of concept. The model enables the configuration management of the most basic functionalities (such as caching, recursion and notification) while supporting the representation of most standard DNS resource records. This information model is referred to as the DNS instance management information model. A DNS service management information model, with a higher management abstraction, was also defined. This model enables the coordinated management of the functionalities available at the DNS instances (computing their configuration) and service distribution (orchestrating the number and physical location of active DNS instances) through the representation of service behavior.

  Furthermore, a prototype was implemented based on the referred information models. This prototype represents another important contribution. It is composed by one configuration management server and three specific DNS implementations, namely Bind9 for Linux and MS Windows and Posadis for MS Windows. The prototype enables a secure and reliable configuration management of the DNS functionalities (like other present DNS management tools) with other important functional gains that improve DNS resilience to instance failures, scalability and resource management efficiency.

  A configuration management MIB, based on the DNS management information models, was defined and its instrumentation was implemented on the prototype. It provides a highly interoperable management interface that, by implementing universal information models, unifies the management of heterogeneous implementations (without the need for management translations). Such interoperability

facilitates MiNSC's mid-level operation and integration with higher-level management applications;

- Other contributions can be derived from MiNSC framework evaluation included in chapter six. Frameworks aiming to support integrated management commonly implement translations, mapping from independent to implementation-specific representations. These are commonly implemented using centralized architectures generally depending on the administrator to be created, validated and maintained, besides being developed in accordance with the specific necessities of higher-level management applications, which represents important interoperability problems. MiNSC enables the integrated management of heterogeneous implementations permitting a complementary approach based on the association of standard technologies that promote interoperability. Its two-layer distributed architecture defines a configuration management interface that overcomes the limitations of management translations.

  MiNSC also promotes management simplification and automation by using an abstracted group of configurations to define service behavior. From those configurations the service's physical distribution is automatically calculated and each service instance configuration is, in turn, derived (referred as service deployment). This type of management automation is not commonly executed at this level and simplifies higher-level management applications, as previously referred.

  In addition, MiNSC allies configuration independence with the utilization of redundant instances. Service instance configuration are automatically and periodically replicated, which improves service resilience to instance failures, migrating the service execution using the instance configurations which were previously replicated. This type of functionality is not implemented in any other administration tool, to the best of the author's knowledge, at the time of this writing;

- As state in Chapter one, a group of technical documents was published an presented in two of the most important international conferences on network management, namely, Internet Management (IM) and Conference on Network and Service Management (CNSM). These presentations brought positive and helpful feedback that contributed to adjustment on MiNSC. A journal article is being prepared for submission in a reference journal.

7.3 Overall Conclusions

The end of each chapter includes a set of conclusions containing its most relevant ideas. This section includes a brief summary of these conclusions providing the reader with the overall sequence of conclusions as well as the manner in which they are related to each other. A summary of the MiNSC's most important limitations is also presented:

- Nowadays there is a tendency to use automatic network management frameworks with different purposes: to reduce the network administrator's manual interference which inherently improves management efficiency (through the reduction of errors), enables quicker deployment of management decisions and support for complex management operations; to improve revenue levels by reducing the number of specialized administrators to run the network, with implications on the managed element stability and efficiency; to ensure that, whatever the complexity inherent to the future network's elements, they are efficiently supported and managed in whatever dimensions are required. To support such flexibility, an autonomic network management is proposed;

- While supporting automatic management of heterogeneous network elements, contemporary frameworks implement integration methods based on translations by converting universal representations into device-specific configurations and commands. The implementation of management translations is performed either using a syntactic or semantic mapping which is a highly complex procedure to be performed in large scale domains, as a consequence of the lack of semantic content in contemporary management data models;

- MiNSC overcomes the implementation of management translations through the use of two important components: a standard network management interface, using MIBs, and standard-based service management information models. Their association creates a unique data model that deals with heterogeneity without the need to implement one-too-many management translations. MiNSC defines a new configuration management interface that supports heterogeneous service implementations, instead of providing direct support for integrated management of heterogeneous interfaces (which can only be accomplished using management translations);

- MiNSC's distributed architecture promotes other gains such as the interoperability of higher-level management applications, the improvement of network and man-

agement service resilience and scalability, efficient resource management and automation;

- A MiNSC based prototype was created and experimented to demonstrate the framework's capabilities using the DNS service as a test bed. The developed prototype was composed by one configuration management server and three heterogeneous DNS server implementations and supported the creation of the following experiments: automatic deployment of a DNS service, regardless of the implementations heterogeneity, based on the DNS meta-configurations defined; automatic migration of a DNS instance execution based on the replication of DNS instance configurations; and a DNS service expansion that consisted on increasing the number of DNS instances used for service deployment. All these experiments demonstrated MiNSC's integrated management capability and effective support for resilience and scalability improvement methods;

- MiNSC's contributions compare well to existing network management frameworks (like WBEM) and even more advanced designs (like FOCALE). Besides implementing management translations, real implementations (mainly those based on WBEM) are commonly centralized, promote low-levels of automation and do not present any resilience or scalability improvement methods. Providers must be developed and maintained for all the heterogeneous network elements, mapping CIM's independent representations. More advanced designs (like FOCALE) are still under development and cannot be adequately compared and experimented. MiNSC's simplified management architecture eases implementation, while enabling additional functionalities only contemplated in more advanced management frameworks.

In addition to the previous conclusions, MiNSC's limitations can also be summarized:

- MiNSC's management independence is based on the implementation of universal management information models based on the service's standard descriptions, which means that only the functionalities adopted as standards can be managed. As a consequence, all implementation-specific (non-standard) functionalities become unmanaged which means that the competition at the implementation level is lost, retracting vendors from the development of value-added, non-standard, functionalities. However, as the competition is lost at the service's implementation level, it is gained at the management application level with a unified access to

management data based on standard technologies. Any management application can be used since its interoperability is ensured, creating a new level of competition;

- The implementation of standard-based service management information models has another important consequence inherent to the standardization process. It is the opinion of several authors that the current standardization process, for network management, is an important limitation mainly due to the fact that the process is motivated by the interest of the biggest players in the area, and does not have efficiency in mind. Also, reaching an agreement between the participating companies is a complex task which slows down the process and reduces the quality of the proposed standards. Since MiNSC relies on standard-based management information models, it inherently suffers from the quality of the adopted models;

- The serialization algorithm implemented by the DNS management prototype is based on the administrator's manual classification of DNS instances to be used for configuration deployment. This represents its most simple alternative not intended for larger scale domains. In this sense, further developments must be achieved in order to enhance this algorithm;

- The prototype uses the SNMP protocol for the deployment of configuration management operations. This may have important implications depending on the domain's requirements. As referred in Chapters two and four, SNMP (and more generally INMF) possesses some limitations that must be considered. Even though some of those limitations are solved using MiNSC's distributed architecture, others remain present: the limited configuration management operations supported and; limited expressiveness of SMI language. For the representation of more complex data models or configuration management operation evolution, these limitation may impose relevant constraints. In this case, a more flexible configuration management protocol may be used (such as NETCONF). From MiNSC's perspective, as long as the requirements summarized on Chapter four are fulfilled, any protocol may be used. For simplification of implementation, interoperability promotion and facilitated integration with existing management solutions, SNMP was chosen.

7.4 Future Work

Based on the work already done and the limitations identified in the previous sections, a list of future works can be compiled:

- The monitoring system (SMON) must be further developed. For each network service a set of conditions must be defined for instance migration or service expansion/contraction. Work on SMON architecture was already started and presented [197];
- At the configuration management server level, a logical language could be added to constrain the configuration management operations supported, defining how network service instance configurations could be merged, extended, added, removed and compared, as well as a mean to describe configuration dependencies inter and intra services;
- The theoretical study presented in this thesis for NETCONF and SNMP must be complemented with further practical evaluation. A new configuration management interface based on the NETCONF protocol could be developed, experimented and evaluated in light of MiNSC's configuration management requirements in a balanced experiment, where both protocols will use secure and reliable communication channels;
- A serialization algorithm should also be developed on future research and development projects, considering the graduation of service instances regarding administration goals. One solution could be to divide the algorithm into two parts: the first uses a method, that based on the administrator requirements, assigns weights to the instances available, for example, dividing between the instances that are inside or outside a management domain or dividing the instances that are physically more distant; then, a cost maximization (or minimization) algorithm could be applied;
- Further network service information models must be developed and implemented for other network service, such as DHCP, E-MAIL, Routing, among others.

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