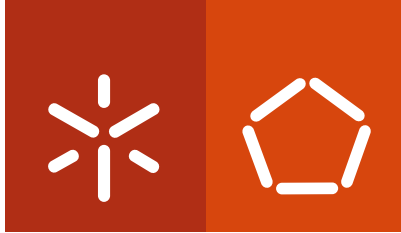


**Universidade do Minho**  
Escola de Engenharia

Carlos Jorge Enes Capitão de Abreu

## **Wireless Sensor Networks for Clinical Applications in Smart Environments**

June 2014



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## **Wireless Sensor Networks for Clinical Applications in Smart Environments**

Doctoral Program on Biomedical Engineering

PhD thesis developed under the scientific supervision of:

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June 2014

## STATEMENT OF INTEGRITY

I hereby declare having conducted my thesis with integrity. I confirm that I have not used plagiarism or any form of falsification of results in the process of the thesis elaboration.

I further declare that I have fully acknowledged the Code of Ethical Conduct of the University of Minho.

University of Minho, \_\_\_\_\_

Full name: \_\_\_\_\_

Signature: \_\_\_\_\_



*to my lovely wife Irene, and my wonderful children Ana and Miguel*



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# **Wireless Sensor Networks for Clinical Applications in Smart Environments**

## **Abstract**

Biomedical wireless sensor networks are a key technology to support the development of new applications and services targeting the domain of healthcare, in particular, regarding data collection for continuous health monitoring of patients or to help physicians on their diagnosis and further treatment assessment. Therefore, due to the critical nature of both medical data and medical applications, such networks have to satisfy demanding quality of service requirements. Such goals are, nevertheless, negatively influenced by several factors. Those factors can be either internal (e.g., the network topology and the limited network throughput) or external (e.g., the characteristics and the use of the network deployment area) to the biomedical wireless sensor network. Indeed, when designing biomedical wireless sensor network, it should be taken into consideration numerous aspects of a very different nature.

Despite the efforts made in the last few years to develop quality of service mechanisms targeting wireless sensor networks and its wide range of applications, the network deployment scenario can severely restrict the networks ability to provide the required performance. In particular, harsh environments, such as hospital facilities, can compromise the radio frequency communications and, consequently, the network's ability to provide the quality of service required by medical applications. Furthermore, the impact of such environments on the network performance is hard to predict and manage due to its random nature. Consequently, network planning and management, in general or step-down hospital units, is a very hard task. In such context, this thesis presents a quality of service based network management method to help engineers, network administrators, and healthcare professionals managing and supervising biomedical wireless sensor networks.

The proposed quality of service network management method comprises two modules, namely: the quality of service monitoring module, and the quality of service based admission control module. The quality of service monitoring module is in charge of continuously monitoring the relevant metrics used to quantify the performance of each data flow carried by the network, and, using a mathematical framework, detecting and classifying performance degradation events. By detecting and classifying quality of service degradation events, the proposed method can be used to prevent the incorrect operation of the network. Moreover, the information about each performance degradation event can be used to advise the network administrator to take the necessary corrective and preventive measures. On its turn, the quality of service based admission control module can be used to find the best location to add new patients into the network, and

thus allows managing the network in order to find the most favourable network topology to maximise the quality of service provided by the biomedical wireless sensor network. Moreover, the quality of service-based admission control module uses the concept of “virtual sensor node” to mimic the presence of the new sensor nodes (i.e., the new patient) within the network, and by this way makes it possible to assess the network from a remote location, without the need for the physical presence of the new patient within the target location.

The quality of service network management method proposed by this thesis was tested using both simulated and real environments. The field tests were performed in a small-sized hospital located in Esposende, known as “*Hospital Valentim Ribeiro*”. In view of the results achieved during the experiments, the quality of service monitoring module of the proposed method proves to be a valuable tool for both detection and classification of potential harmful variations in the quality of service provided by the network, avoiding its degradation to levels where the biomedical signs would be useless. On its turn, the quality of service based admission control module demonstrated its ability, not only to control the admission of new patients (i.e., new sensor nodes) to the biomedical wireless sensor network, but also to find the best location to admit the new patients within the network. By placing the new sensor nodes on the most favourable locations, this module is able to optimise the network topology in view of maximising the quality of service provided by the network.

# **Rede de Sensores Sem Fios para Aplicações Clínicas em Ambientes Inteligentes de Assistência à Vida**

## **Resumo**

A utilização de redes de sensores sem fios como suporte ao desenvolvimento de novas aplicações e serviços para a área da saúde é uma realidade crescente, em particular, no que diz respeito ao desenvolvimento de aplicações para monitorização contínua dos sinais vitais dos pacientes, com vista à melhoria dos cuidados de saúde prestados. No entanto, devido às elevadas exigências de qualidade das aplicações e serviços na área da saúde, as redes de sensores sem fios têm que cumprir requisitos de qualidade de serviço muito exigentes. O fornecimento de um serviço de elevada qualidade é fundamental para que estas redes sejam adotadas quer pela comunidade de profissionais de saúde quer pelos pacientes.

Apesar dos esforços realizados durante os últimos anos no desenvolvimento de técnicas e mecanismos capazes de conferir às redes de sensores sem fios a capacidade para fornecerem serviços de qualidade, esta capacidade é influenciada por vários fatores, entre os quais se destacam a topologia e a capacidade da rede, assim como as características e a utilização dos locais onde estas redes se encontram. Em particular, ambientes hostis, como é o caso dos hospitais, podem comprometer seriamente as comunicações via rádio e, consequentemente, a capacidade destas redes fornecerem um serviço com a qualidade pretendida pelas aplicações que a utilizam. Mais ainda, a influência de tais ambientes na performance destas redes é aleatória, logo, difícil de prever e de gerir. Neste contexto, esta tese contribui com uma metodologia de gestão de redes de sensores sem fios cujo móbil é a maximização da qualidade de serviço proporcionada pela rede.

A metodologia de gestão de redes de sensores sem fios proposta nesta tese é constituída por dois módulos, o módulo de monitorização da qualidade de serviço e o módulo de controlo de admissão de novos nós sensores à rede (e.g., novos pacientes para serem monitorizados no contexto de um sistema de monitorização de sinais vitais). O módulo de monitorização da qualidade de serviço proporcionada pela rede de sensores sem fios é responsável por monitorizar, continuamente, as métricas utilizadas para quantificar a qualidade de serviço associada a cada um dos fluxos de dados transportados pela rede. Este módulo utiliza ferramentas matemáticas no domínio do tempo para detetar e classificar eventos potencialmente perigosos para a performance da rede. Com base na informação gerada para cada evento, o módulo de monitorização da qualidade de serviço proporcionada pela rede é capaz de enviar mensagens de aviso para o gestor da rede. Por sua vez, o gestor da rede pode tomar as medidas que considerar necessárias para mitigar os efeitos nefastos de tais eventos sobre a rede. Por sua

vez, o módulo de controlo de admissão de novos nós sensores à rede pode ser utilizado para verificar se um determinado nó sensor (e.g., um novo paciente) pode ser adicionado à rede e em caso afirmativo permite determinar qual é o melhor local para o colocar. Para tal utiliza o conceito de “nó sensor virtual”. O “nó sensor virtual” é criado por um nó sensor real já existente na rede e tem capacidade para imitar o comportamento do novo nó. Para tal, o “nó sensor virtual” envia para a rede tráfego com características idênticas às do tráfego que será gerado pelo novo nó real. Ao utilizar o conceito de “nó sensor virtual”, este módulo permite avaliar a rede acerca da possibilidade de admitir um novo nó sensor a partir de uma localização remota, sem a necessidade da sua presença física no local onde será inserido na rede de sensores sem fios.

O método de gestão de redes de sensores sem fios proposto nesta tese foi extensivamente testado. Nos testes utilizaram-se ambos, ambientes simulados e ambientes reais. Os ambientes simulados foram maioritariamente utilizados durante o processo de desenvolvimento e implementação da metodologia proposta. Por sua vez, os testes em ambiente real, realizados no Hospital Valermirim Ribeiro em Esposende, foram realizados para validar o método proposto. Com base nos resultados obtidos durante os testes efetuados é possível argumentar que a metodologia proposta é capaz de detetar e classificar eventos com potencial para degradar a qualidade de serviço proporcionada pela rede de sensores sem fios. A deteção de tais eventos potencialmente perigosos é feita logo no seu início, evitando-se assim que a performance da rede se degrada para níveis não admissíveis pelas aplicações que utilizam a rede. Quanto ao módulo de controlo de admissão de novos nós sensores à rede, foi possível demonstrar a sua viabilidade quer na decisão de admitir o novo nó sensor na rede quer na determinação do melhor local para o colocar.

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# Acronyms and Abbreviations

AAL	Ambient Assisted Living
ADC	Analog-to-Digital Converter
BER	Bit Error Rate
BSN	Body Sensor Networks
BWSN	Biomedical Wireless Sensor Network
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
DAG	Direct Acyclic Graph
DIO	DODAG Information Object
DODAG	Destination Oriented Direct Acyclic Graph
E2E Delay	End-to-End Delay
HIS	Healthcare Information System
IC	Integrated Circuit
IETF	Internet Engineering Task Force
GPS	Global Positioning System
LQI	Link Quality Indicator
MAC	Medium Access Control
MAN	Single Global Maximum
MDI	Metric Degradation Index
MIN	Single Global Minimum
MRHOF	Minimum Rank Objective Function with Hysteresis
MT	Metric Tendency
NFP	Non-Functional Properties
OF	Objective Function
OS	Operating System

PD	Performance Degradation
PDV	Packet Delay Variation
PRR	Packet Reception Ratio
QoS	Quality of Service
ROLL	Routing Over Low-power and Lossy Networks
RPL	Routing Protocol for Low-Power and Lossy Networks
RSSI	Received Signal Strength Indicator
S	Slope
SN	Sensor Node
SNIR	Signal to Noise plus Interference Ratio
SoC	System-on-a-Chip
TCP	Transmission Control Protocol
TDMA	Time Division Multiple Access
UDP	User Datagram Protocol
WSN	Wireless Sensor Network
ZCR	Zero Crossing Rate

## Latin Terms:

e.g.	(exempli gratia)	means “for example”
i.e.	(id est)	means “that is”
n.b.	(nota bene)	means “note well”

# **Introduction**

## Thesis Motivation, Objectives, and Key Contributions

- 
- 1.1 Wireless Sensor Networks Overview
  - 1.2 Biomedical Wireless Sensor Networks
  - 1.3 Motivation and Objectives
  - 1.4 Key Contributions
  - 1.5 Thesis Organisation
-



## **1. Introduction**

The last few decades were rich in technological achievements, in particular regarding the miniaturisation of electronic devices as well as in the development of low power wireless communication technologies. Such technological developments have brought to the daylight the concept of Wireless Sensor Network (WSN). In short, a WSN is an autonomous and distributed wireless network of small sensing devices. Such networks can be used in a wide range of application areas, such as environmental monitoring, military surveillance, ambient assisted living for elderly or disabled people, and healthcare [1]. In the scope of this work, the focus goes to the use of WSNs in medical applications and healthcare services, in particular those related to patient monitoring, in both hospital units and nursing homes. Due to the specific requirements of medical applications and healthcare services, the WSNs used in such application areas have to fulfil high levels of Quality of Service (QoS) and constitute a WSN subset called Biomedical Wireless Sensor Networks (BWSNs). The QoS level required by BWSNs depends on both their application and their purpose. However, due to the dynamic nature of hospital environments, the QoS provided by BWSNs is hard to control and maintain. On the contrary, it can change very often and in an unpredictable way [2]. In such context, this thesis contributes with a QoS-based network management method to be used by healthcare providers in order to manage BWSNs, while preserving the QoS levels desired by the applications using it.

In what follows, the WSNs and the BWSNs are introduced, emphasising the relevant topics for this work, and then the motivation for this work is presented. Finally, the key contributions of this thesis are outlined and its organisation is presented.

### **1.1. Wireless Sensor Networks Overview**

A WSN can be defined as a self-organised, infrastructure-less and distributed wireless network composed by dozens, or even hundreds, of small and very limited electronic devices called sensor nodes. Such sensor nodes are typically small, highly limited in memory and computational capabilities, battery powered and as inexpensive as possible. Each sensor node has the capability to sense the real world, process the sensed data and wirelessly spread the raw or pre-processed data [1]. The Figure 1.1 presents the typical architecture of a sensor node comprising the following modules: a low power microcontroller and radio System-on-a-Chip (SoC),

a power module, several sensing devices, a localisation engine, several communication interfaces and an antenna.

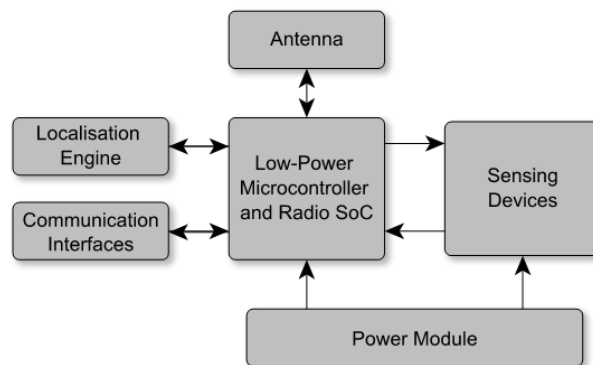


Figure 1.1 – Typical architecture of a sensor node.

Due to its potentialities, WSNs have received a great deal of attention from both the industrial and the academic communities. The research fields around WSNs are very diverse. They go from the hardware efficiency, passing by all the layers of the communication stack, until a wide range of possible applications and services. Regarding the hardware efficiency, great efforts are being made to reduce the transistors' size, inside the microcontrollers, in order to achieve more processing power and power efficiency. As explained by Borkar and Chien in [3], the higher the number of transistors per unit of area, the higher is the processing power and power efficiency. For example, a reduction of about 30 % in transistor size leads to 50 % of power reduction. Such efforts made it possible to develop a new class of low-power Integrated Circuits (ICs) that made possible the deployment of WSNs, composed by sensor nodes, powered by batteries or even using energy harvesting techniques [4] [5].

The research activities around the communication stack cover all its layers, starting at the physical layer and ending at the application layer. Concerning the scope of this thesis, the focus goes to the physical, network, and application layers.

At the physical layer, the most relevant topics for the following discussion are related with the signal propagation effects. As wireless networks, the WSNs have to contend with the intrinsic issues of the wireless channel, such as path loss, fading, shadowing, noise, and interferences. In harsh environments, such undesirable conditions make the Signal to Noise plus Interference Ratio (SNIR) experienced by the sensor nodes low and unstable. Such instability contributes to increase the Bit Error Rate (BER), making the communications unreliable or prone to large

delays, depending on the retransmission policy in use. Regardless of the WSN application, it is mandatory to study the specific characteristics of each deployment area and its surrounding environment in order to determine the best network topology, power control and routing algorithm to achieve the QoS level requested by each application.

The network layer uses a routing protocol to specify how to form the network and provide mechanisms for the nodes to join the network and to get unique addresses. The routing protocol is used to determine the paths over which data packets are transmitted throughout the network. It also specifies how the network nodes report and react to changes in the network topology. Moreover, the paths formation and recovery have to be dynamic in response to changes, in either the logical or the physical network topologies without overreacting. Due to the intrinsic limitations of the WSNs hardware platforms and the difficulties imposed by harsh environments, as explained in the physical layer discussion, the design of efficient routing protocols for WSNs is a challenging task. They have to be simple and small, distributed, and energy efficient, while providing reliable packets transmission over multi-hop paths. The performance of the routing protocol affects the overall network performance measured in terms of End-to-End Delay (E2E Delay), Packet Delay Variation (PDV), throughput, Packet Reception Ratio (PRR), and network energy efficiency and balance. Thus, the routing protocol is a key component to achieve high levels of QoS.

The application layer is the top layer of the communication stack. It provides an interface to the application specific software. On the scope of this work, the application layer is seen as an interface, used by applications, to forward their QoS requirements throughout the communication stack. Thus, each application must clearly define its own QoS requirements and notify the lower layers. For example, an application for patient monitoring may have several QoS requirements, such as a minimum PRR, a maximum E2E delay, a maximum PDV (also known as jitter) and a minimum network lifetime, which will impose constraints to the lower layers of the communication stack.

The previous discussion makes clear that the QoS provided by a WSN depends on several factors, being the hardware design, the deployment scenario, and the performance of the communication stack some of them. Additionally, the network deployment method and the network topology play an important role to guarantee high levels of QoS [6]. The network deployment method depends both on the WSN application and on the deployment scenario.

Depending on the network deployment method, the network physical topology may be called deterministic or random. As far as deterministic deployments are concerned, the sensor nodes are placed in locations with good radio coverage and having a minimum level of link quality (to this end, some connectivity tests should be performed in advance). On its turn, random deployments are often used in disaster or emergency response scenarios, where the sensor nodes are randomly spread around the deployment area. Moreover, either the network deployment method or the network physical topology may affect the WSN coverage area and connectivity and, consequently, the ability of the WSN to provide the required QoS. Therefore, the WSN ability to guarantee high levels of QoS depends on a holistic vision of its architecture, implementation, application, deployment scenario and use.

WSNs are one of today's most promising technologies to achieve high levels of integration between the physical world and the computing systems [7]. Moreover, they can be used to create intelligent systems to assist our daily life, in particular for those with special healthcare needs. In such cases, the use of BWSNs can significantly improve our quality of live [8].

## **1.2. Biomedical Wireless Sensor Networks**

Healthcare providers and professionals broadly use information and communication technologies on their daily practice. Indeed, it is practically impossible to find a healthcare service that does not use any kind of computer-based technology. The information and communication technologies become almost completely pervasive and ubiquitous [9]. The last frontier envisioned by the research community concerns closed-loop real-time and continuous monitoring of each person's health in every aspects of its daily life, using non-intrusive and ubiquitous technologies. Although this futuristic vision is still far from reality, some big steps are being taken in that direction. It is expected that pervasive and ubiquitous healthcare (u-health) systems, combined with wireless sensing systems like BWSNs and Body Sensor Networks (BSN), contribute to change the actual healthcare practice centred in the episodic evaluation of the patients, to the continuous patient assessment, based in real-time and long-term monitoring.

Biomedical Wireless Sensor Networks (BWSNs) are small-sized WSNs equipped with biomedical sensors, designed for medical applications or healthcare services. Typical applications of BWSNs include catastrophe and emergency response, Ambient Assisted Living (AAL) applications to monitor and assist disabled or elderly people, and patient monitoring systems for chronically ill



persons. Among these application fields, this work will focus on the aspects related to the QoS guarantees requested to BWSNs by patient monitoring systems used to collect vital and physiological signs of patients in step-down hospital units of nursing homes.

Typical patient monitoring applications, supported by BWSNs, are used to collect vital or physiological signs, such as respiratory rate, pulse rate, temperature, blood pressure, and oximetry in order to complement the measurements performed manually by nursing professionals a few times a day and thus, enhancing the quality of the health care provided to patients. The sensed data are then sent to a local or remote database to be used to support healthcare professionals on their medical practice. As an abstraction, BWSNs can be seen as a physical layer for Healthcare Information System (HIS), collecting data to support healthcare professionals on their decisions and medical diagnosis, see Figure 1.2.

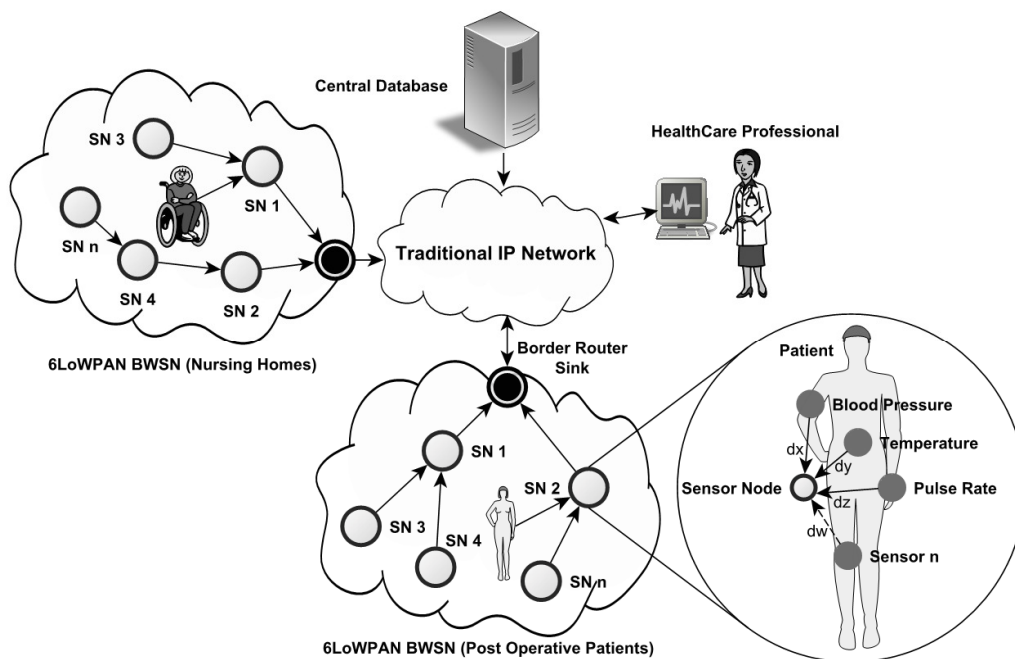


Figure 1.2 – Typical applications of biomedical wireless sensor networks and their architecture.

Such patient monitoring systems present several benefits to both the healthcare professionals and, mainly, the patients. They enable continuous and real-time patient monitoring, even from a remote location, facilitating the identification of emergency or dangerous situations. For those with some degree of cognitive or physical disability, these systems propel a more independent, secure and easy life, reducing the dependency on caregivers. Despite such benefits, BWSNs have

a long way to go in order to be completely accepted by both the healthcare professionals and the patients.

In summary, BWSNs enable the development of new applications and services, bringing several benefits to the healthcare professionals and to the patients. However, to make this vision a reality they must guarantee high standards of QoS.

### **1.3. Motivation and Objectives**

The use of BWSNs in healthcare can enhance the services provided to citizens. In particular, they have the potential to play an important role in the development of new real-time patient monitoring applications. However, due to the critical nature of the data carried by them, they have to fulfil high levels of QoS in order to be fully accepted by both the healthcare providers and the patients. The QoS level requested to a BWSN depend on its use, i.e., on the requirements of the application using the BWSN as communication infrastructure. Regarding the QoS requirements imposed to BWSNs (e.g., considering the signals being monitored), they can include timeliness, reliability, robustness, privacy and security. On its turn, depending on the purpose of the BWSN application, QoS requirements such as mobility support or network lifetime can be very important.

Despite the several QoS mechanisms proposed in the last few years, targeting WSNs and their applications, the network deployment scenario can severely restrict the network's ability to provide the required QoS. Bearing in mind BWSNs and their typical deployment scenarios (i.e., hospitals or nursing homes), several obstacles have to be faced by engineers and network administrators. Harsh environments, like hospital facilities, can expose BWSNs to very hostile situations regarding the radio communications and thus, the network ability to provide the required QoS. In such harsh environments the network performance depends on either random or deterministic factors. Random factors, such as the dynamics of the hospital environment, the radio interferences, and the patient's mobility can affect the network capability to provide the necessary QoS in an unforeseeable way. Thus, the metrics used to quantify the QoS provided by the BWSN must be continually monitored to detect performance degradation events and thus advise the network administrator to take preventive or corrective measures. On its turn, deterministic factors, such as network congestion due to the over populated network can be avoided using QoS-based admission control methods.

In this context, the objective of this thesis is to contribute with a QoS-based network management method comprising two modules, namely a QoS monitoring module and a QoS-based admission control module. The QoS monitoring module will be able to monitor the relevant metrics used to quantify the per-flow QoS provided by the BWSN to detect and classify potential QoS degradation events. By detecting and classifying such potential QoS degradation events, this module can be used to prevent the network malfunction. On its turn, the QoS-based admission control module must be able to, remotely, find the best location to place the new patients, minimising their impact on the performance of the BWSN, in order to preserve the QoS being provided to the patients already within the network.

#### 1.4. Key Contributions

The key contributions of this thesis are summarised as follows:

- **The validation of the concept of “virtual sensor node” in a real hospital environment:** this thesis validates the concept of “virtual sensor node” in the context of QoS-based admission control systems targeting WSNs. A “virtual sensor node” is an abstract entity with the ability to mimic the behaviour of a real sensor node.
- **Assess the conditions in which the concept of “virtual sensor node” can be used to manage the admission of new sensor nodes to the network:** based on several experiments, this thesis defines the conditions in which the “virtual sensor node” can be used to assess the admission of new sensor nodes to the network. Such conditions include the node deployment location and the path used to route its data to the sink.
- **A QoS-aware admission control method using the concept of “virtual sensor node”:** by using the concept of “virtual sensor node” this thesis proposes a QoS-based admission control method. The proposed method can be used to find the best location to add a new sensor node to a WSN, minimising its impact on the QoS being provided by it.
- **An analytical framework to evaluate the QoS metrics and detect potential QoS degradation events:** this thesis proposes an analytic framework to evaluate the

metrics used to quantify the QoS being provided by a WSN. The proposed framework can be used to detect and classify events potentially harmful to the network. Based on the classification of such events alerts can be sent to the network administrator.

## **1.5. Thesis Organisation**

The remainder of this thesis is organised as follows:

Chapter 2 – Quality of Service Provision in Wireless Sensor Networks – presents the state-of-the-art regarding the QoS provision in WSNs.

Chapter 3 – Quality of Service Provision in Biomedical Wireless Sensor Networks – presents the state-of-the-art regarding the QoS provision in BWSNs, including the characterisation of the most usual signals regarding patient monitoring applications.

Chapter 4 – Quality of Service Based Management of Biomedical Wireless Sensor Networks – describes the proposed QoS-based network management method, including its typical application scenario. Finally, to validate the proposed scenario, some simulated and laboratorial results are presented and discussed.

Chapter 5 – Method Assessment in a Real Hospital Environment – analyses and discusses the proposed QoS-based network management method based on experimental tests performed in a real hospital environment.

Chapter 6 – Conclusions and Future Work – includes concluding remarks and points out possible future directions for this research topic.

Appendix A – List of Papers – presents all the publications made within the scope of this thesis.

# **Quality of Service Provision in WSNs**

State-of-the-art

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## 2.1 QoS Requirements in Wireless Sensor Networks

- 2.1.1 Scalability
- 2.1.2 Reliability and Robustness
- 2.1.3 Timeliness
- 2.1.4 Mobility
- 2.1.5 Security and Privacy
- 2.1.6 Heterogeneity
- 2.1.7 Energy Sustainability

## 2.2 QoS across the Communication Stack

- 2.2.1 Application Layer
- 2.2.2 Transport Layer
- 2.2.3 Network Layer
- 2.2.4 Data-Link Layer
- 2.2.5 Physical Layer

## 2.3 Summary

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## 2. Quality of Service Provision in Wireless Sensor Networks

Wireless sensor networks are required to provide different levels of QoS depending on its application and purpose. Due to its wide range of application fields as well as its intrinsic characteristics, providing QoS support to WSNs is a challenging task and remains an open research field [10] [11].

In what follows, the QoS requirements of WSNs are outlined, and then it is discussed how to achieve them on the different layers of the communication stack. Finally, some open research issues are identified and briefly discussed.

### 2.1. QoS Requirements in Wireless Sensor Networks

Traditionally, the QoS has been defined and measured in terms of traffic metrics, such as packet loss, delay, jitter, bandwidth or throughput. These performance-oriented metrics reflect the network functionality. However, due to its intrinsic characteristics and application domains, WSNs demand for a broader vision of QoS. It is necessary to consider the so-called Non-Functional Properties (NFP) to have a holistic perspective of the QoS, as pictured in Figure 2.1. Such NFP include but are not limited to, scalability, reliability and robustness, timeliness, mobility, security and privacy, heterogeneity, and energy sustainability [10].



Figure 2.1 – Holistic view of QoS in wireless sensor networks, adapted from [10].

Depending on the WSN application and purpose, these high-level QoS requirements are then translated into QoS metrics and/or constraints, which can be measured and evaluated.

### **2.1.1. Scalability**

Scalability refers to the ability of a system to adapt itself in order to handle dynamic changes on its workload in an efficient way [11]. In the context of WSNs, scalability must be seen in three different dimensions: the network, the software, and the hardware.

Regarding the network point-of-view, a WSN can scale due to changes, in either the network physical topology or in the network logical topology. Modifications on the physical topology may occur because of changes in the number of nodes within the network, changes in the position of the nodes or in its spatial density. Changes in the network logical topology can be caused by the unreliability of the radio link quality or by the inoperability of some nodes [12] [10].

From the software perspective, scalability includes not only issues related with algorithms efficiency and reliability (e.g., to avoid overflow of the routing tables), but also nodes reconfiguration (e.g., to change the sampling rate) and post-deployment programming (e.g., to add new functionalities) [13].

From the hardware side, scalability involves the ability to accommodate different sensors (e.g., with different interfaces) which implies the flexibility to support distinct power consumption profiles [13].

### **2.1.2. Reliability and Robustness**

Reliability is the ability of a system to perform as required under predefined conditions during a specific period [14]. In addition, robustness refers to the capability of a system to perform as required not only under its design conditions, but also under adverse circumstances unpredicted by its designers [10] [14].

Reliability and robustness are key characteristics in the design process of WSNs regarding all its domain of application. The network must be reliable and robust to ensure on-time data delivery across the network despite sudden or long-term changes in the wireless channel [12]. The software must be robust and reliable regardless of its execution conditions (e.g., algorithms must



operate correctly independently of the hardware in use). The hardware must be robust and reliable even inside harsh environments (e.g., mechanical vibrations, low/high temperatures or humidity) [10].

### **2.1.3. Timeliness**

In general, timeliness refers to the timing behaviour of a system [10]. Depending on its application and purpose, the timing behaviour of WSNs could be of extreme importance, not only in terms of computations and communications, but also regarding the hardware operation (e.g., sensors, actuators or analogue-to-digital converters) [10].

In terms of computations, some applications (e.g., critical infrastructures monitoring or patient monitoring), usually denoted as “real-time applications”, impose timing limitations (i.e., a deadline) to the execution of some tasks (e.g., data aggregation or features extraction). Such real-time applications require the use of both real-time operating system and real-time programming languages [15].

Concerning the communications, real-time applications require on-time data delivery. In other words, the data collected from the sensors or an event detected in a certain region must be transmitted within a certain interval in order to be useful at the time of decision-making (e.g., in healthcare, emergency response or fire detection systems) [16].

Another important aspect concerning the timing behaviour of WSN is related with its usability and human interaction. WSNs are becoming increasingly pervasive and ubiquitous, enabling the development of smart and interactive environments, plenty of sensors and actuators. In such environments, the WSN must react on time to the human stimulus in order to provide adequate interaction [17].

### **2.1.4. Mobility**

Although a significant number of applications assume static WSNs, others (e.g., patient monitoring [18] or objects tracking) must consider both physical mobility and logical mobility [19]. Physical mobility is related with changes in the geographic location of both sensor nodes and sink. On its turn, logical mobility refers to changes in the network logical topology. The

network logical topology can change due to several factors, such as: adjusts in the routing paths in response to radio interferences, dead of some nodes due to energy depletion or changes in the routing paths due to adding or removing nodes to/from the network. In addition, mobility can be classified taking into account others aspects, such as the mobile entity (e.g., node mobility, sink mobility and event mobility [20]), the mobility rate and the mobility location (i.e. intra/inter-cell mobility) [10].

Mobility is a key requirement in WSNs since it can significantly improve the overall performance of such networks e.g., mobility can improve the channel capacity and network scalability of WSNs [21], mobile WSNs can reduce the energy consumption and consequently improve the network lifetime [22]. Providing effective and efficient mobility support to WSNs is a challenging task due to the heterogeneity of mobility sources and to the resources constrained nature of WSNs as well.

#### **2.1.5. Security and Privacy**

Considering the pervasive and critical nature of some applications supported by WSNs (e.g., critical infrastructures monitoring [11] or healthcare applications [9]), security and data privacy became a key topic for their acceptance outside the labs. Indeed, in such applications, a security breach can compromise not only the integrity of the data, but also of the physical infrastructures. Therefore, it is vital to secure data communications within the network in order to achieve the privacy level required by each application.

As already discussed, WSNs have very limited computational resources, memory, energy, and bandwidth. Such limitations impose serious limitations to the degree of security that can be applied to WSNs [23]. Moreover, by using wireless communications they are more exposed to attacks than wired networks due to the easier access to the communication channel. To further worsen this scenario, WSNs are wireless distributed systems without a central and trusted entity in charge of controlling the network security and privacy [10]. Despite all these challenges, WSNs must provide mechanisms to secure not only the network, but also the transported data, against malicious attacks and ensure data protection and privacy.

### **2.1.6. Heterogeneity**

Initial WSNs visions anticipated that sensor networks would mainly consist of homogeneous networks [24]. However, this idea could not be further from reality. Actually, real-world WSNs based applications are highly heterogeneous in a wide-ranging perspective and at different levels, namely: they may use different hardware and software (e.g., sensor nodes with different microcontrollers and radio transceivers, different network protocol implementations [25]); the sensor nodes may be composed by different sensor types (e.g., to monitor different ambient variables or different sensors to monitor the same variable); a WSN can be used to simultaneously support several applications with different requirements and objectives [17].

In one word, WSNs are inherently heterogeneous. Consequently, this condition must be considered not only at the applications design time, but also during the WSN operation, in order to provide the QoS required by each application using the network [10].

### **2.1.7. Energy Sustainability**

Energy is one of the scarcest resources in WSNs. Thus, energy-efficiency has been a major research topic inside the WSNs community. As a result, several approaches have been proposed to achieve energy efficiency and balance, and consequently increase the nodes working time, namely, pursuing energy conservation (e.g., using data aggregation, radio duty-cycling or energy-aware routing [26]), and energy collection (e.g., using energy harvesting) [27]. The combination of these techniques is decisive to extend the WSNs lifetime and achieve the desired energetic sustainability [10].

## **2.2. QoS Across the Communication Stack**

WSNs have been used in a wide variety of areas, each of them having several target applications with distinct QoS requirements. Therefore, the communication stack must be reliable, robust and flexible in order to support such variety of QoS requirements. Following the internet protocol suite, the WSNs communication stack comprises the application layer, the transport layer, the network layer, the data-link layer and the physical layer, as shown in Figure 2.2.

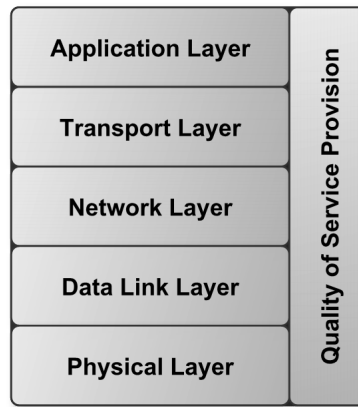


Figure 2.2 – Typical wireless sensor networks communication stack.

In summary, the application layer depends on the WSN specific task; the transport layer ensures efficient and reliable data delivery; the network layer is responsible for routing the data delivered by the transport layer; the data-link layer is in charge of the medium access control and link maintenance; and the physical layer provides robust modulation schemes and radio management for transmitting and receiving data [1] [28]. In this way, the concerns about the QoS provision in WSNs must be addressed at all the layers of the communication stack.

### 2.2.1. Application Layer

The QoS requirements of each application depend not only on its specific needs but also on its use and purpose. First of all, during the development period, the QoS requirements of each application must be well defined in terms of Non-Functional Properties (NFP).

#### 2.2.1.1. *Non-functional QoS requirements regarding different applications*

Figure 2.3 shows some examples of WSNs applications, applied to different areas, and its QoS requirements expressed in terms of NFP. It is important to emphasise that the set of NFP presented in the Figure 2.3 is merely exemplificative; it is not our intention to give an exhaustive list of NFP for each application. As a matter of example, a WSN used to carry out a patient monitoring task must fulfil QoS requirements, such as: to deliver the data on time (timeliness), to perform as designed (reliability) or even under adverse conditions (robustness), be used or managed only by authorised personal (security) and protect the data of each patient (privacy).

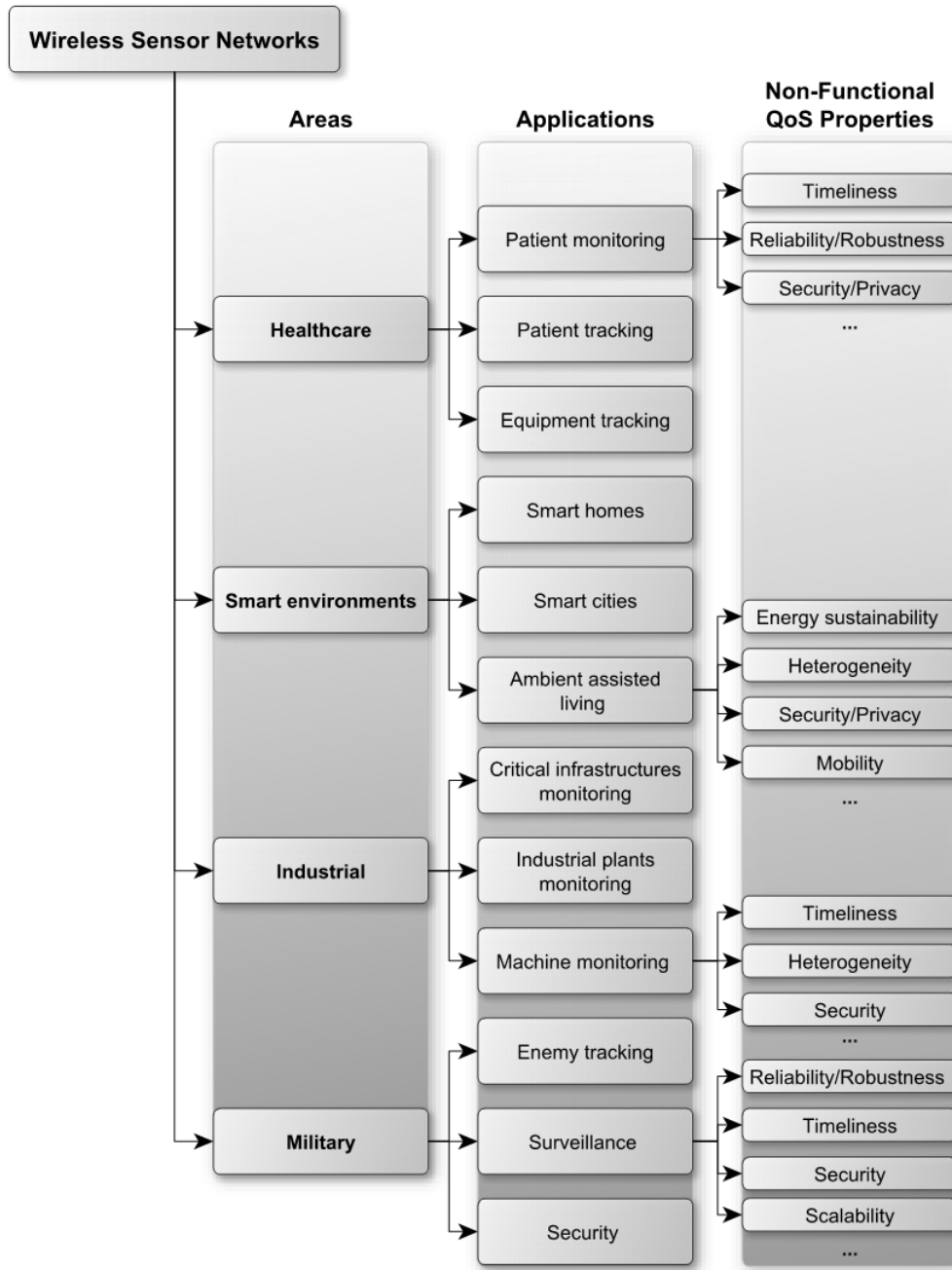


Figure 2.3 – Overview of WSNs applications and some of its QoS requirements expressed in terms of NFP.

#### **2.2.1.2. Functional QoS requirements regarding different application**

Having defined the QoS requirements in terms of NFP, it is necessary to map the NFP into functional QoS requirements (i.e., QoS metrics and/or constraints), accordingly to the specificities of each application and the target deployment scenario, as exemplified in the Figure 2.4. Considering the aforementioned patient monitoring application, it was specified that the data carried by the network must be delivered on time. So, such NFP must be expressed in terms of

end-to-end delay and packet delay variation. It was also stated that the WSN must be reliable, which can be quantified in terms of a minimum packet reception ratio that must be accomplished. Regarding the robustness of the WSN, it must perform as planned even when exposed to external interferences, such as electromagnetic interferences. These electromagnetic interferences can be reflected on the Received Signal Strength Indicator (RSSI) and on the Link Quality Indicator (LQI). Thus, the WSN must perform as desired under a wide range of different RSSI and LQI values. On its turn, the security and privacy mechanisms in use must take into consideration the additional data that the network will carry (throughput) and, consequently the necessary additional energy (energy-efficiency).

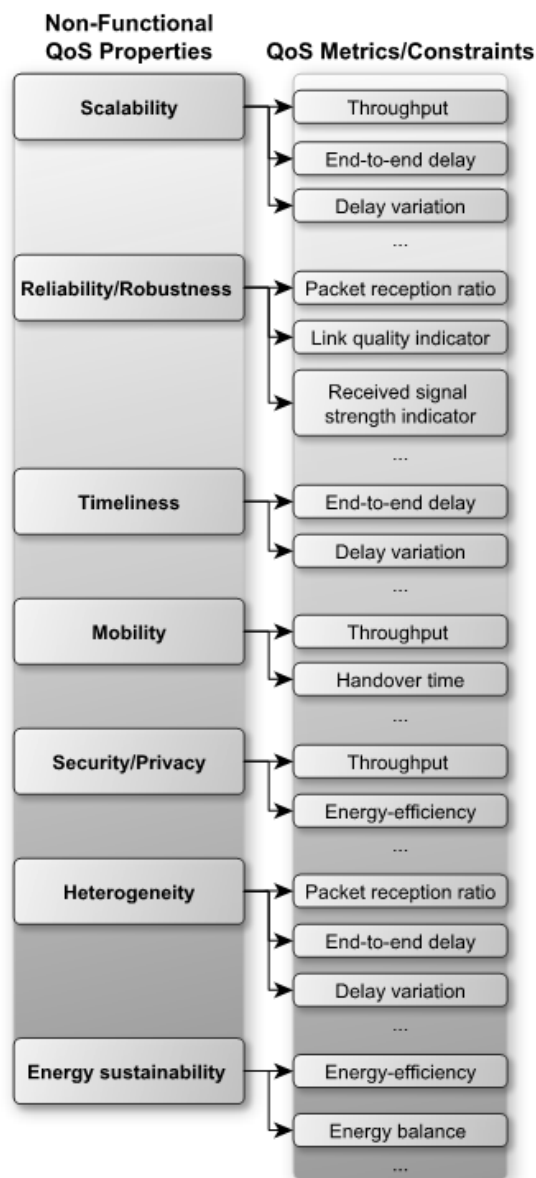


Figure 2.4 – Example of mapping NFP into functional QoS metrics and/or constraints.

After the specification of the QoS metrics and/or constraints in use for each application, they are broadcasted to the lower layers of the communication stack. Then, each one of those layers is responsible to implement the necessary mechanisms to accomplish the QoS required by each application.

### 2.2.2. Transport Layer

So far as WSNs are concerned, transport protocols play a key role in achieving high levels of QoS. Despite the many contributions to develop new transport protocols, based on distinct principles and technical features, they all have raised concerns about the way to ensure reliable and efficient data delivery across the network [28] [29]. Thus, NFP, such as scalability, reliability, and timeliness, can be used to express the main design criteria and challenges related to transport protocols. In addition, most of transport protocols implement some sort of congestion and priority control (e.g., patient monitoring systems may require that different delivery properties should be assigned to distinct data flows) [30].

#### 2.2.2.1. Scalable transport protocols

WSNs may not only comprise several sensor nodes, depending on the target application and deployment area, but also be able to admit new sensor nodes as required. Therefore, network scalability must be addressed when designing transport protocols for WSNs. In fact, several transport protocols prove to perform well when assessed for a large number of sensor nodes, Table 2.1 presents some of them.

Table 2.1 – Scalable transport protocols for WSNs.

Protocol	Scalability	
	Number of sensor nodes	Coverage area ( $m^2$ )
STCP [31]	50, 100	100 x 100
GARUDA [32]	100	650 x 650
DST [33]	200	200 x 200
ESRT [34]	200	100 x 100
TRCCIT [35]	100	60 x 60
$RT^2$ [36]	200	200 x 200
ART [37]	100	300 x 300
ERTP [38]	200	180 x 180
PHTCCP [39]	100	100 x 100
CCF [40]	116	—

### 2.2.2.2. *Reliable transport protocols*

Transport protocols are responsible for end-to-end connections establishment over the network and ensure reliability regarding data delivery. Recent developments have made possible the use of the Internet Protocol version 6 (IPv6) in low-power WSNs [41]. In particular, the practical and efficient use of the transport protocols User Datagram Protocol (UDP) and Transmission Control Protocol (TCP). In fact, UDP does not offer reliability or any other mechanism of control, making it improper to many WSNs applications. On the contrary, the TCP protocol offers end-to-end reliability; however, due to its retransmission mechanism and congestion control policy it offers low throughput [42]. Thus, several alternative transport protocols have been proposed targeting WSNs, along the last few years. Some of these transport protocols claim to be reliable, as presented in Table 2.2.

Table 2.2 – Reliable transport protocols for WSNs with congestion control.

Protocol	Direction	Reliability		Congestion control
		Level	Loss recovery	
STCP [31]	Upstream	Packet	End-to-end	Yes
GARUDA [32]	Downstream	Packet Destination	Two-stage loss recovery	No
DST [33]	Upstream	Event	End-to-end	Yes
ESRT [34]	Upstream	Event	—	Yes
TRCCIT [35]	Upstream	Packet	Hop-by-hop	Yes
CRRT [43]	Upstream	Packet	End-to-end Hop-by-hop	Yes
CTCP [44]	Upstream	Packet	Hop-by-hop	Yes
$RT^2$ [36]	Upstream	Packet	Hop-by-hop	Yes
ART [37]	Both	Event	End-to-end	Yes
ERTP [38]	Upstream	Packet	Hop-by-hop	No

Reliability can be achieved in two different directions, at different levels and using distinct methods for loss recovery. In WSNs, data transferences can occur in two directions depending on the target application. In applications regarding the collection of sensed data, the data transference occurs mainly in the upstream direction (i.e., from the sensor nodes to the sink). However, in applications requiring the exchange of control messages, between the sink and the sensor nodes, the data transference must be reliable in both directions: upstream and downstream (i.e., from the sink to the sensor nodes). Consequently, to fulfil the reliability



requirements regarding data transference, the transport protocols offer upstream and downstream reliability [29].

Moreover, reliability can be achieved at different levels. The reliability level refers to the degree of reliability supported by the protocol. As explained in [42], three levels of reliability can be defined: packet reliability, event reliability and destination reliability. Packet reliability refers to the successful transfer of all the data packets. On its turn, event reliability refers to reliability of event detection. In such cases, the protocol guarantees that at least one data packet, of each detected event, is successfully delivered to the destination. Finally, destination reliability is related with the ability of sending data successfully only to specific nodes.

Regarding the packet loss recovery, the methods used to retransmit the dropped packets are hop-by-hop packet retransmission or end-to-end packet retransmission. End-to-end packet retransmission is considered inappropriate for large-scale networks. In such cases, the packets retransmission along multiple hops implies extra energy consumption. Hop-by-hop packets retransmission is preferable in large-scale network as only two neighbouring nodes are involved in the packet retransmission [29].

Additionally to these methods, some transport protocols implement a congestion control policy (see Table 2.2) to prevent packet drops and unnecessary data retransmissions. Congestion can occur due to different causes, such as when the combined upstream traffic exceeds the packet-processing rate of each node or when the data throughput exceeds the link's available data threshold [42].

### ***2.2.2.3. Priority-based transport protocols***

Timeliness is another important requirement in WSNs. Transport protocols must not only guarantee reliable data delivery but also provide data on time. Concerns about timeliness, typically quantified as end-to-end delay and delay variation, must always be on top when designing transport protocols since options related with other factors, such as reliability or congestion control, easily affects timeliness negatively [29]. For example, the end-to-end packet retransmission policy may introduce a significant end-to-end delay in large-scale WSNs when compared with hop-by-hop packet retransmissions [31]. In addition, some transport protocols implement a priority control policy, as presented in Table 2.3. Depending on the WSN

application, the packets carried by the network may require different delivery requirements in terms of end-to-end delay or delay variation. Thus, introducing priority levels to differentiate data flows, by assigning some kind of identifiers, allows each node to preferentially transmit the packets carrying critical information. Data prioritisation is essential to support heterogeneous applications and, consequently, data flows having different QoS requirements [29] [42].

Table 2.3 – Transport protocols classification regarding priority control.

<b>Protocol</b>	STCP [31]	GARUDA [32]	DST [33]	ESRT [34]	TRCCIT [35]	CRRT [43]	CTCP [44]	$RT^2$ [36]	ART [37]	ERTP [38]
<b>Priority control</b>	Yes	No	Yes	No	Yes	No	Yes	Yes	No	No

The previous discussion makes it clear that several factors must be addressed to achieve high levels of QoS when designing transport protocols targeting WSN and its huge set of target applications. A more detailed review of such protocols can be found in [28], [29], [30] and [42].

### 2.2.3. Network Layer

Despite the different goals of WSNs applications, their main purpose is to sense and collect data to be delivered to a specific destination. So, in order to deliver data efficiently, a routing protocol is required to set up reliable and efficient multi-hop communication paths across the network [45]. However, due to the intrinsic characteristics of WSNs, such as the random nature of the wireless channel, the limited energy of the network nodes, and the limited computational capabilities and memory of the network nodes, the design of reliable and efficient routing protocols a challenging task [28].

The research and industrial communities have been proposing several routing protocols targeting WSNs. Nevertheless, despite the different approaches, all of them share the same design goals. Such goals, expressed in terms of NFP, include scalability, reliability and robustness, timeliness, mobility and energy sustainability.

At the network layer, scalability means that routing protocols must be scalable enough to handle multi-hop routes across WSNs, composed by hundreds of sensor nodes. More, routing protocols have to deal with changes in the network topology (both, physical and logical topologies), while choosing the best wireless links without overreacting to temporary link instability [46]. Regarding the reliability and robustness, routing protocols must be able to select multi-hop paths that offer

the best performance in terms of data delivery, regardless of the wireless links instability [47]. More, real-time applications require data to be delivered on time, in order to accomplish its requirements in terms of end-to-end delay and delay variation (i.e., timeliness) [48]. Depending on the WSN application, mobility can be an important requirement. For example, a WSN used in patient monitoring and tracking applications must deal with the patients' mobility [49]. Routing in mobile WSNs is a demanding task and, regardless of the many research efforts, several problems are still unsolved, such as retaining the network connectivity, improving the energy efficiency and maintaining adequate sensing coverage [22]. Another important QoS requirement is the energy sustainability of the network. Moreover, concerns about the energy sustainability of the WSNs must always be on top when addressing the aforementioned QoS requirements. Most recent works on energy-aware routing protocols for WSNs agree that such protocols must be not only energy-efficient but also improve the energy balance among the sensor nodes within the network [26] [50].

Several methods have been proposed to achieve the aforementioned QoS requirements. However, despite their diversity, existing WSNs routing protocols can be grouped into four main categories, namely data-centric, hierarchical, location-based, or network flow and QoS-aware protocols [45] [51] [46].

#### ***2.2.3.1. Data-centric routing protocols***

Some WSNs applications are data-centric in the sense that they perform a task based on its sensing activities/capabilities [52]. For example, when using a WSN designed to monitor the temperature of industrial facilities it is impossible to ask the network where the temperature is higher than a certain limit. In such scenario, the information source is unknown. To deal with this problem, the research community has introduced the concept of data-centric routing. In most of data-centric routing protocols, the data are requested to the network through queries sent to certain regions of interest within the WSN. Then, the data are routed to their destination through the network using distinct approaches. Table 2.4 presents a qualitative analysis of several data-centric routing protocols considering the following aspects: energy sustainability, data aggregation and data collection method. These aspects allow the assessment of the routing protocols regarding their ability to fulfil some NFP, such as: energy sustainability, scalability and timeliness.

Table 2.4 – Data-centric routing protocols in WSN, adapted from [46] and [45].

<b>Protocol</b>	<b>Energy sustainability</b>	<b>Data aggregation</b>	<b>Query based</b>
SPIN [53]	Weak	Yes	Yes
F&G [54]	Moderate	Yes	Yes
DD [55]	Weak	Yes	Yes
EAR [56]	Strong	No	Yes
RR [57]	Weak	Yes	Yes
CADR [58]	Weak	Yes	Yes
COUGAR [59]	Weak	Yes	Yes
EAD [60]	Strong	Yes	No
GBR [61]	Moderate	Yes	Yes
ACQUIRE [62]	Moderate	Yes	Yes

### **2.2.3.2. Hierarchical routing protocols**

Regarding high-density WSNs, covering large areas, single-tier networks can suffer from both lack of scalability and data overload in some nodes. To deal with these issues, several clustering methods have been proposed to achieve hierarchical routing. The main goal of hierarchical or cluster-based routing protocols is to improve scalability while providing efficient multi-hop paths to route data across the network [45]. Hierarchical routing protocols improve the network energy sustainability by involving sensor nodes in multi-hop communications within a particular cluster and by carrying out data aggregation and fusion, at the cluster head level, in order to minimise the data transmitted to its destination. Hierarchical routing is a two-layer routing protocol where the lower layer is used to select cluster heads among the sensor nodes and the higher layer is for routing [51]. Indeed, great efforts are put into choosing the cluster heads rather than about routing. Typically, the cluster formation is based on both the remaining energy of each node and its proximity to the cluster head [46].

Table 2.5 presents a qualitative evaluation of most relevant hierarchical routing protocols. Considering Table 2.5, it is possible to confirm that almost all the protocols apply data aggregation and achieve better results, regarding the energy sustainability, when compared with data-centric routing protocols.

Table 2.5 – Hierarchical routing protocols in WSN, adapted from [46] and [45].

<b>Protocol</b>	<b>Energy sustainability</b>	<b>Data aggregation</b>	<b>Query based</b>
LEACH [63]	Strong	Yes	No
SOP [64]	Weak	No	No
TEEN [65]	Strong	Yes	No
PEGASIS [66]	Strong	Yes	No
APTEEN [67]	Very Strong	Yes	No
HEED [68]	Strong	Yes	No
EAR-CSN [69]	Strong	Yes	No
BCEE [70]	Strong	Yes	No

### **2.2.3.3. Location-based routing protocols**

In some application scenarios, WSNs are randomly deployed within a region of interest to perform location-related tasks. In such cases, it is impossible to map the sensors' addresses with their geographic location on the terrain. Location-based (or geographic) routing has emerged as one of the most common routing methods regarding scenarios as the one just described. Most location-based routing protocols make their routing decisions based on both the geographic location of the current node and its neighbours [28], and the remaining energy of its neighbours [71]. As presented in Table 2.6, some location-based routing protocols apply data aggregation to improve the energy sustainability of the network. In addition to energy sustainability, the authors of [71] use anchor nodes to minimise the routing path, and consequently the end-to-end delay (i.e., improve the data timeliness). On its turn, the work presented in [72] shows promising results regarding highly dynamic scenarios, including nodes with some kind of mobility.

Table 2.6 – Location-based routing protocols in WSN, adapted from [46] and [45].

<b>Protocol</b>	<b>Energy sustainability</b>	<b>Data aggregation</b>	<b>Query based</b>
GEAR [73]	Moderate	No	No
TBF [74]	Moderate	Yes	Yes
EAGRP [75]	Strong	Yes	No
GAF [76]	Weak	No	No
MECN [77]	Weak	No	No
SMCEN [77]	Weak	No	No

### **2.2.3.4. Network flow and QoS-aware routing protocols**

The routing protocols that do not fit in the previous categories are classified as network flow and QoS-aware routing protocols [46]. In network flow protocols, the routing problem is modelled and solved as a network flow problem [45]. On its turn, the design goals of QoS-aware routing

protocols are the end-to-end delay, the delay variation and energy sustainability [46] [78]. Table 2.7 shows a qualitative analysis of some network flow and QoS-aware routing protocols.

Table 2.7 – Network flow and QoS-aware routing protocols in WSN, adapted from [46] [45].

<b>Protocol</b>	<b>Energy sustainability</b>	<b>Data aggregation</b>	<b>Query based</b>
MLDG [79]	Strong	Yes	No
SAR [80]	Weak	Yes	Yes
MLER [81]	Strong	No	No
SPEED [82]	Weak	No	Yes
EAQSR [45] [83]	Strong	No	Yes
MCBR [84]	Strong	No	No
AODV [85]	Weak	No	Yes

#### **2.2.3.5. The RPL routing protocol**

Among the most recently proposed routing protocols, it is possible to find the Routing Protocol for Low-power and Lossy Networks (RPL) [86], proposed by the Internet Engineering Task Force (IETF) working group Routing Over Low-power and Lossy Networks (ROLL). The RPL is a distance vector routing protocol that specifies how to form a Direct Acyclic Graph (DAG) by using an Objective Function (OF) and a set of constraints and metrics.

Several studies have been assessing the RPL performance from different perspectives. In terms of scalability, the authors of [87] argue that RPL presents a good scalability. However, its performance degrades when exposed to hostile environments in terms of radio interferences which is confirmed by other works such as [88], [89] and [87]. Concerning the PRR and the protocol overhead, the authors of [90] argue that the RPL performance is comparable to the one achieved by the Collection Tree Protocol [91], the de-facto routing protocol in TinyOS. Nevertheless, despite the need for more research to improve its performance, the flexibility of RPL allows to develop application-specific OFs in order to fulfil the particular QoS requirements of each application. Moreover, regarding its integration with existing technologies, namely IP networks, the mechanisms introduced by RPL to perform bi-directional routing and forwarding of IPv6 data packets allows the development of advanced monitoring applications in several domains [89].

#### **2.2.4. Data-Link Layer**

The data-link layer handles the data transfer between two nodes sharing the same wireless link [28]. Due to the intrinsic characteristics of the wireless channel, it is necessary to implement a Medium Access Control (MAC) and a management policy in order to guarantee effective data transfer. In this way, the MAC protocols should pursue the following key objectives defined in terms of NFP: energy sustainability, scalability, adaptability to changes and gracefully accommodate such network changes [92]. Other important objectives include bandwidth efficiency, latency and throughput [28] [92]. Since many WSN applications are seen as a collaborative effort to perform a common task, fairness is not usually considered as a key design goal [92].

Regarding energy sustainability, MAC protocols must prevent the major energy consumption causes, namely: collisions, overhearing, control-packet overhead, excessive retransmissions and idle listening [28] [92]. Collisions must be avoided to prevent the retransmission of discarded packets due to collisions. In this way, to minimise the collisions probability most MAC protocols apply the following techniques to access the transmission medium, namely: Time Division Multiple Access (TDMA), Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) or a hybrid approach. Another cause of energy waste is overhearing. To prevent it, nodes must avoid receiving data packets addressed to other nodes.

Concerning the control messages exchanged between the nodes within the network, they must be reduced to the minimum necessary to prevent control-packet overhead and unnecessary bandwidth utilisation. On its turn, excessive retransmissions can be caused by transmission of data when the destination is not ready to receive it. In this way, to prevent idle listening, the network nodes should apply a proper radio duty-cycle method to avoid listening to an idle channel in order to receive possible traffic. It is important to notice that the use of radio duty-cycle implies a trade-off between energy savings and end-to-end delay. While high duty-cycle methods perform well in terms of delay, they waste more energy. On the contrary, low duty-cycle methods led to substantial energy savings at the cost of a greater end-to-end delay. To mitigate the end-to-end delay while preserving energy, some MAC protocols use adaptive radio duty-cycle techniques instead of static radio duty-cycle. In static duty cycling, nodes share a timetable that is defined in advance, and does not change according to the network traffic load. Such methods can be suitable for applications where traffic load is known in advance, if optimised with respect to end-

to-end delay [93]. On the contrary, adaptive radio duty cycling methods make the radio duty-cycle dependent of the network traffic. When compared to static duty-cycle, adaptive duty cycling MAC protocols can reduce end-to-end delay to heavy traffic loads [93]. Table 2.8 presents a qualitative comparison of some radio duty cycling MAC protocols.

Regarding adaptability to changes and scalability, it is important to state that such design goals are related, as already stated when discussing scalability. Such characteristics are fundamental to arrive at highly efficient MAC protocols that are able to optimally address the dynamics of the network due to changes in the network size, node density, and topology. On its turn, the ability to gracefully accommodate such network changes brings robustness to the protocol allowing it to operate in adverse and unexpected conditions. In addition to these key requirements, MAC protocols should implement both flow and error control mechanisms [28].

Table 2.8 – Radio duty cycling MAC protocols in WSN, adapted from [92], [93] and [94].

<b>Protocol</b>	<b>Energy sustainability</b>	<b>Synchronization</b>	<b>Type</b>	<b>Duty-cycling type</b>
S-MAC [95]	Yes	Yes	CSMA	Static
WiseMAC [96]	Yes	No	NP-CSMA	Adaptive
T-MAC [97]	Yes	No	TDMA/CSMA	Adaptive
DSMAC [98]	Yes	No	CSMA/CA	Adaptive
SCP-MAC [99]	Yes	Yes	CSMA	Adaptive
B-MAC [100]	Yes	No	CSMA	Adaptive
X-MAC [101]	Yes	No	CSMA	Adaptive
Contiki-MAC [102]	Yes	No	CSMA/CA	Adaptive

### 2.2.5. Physical Layer

The physical layer is in charge of frequency selection, carrier generation, signal detection, modulation, and data encryption, providing an interface for transmitting and receiving bit streams over the physical-communication medium [1] [28]. Due to the inherent characteristics of the wireless channel (e.g., vulnerability to electromagnetic interferences and signal attenuation), it is error-prone and its performance changes over time. Moreover, such weaknesses are even more evident when harsh environments, like hospital facilities, are at stake. In this way, the physical layer must interact with the MAC layer not only to detect and correct errors but also to share information about the transmission conditions (e.g., transmission power, or link quality) in order to achieve high performance while optimizing resources' utilization [28].



Energy sustainability is of paramount importance for WSNs since it strongly affects the network lifetime, as already discussed in the context of the upper layers of the communication stack. Indeed, the energy sustainability is a cross-layer requirement that must be addressed from the physical layer. At the physical layer, the energy is used not only by the communication module but also by the sensors used to perform the task in which the network is participating. Regarding the energy spent by the communication module, it has two components, namely the energy used in operating the circuitry and the energy used to transmit/receive the bit streams [28]. While the energy used by the circuitry is fixed (i.e., does not change along the time), the energy used to transmit/receive data, on the contrary, varies along the time and depends on the quality of the radio link (e.g., it depends on the channel loss, interference, transmission distance and transmission power) [1]. In this way, it is necessary to find a trade-off between transmission power and error-rate in order to optimize the energy consumption while achieving the highest probability of successful data transmission [28].

Another important factor that affects the energy necessary to transmit a data stream is modulation, as explained in [103]. Thus, regarding the communication module, the key requirements is to include low power radio design, power-aware transmission schemes and energy-efficient modulation schemes [1] [28] [103].

### **2.3. Summary**

This chapter provided a broader vision about quality of service targeting wireless sensor networks and their applications. There were presented and discussed not only several non-functional properties, but also the main functional metrics and constrains. Finally, the key quality of service requirements at each layer of the communication layer, and the mechanisms used to guarantee them, were presented and discussed.



## **Quality of Service Provision in BWSNs**

State-of-the-art

- 
- 3.1 Biomedical Wireless Sensor Networks Applications
    - 3.1.1 At-hospital
    - 3.1.2 At-home
    - 3.1.3 Ambient Intelligence Systems
    - 3.1.4 Mass Casualty Disasters
  - 3.2 Application's Requirements and Traffic Characterization
  - 3.3 QoS Challenges and Open Issues in WSNs and BWSNs
  - 3.4 Summary
-



### 3. Quality of Service Provision in Biomedical Wireless Sensor Networks

Since its beginnings, computer technologies have always been used in healthcare. They have allowed the development of novel instruments and information systems, assisting healthcare providers evaluating and tracking the health condition of their patients. More recently, wireless technologies together with small and smart sensors bring the possibility to develop distributed patient monitoring systems. Indeed, as just discussed in the last chapter, healthcare is only one of the many application areas of WSNs. Nevertheless, to be fully accepted by the healthcare stakeholders, BWSN-based patient monitoring systems must guarantee stringent QoS requirements in terms of system reliability and robustness, on-time data delivery, privacy, and security. In this way, this chapter discusses the typical applications of BWSNs regarding the healthcare area and its special QoS requirements. Finally, some challenges and open research issues are outlined.

#### 3.1. Biomedical Wireless Sensor Networks Applications

The emergence of both low-power communications technologies and high-quality sensing technologies is unlocking the use of BWSNs in healthcare. Regarding the healthcare domain, BWSNs can be used in several scenarios, including: at-hospital, at-home, in ambient intelligence systems, or mass casualty disasters [2]. For each of these scenarios, BWSNs may be used to support the communications of several applications and services as summarised in Table 3.1.

Table 3.1 – Some examples of BWSNs applications.

Scenario	Application
At-hospital	Patient monitoring [104] [105]
	Patient tracking [106] [107]
	Rehabilitation supervision [108]
At-home	Vital sign gathering [109]
	Falls detection [110] [111]
	Assistive technologies [112] [113]
Ambient intelligence systems	Activity monitoring/recognition [114] [115]
	Emergency detection and support [116]
Mass casualty disasters	Automatic triage and rescuers management [117]
	Resources management [118]

### **3.1.1. At-hospital**

BWSNs have the potential to address some drawbacks related to wired sensing technologies commonly used in hospitals to monitor their patients, such as reducing the number of wires attached to patients, improving its mobility and comfort, and, at the same time, avoiding anxiety [2].

As far as the patients' health condition is concerned, patients' monitoring in general or step-down hospital units is crucial to avoid clinical worsening of patients. However, in most cases, despite the necessity of continuous monitoring, nursing professional measures the patients' vital or physiological signs manually at long time intervals [104]. Such episodic measurements can be complemented by using efficient and reliable real-time patient monitoring systems, bringing out an enhancement of the quality of care provided, while freeing the nursing staff to provide extra attention to the patients [105].

As surveyed in [8] and [119], several patient monitoring systems have been proposed over the last few years. However, only a few of them were deployed in a real-world hospital environment and evaluated by real patients. Among these are the projects presented in [104] and [105].

Chipara *et al.* [104], proposed a patient monitoring system to collect both the pulse rate and the blood oxygen saturation levels. The patient monitoring system was deployed in a step-down unit at the Barnes-Jewish Hospital in Saint Louis, MO, USA and used to monitor 41 patients for a total of 41 days of continuous monitoring. Based on the results obtained, the authors argue that patient monitoring system based in BWSNs are viable and achieve the same level of performance when compared with wired monitoring system. More, this study has provided clinical examples of early detection of clinical deterioration in patients, showing its potential to improve the quality of care provided.

Like the previous work, MEDiSN [105] was used to monitor pulse rate and blood oxygen levels. MEDiSN was deployed in two realistic environments, namely the University of Maryland Shock Trauma Center and the Johns Hopkins Hospital. In the University of Maryland Shock Trauma Center, MEDiSN was used to monitor the patients' vital signs inside the operating room, throughout the operation, and after the operation during their recovery period in the post anesthesia care unit. On its turn, at the Johns Hopkins Hospital, MEDiSN was deployed within the waiting area of the emergency room. During both deployments several problems were found,

such as: aluminium dividers, metallic furniture, considerable human activity, steel doors, and lead painted walls. All these problems made the deployments challenging although, despite the difficulties, both deployments succeed on its task. In the University of Maryland Shock Trauma Center, MEDiSN was able to deliver, in average, 98.25 % of the sensed data, and in the emergency room of the Johns Hopkins Hospital the data delivered was of about 95.43%, in average. Other systems, such as those presented in [106] and [107], combine patient monitoring with indoor localization and tracking technologies.

The LAURA project [106] is an integrated system designed to monitor the patient's movements in order to recognise potential harmful situations like falls or inactivity while gathering information about the patient's location. The movement classification engine achieves accuracy as high as 90 % when detecting dangerous situations and the localization error is lower than 2 m in 80 % of the cases. Similarly, Cheng *et al.* [107] proposed a system to locate psychiatric patients while gathering their heartbeat. In that case, the localization accuracy is 90 % with an error of about 3 m.

Another interesting application of BWSNs is related with rehabilitation supervision [108]. To achieve optimum rehabilitation results, patients should be monitored and corrected during their exercises. Indeed, as discussed in [108], BWSNs may radically improve the way rehabilitation is provided, and its results evaluated.

### **3.1.2. At-home**

National healthcare systems around the world, especially in Europe and USA, face the problem of ageing population. This social phenomenon stresses the national healthcare systems, instigating hospitals and medical caregivers to seek for new methods to reduce costs while maintaining the required quality of care. Therefore, improving prevention is essential to allow people to age actively, maintaining their quality of life. On its turn, early detection of health deterioration is vital to help people dealing with all the diseases that arise and, at the same time, reducing the economic and social burden of illness treatment.

BWSNs provide a valuable cost-effective communications infrastructure to develop at-home patient monitoring applications. At-home patient monitoring applications can be used to monitor elderly and chronically ill people, allowing automatic data collection and early detection of clinical

worsening. Moreover, at-home patient monitoring can improve the quality of life of chronically ill people and reduce hospital stays. AlarmNet [109] is one example of at-home patient monitoring system. AlarmNet was designed for long-term monitoring in ambient assisted living environments, supporting a diverse collection of sensors and human-machine interfaces.

Keeping the discussion focused on the elderly or impaired people, falls are identified as a major health risk. As a consequence, providing on-time care to those who fall down is of extreme importance to minimise the risk of negative effects on people's health. To address this problem, several fall detection systems have been proposed. The WeCare system [110] proposes a multi-modal fall detection system that uses sensor (e.g., body-worn accelerometers, RFID tags and embedded video cameras) fusion technics to improve the probability to successfully detect falls and minimise the false positives. On its turn, Castillo *et al.* [111], suggests a multi-modal system that uses accelerometers, video cameras, Global Positioning System (GPS) coordinates and machine learning techniques to detect falls and classify user's activities in both indoor and outdoor domestic environments.

As a consequence of aging population, the percentage of people living with any degree of dependence, resulting from chronic diseases or any kind of physical or cognitive impairment, is growing all around the world. In this context, several assistive technologies have been proposed. Huo *et al.* [112], proposes a wireless tongue-operated assistive technology capable of detecting the movements of the user's tongue and translating them into commands that can be used to control other devices in the users' environments. Aloulou *et al.* [113], developed a plug-and-play mechanism enabling the integration of several wireless assistive technologies. The development of new assistive technologies and their integration with the users' environment and intelligent systems has the potential to improve the quality of life of their users [120].

### **3.1.3. Ambient Intelligence Systems**

The problem of aging population brings new challenges to both governments and families. In special, the demand for care at home has been increasing due to the growing number of aging people and chronically ill people. Apart from receiving family and professional care at home, aging and chronically ill people can benefit from technological solutions to facilitate aging-in-place. In such context, ambient intelligence systems can support and monitor older adults with or without any kind of physical or cognitive disease.



Ambient intelligence system is the vision of a technology that imperceptibly incorporates sensors, computing devices, and information and communications technologies in our natural environments, such as residential or nursing homes and hospitals, to support the people that inhabiting them [121]. As described by Acampora *et al.* [122], ambient intelligence systems are designed to be pervasive, ubiquitous, adaptive, transparent, personalised, context-aware and anticipatory. Such characteristics make ambient intelligence systems appealing to develop new healthcare systems and services [123] [124].

One of the most explored applications of ambient intelligence system is human activity monitoring and recognition. Human activity monitoring and recognition is essential to assist aging or disabled people on their daily life activities, or even to detect dangerous events. Amoretti *et al.* [114] propose PERSONA, an activity monitoring framework for ambient assisted living environments. PERSONA uses several data sources such as person's posture and localisation and the status of user-controlled devices to produce information about ongoing user activities. On its turn, Martínez-Pérez *et al.* [115] proposes SCAN, an activity recognition framework to be used in nursing homes. The SCAN framework infers the activity being made by monitoring the behaviour of objects related to a particular activity. The authors argue that the behaviour of an object is strongly related to a particular activity, enabling a success rate of about 92.7 % for effective activity inference.

Hoof *et al.* [116] shows the results of a study performed in the Netherlands evolving the use of ambient intelligence systems to assist older adults in their homes. The main purpose of the ambient intelligence system used was to fire an alarm in case of emergency and study the impact of such technology on its users. To detect such dangerous situations, the system includes the following functionalities: mobility monitoring, voice response, fire detection, fall detection, as well as wandering detection and prevention. Through several interviews, the authors found that such systems increase the sense of safety and security on their users and their families. Moreover, such technology helps to postpone the institutionalization of older adults, relieving the pressure from the national healthcare systems.

### 3.1.4. Mass Casualty Disasters

Wireless sensor networks are self-organised, infrastructure-less and distributed networks composed by numerous network nodes. These characteristics make WSNs suitable to be deployed in scenarios of mass casualty events (e.g., fire-in-tunnels [125] or natural disasters [117] [118]), providing a communications infrastructure to assist on-site emergency response.

CodeBlue [117], was one of the first projects addressing the problem of monitoring the vital functions of a large number of patients during an emergency, improving the in-field patient triage and tracking. Additionally, CodeBlue also provides mechanisms to locate and manage the rescuers on the field. Similarly to CodeBlue, Chandra-Sekaran *et al.* [118] presents a WSN based emergency response system designed to assist on-site organisation chief estimating and managing its resources in order to quickly evacuate patients from the disaster site.

### 3.2. Application's Requirements and Traffic Characterization

As revealed by the above discussion, BWSNs can be used in different areas and scenarios to develop a multitude of applications. Moreover, depending on the deployment scenario, on the application and on its use, they demand different QoS requirements. Table 3.2 shows some of the BWSNs applications previously described and their typical QoS requirements expressed in terms of Non-Functional Properties (NFP). See the section 2.1 of chapter 2 for more details about the QoS requirements of WSNs.

Table 3.2 – Some BWSNs applications and typical QoS requirements expressed in terms of NFPs.

<b>Sensor</b>	<b>Patient monitoring</b>	<b>Patient tracking</b>	<b>Rehabilitation supervision</b>	<b>Falls detection</b>	<b>Assistive technologies</b>
Scalability	✓				✓
Reliability	✓	✓	✓	✓	✓
Robustness	✓	✓	✓	✓	✓
Timeliness	✓	✓		✓	✓
Mobility	✓			✓	
Security	✓	✓	✓	✓	✓
Privacy	✓	✓	✓	✓	✓
Heterogeneity	✓		✓		✓
Energy sustainability	✓	✓	✓	✓	✓

Depending on the BWSN application, it can be highly heterogeneous. In other words, the BWSN can use several sensors to acquire different signals or variables as exemplified in Table 3.3. For example, in patient monitoring applications, it is usual to have several sensors, each one acquiring a different signal or indicator (e.g., heart rate, blood pressure, oximetry, and body temperature).

Table 3.3 – Some BWSNs applications and typical sensors used.

<b>Sensor</b>	<b>Patient monitoring</b>	<b>Patient tracking</b>	<b>Rehabilitation supervision</b>	<b>Fall detection</b>	<b>Assistive technologies</b>
Temperature	✓		✓		
Blood pressure	✓				
SpO <sub>2</sub>	✓				
Heart rate	✓		✓		
Respiratory rate	✓		✓		
ECG (per lead)	✓		✓		
EEG (per lead)	✓				
EMG (per lead)	✓		✓		
Blood Glucose	✓				
Accelerometer		✓	✓	✓	✓
Gyroscope		✓	✓	✓	✓
CO <sub>2</sub> gas					✓
Presence		✓			✓
Video		✓		✓	✓

The data generated by each source (i.e., sensor or application), can vary not only in quantity but also in form. The quantity of data generated by each source depends on the signal being monitored (e.g., on the signal bandwidth), on the measurement resolution (i.e., the number of samples per second) required and on the data accuracy (i.e., the number of bits per sample). Regarding the data pattern, it may fall in one of the following categories: streaming data (i.e., uniform data traffic), bursty data (i.e., short bursts of data traffic) or episodic data (i.e., varying data traffic) [126]. Table 3.4 presents the typical sensors used in BWSNs and relevant characteristics of the data generated by each one of them.

The applications just described have the potential to improve the citizens' quality of life in several aspects of their daily life. However, to be an everyday reality, BWSNs must not only satisfy high standards of QoS, but also provide easy-to-use network management tools. Network management tools are essential to assist network administrators managing the network and supervising the QoS provided. As a matter of example, consider a BWSN for patient monitoring purposes

gathering the following vital signs: temperature, heart rate and respiratory rate, and additionally the oxygen saturation ( $SpO_2$ ). Looking to the Table 3.2, it is possible to see the QoS requirements of such monitoring application expressed in terms of NFP. Moreover, as discussed in the section 2.2.1 of chapter 2, these NFP must wherever possible be quantified (e.g., the end-to-end delay as expressed in the Table 3.4) and addressed by the different layers of the communication stack. However, even though these QoS requirements are being addressed by the different layers of the communication stack, they can substantially vary due to both changes in the network topology and the environment interferences. Thus, QoS monitoring tools are needed to monitor the real network performance and be aware of dangerous QoS degradation situations (e.g., the end-to-end delay can be out of the limits required by each data flow).

Table 3.4 – Typical sensors used in BWSNs applications and some traffic characteristics, adapted from [126] [127] [128] [129] [130] [131].

<b>Sensor</b>	<b>Maximum data rate</b>	<b>Bandwidth (Hz)</b>	<b>Accuracy (bits)</b>	<b>Max end-to-end delay (s)</b>	<b>Priority</b>	<b>Data pattern</b>
Temperature	24 bps	0–1	12	60 s	Low	Streaming
Blood pressure	1.41 kbps	25–60	12	10 s	High	Bursty
$SpO_2$	0.70 kbps	0–30	12	30 s	Medium	Streaming
Heart rate	0.12 kbps	0.4–5	12	5 s	High	Streaming
Respiratory rate	0.23 kbps	0.1–10	12	5 s	High	Streaming
ECG (per lead)	4.91 kbps	0.01–125	16	5 s	High	Streaming
EEG (per lead)	3.52 kbps	0.5–125	12	6 s	High	Streaming Episodic
EMG (per lead)	313 kbps	0–10000	16	15 s	Medium	Streaming Episodic
Blood Glucose	1.56 kbps	0–50	16	5 s	High	Streaming Episodic
Accelerometer	3.52 kbps	0–50	12	5 s	High	Streaming Episodic
Gyroscope	3.52 kbps	0–50	12	5 s	High	Streaming Episodic
$CO_2$ gas	16 bps	0–1	8	5 s	High	Bursty
Presence	16 bps	0–1	8	5 s	Low	Bursty
Video	1 Mbps	–	–	5 s	Medium	Streaming

### 3.3. QoS Challenges and Open Issues in WSNs and BWSNs

As discussed in the chapter 2, WSNs present several challenges that are not faced by conventional wireless networks. Such challenges bring the need for new algorithms and protocols

designed to meet the particular requirements of WSNs. Despite the results achieved until now, there are several issues needing further research, namely: energy sustainability, cross-layer solutions, suitable QoS models, hardware and software heterogeneity, cooperation, security, mobility, interoperability, and appropriate deployment and management tools [10] [17] [132].

Most of the current work in WSNs assumes that they consist of homogeneous nodes, working cooperatively to perform a common task. However, real deployments may consist of heterogeneous nodes (e.g., different operating systems, different hardware platforms, and different sensing capabilities) [101]. In such context, a WSN may be shared by several applications, each one with its own objectives and QoS requirements (e.g., mobility, privacy, and security). More, different WSNs may cooperate to perform a different task, to infer some results, or to perform cooperative communications [10] [132]. Thus, there is a need for new QoS models and communication protocols that can serve multiple applications in an efficient and reliable way [17]. In addition, new communication protocols must facilitate the interaction with existing networks; in other words, they must provide interoperability [10] [132].

Apart from the functional aspects and technical solutions just discussed, there is a need for new and powerful software development tools to assist developers and architects on the development and debugging of WSNs and their applications [133]. Moreover, more efforts are necessary to move WSNs from labs to real-world applications. To that end, it is necessary to develop tools to assist on the network deployment and its management during the working time [134] [133]. Network management tools are necessary not only to manage the network but also to supervise its performance. As pointed out by the work presented in [10], the need for, not only debugging and management tools, but also deployment planning tools was identified by the industrial end research communities as a research goal to achieve in the medium term.

As a special set of WSNs, BWSNs share the same challenges while presenting some particularities. As a matter of example, depending on its application and purpose, BWSNs can be highly heterogeneous, have to support nodes mobility, have to operate in hostile environments, have to work for long periods of time without human intervention, and at the same time providing secure and private communications. Such QoS requirements can be achieved using the same tools already presented for WSNs. However, in the case of BWSNs, due to the critical nature of the data that they carry and depending on the characteristics of the deployment scenario, their QoS requirements can be significantly harder to achieve and maintain when comparing with

typical WSNs. Moreover, the on-the-fly QoS provided by BWSNs must be continually monitored in order to detect relevant and dangerous variations on it.

BWSNs designed to support patient monitoring applications inside hospital facilities have to face several challenges, in particular, regarding the dynamic nature of the surrounding environment. Hospital facilities can be very hostile environments for radio-frequency communications. Such adversities result from structural factors such as the presence of metal doors and furniture, as well as, the existence of radiation shields [2]. In fact, Ko *et al.* confirmed that the packet losses for IEEE 802.15.4-based radios are higher in hospitals than in other indoor environments [135]. Moreover, IEEE 802.15.4-based networks are prone to interferences from other communication technologies such as IEEE 802.11 (i.e., Wi-Fi networks), Bluetooth devices, and cordless phones, all of which are habitually used in hospitals [2]. To further worsening this scenario, low-power networks are highly vulnerable to obstacles, interferences and human bodies [2] [136]. So, in order to address these difficulties effectively, during the applications development period, it is necessary to develop new radio models that accurately represent hospital environments, and integrate them with existing simulation environments.

Furthermore, from the previous discussion, it becomes clear that hospital environments could have a significant impact on the QoS provided by BWSNs. Moreover, the dynamic of the deployment environment affects the network performance in an unforeseeable way. The existence of such adverse effects makes clear the necessity not only for QoS monitoring systems but also for QoS-based network management systems.

In fact, QoS monitoring systems are essential not only to detect events able to cause degradation on the network performance but also to provide valuable information that can be used to take corrective measures and prevent performance degradation. On its turn, QoS-based network management tools are needed to help “network administrators” supervising the network during its runtime. As a matter of example, QoS-based network management is of extreme importance to control the admission of new nodes to a BWSN. Having in mind the maximisation of the QoS provided by a BWSN and the QoS requirements of each patient, QoS-Based admission control tools can be used not only to assess if a new patient can be added to a BWSN but also to find the most favourable location to place the patient.

### **3.4. Summary**

This chapter discussed several aspects related with the quality of service provision in biomedical wireless sensor networks. There were presented and discussed several applications of biomedical wireless sensor networks targeting different scenarios. Then, the quality of service requirements of those applications and related sensors were presented and discussed. Finally, important quality of service challenges and open issues targeting wireless sensor networks, in general, and biomedical wireless sensor networks, in particular, were discussed.





# Chapter 4

## **QoS-Based Management of BWSNs**

### Proposed Method

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- 4.1 BWSN Representative Scenario
  - 4.2 Proposed QoS-Based Network Management Method
    - 4.2.1 Controlling the Admission of New Sensor Nodes to the BWSNs
    - 4.2.2 Monitoring the QoS of BWSNs
  - 4.3 QoS-Based Admission Control Module
    - 4.3.1 Working Principle of the QoS-Based Admission Control Module
    - 4.3.2 Developed Software and its Architecture
  - 4.4 QoS Monitoring Module
    - 4.4.1 Time Domain Analysis of the QoS Metrics
    - 4.4.2 QoS Assessment and Network Performance Classification
  - 4.5 QoS-Based Network Management Method Assessment
    - 4.5.1 QoS Monitoring Module Assessment
    - 4.5.2 QoS-Based Admission Control Module Assessment
    - 4.5.3 Discussion
  - 4.6 Setting the Limit of the Connected Region in Low Power Wireless Links
    - 4.6.1 Finding the Output Power Necessary to Achieve the Required Connected Region
    - 4.6.2 Analysing the Virtual Sensor Node's PRR Considering Single-hop Communications
    - 4.6.3 Analysing the Virtual Sensor Node's PRR Considering Multi-hop Communications
    - 4.6.4 Experimental Validation
  - 4.7 Summary
-



## **4. QoS-Based Management of Biomedical Wireless Sensor Networks**

From the previous chapters it becomes clear that the use of WSN to support a wide range of applications, each one producing distinct data with specific characteristics and QoS requirements, brings new challenges to the WSNs research community. Consequently, the last few years have been rich in solutions to provide the network protocol stack with mechanisms to ensure the necessary QoS for each application or application area, as explained in the chapter 2.

Within the BWSNs context, such networks are characterised by a need for reliable and timely data delivery. Moreover, BWSNs have to carry distinct data flows, each one with its intrinsic QoS requirements, in a wide range of application scenarios. In addition, BWSNs should be autonomous, scalable and operate for a long period of time without human intervention. In other words, BWSNs must fulfil a very demanding set of QoS requirements to be fully accepted by its users, as explained in the chapter 3.

According to the state-of-the-art, discussed in the chapters 2 and 3, the mechanisms being proposed to provide QoS across the communication stack are of utmost importance to ensure the required network performance. However, they do not obviate the need for a careful network planning and management; in particular, regarding hostile real-world network deployment environments. Indeed, QoS-based network management tools are essential, not only to monitor the on-the-fly QoS provided by BWSNs, but also to manage the network in order to maximise the QoS provided. Nevertheless, despite such need, the existing network planning and management tools, targeting real-world deployments, are still quite limited in their functionality and are not sufficiently stable, or well documented, as surveyed in [137].

In such context, this thesis proposes a new QoS-based network management method targeting BWSNs. The proposed method aims to provide the following important and innovative functionalities:

- 1 - Detect and classify QoS degradation events before the QoS reaches critical levels, avoiding network to fail.
- 2 - Predict the effect, on the QoS being provided by a BWSN, of adding a new sensor node to the network, without the need for the physical presence of the new sensor node within the network.

The remaining of this chapter starts by presenting the experimental case study used to develop the QoS-based network management method. Then, the proposed method is clearly described and, finally, some results are presented to validate it.

#### 4.1. BWSN Representative Scenario

The proposed QoS-based network management method was developed with the following scenario in mind: inside a hospital or nursing home, several patients are being monitored; and the patient monitoring system uses a BWSN to carry the data collected from each patient, as pictured in the Figure 4.1.

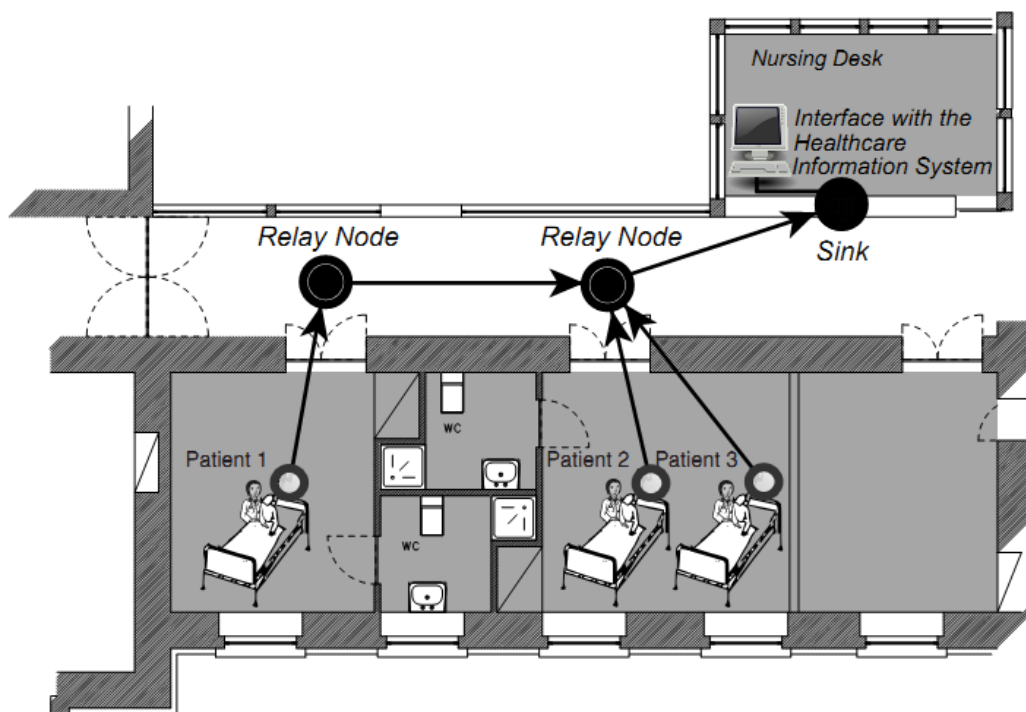


Figure 4.1 – Representative scenario used to develop the proposed QoS-based network management method.

Considering the normal activity inside the representative scenario presented in the Figure 4.1, it is necessary to guarantee that the patient monitoring system is working properly. In this way, the network management system faces two major problems, namely:

- 1 - How to monitor the on-the-fly QoS provided by the BWSN and how to be aware of potential dangerous situations regarding the network's performance;
- 2 - How to choose the best location to place a new patient inside the BWSN, minimising its impact on the QoS being provided to the patients already within the network.

Thus, considering the representative scenario pictured in the Figure 4.1, the proposed QoS-based network management method must be able to assist the nursing staff facing those problems.

## **4.2. Proposed QoS-Based Network Management Method**

With a view towards solving the problems identified in the previous section, the proposed QoS-based network management method comprises two essential functionalities, namely the ability to monitor the QoS effectively provided by a BWSN, and the ability to manage the admission of new patients to a BWSN. Although such functionalities can complement each other, they can also be used independently. For that reason, they were implemented separately. Therefore, this thesis proposes a QoS-based network management method comprising two modules, namely the QoS-based admission control module and the QoS monitoring module.

### **4.2.1. Controlling the Admission of New Sensor Nodes to the BWSN**

Bearing in mind the representative scenario shown in the Figure 4.1, the QoS-based admission control module is responsible for managing the admission of new sensor nodes (i.e., new patients) to the BWSN. In particular, it is responsible to make a decision about the admission of the new sensor nodes, and, for those admitted to the BWSN, find the most favourable location to place them, while maximising the QoS provided by the BWSN.

The QoS-based admission control module starts from the premise that each sensor node, within the BWSN, is able to simulate the presence of other sensor node on its neighbourhood. To make this idea possible the QoS-based admission control module uses the concept of “virtual sensor node”. In this way, every sensor node within the BWSNs must be able to create a “virtual sensor node” and configure it, on demand, to generate data traffic as required.

Since all sensor nodes within the BWSN must be able to simulate the presence of other sensor node on its neighbourhood, they all have to run the QoS-based admission control module. Therefore, the QoS-based admission control must run on the sensor nodes and on the sink.

An important concern when designing the QoS-based admission control module was the energetic sustainability of the BWSN. Thus, to avoid the problem of energy depletion in the energy-constrained sensor nodes, due to the extra processing required, the proposed QoS-based admission control module collects all the data required for decision making at the sink that,

generally, is connected to the power line. Regarding the energy consumption in the sensor nodes, the “virtual sensor node” is required to run only on request and for short time periods, being the extra energy consumption insignificant.

Another important requirement when designing the QoS-based admission control module was its portability among different operation systems (e.g., the Contiki OS or the Tiny OS) and compilers. In this way, to maximise the module portability it was implemented using ANCI C. Moreover, the modules’ architecture was designed for easier integration with other WSN applications.

#### **4.2.2. Monitoring the QoS of BWSNs**

Once again, considering the representative scenario pictured in the Figure 4.1, the QoS monitoring module is in charge of monitoring the QoS provided by the BWSN. In order to do so, the QoS monitoring module must be able to assess each data flow carried by the network, and to detect potential QoS degradation events. The QoS monitoring module detects the potential QoS degradation events by analysing the behaviour of each one of the metrics used to quantify the QoS provided by the network (n.b., the most common metrics used to quantify the QoS provided by WSNs and BWSNs were presented in the chapter 2 and 3, respectively). Moreover, the QoS monitoring module classifies the QoS degradation events detected in order to provide extra information concerning the potential risk that each detected event represents to the QoS being provided by the BWSN.

As the QoS monitoring module must assess each data flow carried by the BWSN, it must run on the sink or on the computer connecting the BWSN to the outside world (e.g., the computer interfacing the BWSN with the healthcare information system as pictured in the Figure 4.1), in order to perform efficiently. In the context of this thesis, the QoS monitoring module was put into operation in the computer connected to the sink node.

To install the QoS monitoring module into the computer that connects the BWSN to the hospital information system brings some important advantages. The most important one is the independence of the QoS monitoring module with respect to the BWSN. By using this architecture, the QoS monitoring module and the BWSN must agree only on the format of the messages exchanged within the networks. Other important advantages relate to the larger processing power and memory available when comparing the computer with the BWSN nodes.

Finally, the use of the computer facilitates the interoperability of the QoS monitoring module with other information systems.

### **4.3. QoS-Based Admission Control Module**

The QoS-based admission control module uses a probe-based admission control procedure to decide where a new sensor node can join the network. The decision regarding where to admit the new sensor node on the network is based on time-domain analysis of the performance metrics used to quantify the QoS provided by the network, namely the packet reception ratio. Within the proposed method, the probe-based procedure of the QoS-based admission control module uses a “virtual sensor node” called QoS Probe to mimic the presence of a new real sensor node on its neighbourhood, when necessary (e.g., on-demand or periodically triggered by software). The use of a “virtual sensor node” avoids the necessity of the new sensor node to be physically present within the network and enables to assess the network performance from a remote location, in order to decide about the best location to admit the new sensor node within the network.

#### **4.3.1. Working Principle of the QoS-Based Admission Control Module**

Traditional admission control systems use a signalling protocol to establish bandwidth reservations at all routers along the data path. This approach has to preserve per-flow state and to process per-flow reservation messages at all routers, resulting in limited scalability and high computational complexity. To avoid those problems, the proposed admission control method follows the endpoint admission control approach in the sense that the admission test is made at the edge nodes, and it is made for the entire path from the source to the sink node [138] [139]. In this way, the proposed admission control method avoids the complexity of per-hop schemes without adding any complexity to the network nodes. The admission control is done through a “virtual sensor node” on the network, to mimic the presence of the new real node on its vicinity, and measuring how it affects the QoS provided by the network.

The admission procedure, which is controlled by the network administrator (or who is in charge, hereinafter referred as operator), has the following phases: first the operator selects the type of sensor node to be added to the network and its preferential location in the network; then the operator requests the system to evaluate the network in order to assess its QoS; finally, based on the information retrieved by the system, the operator decides where the node can be admitted to

the network. During the network evaluation phase, the system configures the QoS Probe, running on one of the sensor nodes placed in the location chosen to add the new sensor node, to mimic the presence of the new sensor node. Then, the QoS Probe starts sending a data flow, identical to that which will be generated by the real node, to the sink. Finally, the system analyses the changes in the network's QoS introduced by the new data flow and reports it to the operator that decides where the new sensor node can be admitted to the network. Figure 4.2 shows the probing procedure and all the messages exchanged to assess if the new sensor node can be admitted to the network.

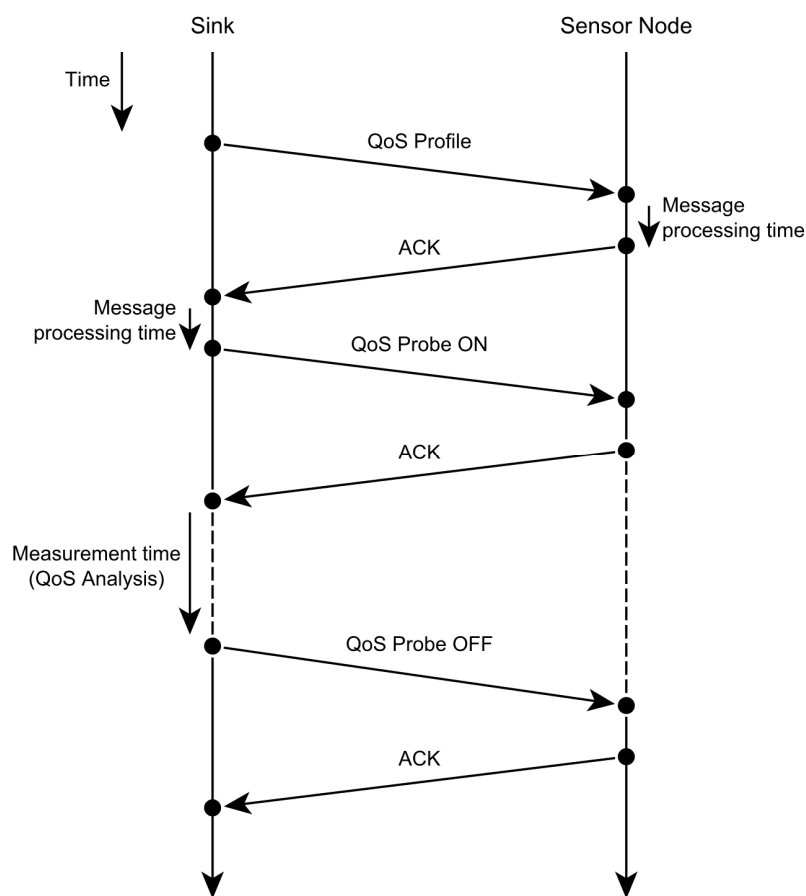


Figure 4.2 – The probing procedure performed to verify if a new node can be admitted by the network.

#### 4.3.2. Developed Software and its Architecture

The software developed to implement the proposed QoS-based network management method, and to run on each node within the BWSN, was built on top of the Contiki OS [140] and follows the architecture presented in the Figure 4.3. The software developed interacts with the Contiki



OS at two levels, namely at the application layer and at the network layer. This architecture facilitates the software portability to other operating systems or to be used with other communication stacks.

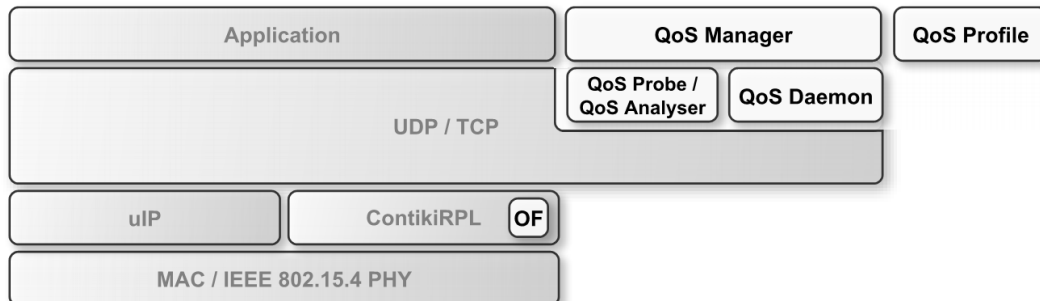


Figure 4.3 – Architecture of the software running on the BWSN's nodes.

The software developed to implement the QoS-based network management method adds the following modules to the base operating system architecture: QoS Manager, QoS Profile, QoS Probe, QoS Analyser and QoS Daemon. The QoS Manager is the interface between the application and the QoS-based network management software. It is responsible to manage the interactions between all the remaining components. The application uses the QoS Manager to receive information about the QoS provided by the network or to trigger actions, such as the admission control procedure. The QoS Profile contains all the relevant information about each data flow including the required QoS. The QoS Probe (i.e., the “virtual sensor node”) runs only on the sensor nodes. It can be configured, on demand, to perform remote tasks. Such tasks include generating specific data flows or collecting information about the node performance (e.g., its radio link quality). The QoS Analyser runs only in the sink node and extracts the relevant information about each data flow to assess the real-time QoS provided by the network and, if necessary, generates alerts to the healthcare information system. Finally, the QoS Daemon is in charge of all the control and signalling communications between the nodes within the BWSN.

#### 4.4. QoS Monitoring Module

The QoS monitoring module collects relevant information about the network's performance and uses it to detect and classify QoS degradation events. Based on this information, reports are generated to inform the network administrator, or who is in-charge, about the network's performance.

The QoS monitoring module analyses the incoming traffic at the sink to extract relevant metrics (e.g., the packet reception ratio) in order to assess the effective QoS provided by the network. Then, such metrics are evaluated using time-domain techniques to detect QoS degradation events. Regarding the QoS degradation events, they can be classified into two categories, defined as:

Hard degradation events: Such events are related to strong and sudden variations on the metrics used to quantify the QoS being provided by the network.

Soft degradation events: Such events are related to soft, however persistent, variations in the metrics used to quantify the QoS being provided by the network.

Hard degradation events may, in some cases, lead to the failure of the static thresholds previously defined for each metric and, consequently, the normal operation of the applications using the network may be affected. On the other hand, soft degradation events do not lead to the failure of the static thresholds previously defined for each metric. Although soft degradation events may not cause the failure of the applications using the network, they must be detected and classified. For instance, a small QoS degradation may lead to a hard degradation event if persisting the necessary time. To prevent such situations, the time-domain analysis is used, not only to compute the actual value of each metric, but also to investigate the dynamic behaviour of each metric.

#### **4.4.1. Time Domain Analysis of the QoS Metrics**

The QoS monitoring module uses a set of pre-defined QoS metrics or constraints to quantify the QoS being provided by the BWSN, as presented in the Figure 2.4. Such QoS metrics can be considered as static or dynamic. Static metrics do not depend on the network operation and are constant along the time (e.g., link capacity). On the other hand, dynamic metrics vary according to network operation and are essential to know the real network status and performance (e.g., end-to-end delay and PRR) [141]. Regarding the dynamic metrics, they can be assessed considering only its current value, or taking into consideration its past behaviour. By taking into consideration its behaviour in the near past, it is possible to assess the metrics in view of its tendency to the near future.

In the following analysis, the dynamic metrics used to assess the QoS provided by the network are seen as time-domain functions. Generically, such metrics can be modelled as:

$$m(t) = m^*(t) + wgn(t), \text{ with } t \geq 0, \quad \text{Eq. 4.1}$$

where  $m(t)$  represents the measured value of the metric,  $m^*(t)$  represents the real value of the metric, and the white Gaussian noise function  $wgn(t)$  represents the metric's variation due to random interferences and the natural fluctuations of the network.

#### **4.4.1.1. Computing the metrics value**

After the setup time, a network tends to be stable and the metrics used to compute the network's QoS can be found stable, despite the small fluctuations that can be observed. Thus, a moving average filter can be used to estimate the value of the metrics used to quantify the QoS provided by the network, cancelling the effect of such small fluctuations. Therefore, consider the following moving average filter:

$$f(g, N, n) = \frac{1}{k} \sum_{i=0}^{k-1} g(n - i), \quad \text{Eq. 4.2}$$

where  $g(\cdot)$  represents the signal to be filtered,  $N$  is the number of observations used in the moving average,  $n$  is the index of the most recent observation of the sample to be processed, and  $k = n$  if  $n < N$  or  $k = N$  in other cases. The use of moving average filters reduces the effects of random instabilities on the metric. Thus, the estimated value of the metric is represented by  $\hat{m}(n)$ , and its value is computed as:

$$\hat{m}(n) = f(m, N, n). \quad \text{Eq. 4.3}$$

The number of observations used to estimate the value of each metric depends both on the network operation and on the deployment environment. As a matter of example, consider a network deployed inside a hostile environment in which the quality of the wireless links can often vary considerably. In such case it is reasonable to use a large number of observations to estimate the metric's value; in other words, it is necessary to analyse the network during the last  $T$  seconds, being  $T$  the time necessary to compute the metric's observations being considered. Therefore, the value of  $N$  must be determined taking into consideration the network typical operation and the target deployment environment.

#### 4.4.1.2. Detecting major variations in the metrics value

The network operation can be affected by both external events (e.g., radio interferences) and internal events (e.g., node dead due to energy depletion). In both circumstances, these events may reflect itself as perturbations in the metrics being used to assess the network's QoS. Detecting such perturbations is of major importance to prevent the degradation of the network's performance.

In such context, the dynamic of the metric is signified by its first derivative and represented by  $\dot{\hat{m}}(n)$ . Therefore, we propose the use of two features to detect major perturbations in the metric's value, namely the energy of  $\dot{\hat{m}}(n)$ :

$$E_{\dot{\hat{m}}}(n) = \sum_{i=0}^{k-1} |\dot{\hat{m}}(n-i)|^2, \quad \text{Eq. 4.4}$$

and an energy threshold dynamically computed as:

$$E_{threshold}(n) = f(E_{\dot{\hat{m}}}, N, n). \quad \text{Eq. 4.5}$$

The perturbations potentially harmful to the network's performance are detected by comparing the actual  $E_{\dot{\hat{m}}}$  against the  $E_{threshold}$ . Thus, a potential harmful perturbation is detected if the actual energy of the metric differentiation is greater than the energy threshold,  $E_{\dot{\hat{m}}} > E_{threshold}$ . In order to quantify the potential degradation caused by harmful perturbations, a Metric Degradation Index (MDI) was defined as:

$$MDI = \lfloor E_{\dot{\hat{m}}} / E_{threshold} \rfloor. \quad \text{Eq. 4.6}$$

The *MDI* gives quantitative information about the change on the metric energy.

After calibration, the *MDI* can be used to detect potential degradation events. The higher the *MDI*, the greater is the potential degradation of the network performance. To calibrate the *MDI*, several approaches can be used, depending on the QoS monitoring strategy. One possibility consists of using the maximum *MDI* achieved during the normal network operation as a threshold to detect degradation events and fire alert messages. Other possibility is using the *MDI*'s mean value achieved during the network normal operation.

#### 4.4.1.3. Detecting small variations in the metrics value

Although useful to detect significant perturbations on the metrics being analysed, the previous analysis is insensitive to small and monotonic metrics variations. In other words, the previous analysis is insensitive to variations resulting in  $E_{\hat{m}} \leq E_{threshold}$ . To detect such small variations three figures-of-merit are used, namely: the Metric Tendency ( $MT$ ), the Zero-Crossing-Rate ( $ZCR$ ), and the classification of the most recent observation of the metric as a Single Global Minimum ( $MIN$ ) or a Single Global Maximum ( $MAX$ ) within the sample being processed.

Let's consider the functions  $h_i, i = 1, \dots, p$ . The product function of these functions  $h_i$  is represented by  $h_1 \cdot h_2 \cdot \dots \cdot h_p(\cdot) = \prod_{i=1}^p h_i(\cdot)$ . In the case of  $h_1 \equiv h_2 \equiv \dots \equiv h_p \equiv h$ , we obtain  $h^p(\cdot) = \prod_{i=1}^p h(\cdot)$ . By  $id$  we denote the identity function.

The  $MT$  can be determined looking to the Slope ( $S$ ) of a linear regression curve obtained using the method of the least squares, as:

$$S_{\hat{m}}(n) = \frac{f(id \cdot \hat{m}, N, n) - f(id, N, n)f(\hat{m}, N, n)}{f(id^2, N, n) - f^2(id, N, n)}. \quad \text{Eq. 4.7}$$

Within the sample being processed, if  $S_{\hat{m}} < 0$  the  $MT_{\hat{m}}$  is to decrease ( $\downarrow$ ), if  $S_{\hat{m}} > 0$  the  $MT_{\hat{m}}$  is to increase ( $\uparrow$ ) and, finally, if  $S_{\hat{m}} = 0$  the  $MT_{\hat{m}}$  is to be constant ( $\rightarrow$ ).

On its turn, the  $ZCR$  feature is defined as:

$$ZCR_{\hat{m}}(n) = \frac{1}{2k} \sum_{i=0}^{k-1} \left| \text{sgn}(\dot{\hat{m}}(n-i)) - \text{sgn}(\dot{\hat{m}}(n-1-i)) \right|, \quad \text{Eq. 4.8}$$

where  $\text{sgn}$  is the sign function.

Finally, to verify if the observation  $\hat{m}(n)$  is a single global minimum or a single global maximum, within the sample being processed, the following expressions are used, respectively:

$$MIN_{\hat{m}}(n) = \begin{cases} 1, & \hat{m}(i) > \hat{m}(n), \forall i \in \{n-k+1, n-1\} \\ 0, & \text{in other cases} \end{cases}, \quad \text{Eq. 4.9}$$

and

$$MAX_{\hat{m}}(n) = \begin{cases} 1, & \hat{m}(i) < \hat{m}(n), \forall i \in \{n-k+1, n-1\} \\ 0, & \text{in other cases} \end{cases}. \quad \text{Eq. 4.10}$$

The filter's order (i.e., the length of the sample being processed) used to compute the previous figures-of-merit depend on the QoS monitoring policy in use. Considering a small value of  $N$ , the QoS monitoring system becomes very sensitive and reactive. In opposition, a QoS monitoring system less reactive must use a higher  $N$  value. Nevertheless, it is necessary to find equilibrium between the filter's order and the desired reactivity of the QoS monitoring system.

By using these three figures-of-merit it is possible to detect small and monotonic variations, over the sample being processed, on the metric being analysed. By detecting such situations, corrective measures can be taken to prevent the further degradation of the QoS provided by the network.

#### 4.4.2. QoS Assessment and Network Performance Classification

Considering the classification presented in [142], the QoS metrics used to assess the network's performance can be sorted into two sets: those that need to be maximised, denoted as  $m_{max}$  and, the remaining that need to be minimised  $m_{min}$ . Based on this classification, and using the features previously presented, it is possible to analyse the performance of the network and classify suspicious events.

The network performance assessment and classification if the QoS metric belongs to  $m_{max}$ , is analysed using the criteria presented in the Table 4.1, resulting in the following rule to detect Performance Degradation (PD):

$$PD_{max} = (\hat{m} < 0 \text{ and } E_{\hat{m}} > E_{threshold}) \text{ or } \{(\hat{m} < 0 \text{ and } S_{\hat{m}} < 0) \text{ and } (ZCR_{\hat{m}} = 0 \text{ or } MIN_{\hat{m}} = 1)\} \quad \text{Eq. 4.11}$$

Table 4.1 – Network performance assessment and classification if QoS metric belongs to  $m_{max}$ .

$\hat{m}$	$E_{\hat{m}}$	$MT_{\hat{m}}$	$ZCR_{\hat{m}}$	$MIN_{\hat{m}}$	Network performance	Example
$< 0$	$\leq E_{threshold}$	$\downarrow$	$> 0$	1	degrading	Figure 4.4 a)
$< 0$	$\leq E_{threshold}$	$\downarrow$	$> 0$	0	not degrading or recovering	Figure 4.4 b)
$< 0$	$\leq E_{threshold}$	$\downarrow$	$= 0$	<i>n.a.</i>	degrading	Figure 4.4 c)
$< 0$	$\leq E_{threshold}$	$\rightarrow \text{ or } \uparrow$	<i>n.a.</i>	<i>n.a.</i>	not degrading	Figure 4.4 d)
$< 0$	$> E_{threshold}$	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>	degrading	Figure 4.4 e)
$\geq 0$	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>	not degrading	Figure 4.4 f)

Figure 4.4 shows typical patterns detected using the rules presented in the Table 4.1. By using those rules, QoS degradation is detected when the patterns of figures Figure 4.4 a), c) and e)

appear. On the contrary, the patterns of Figure 4.4 b), d) and f) indicate that the network is working as required; therefore no QoS degradation is detected. As a matter of example, consider the patterns presented in the Figure 4.4 a) and b), in both cases the metric is slightly fluctuating and decreasing (i.e., the metric tendency (MT) is to decrease and the ZCR is greater than zero). The difference between those two patterns is detected by looking to the value of the metric at the time that the metric is being assessed (i.e., at  $t = n$ ). In the case of the Figure 4.4 a), the value of the metric is a global minimum and the metric is considered to be degrading. On the contrary, in the case of the Figure 4.4 b), the value of the metric is not a global minimum and the metric is considered to be recovering from a short-time and negligible diminution of its value.

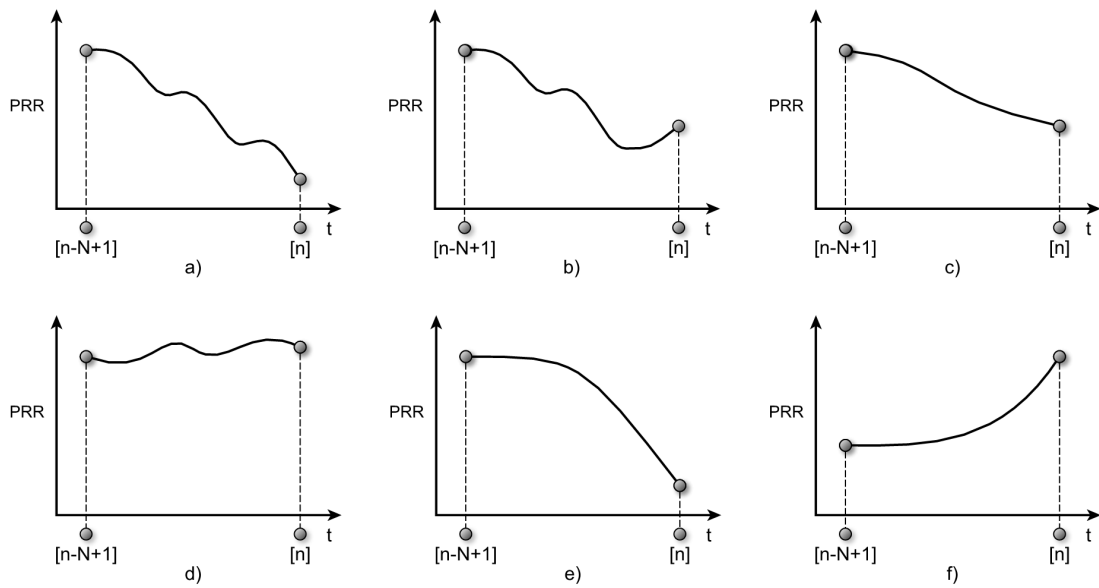


Figure 4.4 – Some examples of patterns detected using the rules presented in the Table 4.1.

On the other hand, if the QoS metric belongs to  $m_{min}$ , the rule to detect PD, derived from Table 4.2, is:

$$PD_{min} = (\dot{m} > 0 \text{ and } E_{\dot{m}} > E_{threshold}) \text{ or } \{(\dot{m} > 0 \text{ and } S_{\dot{m}} > 0) \text{ and } (ZCR_{\dot{m}} = 0 \text{ or } MAX_{\dot{m}} = 1)\} \quad \text{Eq. 4.12}$$

Table 4.2 – Network performance assessment and classification if QoS metric belongs to  $m_{min}$ .

$\dot{m}$	$E_{\dot{m}}$	$MT_{\dot{m}}$	$ZCR_{\dot{m}}$	$MAX_{\dot{m}}$	Network performance	Example
$> 0$	$\leq E_{threshold}$	$\uparrow$	$> 0$	1	degrading	Figure 4.5 a)
$> 0$	$\leq E_{threshold}$	$\uparrow$	$> 0$	0	not degrading or recovering	Figure 4.5 b)
$> 0$	$\leq E_{threshold}$	$\uparrow$	$= 0$	<i>n.a.</i>	degrading	Figure 4.5 c)
$> 0$	$\leq E_{threshold}$	$\rightarrow \text{ or } \downarrow$	<i>n.a.</i>	<i>n.a.</i>	not degrading	Figure 4.5 d)
$> 0$	$> E_{threshold}$	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>	degrading	Figure 4.5 e)
$\leq 0$	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>	not degrading	Figure 4.5 f)

Figure 4.5 shows representative patterns detected using the rules presented in the Table 4.2. Using those rules it is possible to detect QoS degradation when the patterns of figures Figure 4.4 a), c) and e) appear. On the contrary, the patterns of Figure 4.4 b), d) and f) indicate that the network is working well; therefore no QoS degradation is observed. As a matter of example, consider the patterns presented in the Figure 4.5 a) and b), in both cases the metric is slightly fluctuating and increasing (i.e., the metric tendency (MT) is to increase and the ZCR is greater than zero). The difference between those two patterns is detected by looking to the value of the metric at the time that the metric is being analysed (i.e., at  $t = n$ ). In the case of the Figure 4.5 a), the value of the metric is a global maximum and the metric is considered to be degrading. On the contrary, in the case of the Figure 4.5 b), the value of the metric is not a global maximum and the metric is considered to be recovering from a short-time and negligible growth of its value.

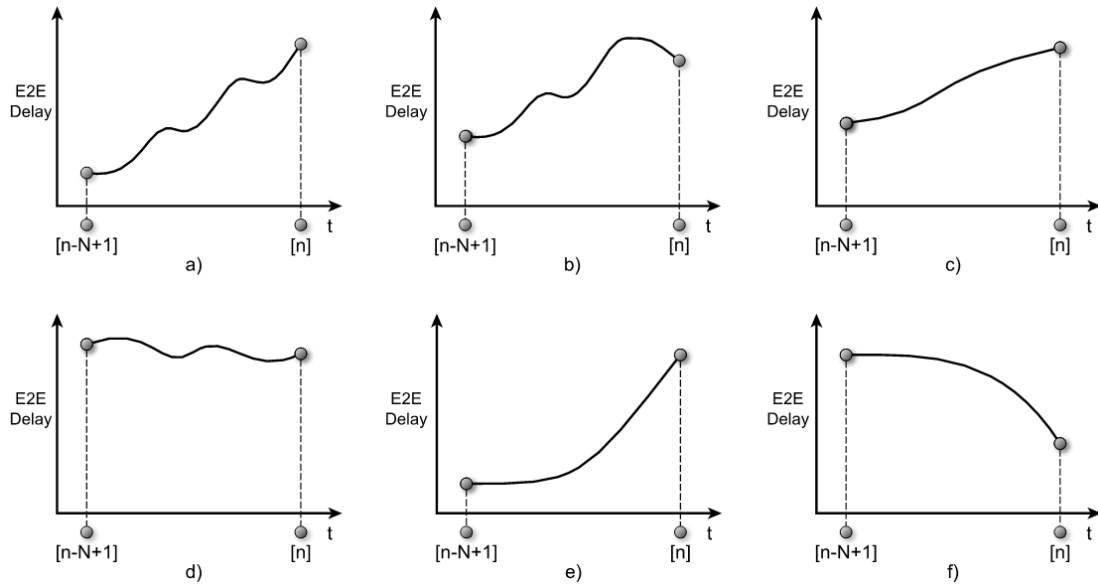


Figure 4.5 – Some examples of patterns detected using the rules presented in the Table 4.2.

By using the rules presented in the Table 4.1 and Table 4.2, it is possible to detect and classify potential QoS degradation events. Consequently, this information can be used to inform the network administrator to take measures to mitigate the degradation of the network performance.

#### 4.5. QoS-Based Network Management Method Assessment

To assess the suggested QoS-based network management method, a case study considering a typical BWSN was simulated. Network simulators are widely used to evaluate and compare the performance of WSNs. Their use has advantages and disadvantages. Despite they are an



approximation to the reality (e.g., by using oversimplified channel models), they allow easy and network deployments, controllable and flexible scenarios and the repeatability of the results obtained. On the other hand, real-world deployments avoid problems relating to simplification of models, but such network deployments are more expensive and considerably harder to implement and deploy. However, despite its complexity, real-world deployments represent a great driving force in order to ensure the users' acceptance of WSN in general and of BWSNs in particular.

Bearing in mind the above, the proposed QoS-based network management method was tested taking advantage of these two realities. The simulated environment was used during the development stage to rapidly assess the method and make adjustments whenever required. The simulated environment was based on the cross layer emulation and simulation tool known as COOJA [143]. COOJA is a flexible WSNs hardware emulator and network simulator designed to simulate WSNs running the Contiki OS [140].

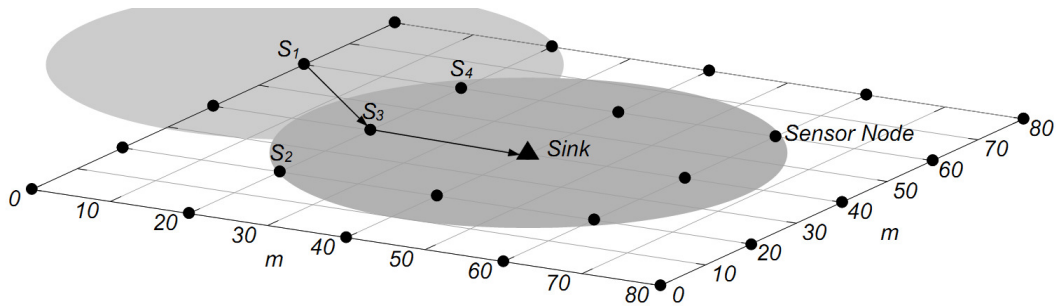


Figure 4.6 – Network deployment. The sensor nodes are regularly distributed over an 80 m x 80 m area. Each node has a radio range of 30 m. The sink is at position (40, 40).

Facing the impossibility to simulate all the possible situations regarding a patient monitoring system deployed in a real hospital environment, the scenario presented in the Figure 4.6 was envisioned to assess the proposed QoS-based network management method. Such scenario aims to recreate the spatial location of 24 patients being monitored within a hospital floor. In such context, to maximise the covered area and, at the same time, minimise the probability of collisions and the effect of funnelling to the sink, the BWSN was regularly deployed in a square area [144], as pictured in the Figure 4.6.

The 25 nodes (i.e., 1 sink and 24 sensor nodes, one for each patient) have a radio range of 30 m and, after the network setup time, which is of about 60 s, each sensor node starts sending

data packets at a specific rate. See Table 4.3 for a detailed description of both the network and the simulation configurations.

Table 4.3 – Network, application, and simulation configurations.

<b>Network:</b>	
Deployment Area (m)	80 x 80
Deployment Type	5 x 5 grid (see Figure 4.6)
Number of Nodes	1 sink and 24 sensor nodes
Sink Position (m)	(40, 40)
Radio Range (m)	30
Radio Model	Unit Disk Graph Medium Distance Loss
Network Layer	IPv6 with 6LowPAN
Transport Layer	User Datagram Protocol (UDP) [145]
Routing Protocol	RPL with the MRHOF [146]
Logical Topology	Random
PRR Required	98%, 91%
<b>Application:</b>	
Task Type	Time driven
Data Length (byte)	< 70 (one packet)
Reporting Interval (s)	1, 2
<b>Simulation:</b>	
Time (s)	1000

To evaluate the proposed QoS-based network management method, several simulations were made and the corresponding results analysed. The evaluation consists of two parts. First, the QoS monitoring module is used to detect and classify potential harmful events relating to QoS degradation. Then, the admission control module is used to verify if a new sensor node can be admitted by the network in the requested area. In both scenarios the PRR is taken as a figure-of-merit to evaluate the QoS provided by the network. The PRR was defined as:

$$PRR = \frac{1}{M} \sum_{i=1}^M \frac{R_i}{S_i}, \quad \text{Eq. 4.13}$$

where  $M$  is the number of sensor nodes on the network,  $R_i$  is the number of data packets received by the sink from the sensor node  $i$ , and  $S_i$  is the number of data packets sent by the sensor node  $i$ .

#### 4.5.1. QoS Monitoring Module Assessment

Regarding the QoS monitoring module, it was tested in order to evaluate its capacity to detect not only small and monotonic variations in the PRR (i.e., the metric being used to assess the QoS

provided by the network), able to cause QoS degradation in the long term, but also sudden variations in the PRR potentially dangerous for QoS.

Figure 4.7 shows the PRR and its first derivative when the network was running on its normal operation. When comparing the Figure 4.7 with the Figure 4.8 it was possible to verify that, by using the features and rules of the Table 4.1, the QoS monitoring module is able to detect and classify different suspicious events related to the QoS degradation.

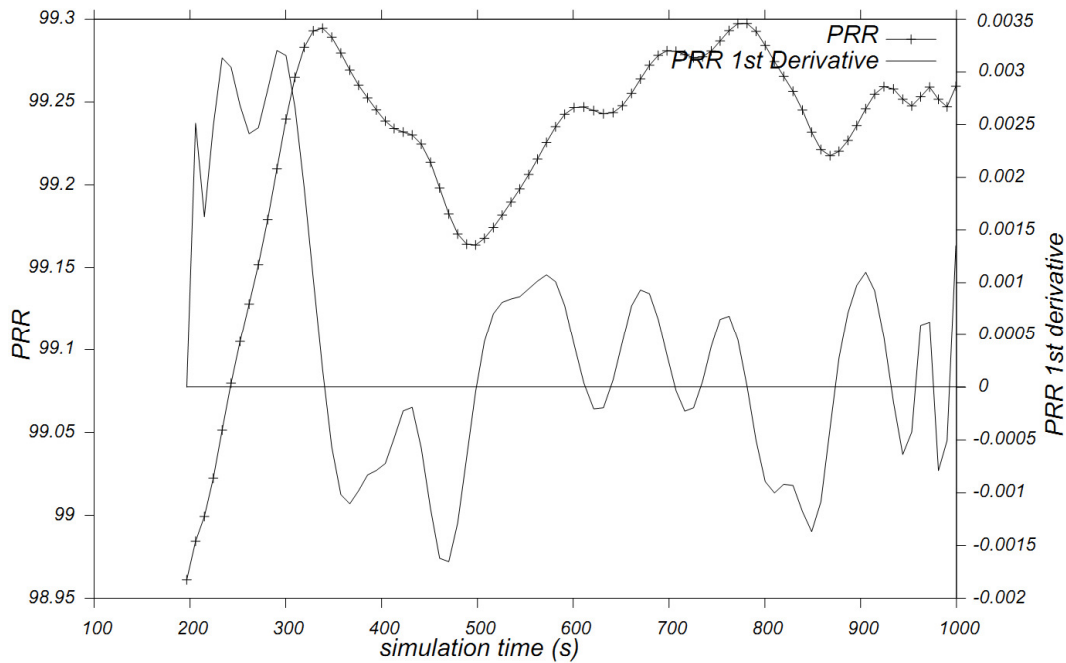


Figure 4.7 – PRR of the network in its normal operation. The PRR dynamics is represented with its first derivative.

A detailed observation of Figure 4.8 permits to verify (around 440 s and 490 s) that using both information about the PRR dynamics and the previous defined figures-of-merit (i.e., the figures-of-merit defined in the Table 4.1), the QoS monitoring module was able to detect slight and monotonic variations in the PRR. Moreover, if we look carefully to the PRR presented in the Figure 4.7 and compare its shape with the patterns presented in the Figure 4.4, it is possible to verify that the QoS degradation events are detected when the patterns shown in Figure 4.4 a) and c) are detected. Concerning the detection and classification of potentially harmful QoS degradation events using the energy feature (i.e., by detecting the pattern presented in the Figure 4.4 e)), it is important to notice that small values of the MDI correspond to small variations on the metric being analysed.

To verify how the QoS monitoring module responds to external interferences, such as radio interferences or link degradation, variations were introduced on the Unit Disk Graph Medium Distance Loss (UDGM-DL) radio model, used within the COOJA simulator. The UDGM-DL is a wireless channel model where the transmission range is modelled as an ideal disk. The sensor nodes outside this disk don't receive packets. The sensor nodes inside the disk receive packets accordingly a probability that depends on several parameters, according to the following equation:  $P = Tx - Tx(d^2/d_{max}^2)(1 - Rx)$ , where  $Tx$  represents the probability of a node to successfully transmit a packet, the  $Rx$  is the probability of a node to successfully receive a packet,  $d$  is the distance between the two sensor nodes, and  $d_{max}$  is the maximum transmission range. The external interferences were simulated by changing the  $Rx$  and  $Tx$  probabilities of the UDGM-DL radio model as shown in the Table 4.4.

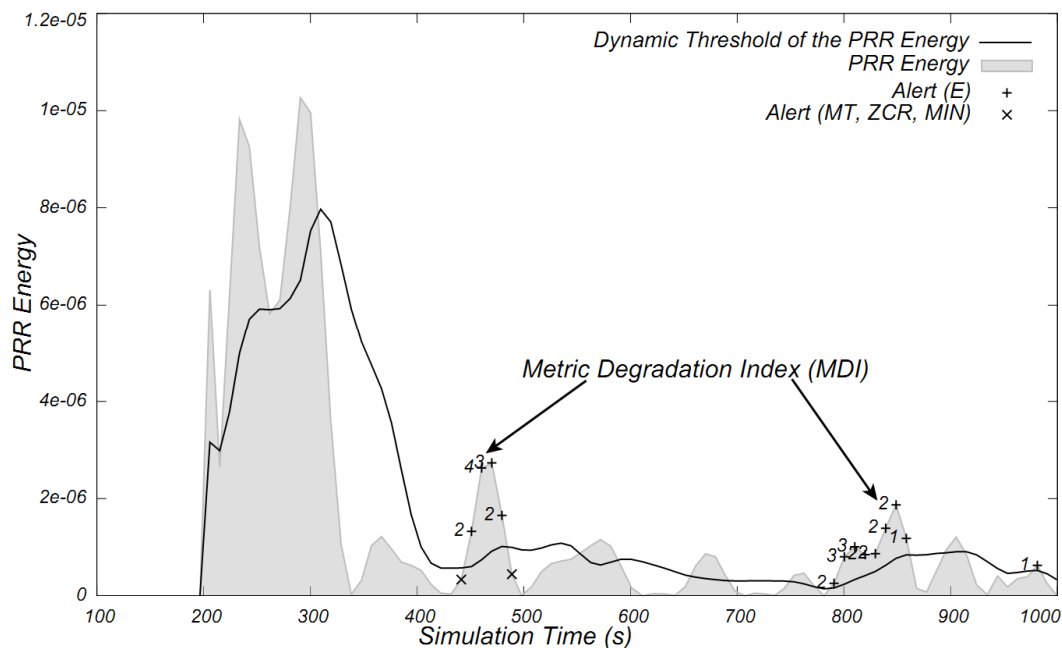


Figure 4.8 – PRR energy and its dynamic threshold. It is possible to see the QoS degradation alerts and it's MDI.

Table 4.4 – UDGM-DL radio model used to simulate radio interferences, see Figure 4.9.

Simulation time on the Figure 4.9 (s)	0	400	500	600	700	800	900
Tx and Rx success ratio (%)	100	75	100	50	75	80	100

In order to introduce selectivity on the detection of significant degradation events, and at the same time avoid alarm fatigue due to over-alarming, a threshold was introduced in the MDI. In this way, the maximum MDI value obtained during the normal network operation (i.e.,  $MDI = 4$ )

was used as a minimum limit to detect a degradation event and fire the corresponding alarm. In other words, degradation events are detected and fired if the MDI exceeds the value used to calibrate the QoS monitoring system. In addition, a real application of the proposed method can introduce other mechanisms to improve selectivity.

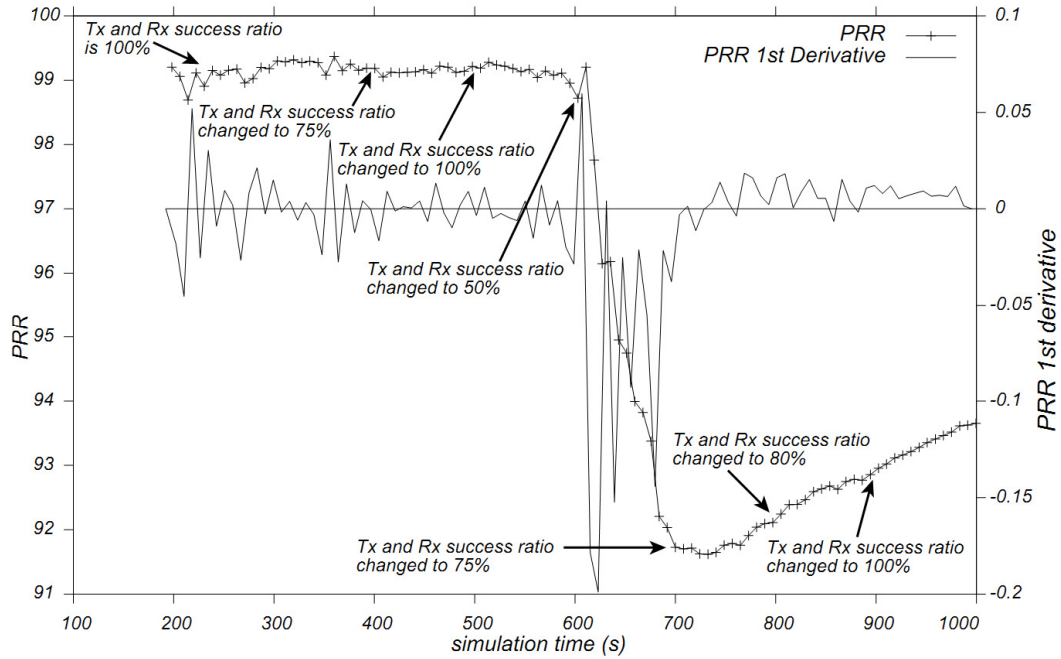


Figure 4.9 – PRR of the network exposed to a hostile environment in terms of the radio channel with interferences as indicated in the Table 4.4. The PRR dynamics is represented with its first derivative.

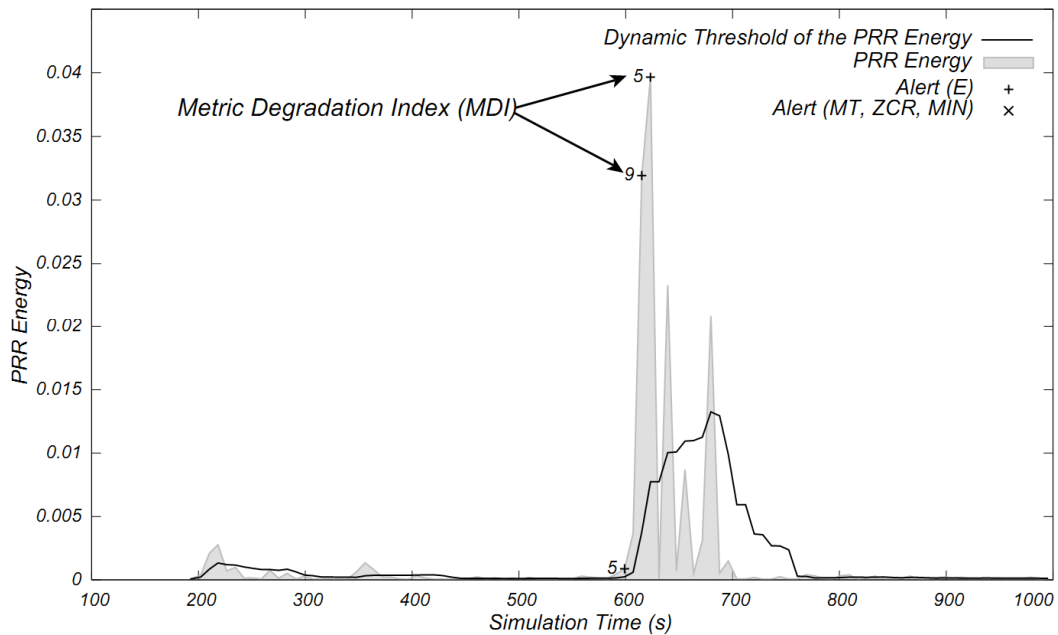


Figure 4.10 – PRR energy and its dynamic threshold. It is possible to see the QoS degradation alerts and its MDI. Comparing with the Figure 4.8, it is possible to confirm that higher MDI greater is the degradation of the network performance.

The Figure 4.9 shows that the radio interferences introduced in the simulation produced a strong degradation in the PRR and consequently in the QoS provided by the network. Analysing the Figure 4.9, and comparing it with the Figure 4.10, it is possible to confirm that the QoS monitoring module detected the QoS degradation at its very beginning. More, from these results it is possible to confirm that high values of the  $MDI$  suggest that the metric being analysed will suffer a strong degradation. Comparing the Figure 4.8 (i.e., the network normal operation) with the Figure 4.10 (i.e., the network suffering a strong perturbation), it is possible to confirm that the higher  $MDI$  the greater is the degradation of the network performance.

By detecting the QoS degradation events at its beginning, the QoS monitoring module can also be used to fire messages informing the network manager about the possible QoS degradation. On its turn, the network manager can take measures to mitigate the effects of the QoS degradation even before it takes critical values.

In addition to the present analysis, the proposed method can be used to assess the performance of each individual node within the network. This possibility, while requiring additional computational power and memory, allows obtaining additional information about the network performance. In particular, monitoring individual nodes is crucial to identify the source of the performance degradation events, which is impossible when analysing the overall performance of the network.

#### **4.5.2. QoS-Based Admission Control Module Assessment**

To test the admission control module, the aforementioned probing procedure was used to evaluate if a new sensor node can be admitted to the network in the place under test. The probing procedure starts on request (e.g., by a healthcare professional) and stops when one of the following conditions is observed: the metric value crosses a pre-established limit or the metric tendency (to increase or decrease) is interrupted, in other words  $S_{\hat{m}} \geq 0$  for the metrics belonging to  $m_{max}$ , and  $S_{\hat{m}} \leq 0$  for the metrics belonging to  $m_{min}$ . Nevertheless, if none of these conditions occur, the probing procedure ends after a pre-established timeout.

Regarding the evaluation of the admission control module, two scenarios were considered. For the first, each sensor node within the network was set to generate constant bit rate traffic of about 0.5 packets per second, where the network is considered uncongested and able to admit a new sensor node while maintaining a PRR of, at least, 98%. In the second scenario, the sensor

nodes were set to send one data packet per second to the network, and it has to fulfil a PRR of, at least, 91%. Herein, the network is congested and unable to admit a new sensor node while maintaining the requested QoS.

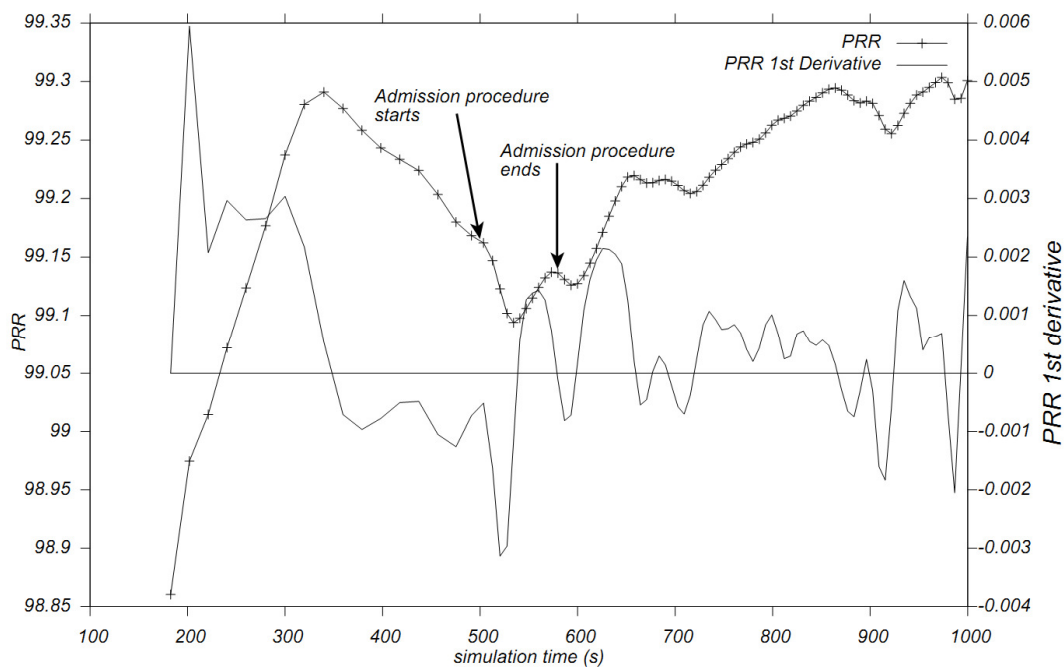


Figure 4.11 – PRR of the uncongested network during the admission control procedure (QoS Probe ON) and its derivative. The probe procedure ends when  $S_{\hat{m}} \geq 0$  at 590 s.

For the uncongested network, analysing the Figure 4.11 allows to withdraw the results summarised in the Table 4.5. The admission control procedure starts at simulation time around 500 s and lasts until the  $S_{\hat{m}} \geq 0$ , which happens at simulation time around 590 s, as shown in the Figure 4.11. At the end of the admission control procedure, the admission control module computes the PRR that is taken as an estimation of the PRR if the real sensor node was added to the network. Since the QoS Probe does not introduce the same effects (e.g., radio interference) on the network as a real sensor node, this estimation is considered as the upper limit of the real PRR. The PRR estimated to be off about 99.14%, i.e., greater than the pre-established limit of 98%, and the decision about the admission of the new node is positive.

Table 4.5 – Results obtained from the admission control procedure after a measurement time of about 90 s, see Figure 4.11. It's possible to conclude that the PRR of the uncongested network with the new node will be, on the best, of about 99.14%.

Beginning of the admission procedure	End of admission procedure	PRR at the beginning of the admission procedure	PRR at the end of the admission procedure	Measurement time
500 (s)	590 (s)	99.16 %	99.14 %	90 (s)

After the admission control procedure, the new sensor node was added to the network. Then the network was evaluated and the PRR depicted in the Figure 4.12 was obtained. Such results ratify the estimation obtained with the admission control procedure, showing that the new sensor node can be added to the network, without degradation the PRR below the pre-established limit of about 98%.

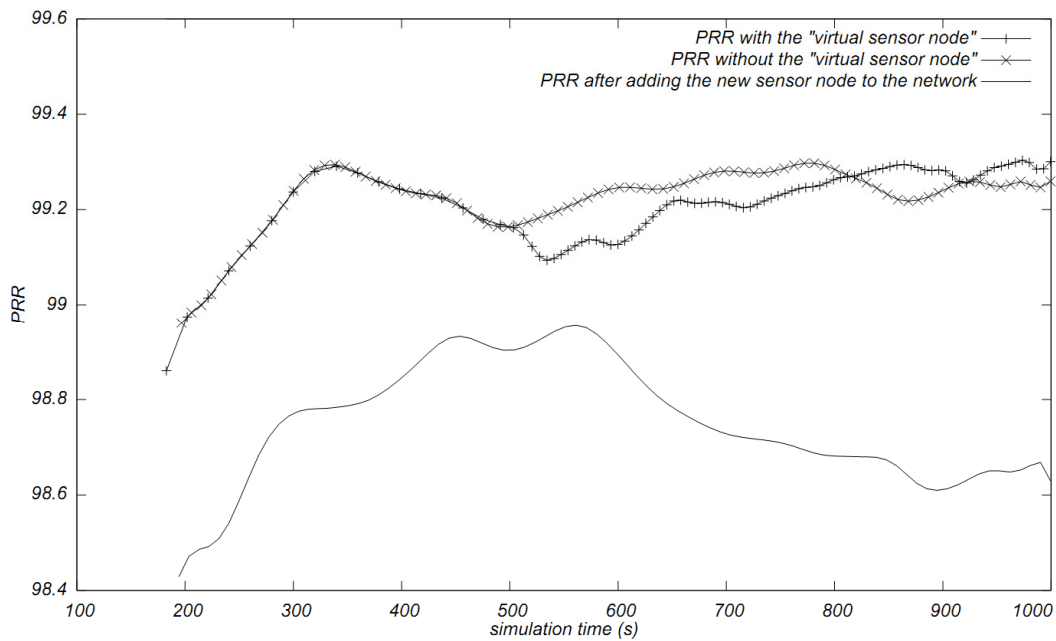


Figure 4.12 – PRR of the uncongested network in its normal operation, with the “virtual sensor node, and after adding the new sensor node to the network.

Regarding the evaluation of the admission procedure in the scenario of a congested network, the results achieved are summarised in the Table 4.6. The admission control procedure starts at simulation time of about 400 s and lasts until  $PRR \leq 91\%$ , which happens at simulation time of about 600 s, as shown in the Figure 4.13. Here, the proposed admission control procedure was able to predict that the congested network was unable to accommodate the new node. In that case the PRR estimated drops below the pre-established limit of 91 % and the decision to admit the new node is negative.

Table 4.6 – Results obtained from the admission control procedure, after a measurement time of about 200 s, see Figure 4.13. It is possible to conclude that the PRR of the congested network with the new node will be less than the pre-established limit of about 91%.

<b>Beginning of the admission procedure</b>	<b>End of the admission procedure</b>	<b>PRR at the beginning of the admission procedure</b>	<b>PRR at the end of the admission procedure</b>	<b>Measurement time</b>
400 (s)	600 (s)	92.07 %	91 %	200 (s)



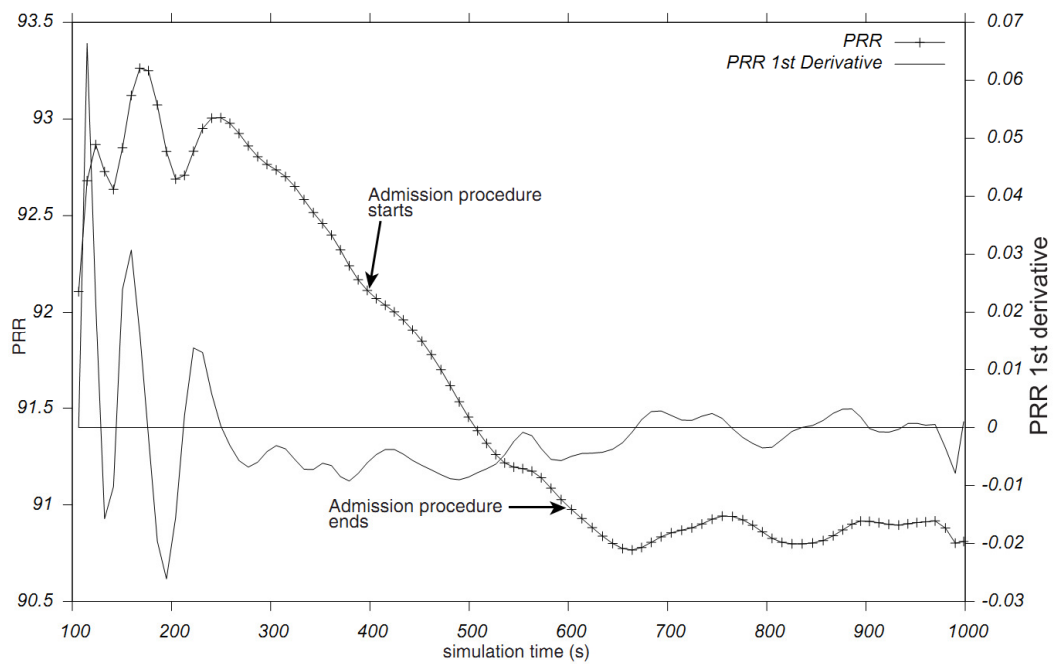


Figure 4.13 – The PRR of the congested network during the admission control procedure (i.e., with the QoS Probe ON) and its first derivative. The probe procedure ends when the  $PRR \leq 91\%$  at 600 s.

As it was done in the previous experiment, the new sensor node was added to the network. Then, the network was evaluated to validate the values previously estimated and, consequently, to assess the decision that was made. The Figure 4.14 shows the results obtained. Such results confirm the estimation presented in the Table 4.6 and confirm that the new sensor node cannot be added to the network without degrading the PRR below the pre-established limit of about 91%.

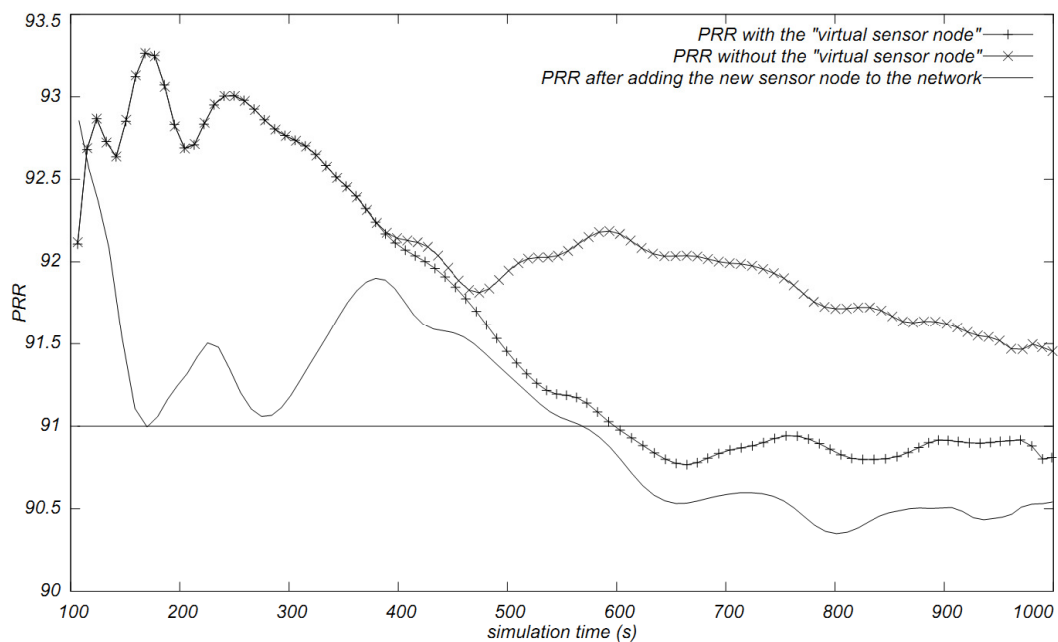


Figure 4.14 – PRR of the congested network in its normal operation, with the “virtual sensor node”, and after adding the new sensor node to the network.

### **4.5.3. Discussion**

During the development stage, several experiments were simulated to assess and, if necessary, to adjust the proposed QoS-based network management method. The experiments just described are the result of a continuous process of development and, in that way, they are representative of the entire development process. Considering the assessment of the QoS monitoring module, these experiments represent two types of situations, i.e., the detection and classification of both small QoS degradation events and strong QoS degradation events. On its turn, regarding the assessment of the QoS-based admission control module, the experiments just described show how to use the admission control module to verify if a new sensor node can be admitted by both an uncongested network and a congested network.

In view of the results obtained from the previous simulations, it is possible to argue that the QoS monitoring module is able to detect and classify suspicious events regarding the degradation of the QoS provided by the network. Moreover, by using not only the metric value but also its dynamic, the QoS monitoring module is able to detect and classify QoS degradation events even before the metric reaches critical values. By using this ability, the QoS monitoring system can be used to fire advertising messages to the network manager informing about the potential QoS degradation event. On its turn, the network manager can take measures to mitigate the effects of such events, preventing the performance of the network from degrading. Regarding the QoS-based admission control module, it can be used to assess if the network can admit a new sensor node, i.e., a new patient being monitored. By using a “virtual sensor node” to mimic the presence of the new real sensor node on its neighbourhood while assessing the network, the proposed admission control method is able to test the network even from a remote location. In this way, the proposed QoS-based network management system allows to monitor and manage the network from a centralised location, which is an important feature regarding patient monitoring scenarios in hospital facilities or nursing homes.

In view of these results, the QoS-based network management method was considered ready to be evaluated in a real-world environment.

#### 4.6. Setting the Limit of the Connected Region in Low Power Wireless Links

After the previous evaluation of the proposed QoS-based network management method, it is necessary to find the conditions under which the proposed method can be used in real-world environments, as the one presented in the succeeding chapter.

One of the key tenders of this work is that a “virtual sensor node” can simulate the presence of a real sensor node placed on its neighbourhood. In this way, the scenarios represented in the Figure 4.15 may be considered equivalent. Taking into consideration the envisioned scenario (i.e., a set of nursing rooms inside a hospital, as pictured in the Figure 4.1) to use the proposed method, the Figure 4.15 illustrates the first-hop communications, counting from the sensor nodes to the sink.

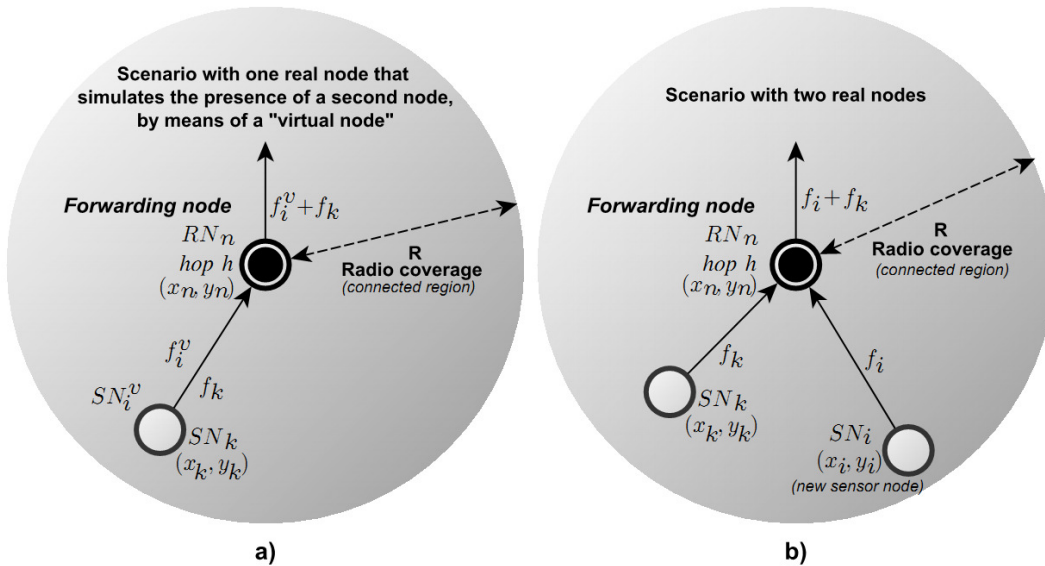


Figure 4.15 – a) A real sensor node simulating the presence of a new sensor node, and b) the new sensor node already within the network.

To mimic the behaviour of the real sensor node, the “virtual sensor node” has to generate data traffic with the same characteristics as the one generated by the real sensor node. To clarify the proposed idea, let’s consider the Figure 4.15. The left side scenario shown in the Figure 4.15 (i.e., the Figure 4.15 a)) represents a real sensor node (i.e., the  $SN_k$ ) and a “virtual sensor node” (i.e., the  $SN_i^v$ ) created by the  $SN_k$ , the latter simulating the presence of a new sensor node on its neighbourhood. Each one of these two sensor nodes generate its own data flow, the  $SN_k$  generates the data flow  $f_k$  and the  $SN_i^v$  generates the data flow  $f_i^v$ . In turn, the scenario represented in the right side of the Figure 4.15 (i.e., the Figure 4.15 b)) portrays the initial

scenario in which the virtual sensor node was replaced by the real sensor node (i.e., the  $SN_i$ ). Our proposal is that, if the data flow  $f_i^v$  has the same characteristics of the data flow  $f_i$ , then, those scenarios can be considered equivalent.

Looking to the Figure 4.15, one of the principal differences between the two scenarios presented is the different location of the sensor nodes  $SN_i^v$  and  $SN_i$ . As a consequence, the data flows  $f_i^v$  and  $f_i$  may reach the  $RN_n$  with different delivery probabilities (n.b., the signal strength decays exponentially with respect to the distance between the nodes that are communicating. Moreover, for a given distance  $d$ , the signal strength is randomly distributed among the mean distance dependent value [147]). However, some studies suggest that sensor nodes that are geographically close to each other may have high spatial correlation in their PRRs [12]. Moreover, several experimental studies, considering real-world deployments, performed during the last few years have shown that wireless links can be found in one of three regions, namely connected, transitional, and disconnected [12] [147] [148]. The links within the connected region are often of good quality, stable and symmetric. On the other hand, the links in the transitional region are of intermediate quality (n.b., considering a long-term evaluation), unstable, not correlated with the distance between the transmitter and the receiver, and a lot asymmetric. Finally, within the disconnected region, the links have poor quality and are inadequate to support communications [12]. In view of these outcomes it is possible to make the following observations to support the proposed method:

- 1 - Sensor nodes within the connected region have high PRRs, and;
- 2 - Sensor nodes geographically close to each other may have high spatial correlation in their PRRs.

Therefore, the scenarios presented in the Figure 4.15 can be considered equivalent if both the “virtual sensor node” (i.e., the  $SN_i^v$ ) and the new real sensor node (i.e., the  $SN_i$ ) are located inside of the connected region. In this way, it is of extreme importance to find the limits of the transitional region.

The authors of [147] have identified the causes of the transitional region and have quantified their influence in the network performance. Indeed, they have derived not only expressions for the Packet Reception Ratio (PRR) as a function of the distance between the transmitter and the receiver, but also expressions to find the limits of the transitional region. Furthermore, such

expressions show how the radio parameters (i.e., the modulation, the encoding, the output power at the transmitter, the noise floor, and the noise at the receiver), and the environmental parameters (i.e., the path loss exponent, the log-normal shadow variance, and the noise floor) influence the length of the transitional region. Bearing those parameters in mind, the transmitter output power is of utmost importance. It can be easily used to tune the limits of the transitional region to the needs of each specific application, taking into consideration the particular characteristics of each environment and the network deployment area. More insights about how the transmitter output power impact the beginning of the transitional region can be found in [12] [147] [148].

In view of the scenarios presented in the Figure 4.1 and Figure 4.15, the connected region must have about 5 m in length around the receiver node (i.e., considering the dimensions of typical nursing rooms). In other words, the beginning of the transitional region must be at 5 m from the receiver. Moreover, considering the severe QoS requirements imposed to BWSNs a lower limit of 90 % was imposed to the PRR inside the connected region (n.b., this value can be adjusted according to the needs of each particular application). Thus, it is necessary to find the minimum transmitter output power necessary to fulfil those requirements.

In the following, the model presented in [147] will be used to find the minimum output power at the transmitter necessary to achieve the desired length for the connected region, considering the PRR limit imposed by the application. Then, in order to fundament the proposed method, it will be analysed at two levels. First, at the node level, the effects of positioning the sensor nodes at different locations were investigated in view of single-hop communications. In particular, at the first hop counting from the sensor node to the sink. Then, the effects of having different delivery probabilities at single-hop communications are studied at the network level, i.e., considering multi-hop communications. Our analyse does not consider sensor nodes mobility nor dynamic objects inside the deployment environment, and the channel conditions for each wireless link are considered to be constant along the time, or at least during significant time intervals.

#### **4.6.1. Finding the Output Power Necessary to Achieve the Required Connected Region**

In the following we assume NRZ encoding and consider noncoherent FSK modulation scheme used in TelosB motes [149]. This analysis uses the log-normal shadowing path loss model [150]

and the outcomes presented in [147] to find the minimum transmitting power,  $P_t$ , necessary to achieve a connected region with a radius of 5 m. The parameters used to model the indoor environment are: path loss exponent  $\eta = 3$ ; standard deviation  $\sigma = 4$ ; power decay at reference distance  $d_0$ ,  $PL(d_0) = 55$  dB; noise floor  $P_n = -105$  dBm; and the size of the frames used to communicate is  $f = 70$  bytes.

Let us bound the connected region to PRRs greater than 0.9 and the transitional region to PRRs between 0.9 and 0.1. From the theoretical model deduced in [147], we obtain the following SNR values for PRRs of 0.1 and 0.9,  $\gamma_{L \text{ dB}}$  and  $\gamma_{U \text{ dB}}$ , respectively,

$$\gamma_{L \text{ dB}} = 10 \log_{10} \left( -1.28 \ln \left( 2 \left( 1 - 0.1^{\frac{1}{8f}} \right) \right) \right) \approx 7.9 \text{ dB}, \quad \text{Eq. 4.14}$$

$$\gamma_{U \text{ dB}} = 10 \log_{10} \left( -1.28 \ln \left( 2 \left( 1 - 0.9^{\frac{1}{8f}} \right) \right) \right) \approx 10.0 \text{ dB}, \quad \text{Eq. 4.15}$$

and we have

$$P_t = P_n + \gamma_U + PL(d_0) + 2\sigma + 10\eta \log_{10} d_s \approx -11 \text{ dBm} \quad \text{Eq. 4.16}$$

for the minimum transmitting power necessary to achieve the necessary length for the connected region. In the following sections we analyse if a “virtual sensor node” can simulate the presence of a real sensor node placed in the connected region of 5 m in length.

#### 4.6.2. Analysing the Virtual Sensor Node's PRR Considering Single-hop Communications

Consider the scenario presented in the Figure 4.15. To obtain the maximum difference between the PRR achieved by both the virtual data flow  $f_i^V$  and the real data flow  $f_i$ , considering only first-hop (i.e., the link between the  $SN_i^V$ , or the  $SN_i$ , and the  $RN_n$ ), we use the equation of PRR at a transmitter-receiver distance  $d$  obtained in [147]:

$$p(d) = \left( 1 - \frac{1}{2} \exp \left( -\frac{\gamma(d)}{1.28} \right) \right)^{8f}, \quad \text{Eq. 4.17}$$

where  $\gamma(d)_{\text{dB}} = P_{t \text{ dB}} - PL(d)_{\text{dB}} - P_{n \text{ dB}}$ ,  $PL(d)_{\text{dB}} = P_{t \text{ dB}} - P_{r \text{ dB}}$ , and  $P_{r \text{ dB}}$  is the received signal strength at a given distance  $d$  from the transmitter. From [150] we have  $PL(d) = PL(d_0) + 10\eta \log_{10}(d/d_0) + X_{0,\sigma}$ , where  $X_{0,\sigma}$  is a zero-mean Gaussian random variable (in dB) with the standard deviation  $\sigma$  (shadowing effects). First, we obtain a relationship

between  $p(d_{i,n})$  and  $p(d_{i,n} + \Delta d_{i,n})$  for an increment  $\Delta d_{i,n}$  at the distance  $d_{i,n}$  between  $SN_i$  and  $RN_n$ . Using the Taylor's theorem for the case  $n = 1$  at the point  $d_{i,n}$ , we have:

$$p(d) = p(d_{i,n}) + \dot{p}(d_{i,n})\Delta d_{i,n} + R_{i,n}, \quad \text{Eq. 4.18}$$

where  $R_{i,n}$  is the remainder term. By properties of (1) we can state that the remainder term  $R_{i,n}$  is residual in the interval  $]0, 5]$  and (2) with  $R_{i,n} = 0$  is a good linear approximation to (1) on  $]0, 5]$ . Then, we have  $p(d_{i,n} + \Delta d_{i,n}) - p(d_{i,n}) = \dot{p}(d_{i,n})\Delta d_{i,n}$ , where

$$\dot{p}(d_{i,n}) = -\frac{8f\alpha\beta\eta}{2.56d_{i,n}} \left(1 - \frac{\alpha}{2}\right)^{8f-1}, \quad \text{Eq. 4.19}$$

$\alpha = \exp(-\beta/1.28)$  and  $\beta = 10^{(P_t - PL(d_0) - 10\eta \log_{10}(d_{i,n}) - P_n)/10} = 10^{3.9 - 3\log_{10}(d_{i,n})}$ . Since (3) is a decreasing non-positive function we obtain that  $\max_{d_{i,n} \in ]0, 5]} |\dot{p}(d_{i,n})| = |\dot{p}(5)|$ . Thus, we obtain  $|\dot{p}(d_{i,n})| \leq 2.3 \times 10^{-18}$ . Therefore, since  $\Delta d_{i,n} \in ]0, 5]$ , we have  $|p(d_{i,n} + \Delta d_{i,n}) - p(d_{i,n})| \leq 1.2 \times 10^{-17} \approx 0$  in the connected region of 5 m in length. Thus, the difference between the PRR achieved by both the virtual data flow  $f_i^v$  and the real data flow  $f_i$ , considering only first-hop, is approximately equal to zero.

#### 4.6.3. Analysing the Virtual Sensor Node's PRR Considering Multi-hop Communications

Rather than single-hop communications, typical BWSNs have multiple hops between the source sensor nodes and the sink. In fact, they may have not only several hops between those nodes but also several paths to route the data gathered by the sensor nodes to the sink. In that way, two sensor nodes can send their data to the sink using distinct data paths, each one having a particular PRR associated. In our proposal we consider that the data flow  $f_i^v$ , generated by the "virtual sensor node"  $SN_i^v$  of the Figure 4.15 a), follows the best path to reach the sink (n.b., the rule to find the best path depend on the routing protocol in use). Moreover, the sensor node  $SN_i$  will use the same path to send its data to the sink. In other words, we are assuming that both the "virtual sensor node",  $SN_i^v$ , and the real sensor node,  $SN_i$ , use the same data path to send their data to the sink. In this way, the PRR associated with the path between the  $RN_n$  and the sink is the same for both data flows. Additionally, as it was shown in the last subsection, the PRRs achieved by both the virtual data flow  $f_i^v$  and the real data flow  $f_i$  at the first hop are similar.

Consequently, it is possible to argue that the PRRs of both data flows, for the entire path (i.e., from the sensor node until the sink) are equivalent.

In summary, our proposal is that a “virtual sensor node” can produce the same effect in the performance of a WSN, when compared with a real sensor node, if both sensor nodes produce data with the same characteristics, both data flows follow the same path to the sink, and they are within the connected region experiencing the same radio conditions.

#### 4.6.4. Experimental Validation

On the basis of the previous requirements, the experiment described in the Figure 4.16 was performed to assess the model used in the sections 4.6.1 and 4.6.2.

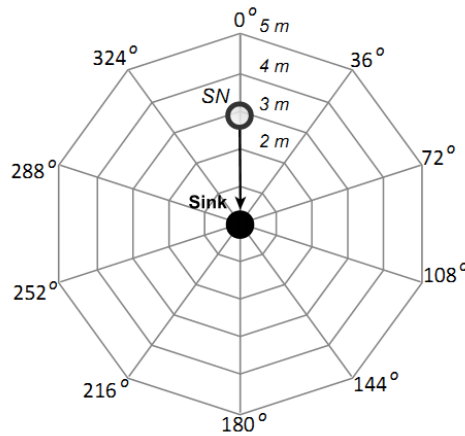


Figure 4.16 – Experiment performed to find the minimum transmitter output power needed to have at least a PRR of about 90 % inside a region of 5 m around the receiver (i.e., inside the connected region).

The experiment is as follows: inside a typical deployment area (n.b., the experiment was performed using an environment designed to recreate the conditions inside a nursing room), with fixed obstacles and metal furniture, a sink node and a sensor node were used to measure the PRR at different distances between the two nodes and for several angles all around the receiver as pictured in the Figure 4.16, in order to find the minimum transmitter output power to achieve a PRR of, at least, 90 % inside the connected region and set the beginning of the transitional region to 5 m from the transmitter. The PRR for each pair (distance, angle) was calculated after the sensor node had sent five hundreds messages to the receiver.

The Figure 4.17 shows the results obtained when assessing the PRR for different distances between the sender sensor node and the receiver. In that case the transmitter output power was set to  $-25\text{ dBm}$ . The results obtained show that for a distance of 2 m between the source



sensor node and the receiver (i.e., the Figure 4.17 a)), the PRR fits within the pre-established limit of 90%. However, when changing the distance between the sender and the receiver to 3 m (i.e., the Figure 4.17 b)) the PRR for an angle of  $72^\circ$  between the sender and the sink is of about 85 % which is beyond the pre-established limit of 90 %. So, it is possible to conclude that the transmitter output power must be greater than  $-25 \text{ dBm}$  in order to fulfil the required PRR.

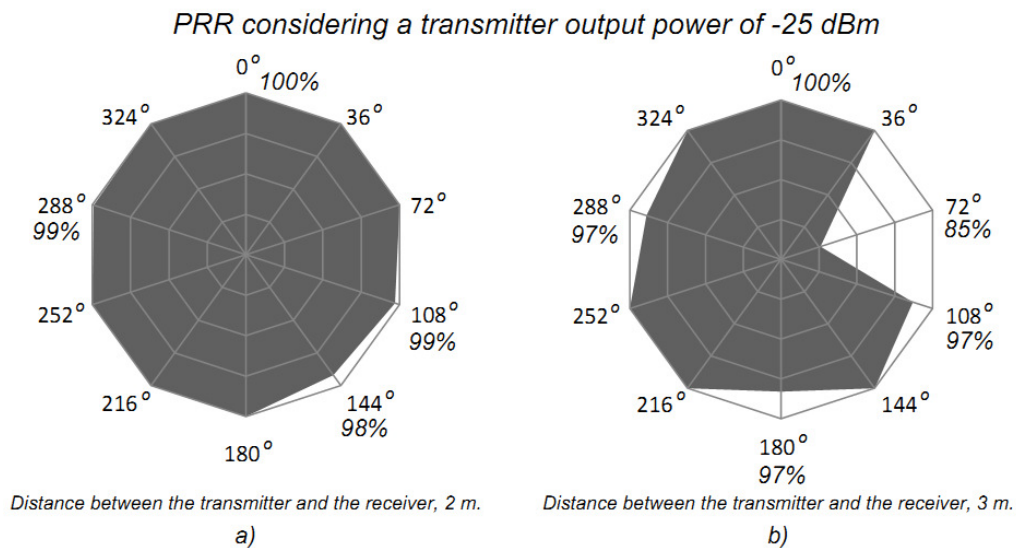


Figure 4.17 – PRR for an output power of  $-25 \text{ dBm}$  at the transmitter, for distances of 2 and 3 meters between the transmitter and the receiver.

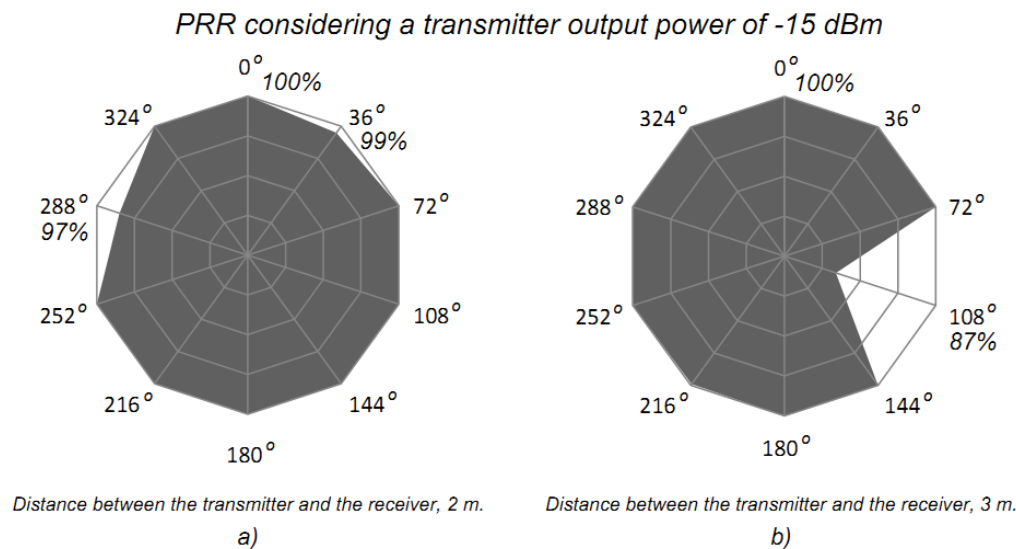


Figure 4.18 – PRR for an output power of  $-15 \text{ dBm}$  at the transmitter, for distances of 2 and 3 meters between the transmitter and the receiver.

Proceeding with the experiment, the output power of the sender sensor node was changed to  $-15 \text{ dBm}$  and the experiment repeated. The Figure 4.18 shows the results obtained. Analysing

the Figure 4.18 b) it is possible to verify that the PRR for an angle of  $108^\circ$ , between the sender and the sink, is of about 87%, which is lower than the pre-established limit of 90%. Consequently, an output power of  $-15 \text{ dBm}$  at the sender is insufficient to achieve a connected region of about 5 m with the desired characteristics.

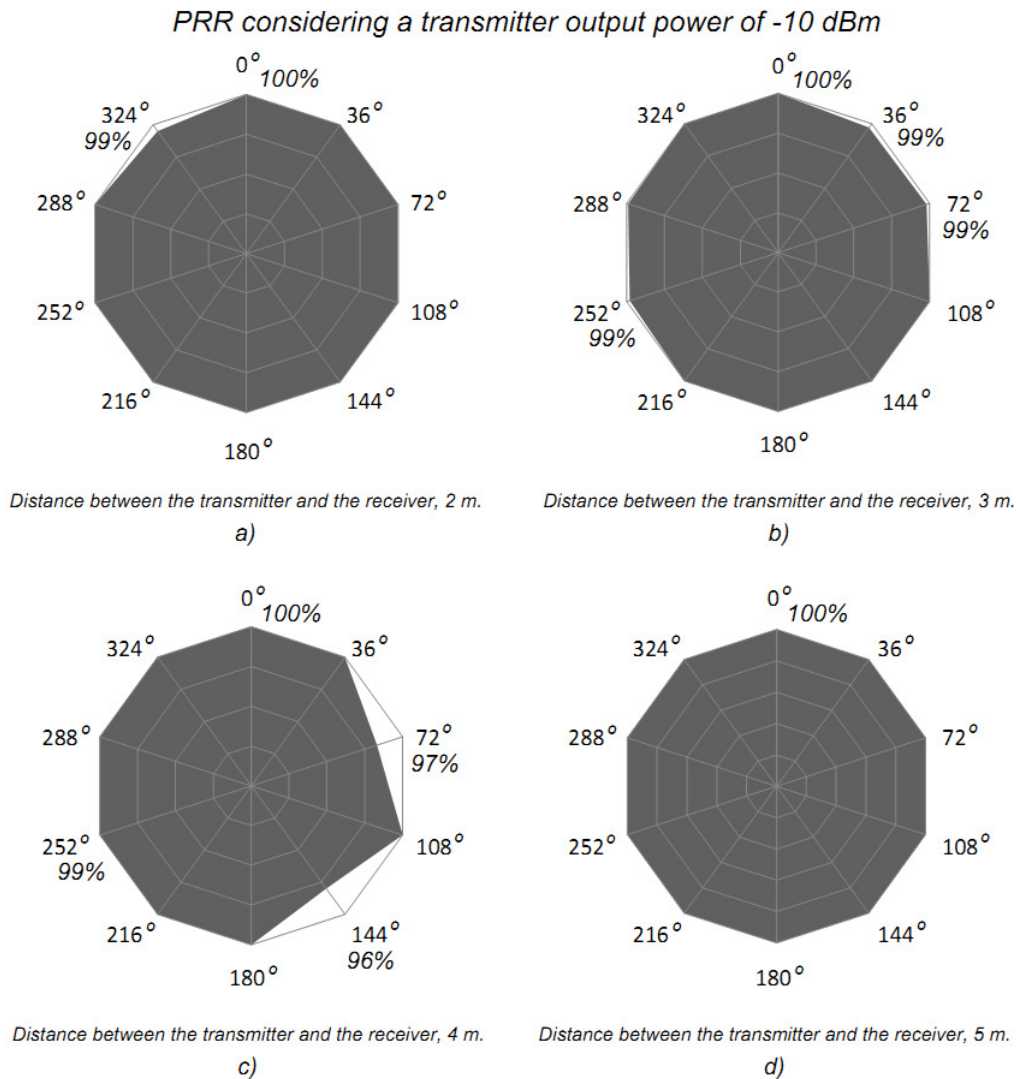


Figure 4.19 – PRR for an output power of  $-10 \text{ dBm}$  at the transmitter, for distances of 2, 3, 4 and 5 meters between the transmitter and the receiver.

The Figure 4.19 shows the results obtained when repeating the previous experiment considering an output power of  $-10 \text{ dBm}$  at the sender. From the results, it is possible to see that the PRR for all the tested distances (i.e., distances of 2, 3, 4 and 5 meters between the sender and the sink), all around the sink, is always greater than the pre-established threshold of 90%. Therefore, it is possible to argue that the minimum output power at the transmitter necessary to achieve a connected region of 5 m in length is  $-10 \text{ dBm}$ , as predict in the section 4.6.1 by the analytic

model. It is important to notice that these results depend on each specific environment and network deployment area. Consequently, these results must be tuned for each network deployment.

#### **4.7. Summary**

This chapter presented the proposed QoS-based network management method, its application scenario, and some experiments performed during the development stage to assess it.

The proposed QoS-based network management method is composed by two modules: the QoS-based admission control module and the QoS monitoring module. The QoS-based admission control module uses the concept of “virtual sensor node” to estimate the impact of adding new sensor nodes to the BWSN and thereby assess the network about its ability to accommodate a new sensor node while maintaining the QoS required by all the applications using the BWSN. On its turn, the QoS monitoring system uses a mathematical framework to detect and classify potential degradation events.

Since its presentation, the QoS-based network management method was carefully tested. In view of the results obtained not only from several simulations performed during the development stage, but also from analytic and experimental analysis regarding the quality of low power wireless links, it is possible to argue that the proposed method can be used both to estimate the impact of adding new sensor nodes to the network and to detect and classify potential QoS degradation events.

Finally, have been defined the conditions under which the proposed method can be used in real-world environments.



# **Method Assessment in a Real Hospital Environment**

## Real-World Assessment

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### 5.1 Preliminary Findings and Initial Deployment

#### 5.1.1 Preliminary Findings

#### 5.1.2 Initial Deployment

### 5.2 QoS-Based Admission Control Module Assessment

#### 5.2.1 Network Deployment Area Covering One Nursing Room

#### 5.2.2 Network Deployment Area Covering Two Nursing Rooms

#### 5.2.3 Network Deployment Area Covering Three Nursing Rooms

#### 5.2.4 Discussion

### 5.3 Summary

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## **5. Method Assessment in a Real Hospital Environment**

The proposed QoS-based network management method was carefully tested during the development stage using different approaches, namely: simulated environments, probabilistic models, and empiric experiments. Although these tests may be considered sufficient to validate the QoS monitoring module (n.b., the QoS monitoring module operation depends only on the metric behaviour, rather than on the network deployment environment), they are insufficient to validate the QoS-based admission control module. Therefore, the QoS-based admission control module was evaluated in a real hospital environment.

The remainder of this chapter describes not only the real-world experiments performed to evaluate the QoS-based admission control module, but also their preparation. The experiments were made in a small-sized hospital situated in Esposende, a small city near Braga, Portugal; the hospital is known as "*Hospital Valentim Ribeiro*".

### **5.1. Preliminary Findings and Initial Deployment**

The deployment of BWSNs in real-world environments is a challenging task even to engineers with high levels of expertise in BWSNs systems. Moreover, when harsh environments are at stake, such as hospital facilities or nursing homes, the difficulties to get BWSNs working properly worsens. Hence, each real-world BWSN deployment must be carefully designed not merely according to the demands of each target application, but also considering the particular characteristics of each deployment area.

#### **5.1.1. Preliminary Findings**

Based on the knowledge obtained from this particular deployment, it is possible to argue that each real-world deployment is unique. More, it is strictly necessary to study and understand the intrinsic characteristics of each deployment site, namely those that can compromise the quality of the wireless channel, such as: attenuation of the radio signal caused by metallic furniture, interferences caused by other medical equipment's, and other negative effects caused by peoples' routines (e.g., staff shifts or visiting times). Such study is vital to design a suitable network deployment strategy in order to achieve the required performance.

Regarding the deployment scenario used to evaluate the proposed QoS-based admission control method, the following procedure was made in order to understand the intrinsic characteristics of the network deployment site. First, information was collected about the use made of the network deployment area. Second, an inspection was made to identify other radio communication infrastructures (e.g., an IEEE802.11 network) existing on the network deployment area. Third, an examination was made to find hospital furniture and/or medical equipment able to cause attenuation/interferences in the radio signals (e.g., fading due to multipath or due to shadowing from obstacles). Finally, information was requested about the hospital staff shifts and about the visiting schedule.

It is important to emphasise that the research team had no control on the environment conditions, or on the use of any hospital/medical equipment, during the field tests. All the tests were made under the supervision of the hospital staff.

The area used to perform the field tests (i.e., the shaded area presented in the Figure 5.1) has a nursing desk and three nursing rooms in which low-acuity patients stay for a period that, typically, do not exceed eight days. Those nursing rooms are not private, if necessary two or three patients can share the same room.

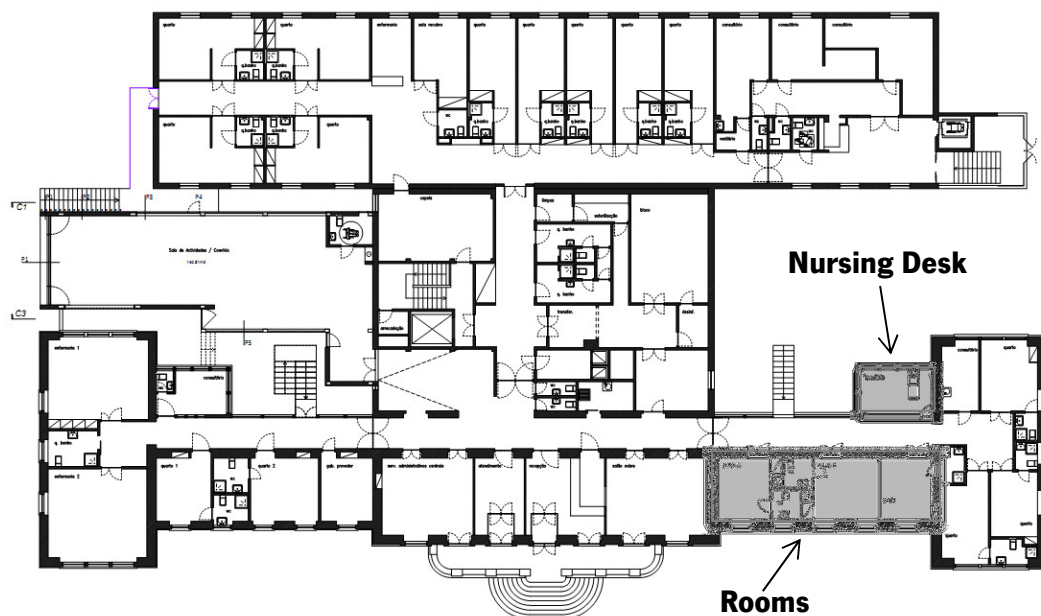


Figure 5.1 – Floor plan of the *Hospital Valentim Ribeiro*. The shaded areas show the nursing rooms and the nursing desk used to deploy the BWSN.



From our survey, it was found that the deployment area does not have any other wireless communication technology. Instead, the information system uses a wired communication infrastructure. Therefore, it was not necessary to perform any tests to study the radio activity on the deployment area. When other wireless communication technologies are detected, it is necessary to study the coexistence of both technologies, as explained by JeongGil Ko in [151].

Concerning the signal propagation and electromagnetic interferences (or any other effect able to deteriorate the radio signal), neither the hospital furniture nor the medical equipment found in the deployment area is susceptible of causing significant damages to the radio channel. On its turn, the staff daily routines can be classified as regular concerning the normal activities of a non-acute hospital area. So, on this particular deployment area, the radio signal propagation is affected only by the building structure (e.g., walls, corridors or steel doors) and by the human bodies present on the site. During the field tests the average amount of people inside of the network deployment area, simultaneously, did not exceeded a dozen. So, the network deployment area can be considered as having low density of people.

### **5.1.2. Initial Deployment**

After the preliminary study just described, it was necessary to design the network deployment strategy. First, the network physical topology was defined. Following the strategy proposed by the MEDiSN project [2] [49], the solution adopted makes use of a backbone of Relay Nodes (RNs) and several Sensor Nodes (SNs), defining a tree topology as represented in the in Figure 5.2. As explained by the authors of the MEDiSN project, the backbone is used both to form a bidirectional link to the Sink and to ensure the required network coverage. Moreover, the use of a backbone has several benefits. It allows expanding the network, both to improve its performance (e.g., by carefully placing more RNs in the same area) and to increase the network coverage (i.e., improving the network scalability).

Since the nursing staff will use information retrieved by the proposed QoS-based admission control method to make a decision about the best location to place the patients, the natural location to place the sink is the nursing desk, so it can be connected to the computer running the frontend interface of the network management system. The backbone contains two RNs strategic placed to ensure good connectivity inside the nursing rooms three and four. On its turn, the SNs inside the nursing room five can connect directly to the sink.

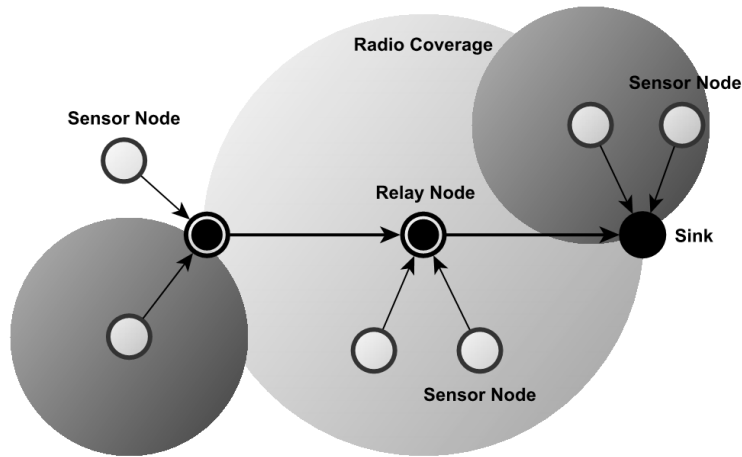


Figure 5.2 – The network topology makes use of a backbone of relay nodes to ensure the necessary coverage and to route the data packets to the sink.

Figure 5.3 shows the deployment of both the sink and the backbone (n.b., the links between the RNs within the backbone and between the RNs and the sink are merely for example purposes. In reality, the backbone is self-organized).

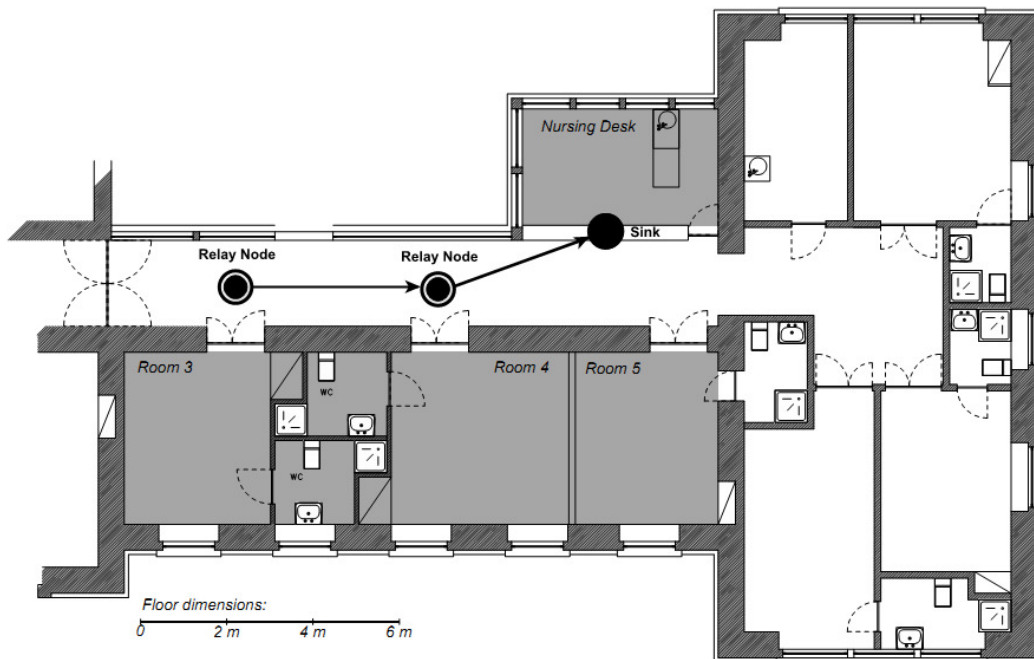


Figure 5.3 – Initial deployment, showing the relay nodes forming a backbone to the sink.

Several tests were made in order to determine the best spots to set up the RNs, while ensuring both the necessary network coverage and the required network performance. To assess the network's performance the end-to-end PRR was used as figure-of-merit. Based on the tests performed the RNs were deployed as shown in the Figure 5.3. After deploying the RNs backbone, the BWSN became fully functional and ready to admit the patients, i.e. the sensor nodes.

## 5.2. QoS-Based Admission Control Module Assessment

In the following all the experiments performed to evaluate the QoS-based admission control module are explained in detail, in particular the use of a “virtual sensor node” to mimic the presence of a new real sensor node within the network.

The evaluation procedure was made in three distinct scenarios, according to the number of nursing rooms used and patients being monitored. By using different nursing rooms, it was possible to assess the proposed method taking into account the impact of the hospital structure (e.g., granite walls, corridors and doors) on the propagation of the radio signals and, consequently, on the network performance. On its turn, the use of several patients makes the experiments closer to reality, assessing the suggested method under realistic conditions.

In the first scenario, no more than three patients were monitored while sharing the same nursing room (i.e., the room 4 from Figure 5.3). This scenario was designed to assess the proposed method without interferences from patients being monitored in the neighbourhood and, at the same time, experiencing the minimum impact from the deployment environment. By using this scenario, the proposed method will be used to assess the impact of adding a new patient to the network.

Then, in the second scenario, a maximum of five patients were monitored while distributed by two non-adjacent nursing rooms (i.e., the rooms 3 and 4, separated by two bathrooms, as pictured in the Figure 5.3). This scenario was designed to assess the suggested QoS-based admission control method under interferences from patients being monitored in the neighbourhood of the “virtual sensor node”. Moreover, this scenario is also useful to study the impact of using the proposed method, on the patients being monitored in the neighbourhood of the “virtual sensor node”.

Finally, in the third scenario, a maximum of five patients were monitored while distributed by three nursing rooms (i.e., the rooms 3, 4, and 5 from Figure 5.3). This scenario was designed to evaluate the impact of the building structure when using the proposed method. All these scenarios were designed with the purpose to verify the following hypothesis:

**Hypothesis:** Adding a “virtual sensor node” to a BWSN produces an equivalent impact in the network's performance, when comparing with the addition

H. 5.1

of a new real sensor node.

If this hypothesis was confirmed, the proposed QoS-based admission control module can be used to answer the following questions:

- Which is the impact of adding a new patient to a BWSN, in the QoS being provided to the patients already within the network?
- Which is the best location to add a new patient to a BWSN, while minimising its impact in the QoS being provided by the network?

In such context, all the experiments were performed under the following assumptions:

- The term patient is only a nomenclature used to improve the understanding of the experiments. In reality, they are represented by the sensor nodes;
- The physiologic data are generated by the sensor nodes;
- The mobility of the sensor nodes is very limited and unable to cause changes in the network topology (i.e., in both the physical and logical topologies).

Table 5.1 – Application and network level configurations common to all the experiments.

<b>Application:</b>	
Operating System	Contiki OS
Task type	Time driven
Data length	70 bytes (per packet)
Data reporting interval	500 ms
QoS-probe reporting interval	500 ms
<b>Network:</b>	
Number of sinks	1
Number of relay nodes	2
Number of sensor nodes	3, 4, 5 (depending on the scenario being assessed)
Transmission power	0 dBm (in both, the sink and the RNs), -7 dBm or -10 dBm (in the SNs)
Network Layer	IPv6 with 6LowPAN
Transport Layer	UDP
Routing protocol	RPL – DIO minimum interval 65 s and DIO maximum interval 70 minutes
<b>Experiments:</b>	
Time	Between 90 and 120 minutes

Regarding the patient monitoring application used to perform the experiments, its purpose is to monitor three vital signs (i.e., temperature, heart rate, and respiratory rate) and the oxygen saturation (SpO<sub>2</sub>). To do so, each sensor node generates data traffic according to the

characteristics of each one of these signals, resulting in an aggregated data rate of about 1 kbps, considering the reference values of the Table 3.4. For a detailed description of the application and network configurations see Table 5.1.

Regarding the results obtained from the experiments, they were analysed considering not only all the stages of the admission control procedure, but also the results obtained when adding the new real sensor node to the BWSN. Regarding the admission control procedure, it can be divided into two different time intervals: the time interval from the beginning of the experiment until the instant when the QoS Probe is turned ON, denoted as:  $t \in ]0, t_{\text{QoS Probe ON}}]$ ; and the time interval in which the QoS Probe is sending data packets to the sink, denoted as:  $t \in ]t_{\text{QoS Probe ON}}, t_{\text{QoS Probe OFF}}]$ . After the admission control procedure, it is possible to identify two more important time intervals, namely: the time interval between the end of the admission procedure and the instant when the new real sensor node is admitted to the BWSN, denoted as:  $t \in ]t_{\text{QoS Probe OFF}}, t_{\text{New SN ON}}]$ ; and the time interval in which the new real sensor node is sending data packets to the sink, denoted as:  $t \in ]t_{\text{New SN ON}}, t_{\text{New SN OFF}}]$ .

As it was done when assessing the proposed QoS-based admission control module using simulated environments, as described in the chapter 4, the PRR is taken as figure-of-merit to evaluate the QoS provided by the network. The PRR of each sensor node was defined as:

$$PRR_i = \frac{R_i}{S_i}, \quad \text{Eq. 5.1}$$

where the  $PRR_i$  is the PRR of the sensor node  $SN_i$ ,  $R_i$  is the number of data packets received by the sink from the  $SN_i$ , and  $S_i$  is the number of data packets sent by the  $SN_i$ .

### 5.2.1. Network Deployment Area Covering One Nursing Room

This scenario, i.e., monitoring a maximum of three patients sharing the same nursing room, was designed to verify if the proposed QoS-based admission control module could be used to answer the following question:

**Question:** Is it possible to use the concept of “virtual sensor node” to estimate the QoS impact of adding a new patient to a BWSN, considering that all the sensor nodes share the same physical space? Q. 5.1

Seeking the answer for this question, the following scenario, comprising two patients being monitored while sharing the same physical space (i.e., the same nursing room), was designed.

In such case, the proposed QoS-based admission control method can be used to investigate the impact of adding a third patient to the BWSN, while sharing the same physical space with the other two patients, in the QoS being provided by the network. Finally, considering the results retrieved by the QoS-based admission control module, it is possible to decide whether the new patient can be added to that nursing room or, in the contrary, the new patient must be placed in a different nursing room.

Several experiments were performed in the context of this scenario. Among all the performed experiments, the following two were chosen to be analysed. These experiments were chosen to be analysed due to the different paths used by the QoS probe to send its data to the sink. The first experiment shows a BWSN in which all the sensor nodes send their data packets to the sink through the  $RN_1$ , as pictured in the Figure 5.4. In such case, all the sensor nodes are using the same wireless link to communicate with the sink, consequently, the wireless link can become saturated and the addition of a new sensor node to the network can result in a substantial degradation of the QoS being provided by the network. On its turn, in the second experiment, the data packets reach the sink following two distinct paths, since one sensor node sends its data packets to the sink through the  $RN_1$  and the other sensor node is directly connected to the sink as depicted in the Figure 5.9. In such case, the communications links are less congested and the addition of a new sensor node to the BWSN has less impact in the QoS being provided by the network, when comparing with the previous network logical topology. The following discussion analyses the results obtained when assessing this scenario considering the network logical topologies just described.

#### ***5.2.1.1. Using the same data path to route the data to the sink***

Considering this particular scenario, and the network logical topology represented in the Figure 5.4 and Table 5.2, the results obtained by using the proposed admission control method to assess the BWSN and decide if a new patient can be added to it are presented in the Figure 5.5, Figure 5.6, Figure 5.7, and Figure 5.8. To facilitate its analysis and discussion, such results are summarised in the Table 5.3. It is important to highlight that, regarding this particular experiment, the network was under the influence of external interferences during the admission

control procedure, as pictured in the Figure 5.5, Figure 5.6, and Figure 5.7. Such interferences were related with the presence of an abnormal number of persons in the corridors due to the visiting schedule, the lunchtime and the cleaning staff. The results presented in the Table 5.3 were obtained after removing the effect of such interferences.

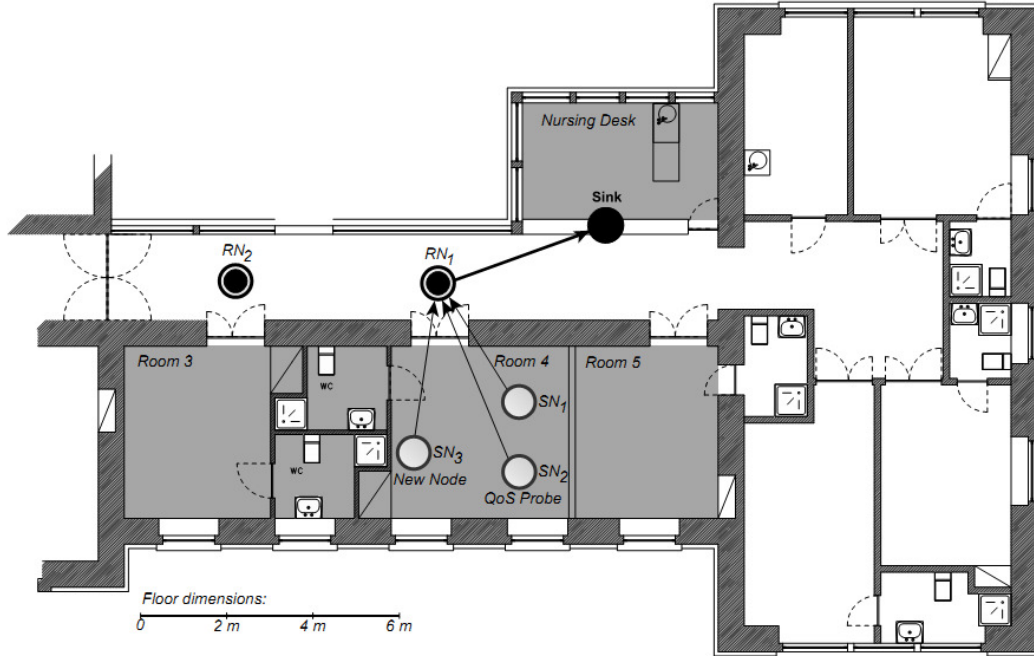


Figure 5.4 – The BWSN used to monitor three patients sharing the same nursing room. In such network logical topology, all the patients (i.e., the  $SN_1$ , the  $SN_2$  and the  $SN_3$ ) sent their data packets to the sink through the backbone. Table 5.2 shows the sink's routing table regarding this topology.

Table 5.2 – The sink's routing table for the network topology pictured in the Figure 5.4.

Destination		Next hop	
Node ID:	Node IP:	Node ID:	Node IP:
$RN_1$	AAAA::0212:7400:13CB:2777	$RN_1$	FE80::0212:7400:13CB:2777
$SN_1$	AAAA::0212:7400:13CA:FDCA	$RN_1$	FE80::0212:7400:13CB:2777
$SN_2$	AAAA::0212:7400:13CA:E837	$RN_1$	FE80::0212:7400:13CB:2777
$SN_3$	AAAA::0212:7400:13CB:2128	$RN_1$	FE80::0212:7400:13CB:2777

Table 5.3 – Results obtained when assessing the BWSN considering the network topology presented in the Figure 5.4.

Network Running Time (t)	Packet Reception Ratio ( $\overline{PRR} \pm \sigma$ ) %			
	$SN_1$ (Figure 5.5)	$SN_2$ (Figure 5.6)	QoS Probe (Figure 5.7)	New SN ( $SN_3$ ) (Figure 5.8)
$t \in ]0, t_{QoS\ Probe\ ON}]$	$99.1 \pm 0.9$	$98.9 \pm 1.1$	n.a.	n.a.
$t \in ]t_{QoS\ Probe\ ON}, t_{QoS\ Probe\ OFF}]$	<b><math>89.4 \pm 4.4</math></b>	<b><math>90.6 \pm 5.0</math></b>	<b><math>92.0 \pm 2.7</math></b>	n.a.
$t \in ]t_{QoS\ Probe\ OFF}, t_{New\ SN\ ON}]$	$98.9 \pm 1.1$	$98.2 \pm 1.8$	n.a.	n.a.
$t \in ]t_{New\ SN\ ON}, t_{New\ SN\ OFF}]$	<b><math>95.3 \pm 2.0</math></b>	<b><math>93.6 \pm 4.3</math></b>	n.a.	<b><math>94.1 \pm 4.2</math></b>

Initially the network was being used to carry the data generated by two patients (i.e., the  $SN_1$  and the  $SN_2$ ). In such case, the network can be considered highly efficient and providing high standards of QoS. Such fact can be confirmed by analysing the PRR of the data flows generated by both sensor nodes, during the time periods:  $t \in ]0, t_{QoS\ Probe\ ON}]$  and  $t \in ]t_{QoS\ Probe\ OFF}, t_{New\ SN\ ON}]$ . To be precise, during these two time intervals, the  $\overline{PRR}$  of the data flow generated by the  $SN_1$  is of about 99.1 % and 98.9 %, respectively. On its turn, the  $\overline{PRR}$  related to the data flow generated by the  $SN_2$ , during the same time intervals, is of about 98.9 % and 98.2 %, respectively. Then, when using the QoS Probe to assess the possibility of adding a new patient to the network, sharing the same nursing room, which comprises the interval  $t \in ]t_{QoS\ Probe\ ON}, t_{QoS\ Probe\ OFF}]$ , the PRR of the data flows generated by both the  $SN_1$  and the  $SN_2$  drops considerably. Indeed, the  $\overline{PRR}$  of the data flow generated by the  $SN_1$  drops about 9.7 pp from 99.1 % to 89.4 % and the  $\overline{PRR}$  of the data flow generated by the  $SN_2$  drops from about 98.9 % to 90.6 %, corresponding to a degradation of about 8.3 pp. On its turn, the  $\overline{PRR}$  achieved by the QoS Probe is around 92%, which is comparable with the values achieved by the other sensor nodes. Such degradation in the PRR of both data flows can be justified by the additional traffic generated by the QoS Probe. In fact, such additional traffic makes the competition for the transmission medium more difficult, increasing the probability of collisions as well as the interferences experienced by each sensor node, not only due to the presence of the QoS Probe within the network but also due to the additional retransmissions performed by the  $RN_1$ .

Finally, after the admission of the  $SN_3$  (i.e., the new patient), that corresponds to the time interval  $t \in ]t_{New\ SN\ ON}, t_{New\ SN\ OFF}]$ , the  $\overline{PRR}$  of the data flows generated both by the  $SN_1$  and by the  $SN_2$  falls about 3.6 pp, from 98.9 % to 95.3 %, and 4.6 pp, from 98.2 % to 93.6 %, respectively. On its turn, the  $\overline{PRR}$  of the data flow generated by the  $SN_3$  is of about 94.1 %, which is comparable with the PRR achieved by the other sensor nodes. In that case, the degradation on the PRR can also be explained using the arguments presented earlier. However, since the data generation processes are not time synchronised, the impact of adding the sensor nodes (i.e., the QoS Probe and the  $SN_3$ ) in different moments affects the performance of the network in diverse ways.



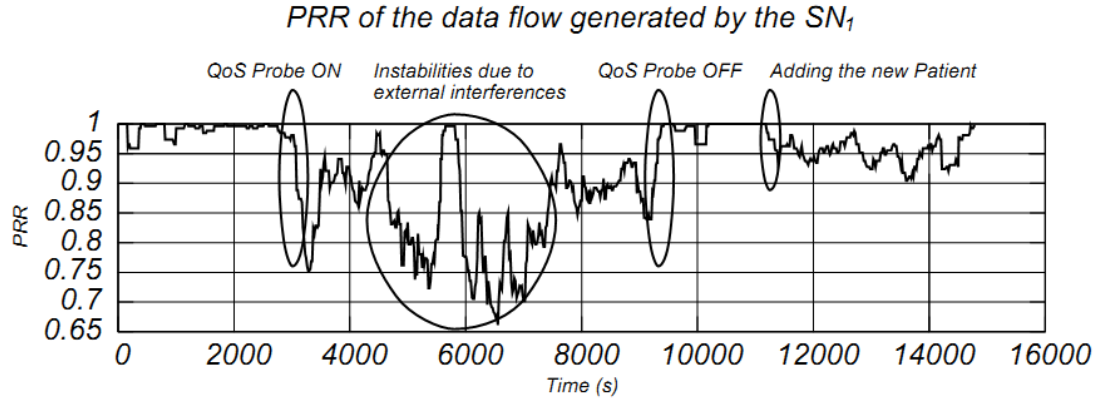


Figure 5.5 –PRR of the data flow generated by the  $SN_1$  during the admission control procedure regarding the network logical topology presented in the Figure 5.4.

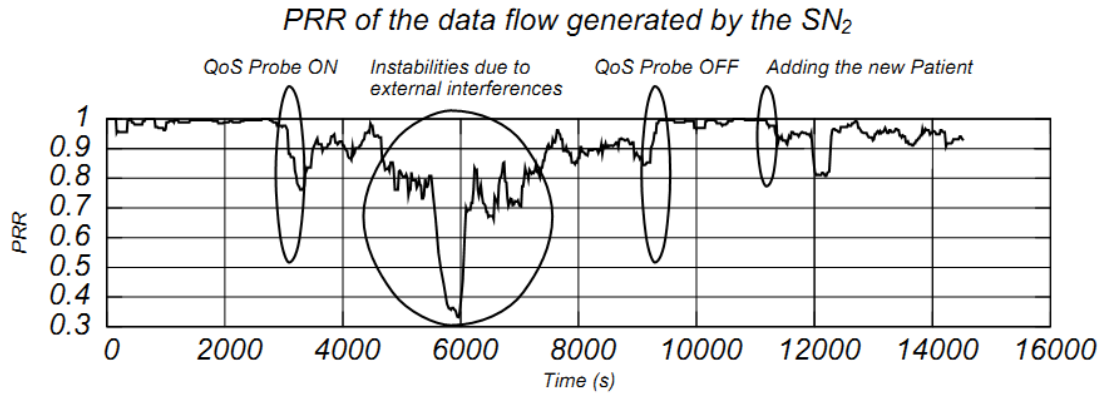


Figure 5.6 – PRR of the data flow generated by the  $SN_2$  during the admission control procedure regarding the network logical topology presented in the Figure 5.4.

The PRR of the data flows generated by  $SN_1$  and  $SN_2$  are shown in the Figure 5.5 and Figure 5.6, respectively. Looking to those figures, it is possible to identify all the phases of the experiment, namely the network on its typical operation, the network being assessed using the proposed QoS-based admission control method, and the network operation after the addition of the new patient. Regarding the PRR during the network typical operation, it can be found in two different time intervals,  $t \in ]0, 3000]$  s and  $t \in ]9300, 11200]$  s , where the PRR is similar in both sensor nodes.

Figure 5.7 shows the PRR of the data flow generated by the QoS Probe (i.e., the “virtual sensor node”). The strong PRR degradation that can be observed in the time interval 5000 s – 7000 s results from external interferences, as already explained. Apart from that region, the  $\overline{PRR}$  is of about 92%.

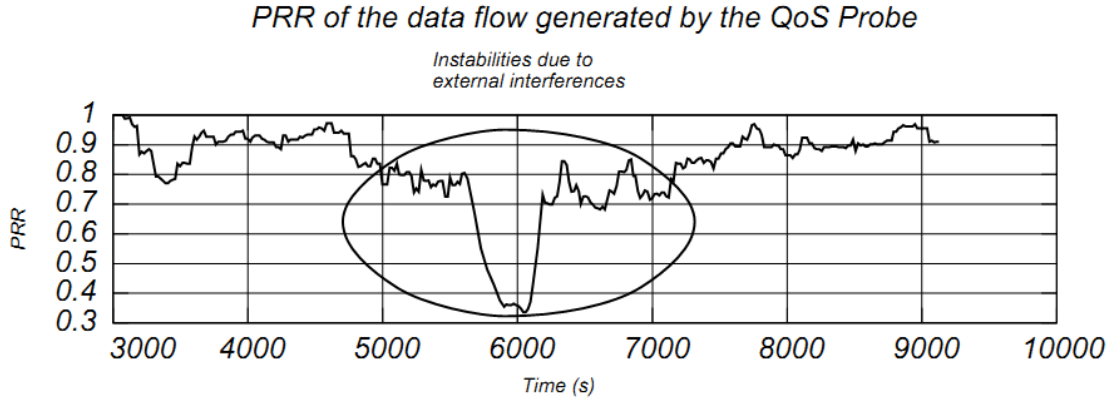


Figure 5.7 – PRR of the data flow generated by the QoS Probe during the admission control procedure regarding the network logical topology presented in the Figure 5.4.

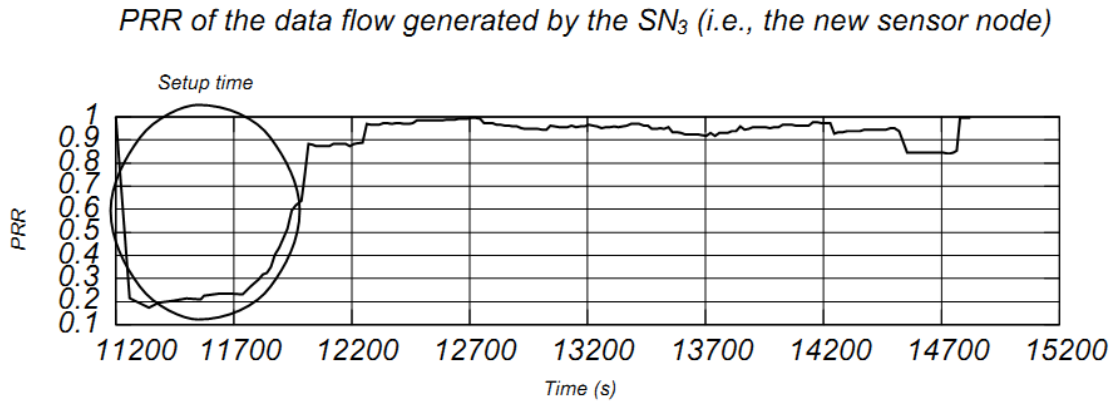


Figure 5.8 – PRR of the data flow generated by the new sensor node (i.e., the SN<sub>3</sub>) during the admission control procedure regarding the network logical topology presented in the Figure 5.4.

Finally, the PRR of the data flow produced by the new patient (i.e., the SN<sub>3</sub>) is shown in Figure 5.8 where it can be observed that the SN<sub>3</sub> had a setup time extremely long, of about 12 minutes. Such abnormal and unexpected situation was not repeated during the field tests. After this setup time, the  $\overline{PRR}$  becomes stable at a value of about 94.1%.

The previous per sensor node analysis investigated the effect of each phase of the experiment in the PRR achieved by each data flow carried by the network. Nevertheless, such individual analysis is not sufficient to forecast the QoS provided by the network after adding the new sensor node, based on the QoS provided during the assessment phase. To that end, it is necessary to compare the PRR achieved during those time intervals. So, to study the similarity between the PRRs of each data flow during the assessment period and after adding the new sensor node to the network, the percentage difference was used:

$$PD = 200 \left| \frac{PRR_x - PRR_y}{(PRR_x + PRR_y)} \right|, \quad \text{Eq. 5.2}$$

where the  $PRR_x$  and  $PRR_y$  represent the PRRs being studied.

Table 5.4 – Percentage difference between the  $\overline{PRR}$  of the sensor nodes during the assessment period and the period after the admission of the new patient (i.e., the  $SN_3$ ), considering the results of Table 5.3.

Network Running Time (t)	Packet Reception Ratio ( $\overline{PRR} \pm \sigma$ ) %			
	$SN_1$ (Figure 5.5)	$SN_2$ (Figure 5.6)	QoS Probe (Figure 5.7)	New SN ( $SN_3$ ) (Figure 5.8)
$t \in ]t_{\text{QoS Probe ON}}, t_{\text{QoS Probe OFF}}]$	$89.4 \pm 4.4$	$90.6 \pm 5.0$	$92.0 \pm 2.7$	n.a.
$t \in ]t_{\text{New SN ON}}, t_{\text{New SN OFF}}]$	$95.3 \pm 2.0$	$93.6 \pm 4.3$	n.a.	$94.1 \pm 4.2$
Percentage difference using the $\overline{PRR}$ of each SN	<b>6.4 %</b>	<b>3.3 %</b>		<b>2.3 %</b>

Table 5.5 – Percentage difference between the  $\overline{PRR}$  of each sensor node after the admission of the new patient and the  $\overline{PRR}$  achieved by the QoS Probe, considering the results of Table 5.3.

	Packet Reception Ratio ( $\overline{PRR}$ )		
	$SN_1$	$SN_2$	New SN ( $SN_3$ )
$\overline{PRR}$ of each SN after the admission of the new SN	95.3 %	93.6 %	94.1 %
$\overline{PRR}$ of the QoS Probe	92 %	92 %	92 %
Percentage difference	<b>3.5 %</b>	<b>1.7 %</b>	<b>2.3 %</b>

Table 5.4 shows the percentage difference between the  $\overline{PRR}$  of each sensor node regarding the time periods,  $t \in ]t_{\text{QoS Probe ON}}, t_{\text{QoS Probe OFF}}]$  and  $t \in ]t_{\text{New SN ON}}, t_{\text{New SN OFF}}]$ . From the results it is possible to verify that, considering this experiment, the impact of adding a “virtual sensor node” to the network is comparable (i.e., with a maximum average difference of about 6.4 %) to the impact of adding a real sensor node to the network. Moreover, considering the results of the Table 5.5, it is possible to conclude that the  $\overline{PRR}$  of each sensor node after adding the new sensor node to the network is equivalent (i.e., with a maximum average difference of about 3.5 %) to the one achieved by the QoS Probe. Considering these results, the proposed QoS-based admission control method was able to predict the impact of adding the new patient to the network.

### 5.2.1.2. Using different data paths to route the data to the sink

This scenario was also evaluated using the network topology presented in the Figure 5.9 and Table 5.6. In this case the data produced by the sensor nodes follow two distinct paths to reach the sink. This change in the network logical topology reduces the impact of adding a new patient to the network in the QoS being provided, as it can be seen in the results presented in the Table 5.7. The existence of two alternative paths to route the data to the sink decreases not only the occupation of the wireless link containing the  $RN_1$  (i.e., the data traffic through the  $RN_1$ ) but also the level of interferences, since the data sent by the  $SN_1$ , which is directly connected to the sink, do not need to be forwarded as in the logical topology presented in the Figure 5.4.

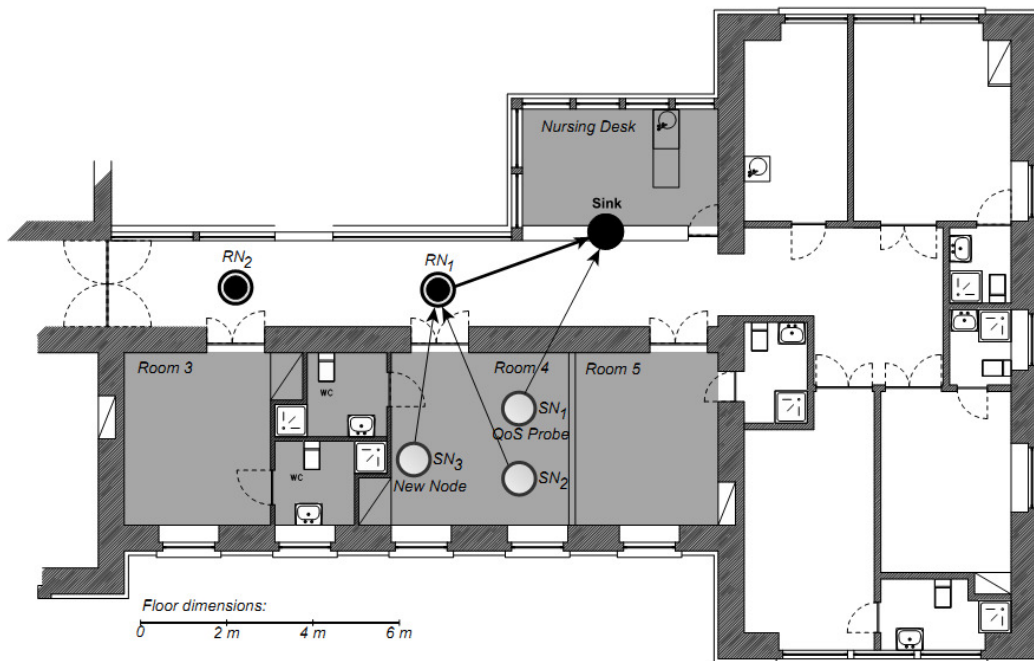


Figure 5.9 – The BWSN used to monitor three patients sharing the same nursing room. In such network logical topology, two patients (i.e., the  $SN_2$  and the  $SN_3$ ) sent their data to the sink through the backbone and the other one (i.e., the  $SN_1$ ) is directly connected to the sink. Table 5.6 shows the sink's routing table regarding this topology.

Table 5.6 – The sink's routing table for the network topology pictured in the Figure 5.9.

Destination		Next hop	
Node ID:	Node IP:	Node ID:	Node IP:
$RN_1$	AAAA::0212:7400:13CC:392F	$RN_1$	FE80::0212:7400:13CC:392F
$SN_1$	AAAA::0212:7400:13CA:FDCA	$SN_1$	FE80::0212:7400:13CA:FDCA
$SN_2$	AAAA::0212:7400:13CA:E837	$RN_1$	FE80::0212:7400:13CC:392F
$SN_3$	AAAA::0212:7400:13CB:2128	$RN_1$	FE80::0212:7400:13CC:392F

The results obtained when using the suggested QoS-based admission control method to assess the BWSN pictured in the Figure 5.9, in order to make a decision about the admission of a new patient to the network, are presented in the Figure 5.10, Figure 5.11, Figure 5.12 and Figure 5.13, and are summarised in the Table 5.7.

Table 5.7 – Results obtained when assessing the BWSN considering the network topology presented in the Figure 5.9.

Network Running Time (t)	Packet Reception Ratio ( $\overline{PRR} \pm \sigma$ ) %			
	$SN_1$ (Figure 5.10)	$SN_2$ (Figure 5.11)	QoS Probe (Figure 5.12)	New SN ( $SN_3$ ) (Figure 5.13)
$t \in ]0, t_{QoS\ Probe\ ON}]$	$99.8 \pm 0.2$	$99.9 \pm 0.1$	n.a.	n.a.
$t \in ]t_{QoS\ Probe\ ON}, t_{QoS\ Probe\ OFF}]$	<b><math>99.5 \pm 0.4</math></b>	<b><math>98.0 \pm 0.7</math></b>	<b><math>99.7 \pm 0.3</math></b>	n.a.
$t \in ]t_{QoS\ Probe\ OFF}, t_{New\ SN\ ON}]$	$99.6 \pm 0.4$	$99.6 \pm 0.3$	n.a.	n.a.
$t \in ]t_{New\ SN\ ON}, t_{New\ SN\ OFF}]$	<b><math>98.9 \pm 0.7</math></b>	<b><math>98.6 \pm 0.9</math></b>	n.a.	<b><math>98.8 \pm 1.2</math></b>

As in the previous experiment, at the beginning the BWSN was being used to carry the data produced by two patients (i.e., the  $SN_1$  and the  $SN_2$ ). In such time period, the network was providing high levels of QoS, as it can be confirmed by the values of the PRR achieved by both sensor nodes, during the time periods:  $t \in ]0, t_{QoS\ Probe\ ON}] \cup ]t_{QoS\ Probe\ OFF}, t_{New\ SN\ ON}]$ . Indeed, to be accurate, the  $\overline{PRR}$  of the data flow generated by the  $SN_1$  was of about 99.8 % and 99.6 %, respectively. On its turn, the  $\overline{PRR}$  related to the data flow generated by the  $SN_2$  was of about 99.9 % and 99.6 %, respectively. Then, contrasting with the previous experiment, the PRR of the data flows within the network does not significantly change during the assessment period (i.e., during the period of  $t \in ]t_{QoS\ Probe\ ON}, t_{QoS\ Probe\ OFF}]$ ) and after the addition of the new patient (i.e., during the period of  $t \in ]t_{New\ SN\ ON}, t_{New\ SN\ OFF}]$ ). In fact they all remain, in average, above 98 %.

The PRR of the data flows produced by the  $SN_1$  and by the  $SN_2$  is pictured in the Figure 5.10 and Figure 5.11, respectively. Analysing those figures, it is possible to conclude that, apart from the time period corresponding to the network assessment, using the proposed admission control method (i.e., the time interval including  $t \in ]2000, 3700]$  s), the PRRs of both sensor nodes are very similar. To be precise, the  $\overline{PRR}$  of both sensor nodes are 98.9 % and 98.6 % to the  $SN_1$  and  $SN_2$ , respectively. On its turn, during the time interval comprising the assessment

period, the  $\overline{PRR}$  of the data flow generated by the  $SN_2$  is of about 98 %. Which is 1.5 pp below the value achieved by the  $SN_1$  (i.e., 99.5 %).

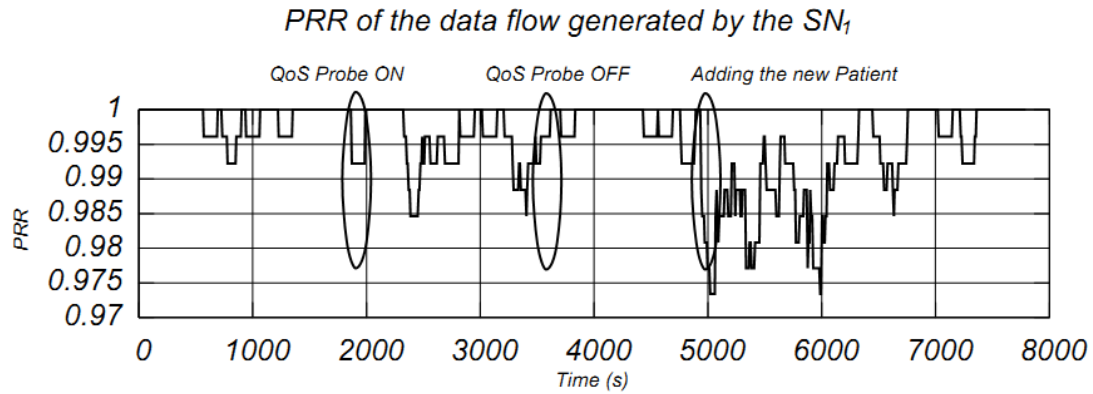


Figure 5.10 – PRR of the data flow generated by the  $SN_1$  during the admission control procedure regarding the network logical topology presented in the Figure 5.5.

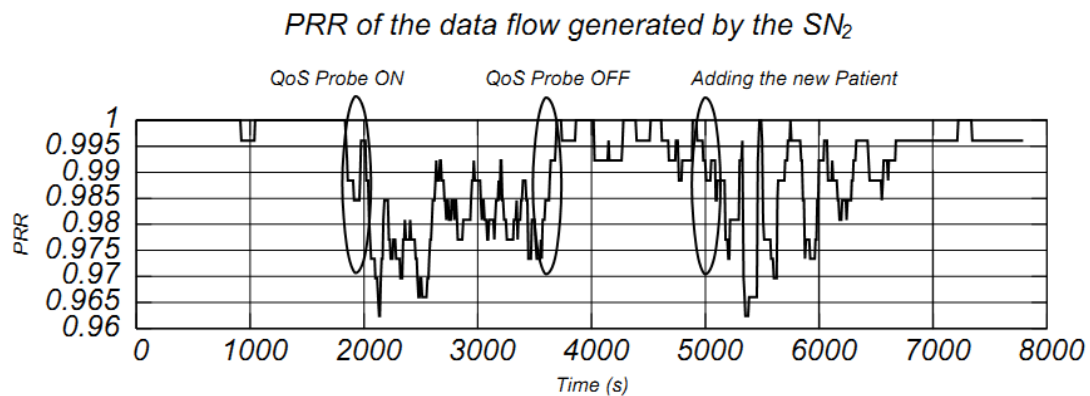


Figure 5.11 – PRR of the data flow generated by the  $SN_2$  during the admission control procedure regarding the network logical topology presented in the Figure 5.5.

Figure 5.12 shows the PRR of the data flow generated by the QoS Probe. During the QoS Probe operation, the PRR associated with its data flow is of about 99.7 %. On its turn, the Figure 5.13 shows the PRR of the data flow produced by the  $SN_3$  (i.e., the new patient). In this case, the PRR is of about 98.8 %.

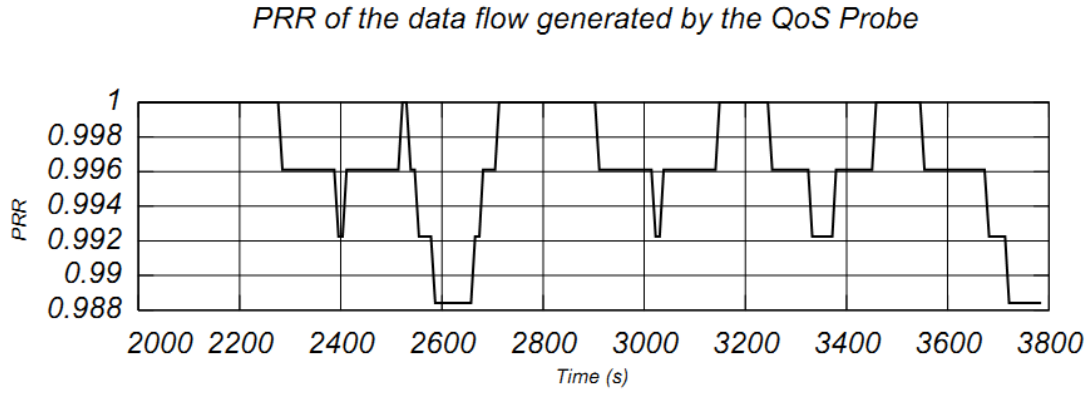


Figure 5.12 – PRR of the data flow generated by the QoS Probe during the admission control procedure regarding the network logical topology presented in the Figure 5.5.

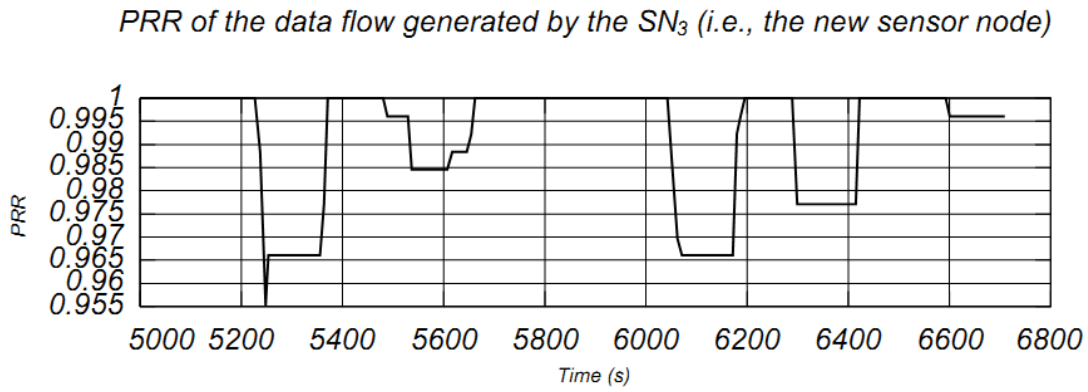


Figure 5.13 – PRR of the data flow generated by the new SN (SN<sub>3</sub>) during the admission control procedure regarding the network logical topology presented in the Figure 5.5.

Following the analysis of the former experiment, it is necessary to relate the PRR achieved by the sensor nodes during both the assessment period using the proposed method and the period after the admission of the new patient within the network. As before, this analysis was made using the percentage difference (i.e., Eq. 5.2). Table 5.8 presents the percentage difference concerning the PRR of each sensor node within the network for the time periods being studied. Analysing the results, it is clear that the difference between the PRR of the data flows produced by the sensor nodes within the network during the periods being studied is minimal, as expected, once the data paths within the network are uncongested. Furthermore, looking to the results presented in the Table 5.9, it is possible to verify that the  $\overline{PRR}$  of each patient after the admission of the new patient is comparable to the one achieved by the QoS Probe during the network assessment period. As earlier, the proposed QoS-based admission control method was able to predict the impact of adding the new patient to the network.

Table 5.8 – Percentage difference between the  $\overline{PRR}$  of the sensor nodes regarding the assessment period and the period after the admission of the new patient (i.e., the  $SN_3$ ), considering the results of Table 5.7.

Network Running Time (t)	Packet Reception Ratio ( $\overline{PRR} \pm \sigma$ )%			
	$SN_1$ (Figure 5.10)	$SN_2$ (Figure 5.11)	QoS Probe (Figure 5.12)	New SN ( $SN_3$ ) (Figure 5.13)
$t \in ]t_{QoS\ Probe\ ON}, t_{QoS\ Probe\ OFF}]$	$99.5 \pm 0.4$	$98.0 \pm 0.7$	$99.7 \pm 0.3$	n.a.
$t \in ]t_{New\ SN\ ON}, t_{New\ SN\ OFF}]$	$98.9 \pm 0.7$	$98.6 \pm 0.9$	n.a.	$98.8 \pm 1.2$
Percentage difference using the $\overline{PRR}$ of each SN	<b>0.6 %</b>	<b>0.6 %</b>		<b>0.9 %</b>

Table 5.9 – Percentage difference between the  $\overline{PRR}$  of each sensor node after the admission of the new patient and the  $\overline{PRR}$  achieved by the QoS Probe, considering the results of Table 5.8.

	Packet Reception Ratio ( $\overline{PRR}$ )		
	$SN_1$	$SN_2$	New SN ( $SN_3$ )
$\overline{PRR}$ of each SN after the admission of the new SN	98.9 %	98.6 %	97.8 %
$\overline{PRR}$ of the QoS Probe	99.7 %	99.7 %	99.7 %
Percentage difference	<b>0.8 %</b>	<b>1.1 %</b>	<b>1.9 %</b>

Comparing the results obtained during the previously described experiments, and considering only this scenario, it is possible to confirm that the response to the question formulated in the beginning of this experiment (i.e., the question Q. 5.1) is affirmative. Moreover, in the context of the present scenario, the hypothesis H. 5.1 was confirmed to be true.

### 5.2.2. Network Deployment Area Covering Two Nursing Rooms

Regarding the second scenario, i.e., monitoring a maximum of five patients spatially distributed into two non-adjacent nursing rooms (i.e., the rooms 3 and 4 from Figure 5.14), it was designed to verify if the proposed QoS-based admission control method can be used to answer the following question:

**Question:** Is it possible to use the concept of “virtual sensor node” to estimate the QoS impact when adding a new patient to a BWSN, if the new patient does not share the same physical space with all the others patients within the

Q. 5.2



network?

Among all the experiments performed using this scenario, the following two were chosen to be discussed in order to find the response to the question Q. 5.2.

#### 5.2.2.1. Using different data paths to route the data to the sink

This experiment comprises a BWSN being used to monitor three patients (i.e., the  $SN_1$  and the  $SN_2$  in the room 3 and the  $SN_3$  in the room 4), see the Figure 5.14 and the Table 5.10 for additional information about the network topology.

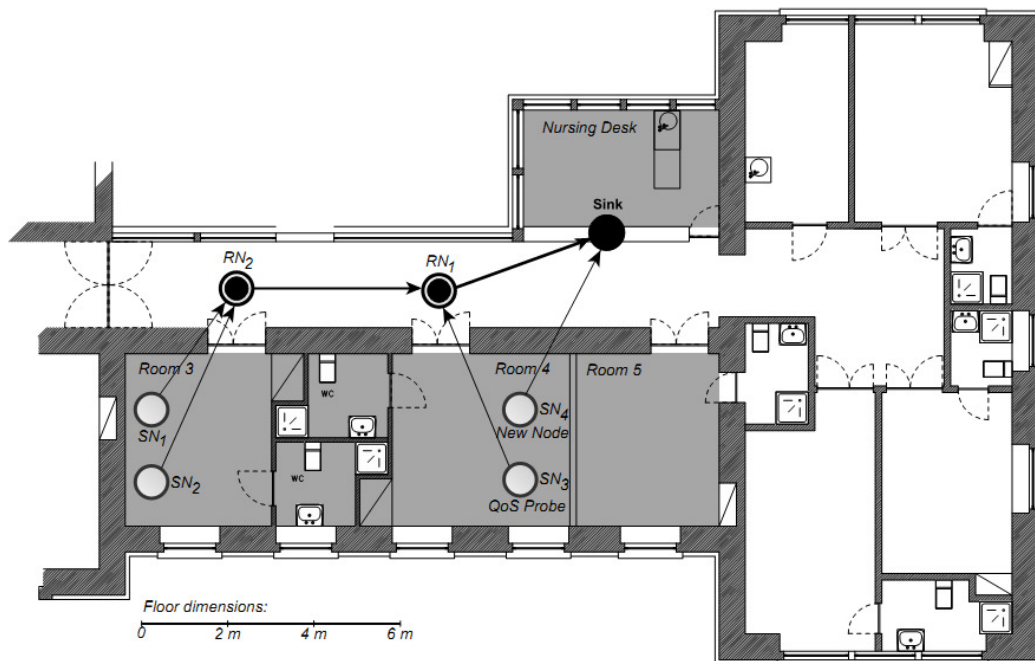


Figure 5.14 – BWSN used to monitor four patients distributed by two non-adjacent rooms (i.e., the rooms 3 and 4). Table 5.10 shows the sink's routing table regarding this network topology.

Table 5.10 – The sink's routing table for the network topology pictured in the Figure 5.14.

Destination		Next hop	
Node ID:	Node IP:	Node ID:	Node IP:
$RN_1$	AAAA::0212:7400:13CA:EDE2	$RN_1$	FE80::0212:7400:13CA:EDE2
$RN_2$	AAAA::0212:7400:13CB:45D9	$RN_1$	AAAA::0212:7400:13CA:EDE2
$SN_1$	AAAA::0212:7400:13CA:E837	$RN_2$	AAAA::0212:7400:13CB:45D9
$SN_2$	AAAA::0212:7400:13CA:FDCA	$RN_2$	AAAA::0212:7400:13CB:45D9
$SN_3$	AAAA::0212:7400:13CB:2128	$RN_1$	AAAA::0212:7400:13CA:EDE2
$SN_4$	AAAA::0212:7400:13CC:3930	$SN_4$	FE80::0212:7400:13CC:3930

Using the proposed QoS-based admission control method, the network was tested to assess the impact of placing a new patient being monitored into the room 4 (i.e., the  $SN_4$ ), in the QoS being provided by the BWSN. In such experiment, both the  $SN_1$  and the  $SN_2$  send their data to the sink through the  $RN_2$  and the  $RN_1$ , while the  $SN_3$  uses the  $RN_1$  to forward its data to the sink (see the Figure 5.14 and the Table 5.10 for more details). During the network assessment period, the QoS Probe sends its data using the same path as the  $SN_3$ . On the contrary, the new sensor node (i.e., the  $SN_4$ ) sends its data directly to the sink. By using different paths to send their data to the sink, it is expectable that the impact of adding the QoS Probe and the new sensor node in the QoS being provided by the network will be distinct. Moreover it is expected that the PRR achieved by the QoS Probe will be different from the one achieved by the new sensor node.

Table 5.11 shows the results obtained when assessing the proposed QoS-based admission control method, using the experiment presented in the Figure 5.14. In view of those results, it is possible to state that during both the assessment period using the QoS Probe (i.e.,  $t \in ]t_{\text{QoS Probe ON}}, t_{\text{QoS Probe OFF}}]$ ) and the period after introducing the new sensor node (i.e.,  $t \in ]t_{\text{New SN ON}}, t_{\text{New SN OFF}}]$ ), the network's performance decrease substantially. However, the performance loss is considerably smaller when introducing the new sensor node. This behaviour was expected since the data generated by both the QoS Probe and the new sensor node follow different paths to reach the sink.

Table 5.11 – Results obtained when assessing the BWSN, considering the network topology presented in the Figure 5.14.

Network Running Time (t)	Packet Reception Ratio ( $\overline{PRR} \pm \sigma$ )%				
	$SN_1$ (Figure 5.15)	$SN_2$ (Figure 5.16)	$SN_3$ (Figure 5.17)	QoS Probe (Figure 5.18)	New SN ( $SN_4$ ) (Figure 5.19)
$t \in [0, t_{\text{QoS Probe ON}}]$	$97.9 \pm 1.6$	$98.1 \pm 1.4$	$97.7 \pm 1.6$	n.a.	n.a.
$t \in [t_{\text{QoS Probe ON}}, t_{\text{QoS Probe OFF}}]$	<b>84.6 <math>\pm</math> 4.4</b>	<b>84.8 <math>\pm</math> 4.8</b>	<b>86.9 <math>\pm</math> 4.5</b>	<b>87.7 <math>\pm</math> 4.0</b>	n.a.
$t \in [t_{\text{QoS Probe OFF}}, t_{\text{New SN ON}}]$	$98.0 \pm 1.3$	$97.4 \pm 2.8$	$98.6 \pm 2.1$	n.a.	n.a.
$t \in [t_{\text{New SN ON}}, t_{\text{New SN OFF}}]$	<b>92.9 <math>\pm</math> 2.0</b>	<b>92.0 <math>\pm</math> 2.4</b>	<b>99.4 <math>\pm</math> 0.9</b>	n.a.	<b>95.5 <math>\pm</math> 1.7</b>

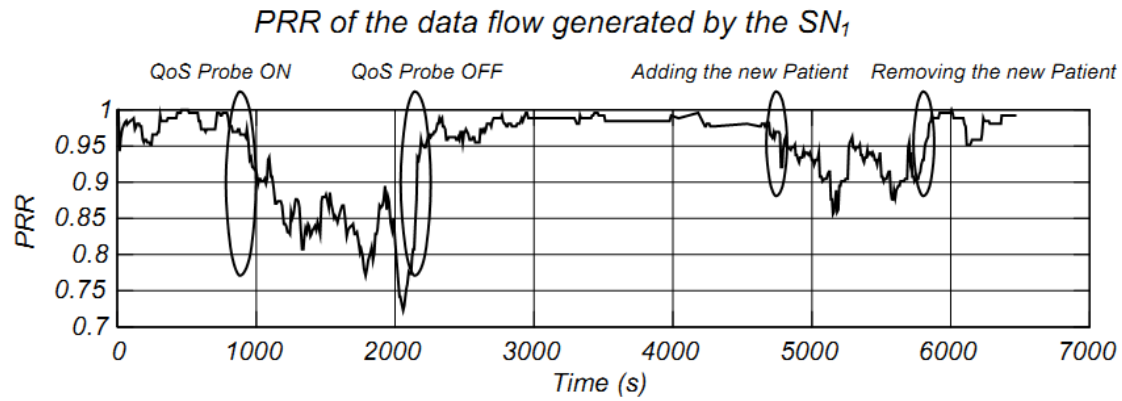


Figure 5.15 – PRR of the data flow generated by the  $SN_1$  during the admission control procedure regarding the network topology presented in the Figure 5.14.

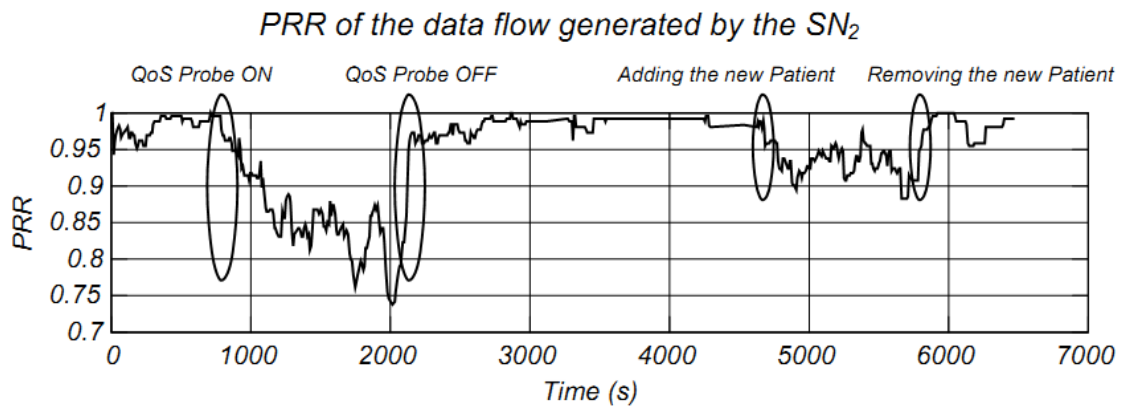


Figure 5.16 – PRR of the data flow generated by the  $SN_2$  during the admission control procedure regarding the network topology presented in the Figure 5.14.

Analysing the performance of each sensor node individually, it is possible to see that the PRR of both the  $SN_1$  and the  $SN_2$  are identical (see the Figure 5.15 and the Figure 5.16 respectively). In particular, when starting the network assessment using the QoS Probe, the  $\overline{PRR}$  drops from about 97.9 % to 84.6 % in the  $SN_1$  and from about 98.1 % to 84.8 % in the  $SN_2$ , which corresponds to a difference of about 13.3 pp for both sensor nodes. On its turn, after the introduction of the new sensor node, the  $\overline{PRR}$  drops from about 98 % to 92.9 % in the  $SN_1$  and from about 97.4 % to 82 % in the  $SN_2$ , which corresponds to a difference of about 5.1 pp for the  $SN_1$  and of about 5.4 pp for the  $SN_2$ . Considering these results it is possible to conclude that the performance degradation in the  $\overline{PRR}$  of both the  $SN_1$  and the  $SN_2$  is approximately  $\frac{1}{2}$  after the introduction of the new sensor node when comparing with the one achieved during the QoS Probe operation. This difference can be explained by the distinct data paths used by the QoS Probe and by the new sensor node to send their data to the sink. By

selecting a distinct path to send its data to the sink, the new sensor node does not contribute to congest the data path being used by the others sensor nodes and, consequently, its interference in the performance of those sensor nodes is reduced when compared with the one introduced by the QoS Probe.

Regarding the performance of the  $SN_3$ , its  $\overline{PRR}$  falls from about 97.7 % to 86.9 % (i.e., dropping about 10.8 pp) when starting the assessment period using the QoS Probe and slightly increases after the introduction of the new sensor node in the network, from about 98.6 % to 99.4 % (i.e., rising about 0.8 pp), see the Figure 5.17. Once again, this comportment can be explained by the different paths used by the QoS Probe and by the new sensor node to send their data to the sink. By using a different and uncongested path to send its data to the sink, the interferences caused by the new sensor node are highly reduced. Moreover, the distance between the  $SN_3$  and the sink is two hops; on its turn, the distance between the  $SN_1$  or the  $SN_2$  and the sink is three hops. This difference in the distance between these sensor nodes and the sink helps to justify the difference in the performance of the  $SN_3$  when comparing with both the  $SN_1$  and the  $SN_2$ . Indeed, the smaller the number of hops between two sensor nodes the higher the PRR.

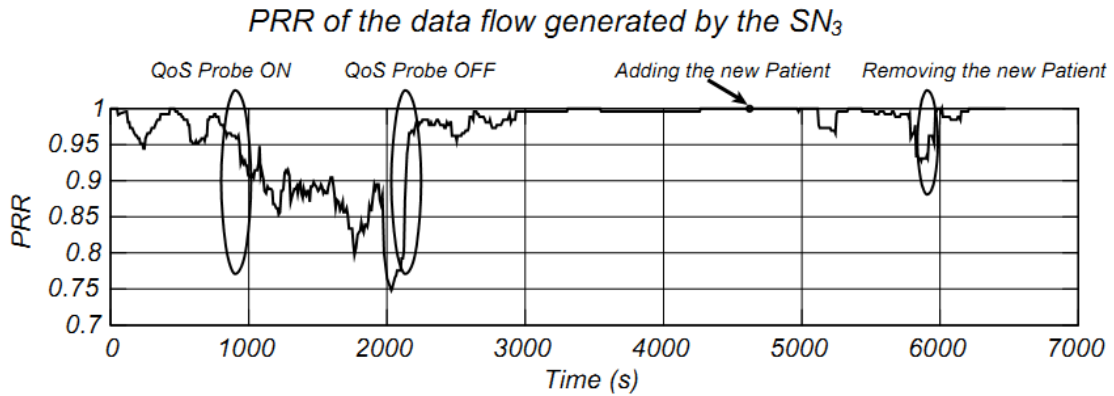


Figure 5.17 – PRR of the data flow generated by the  $SN_3$  during the admission control procedure regarding the network topology presented in the Figure 5.14.

Figure 5.18 shows the PRR of the data flow generated by the QoS Probe. During the QoS Probe operation, the  $\overline{PRR}$  associated with its data flow was of about 87.7 %. On its turn, the  $\overline{PRR}$  of the data flow generated by the new sensor node was of about 95.5 %, see Figure 5.19. By using a different and uncongested path to send its data to the sink the new sensor node has a higher probability of successfully deliver its data when compared with the QoS Probe.

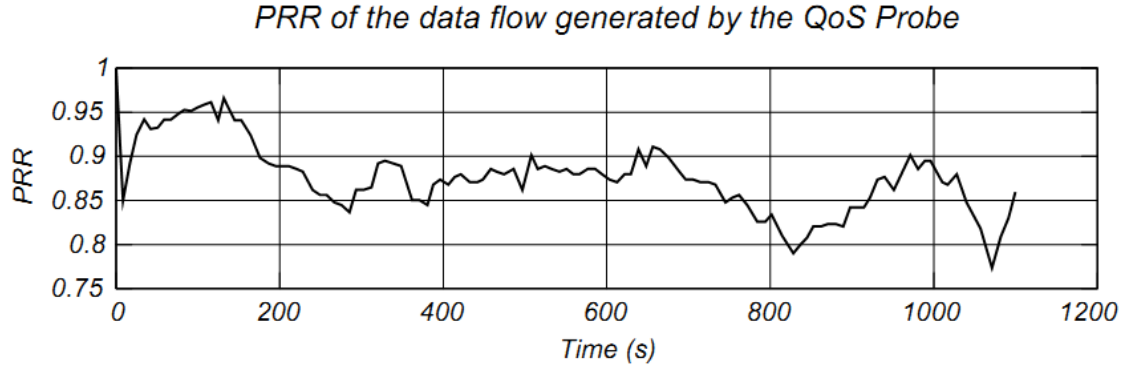


Figure 5.18 – PRR of the data flow generated by the QoS Probe during the admission control procedure regarding the network topology presented in the Figure 5.14.

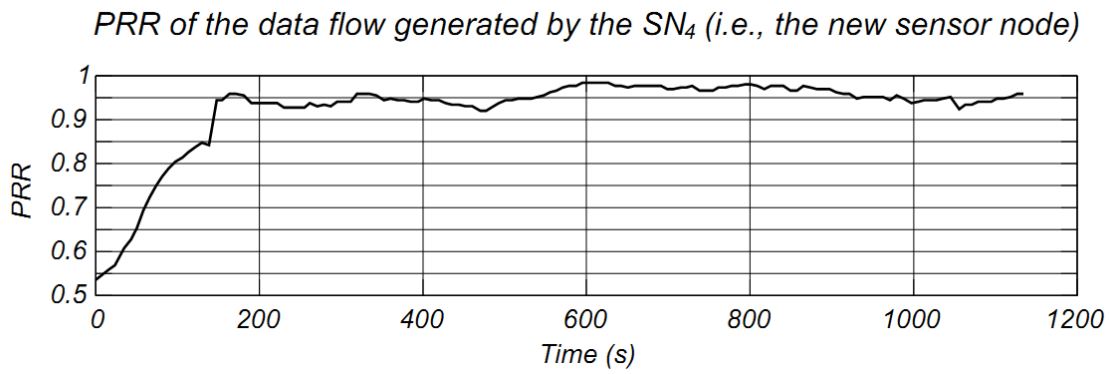


Figure 5.19 – PRR of the data flow generated by the new sensor node (i.e., the  $SN_4$ ) during the admission control procedure regarding the network topology presented in the Figure 5.14.

Comparing the performance of the sensor nodes within the network during the assessment period (i.e.,  $t \in ]t_{QoS\ Probe\ ON}, t_{QoS\ Probe\ OFF}]$ ) and the period after the admission of the new sensor node to the network (i.e.,  $t \in ]t_{New\ SN\ ON}, t_{New\ SN\ OFF}]$ ) using the percentage difference as defined in Eq. 5.2, it is possible to confirm that the QoS Probe and the new sensor node affect the network performance in distinct ways, as expected. See the Table 5.12 for more details. Moreover, comparing the performance achieved by each sensor node with the one achieved by the QoS Probe, as shown in the Table 5.13, it is possible to verify that they are considerably different. Consequently, considering this scenario and this particular experiment, as described in the Figure 5.14, the proposed QoS-Based admission control method was unable to predict the network's performance after the admission of the new sensor node. In this case, the answer to the question Q. 5.2 is negative and the hypothesis H. 5.1 is considered to be false.

Table 5.12 – Percentage difference between the  $\overline{PRR}$  of the sensor nodes regarding the assessment period and the period after the admission of the new patient (i.e., the  $SN_4$ ), considering the results of Table 5.11.

Network Running Time (t)	Packet Reception Ratio ( $\overline{PRR} \pm \sigma$ )%				
	$SN_1$ (Figure 5.15)	$SN_2$ (Figure 5.16)	$SN_3$ (Figure 5.17)	QoS Probe (Figure 5.18)	New SN ( $SN_4$ ) (Figure 5.19)
$t \in [t_{QoS\ Probe\ ON}, t_{QoS\ Probe\ OFF}]$	84.6 $\pm$ 4.4	84.8 $\pm$ 4.8	86.9 $\pm$ 4.5	87.7 $\pm$ 4.0	n.a.
$t \in [t_{New\ SN\ ON}, t_{New\ SN\ OFF}]$	92.9 $\pm$ 2.0	92.0 $\pm$ 2.4	99.4 $\pm$ 0.9	n.a.	95.5 $\pm$ 1.7
Percentage difference using the $\overline{PRR}$ of each SN	9.4 %	8.1%	13.4%	8.5%	

Table 5.13 – Percentage difference between the  $\overline{PRR}$  of each sensor node after the admission of the new patient and the  $\overline{PRR}$  achieved by the QoS Probe, considering the results of Table 5.11.

	Packet Reception Ratio ( $\overline{PRR}$ )			
	SN <sub>1</sub>	SN <sub>2</sub>	SN <sub>3</sub>	New SN (SN <sub>4</sub> )
$\overline{PRR}$ of each SN after the admission of the new SN	92.9 %	92 %	99.4 %	95.5 %
$\overline{PRR}$ of the QoS Probe	87.7 %	87.7 %	87.7 %	87.7 %
Percentage difference	<b>5.8 %</b>	<b>4.8 %</b>	<b>12.5 %</b>	<b>8.5 %</b>

#### 5.2.2.2. Using the same data path to route the data to the sink

Regarding this experiment, the  $SN_1$  sends its data to the sink through the  $RN_2$  while the remaining sensor nodes, including the QoS Probe and the new sensor node (i.e., the  $SN_4$ ), use the  $RN_1$  to forward their data packets to the sink (see the Figure 5.14 and the Table 5.10 for more details). In this case, the data generated by the QoS Probe and by the new sensor node follow the same path to reach the sink. Unlike the former experiment, in this case it is likely that the QoS Probe and the new sensor node achieve comparable performance in terms of PRR. The results obtained when assessing the current scenario, using the network topology pictured in the Figure 5.20 and explained in detail in the Table 5.14, are summarized in the Table 5.15.

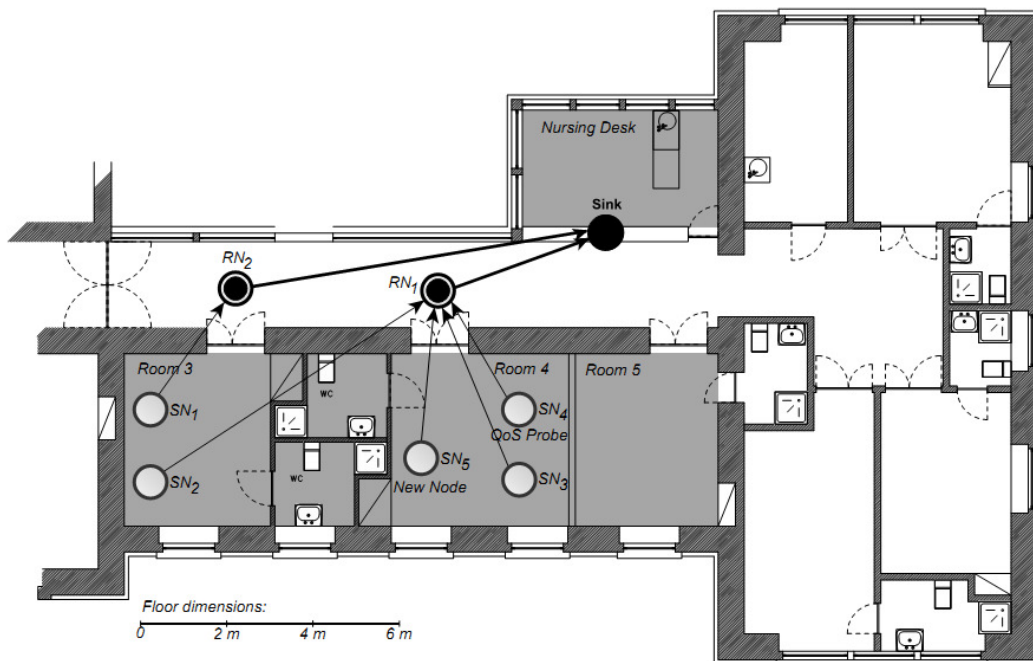


Figure 5.20 – BWSN used to monitor five patients distributed by two non-adjacent rooms (i.e., the rooms 3 and 4). Table 5.14 shows the sink's routing table regarding this network topology.



Table 5.14 – The sink's routing table for the network topology pictured in the Figure 5.20.

Destination		Next hop	
Node ID:	Node IP:	Node ID:	Node IP:
$RN_1$	AAAA::0212:7400:13CB:2777	$RN_1$	FE80::0212:7400:13CB:2777
$RN_2$	AAAA::0212:7400:13CC:392F	$RN_2$	FE80::0212:7400:13CC:392F
$SN_1$	AAAA::0212:7400:13CB:3050	$RN_2$	AAAA::0212:7400:13CC:392F
$SN_2$	AAAA::0212:7400:13CB:3F66	$RN_1$	AAAA::0212:7400:13CB:2777
$SN_3$	AAAA::0212:7400:13CA:FDCA	$RN_1$	AAAA::0212:7400:13CB:2777
$SN_4$	AAAA::0212:7400:13CA:E837	$RN_1$	AAAA::0212:7400:13CB:2777
$SN_5$	AAAA::0212:7400:13CB:2128	$RN_1$	AAAA::0212:7400:13CB:2777

Considering the results presented in the Table 5.15, it is possible to verify that during both the assessment period using the QoS Probe and the period next to the introduction of the new sensor node, the network's performance suffers a significant degradation. Moreover, it is important to notice that the performance degradation experienced by all the sensor nodes inside the room 4 is comparable, including the QoS Probe and the new sensor node (i.e., the  $SN_5$ ). This outcome was expected since the data generated both by the QoS Probe and by the  $SN_5$  use the same path to reach the sink. By using the same data path, it is expected that both have the comparable impact on the performance of the sensor nodes on their neighbouring (i.e., inside the room 4).

Taking a look at the individual performance of each sensor node, it is possible to verify that the PRRs achieved by both the  $SN_1$  (Figure 5.21) and the  $SN_2$  (Figure 5.22) during this experiment are comparable. Namely, when starting the QoS Probe, the  $\overline{PRR}$  drops from about 83.9 % to 57.1 % in the  $SN_1$  and from about 83.5 % to 57.1 % in the  $SN_2$ , corresponding to a difference of about 26.8 pp and 26.4 pp, respectively. On its turn, after adding the new sensor node to the network, the  $\overline{PRR}$  drops from about 86.8 % to 64.5 % in the  $SN_1$  and from about 86.3 % to 65.1 % in the  $SN_2$ , corresponding to a difference of about 22.3 pp and 21.2 pp, respectively. Comparing these results it is possible to verify that the  $\overline{PRR}$  of both sensor nodes suffers a greater degradation during the QoS Probe operation, rather than after the addition of the new sensor node to the network. Although, despite the PRR achieved during the new sensor node operation have been greater than the one achieved during the QoS Probe operation, it is possible to conclude that in both cases the performance of these sensor nodes worsens considerably.

Table 5.15 – Results obtained when assessing the BWSN, considering the network topology presented in the Figure 5.20.

Network Running Time (t)	Packet Reception Ratio ( $\overline{PRR} \pm \sigma$ )%				
	$SN_1$ (Figure 5.21)	$SN_2$ (Figure 5.22)	$SN_3$ (Figure 5.23)	$SN_4$ (Figure 5.24)	QoS Probe (Figure 5.25)
$t \in ]0, t_{QoS \text{ Probe ON}}]$	83.9 $\pm$ 4.4	83.5 $\pm$ 4.1	86.2 $\pm$ 3.1	86.3 $\pm$ 3.3	n.a
$t \in ]t_{QoS \text{ Probe ON}}, t_{QoS \text{ Probe OFF}}]$	57.1 $\pm$ 7.3	57.1 $\pm$ 7.3	63.5 $\pm$ 9.5	65.7 $\pm$ 7.7	63.7 $\pm$ 6.7
$t \in ]t_{QoS \text{ Probe OFF}}, t_{New SN ON}]$	86.8 $\pm$ 2.5	86.3 $\pm$ 3.2	82.5 $\pm$ 8.4	80.6 $\pm$ 8.8	n.a
$t \in ]t_{New SN ON}, t_{New SN OFF}]$	64.5 $\pm$ 7.0	65.1 $\pm$ 8.5	66.9 $\pm$ 9.6	67.1 $\pm$ 8.3	n.a
					65.9 $\pm$ 6.8

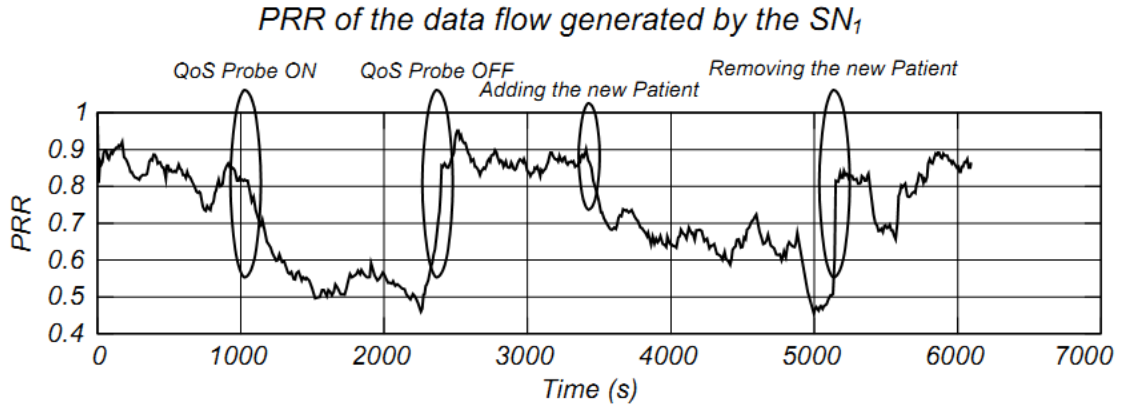


Figure 5.21 – PRR of the data flow generated by the  $SN_1$  during the admission control procedure regarding the network topology presented in the Figure 5.20.

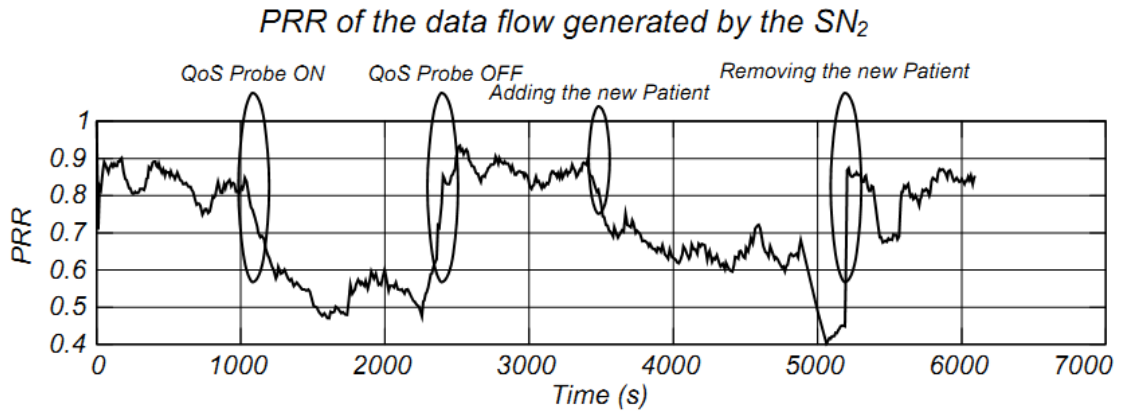


Figure 5.22 – PRR of the data flow generated by the  $SN_2$  during the admission control procedure regarding the network topology presented in the Figure 5.20.

Vis-à-vis the performance of the sensor nodes within the room 4 (i.e., the  $SN_3$  and the  $SN_4$ ) their PRR can be seen in the Figure 5.23 and Figure 5.24, respectively. Once again, the  $\overline{PRR}$ s accomplished by both sensor nodes during this experiment are comparable. Regarding the  $\overline{PRR}$  of the  $SN_3$ , it drops from about 86.2 % to 63.5 % when starting the QoS Probe operation and drops from about 82.5 % to 66.9 % once adding the new sensor node to the network, which corresponds to a variance of about 22.7 pp and 15.6 pp, respectively. Considering the  $\overline{PRR}$  of the  $SN_4$ , it drops from about 86.3 % to 65.7 % when starting the assessment with the QoS Probe and drops from about 80.6 % to 67.1 % when adding the new sensor node to the network, which corresponds to a difference of about 20.6 pp and 13.5 pp, respectively. Taking these results into account, it is possible to verify that the performance degradation introduced by the QoS Probe is greater than the one introduced by the new sensor node, although, both results are comparable. This can be explained by the fact that both the QoS Probe and the new sensor

node send their data to the sink through the same path. So, as expected, their impact in the performance of both the  $SN_3$  and the  $SN_4$  is equivalent.

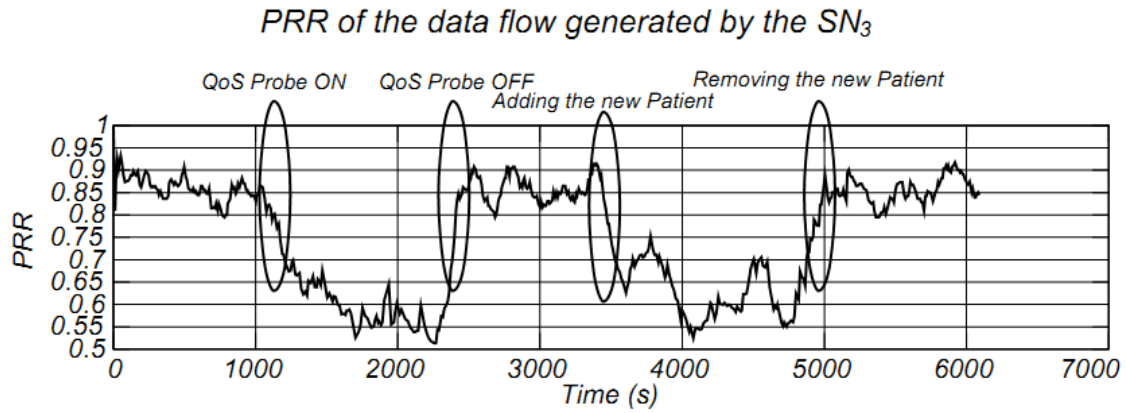


Figure 5.23 – PRR of the data flow generated by the  $SN_3$  during the admission control procedure regarding the network topology presented in the Figure 5.20.

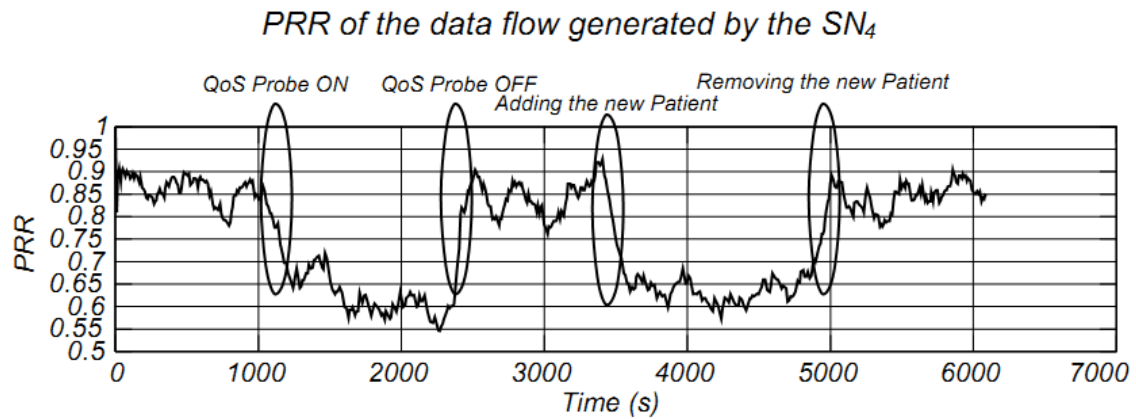


Figure 5.24 – PRR of the data flow generated by the  $SN_4$  during the admission control procedure regarding the network topology presented in the Figure 5.20.

Regarding the performance of the QoS Probe, the Figure 5.25 shows its PRR. During the QoS Probe operation period, the  $\overline{PRR}$  achieved by its data flow was of about 63.7 %. On its turn, the Figure 5.26 shows the PRR associated with the data flow generated by the new sensor node (i.e., the  $SN_5$ ) and its  $\overline{PRR}$  was of about 65.9 %. As expected, the  $\overline{PRR}$  of both the QoS Probe and the new sensor node are similar. By using the same path to route their data packets to the sink it was expected that both reach similar values of PRR.

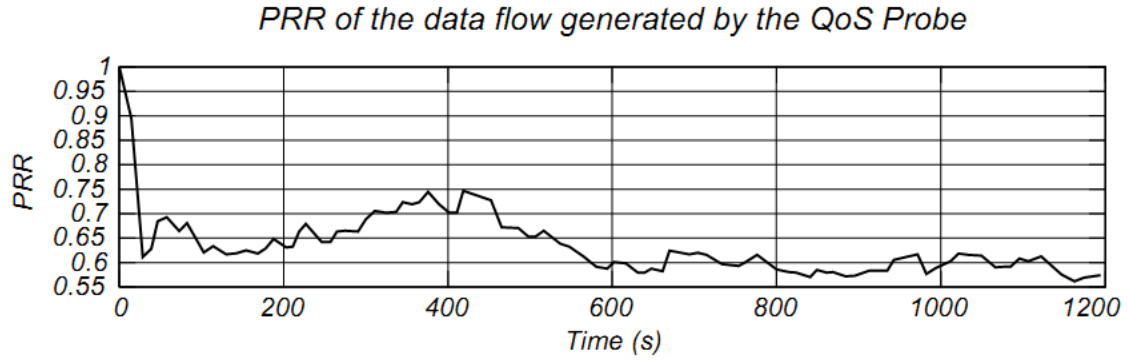


Figure 5.25 – PRR of the data flow generated by the QoS Probe during the admission control procedure regarding the network topology presented in the Figure 5.20.

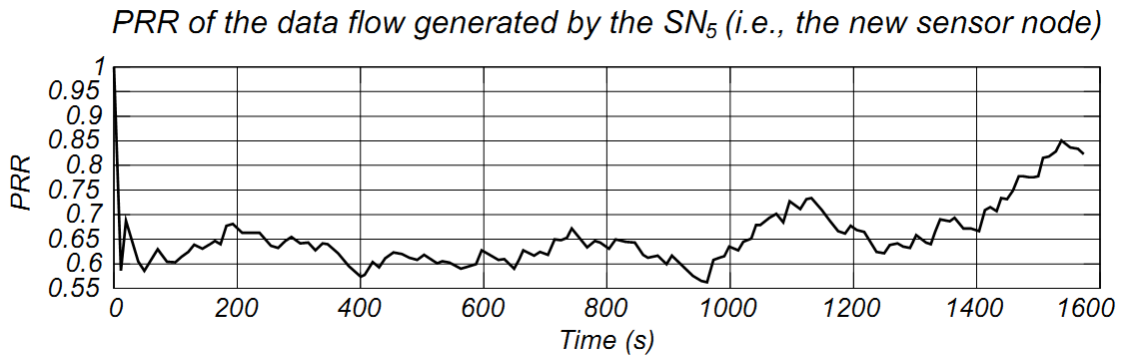


Figure 5.26 – PRR of the data flow generated by the new sensor node (i.e., the  $SN_5$ ) during the admission control procedure regarding the network topology presented in the Figure 5.20.

Comparing the  $\overline{PRR}$  of all the sensor nodes within the network during the network assessment period (i.e.,  $t \in ]t_{QoS\ Probe\ ON}, t_{QoS\ Probe\ OFF}]$ ) and the period after the admission of the new sensor node to the network (i.e.,  $t \in ]t_{New\ SN\ ON}, t_{New\ SN\ OFF}]$ ) using the percentage difference as defined in Eq. 5.2, it is possible to conclude that both the QoS Probe and the new sensor node affect the sensor nodes within the network distinctly. In fact, looking to the results of the Table 5.16 it is clear that the performance of the sensor nodes inside the room 3 (i.e., the  $SN_1$  and the  $SN_2$ ) are distinctly affected by the QoS Probe and by the new sensor node. Nevertheless, the sensor nodes inside the room 4 (i.e., the  $SN_3$  and the  $SN_4$ ) have seen their performance affected in a comparable way by the QoS Probe and by the new sensor node. Moreover, when comparing the  $\overline{PRR}$  achieved by each sensor node within the network, including the new one, with the  $\overline{PRR}$  achieved by the QoS Probe during its operation, it is possible to verify that the  $\overline{PRR}$  of all the sensor nodes after the admission of the new sensor node is comparable with the one achieved by the QoS Probe, as presented in the Table 5.17. In view of these results it is possible to argue that the proposed method was able to predict the impact of adding the new node to the network.

Table 5.16 – Percentage difference between the  $\overline{PRR}$  of the sensor nodes regarding the assessment period and the period after the admission of the new patient (i.e., the  $SN_5$ ), considering the results of Table 5.15.

Network Running Time (t)	Packet Reception Ratio ( $\overline{PRR} \pm \sigma$ ) %					
	$SN_1$ (Figure 5.21)	$SN_2$ (Figure 5.22)	$SN_3$ (Figure 5.23)	$SN_4$ (Figure 5.24)	QoS Probe (Figure 5.25)	New SN ( $SN_5$ ) (Figure 5.26)
$t \in [t_{QoS\ Probe\ ON}, t_{QoS\ Probe\ OFF}]$	57.1 $\pm$ 7.3	57.1 $\pm$ 7.3	63.5 $\pm$ 9.5	65.7 $\pm$ 7.7	63.7 $\pm$ 6.7	n.a
$t \in [t_{New\ SN\ ON}, t_{New\ SN\ OFF}]$	64.5 $\pm$ 7.0	65.1 $\pm$ 8.5	66.9 $\pm$ 9.6	67.1 $\pm$ 8.3	n.a	65.9 $\pm$ 6.8
Percentage difference using the $\overline{PRR}$ of each SN	12.2 %	13.1 %	5.2 %	2.1 %	3.4 %	

Table 5.17 – Percentage difference between the  $\overline{PRR}$  of each sensor node after the admission of the new patient and the  $\overline{PRR}$  achieved by the QoS Probe, considering the results of Table 5.15.

	Packet Reception Ratio ( $\overline{PRR}$ )				
	SN <sub>1</sub>	SN <sub>2</sub>	SN <sub>3</sub>	SN <sub>4</sub>	New SN (SN <sub>5</sub> )
$\overline{PRR}$ of each SN after the admission of the new SN	64.5 %	65.1 %	66.9 %	67.1 %	65.9 %
$\overline{PRR}$ of the QoS Probe	63.7 %	63.7 %	63.7 %	63.7 %	63.7 %
Percentage difference	<b>1.2 %</b>	<b>2.2 %</b>	<b>4.9 %</b>	<b>5.2 %</b>	<b>3.4 %</b>

Regarding the results obtained during the aforementioned experiments, and considering only this scenario, it is possible to claim that the proposed QoS-based admission control method was able to predict the impact of adding the new patient to the network only in the experiment pictured in the Figure 5.20. So, the response to the question Q. 5.2 is affirmative only in that case. Consequently, the hypothesis H. 5.1 is considered to be true only for that experiment.

### 5.2.3. Network Deployment Area Covering Three Nursing Rooms

This scenario is about monitoring a maximum of five patients distributed by three rooms (i.e., the rooms 3, 4, and 5 from the Figure 5.27). This scenario was designed to evaluate the impact of the building structure when assessing the BWSN using the proposed method and in view of the results achieved respond to the following question:

**Question:** Is it possible to use the concept of “virtual sensor node” to estimate the QoS impact when adding a new patient to a BWSN, when the new patient does not share the same physical space with all the others patients within the network neither with the “virtual sensor node”? Q. 5.3

This scenario involves four patients being monitored while sharing two non-adjacent rooms. More precisely, the SN<sub>1</sub> and the SN<sub>2</sub> inside the room 3, and the SN<sub>3</sub> and the SN<sub>4</sub> inside the room 4, as pictured in the Figure 5.27. Then, the suggested QoS-based admission control method is used to evaluate if a new patient (i.e., the SN<sub>5</sub>) can be added to the BWSN inside the room 5, see Figure 5.27. At the end of the assessment period, the decision of adding the new patient in room 5 is made facing the results obtained.

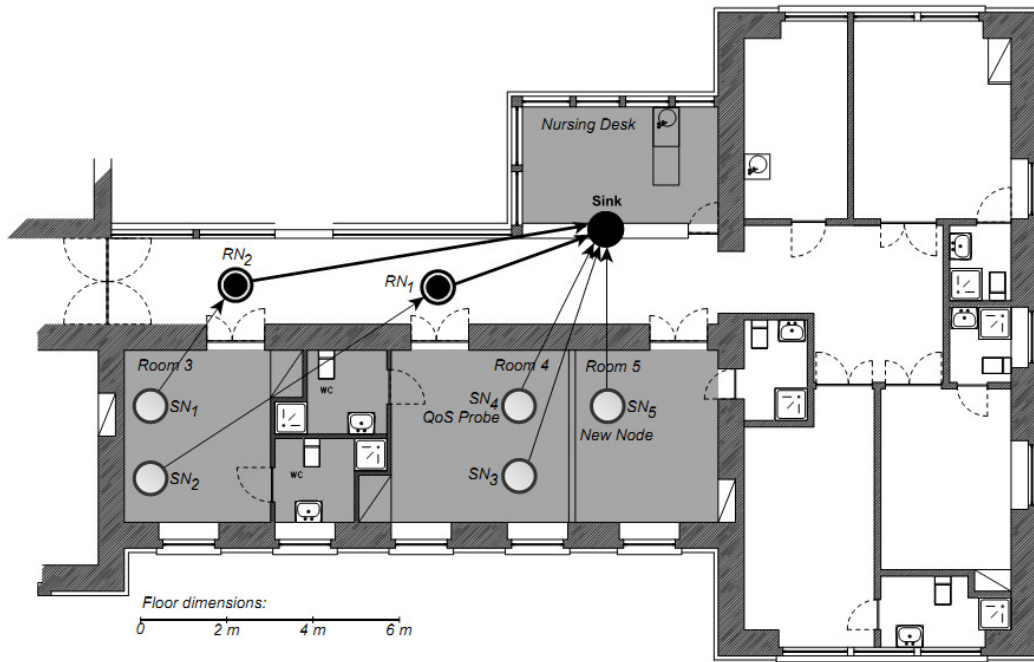


Figure 5.27 – BWSN used to monitor five patients distributed by three rooms (i.e., the rooms 3, 4 and 5). Table 5.18 shows the sink's routing table regarding this network topology.

In the course of this experiment, the  $SN_1$  sends its data to the sink through the  $RN_2$  and the  $SN_2$  uses the  $RN_1$  to forward its data packets to the sink. On its turn, the remaining sensor nodes, including the new one, send their data directly to the sink (see the Figure 5.27 and the Table 5.18 for additional information). In this particular experiment, the QoS Probe and the new sensor node (i.e., the  $SN_5$ ) do not share the same physical space (i.e., the same nursing room). Moreover, since they are in different locations, it is reasonable to expect that they experience different radio environments. Consequently, it is expectable that the QoS Probe and the  $SN_5$  do not have comparable impact on the network's performance.

Table 5.18 – The sink's routing table for the network topology pictured in the Figure 5.27.

Destination		Next hop	
Node ID:	Node IP:	Node ID:	Node IP:
$RN_1$	AAAA::0212:7400:13CB:2777	$RN_1$	FE80::0212:7400:13CB:2777
$RN_2$	AAAA::0212:7400:13CC:392F	$RN_2$	FE80::0212:7400:13CC:392F
$SN_1$	AAAA::0212:7400:13CB:3050	$RN_2$	AAAA::0212:7400:13CC:392F
$SN_2$	AAAA::0212:7400:13CB:3F66	$RN_1$	AAAA::0212:7400:13CB:2777
$SN_3$	AAAA::0212:7400:13CA:FDCA	$SN_3$	FE80::0212:7400:13CA:FDCA
$SN_4$	AAAA::0212:7400:13CA:E837	$SN_4$	FE80::0212:7400:13CA:E837
$SN_5$	AAAA::0212:7400:13CB:2128	$SN_5$	FE80::0212:7400:13CB:2128

Table 5.19 shows the results found when evaluating this scenario using the proposed method, in order to forecast if a new sensor node can be added to a BWSN considering the network topology pictured in the Figure 5.27.



Table 5.19 – Results obtained when assessing the BWSN, considering the network topology presented in the Figure 5.27.

Network Running Time (t)	Packet Reception Ratio ( $\overline{PRR} \pm \sigma$ ) %				
	$SN_1$ (Figure 5.28)	$SN_2$ (Figure 5.29)	$SN_3$ (Figure 5.30)	$SN_4$ (Figure 5.31)	New SN ( $SN_5$ ) (Figure 5.33)
$t \in [0, t_{QoS \text{ Probe ON}}]$	$97.3 \pm 2.3$	$97.7 \pm 1.9$	$98.0 \pm 0.8$	$97.7 \pm 1.0$	n.a
$t \in [t_{QoS \text{ Probe ON}}, t_{QoS \text{ Probe OFF}}]$	<b><math>97.3 \pm 3.1</math></b>	<b><math>97.9 \pm 2.4</math></b>	<b><math>91.1 \pm 1.5</math></b>	<b><math>90.8 \pm 1.8</math></b>	<b><math>92.0 \pm 2.0</math></b>
$t \in [t_{QoS \text{ Probe OFF}}, t_{New \text{ SN ON}}]$	$95.5 \pm 2.2$	$95.2 \pm 2.6$	$94.9 \pm 1.9$	$94.3 \pm 1.9$	n.a
$t \in [t_{New \text{ SN ON}}, t_{New \text{ SN OFF}}]$	<b><math>96.8 \pm 2.3</math></b>	<b><math>96.1 \pm 2.8</math></b>	<b><math>85.6 \pm 3.4</math></b>	<b><math>82.7 \pm 3.7</math></b>	<b><math>85.1 \pm 2.4</math></b>

The results of the Table 5.19 show that both the QoS Probe and the new sensor node (i.e., the  $SN_5$ ) had different impact on the PRR of each sensor node within the network. Considering the sensor nodes within the room 3 (i.e., the  $SN_1$  and the  $SN_2$ ), neither the QoS Probe nor the new sensor node had a significant impact on their PRR. On the contrary, the sensor node inside the room 4 experienced a substantial impact in their PRR during both the QoS Probe assessment period and after the admission of the new sensor node within the network.

Looking to each one of the sensor nodes individually, it is possible to see that the PRRs of both the  $SN_1$  and the  $SN_2$  are similar (see the Figure 5.28 and the Figure 5.29, respectively). Moreover, either the QoS Probe or the new sensor node had an insignificant impact on the sensor nodes' PRR. To be accurate, when started the network assessment using the QoS Probe, the  $\overline{PRR}$  of the  $SN_1$  has remained constant at around 97.3 % while the  $\overline{PRR}$  of the  $SN_2$  present a little change of about 0.2 pp. On its turn, after the addition of the new sensor node to the network, the  $\overline{PRR}$  increases from about 95.5 % to 96.8 % in the sensor node  $SN_1$  and from about 95.2 % to 96.1 % in the  $SN_2$ , which corresponds to a variation of about 1.3 pp and 0.9 pp for the  $SN_1$  and  $SN_2$ , respectively. Such behaviour can be explained by the following: the data paths used by  $SN_1$  and by the  $SN_2$  are different among them and from those used by the remaining sensor nodes, thus the data paths used by the  $SN_1$  and by the  $SN_2$  are uncongested and its performance is high. Moreover, both the QoS Probe and the new sensor node are relatively far away from both the  $SN_1$  and the  $SN_2$ , consequently these sensor nodes are not affected by the radio interferences introduced by the operation of either the QoS Probe or the new sensor node.

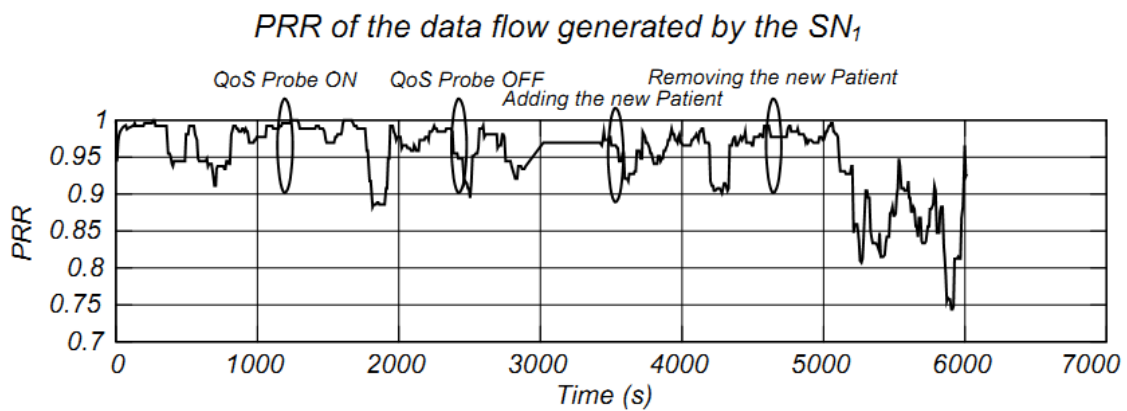


Figure 5.28 – PRR of the data flow generated by the  $SN_1$  during the admission control procedure regarding the network topology presented in the Figure 5.27.

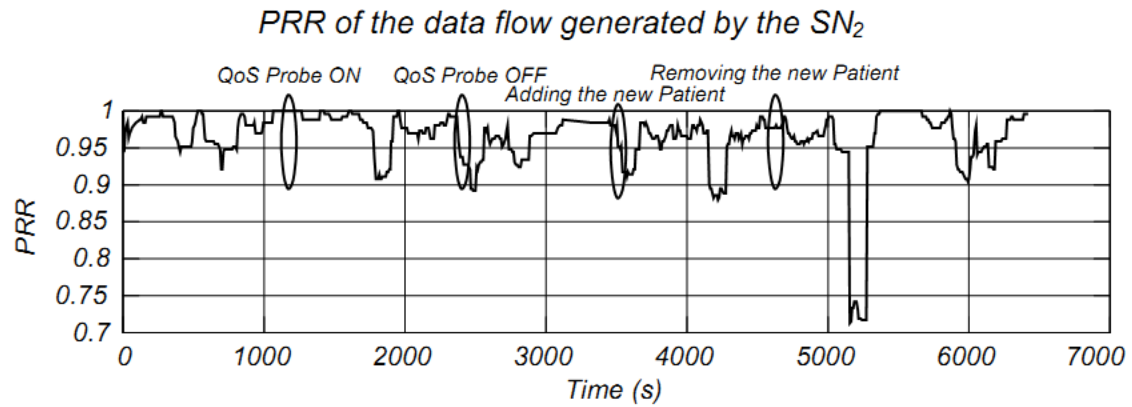


Figure 5.29 – PRR of the data flow generated by the SN<sub>2</sub> during the admission control procedure regarding the network topology presented in the Figure 5.27.

Considering the sensor nodes inside the nursing room 4, the PRR achieved by both the SN<sub>3</sub> and the SN<sub>4</sub> are pictured in the Figure 5.30 and the Figure 5.31, respectively. Analysing both PRRs, it is possible to conclude that they achieve comparable rates and have a similar behaviour. To be accurate, the  $\overline{PRR}$  of the SN<sub>3</sub> falls from about 98.0 % to 91.1 % and the  $\overline{PRR}$  of the SN<sub>4</sub> falls from about 97.7 % to 90.8 %, when the QoS Probe starts its operation which corresponds to a variation of about 6.9 pp for both the SN<sub>3</sub> and the SN<sub>4</sub>. On its turn, when the new sensor node is added to the network, the  $\overline{PRR}$  of the SN<sub>3</sub> falls from about 94.9 % to 85.6 % and the  $\overline{PRR}$  of the SN<sub>4</sub> falls from about 94.3 % to 82.7 %, which corresponds to a variation of about 9.3 pp for the SN<sub>3</sub> and of about 11.6 pp for the SN<sub>4</sub>. The SN<sub>3</sub> and the SN<sub>4</sub> share the same physical space with the QoS Probe, in this way the QoS Probe could have a significant impact in their radio environment, and contribute to a degradation on their PRR. Moreover, the QoS Probe also shares the same data path with both the SN<sub>3</sub> and the SN<sub>4</sub>, consequently this data path becomes more congested, contributing to the degradation of the PRR of all the nodes using it. On its turn, the new sensor node does not share the same room with the remaining sensor nodes. However, it is close enough to introduce significant interferences in the radio environment of the sensor nodes within the room 4. In this way, such interferences could justify part of the degradation experienced by both the SN<sub>3</sub> and the SN<sub>4</sub>. Regarding the data path used by the new sensor node, it is directly connected to the sink as both the SN<sub>3</sub> and the SN<sub>4</sub> are. As before, the new sensor node increases the occupation rate of the wireless link and the performance of the sensor nodes using it can decrease substantially.

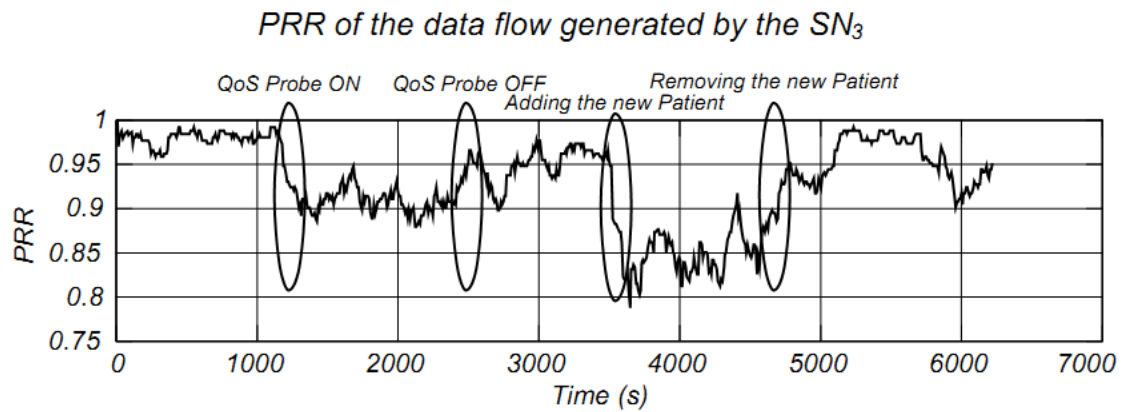


Figure 5.30 – PRR of the data flow generated by the SN<sub>3</sub> during the admission control procedure regarding the network topology presented in the Figure 5.27.

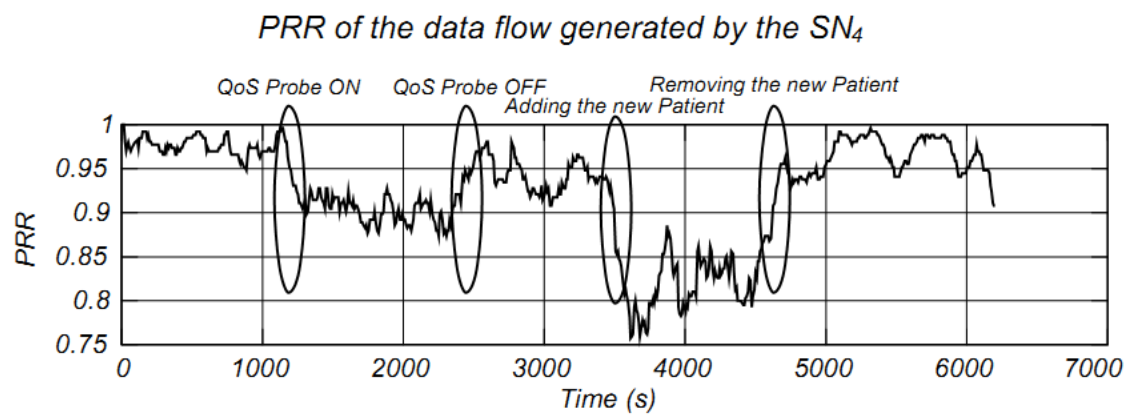


Figure 5.31 – PRR of the data flow generated by the SN<sub>4</sub> during the admission control procedure regarding the network topology presented in the Figure 5.27.

Figure 5.32 shows the PRR of the data flow produced by the QoS Probe. During the QoS Probe operation, the  $\overline{PRR}$  associated with its data flow was of about 92 %. On its turn, the  $\overline{PRR}$  of the data flow produced by the new sensor node (i.e., SN<sub>5</sub>) was of about 85.1 % (see the Figure 5.33). Since the QoS Probe and the new sensor node do not share the same nursing room, they are under different radio conditions. Thus, it is expectable that they reach different PRRs.

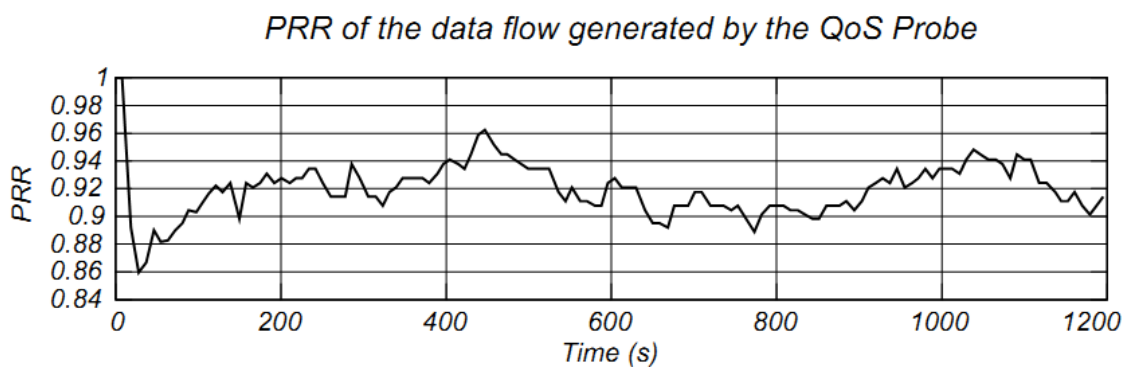


Figure 5.32 – PRR of the data flow generated by the QoS Probe during the admission control procedure regarding the network topology presented in the Figure 5.27.

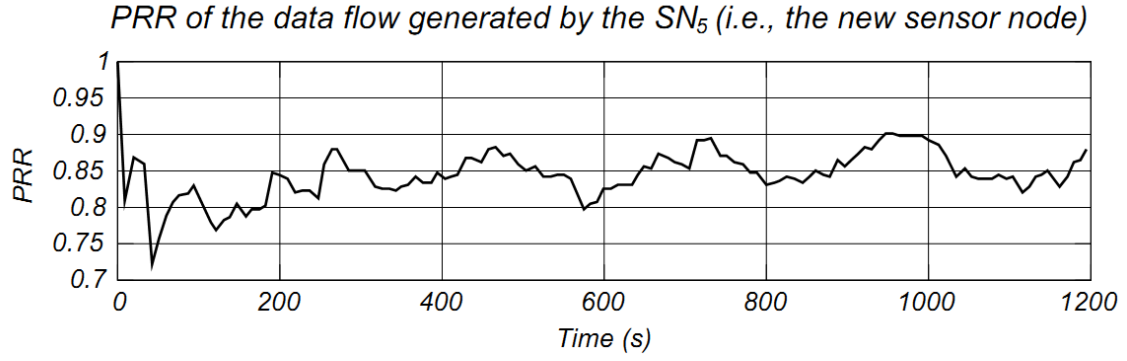


Figure 5.33 – PRR of the data flow generated by the new sensor node (i.e., the  $SN_5$ ) during the admission control procedure regarding the network topology presented in the Figure 5.27.

Comparing the  $\overline{PRR}$  of each one of the sensor nodes within the network during the QoS Probe operation (i.e.,  $t \in ]t_{\text{QoS Probe ON}}, t_{\text{QoS Probe OFF}}]$ ) and after the addition of the new sensor node (i.e.,  $t \in ]t_{\text{New SN ON}}, t_{\text{New SN OFF}}]$ ) using the percentage difference as defined in Eq. 5.2, it is possible to argue that the QoS Probe and the new sensor node (i.e.,  $SN_5$ ) affect the PRR of the sensor nodes within the network in different ways. Indeed, looking to the results presented in the Table 5.20 it becomes clear that the PRR of the sensor nodes inside the nursing room 3 (i.e., the  $SN_1$  and the  $SN_2$ ) is not affected neither by the QoS Probe nor by the new sensor node. On its turn, the sensor nodes within the nursing room 4 (i.e., the  $SN_3$  and the  $SN_4$ ) are significantly affected either by the QoS Probe and by the new sensor node; however, they are affected differently. In fact, the difference on the  $\overline{PRR}$  achieved by the  $SN_3$  and by the  $SN_4$  during the QoS Probe operation and the period after adding the new sensor node is of about 6.2 % and 9.3 %, respectively. Moreover, the  $\overline{PRR}$  achieved by the QoS Probe is not comparable with the one achieved by the new sensor node (see Table 5.20). Comparing the  $\overline{PRR}$  of each sensor node after adding the new sensor node to the network, with the  $\overline{PRR}$  achieved by the QoS Probe, it is not comparable for most of the sensor nodes (see Table 5.21). In fact, for those outside the room 3 (i.e., the  $SN_3$ , the  $SN_4$ , the  $SN_5$  and the QoS Probe) the difference in the  $\overline{PRR}$  achieved during those two periods is of about 6.2 %, 9.3 % and 7.8 % for the  $SN_3$ ,  $SN_4$  and  $SN_5$ , respectively. Taking into consideration these results, it is possible to argue that the proposed admission control method was unable to predict the impact of adding the new sensor node to the network.

Table 5.20 – Percentage difference between the  $\overline{PRR}$  of the sensor nodes regarding the assessment period and the period after the admission of the new patient (i.e., the  $SN_5$ ), considering the results of Table 5.19.

Network Running Time (t)	Packet Reception Ratio ( $\overline{PRR} \pm \sigma$ ) %				
	$SN_1$ (Figure 5.28)	$SN_2$ (Figure 5.29)	$SN_3$ (Figure 5.30)	$SN_4$ (Figure 5.31)	New SN ( $SN_5$ ) (Figure 5.33)
$t \in [t_{QoS\ Probe\ ON}, t_{QoS\ Probe\ OFF}]$	$97.3 \pm 3.1$	$97.9 \pm 2.4$	$91.1 \pm 1.5$	$90.8 \pm 1.8$	$92.0 \pm 2.0$ n.a
$t \in [t_{New\ SN\ ON}, t_{New\ SN\ OFF}]$	$96.8 \pm 2.3$	$96.1 \pm 2.8$	$85.6 \pm 3.4$	$82.7 \pm 3.7$	n.a $85.1 \pm 2.4$
Percentage difference using the $\overline{PRR}$ of each SN	<b>0.5 %</b>	<b>1.9 %</b>	<b>6.2 %</b>	<b>9.3 %</b>	<b>7.8 %</b>

Table 5.21 – Percentage difference between the  $\overline{PRR}$  of each sensor node after the admission of the new patient and the  $\overline{PRR}$  achieved by the QoS Probe, considering the results of Table 5.19.

	<b>Packet Reception Ratio (<math>\overline{PRR}</math>)</b>				
	$SN_1$	$SN_2$	$SN_3$	$SN_4$	New SN ( $SN_5$ )
$\overline{PRR}$ of each SN after the admission of the new SN	96.8 %	96.1 %	85.6 %	82.7 %	85.1 %
$\overline{PRR}$ of the QoS Probe	92 %	92 %	92 %	92 %	92 %
Percentage difference	<b>5.1 %</b>	<b>4.4 %</b>	<b>7.2 %</b>	<b>10.6 %</b>	<b>7.8 %</b>

In view of the results obtained during this particular experiment, and considering the scenario and network topology pictured in the Figure 5.27, it is possible to conclude that the proposed QoS-based admission control method was unable to predict the impact of adding a new sensor node to the network. Thus, the answer to the question Q. 5.3 is negative and the hypothesis H. 5.1 is considered to be false in this case.

#### 5.2.4. Discussion

The suggested QoS-based admission control method was assessed by carrying out several experiments in three different scenarios, as just described. From the first scenario, it is possible to conclude that the proposed method can be used if the QoS Probe does not have a significant impact in the network performance, or having a significant impact in the network's performance, the QoS Probe and the new real sensor node share the same physical space and the data produced by both follow the same path to reach the sink. On its turn, considering the second scenario, the proposed method can be used if the following conditions are observed: the QoS Probe has a significant impact in the performance of the network, the QoS Probe and the new real sensor node share the same physical space and, the data produced by both the QoS Probe and the new real sensor node follow the same path to reach the sink. Finally, regarding the third scenario, it is possible to conclude that the proposed method cannot be used if the QoS Probe and the new real sensor node do not share the same physical space.

Considering the results found from the previous experiments, which are summarised in the Table 5.22 in a comprehensive way, it is possible to argue that, the proposed QoS-based admission control method can be used to predict the impact of adding a new sensor node to a BWSN in the following conditions:

1. The “virtual sensor node” and the new real sensor node have to share the same physical space;
2. The data produced by both the “virtual sensor node” and the new real sensor node, must follow the same path to reach the sink.

Table 5.22 – Results summary in view of the evaluation of the proposed admission control method.

	<b>Network Covering One Room</b>		<b>Network Covering Two Rooms</b>		<b>Network Covering Three Rooms</b>
	Using the same data path	Using different data paths	Using different data paths	Using the same data path	Using different data paths
Do the QoS Probe and the new sensor node share the same physical space?	Yes	Yes	Yes	Yes	No
Do the data produced by the QoS Probe and by the new sensor node follow the same path to the sink?	Yes	No	No	Yes	Yes
Has the QoS Probe a significant impact on the network performance?	Yes	No	Yes	Yes	Yes
Have the QoS Probe and the new sensor node a comparable impact on the network performance, and is the hypothesis H. 5.1 true?	<b>Yes</b>	<b>Yes</b>	No	<b>Yes</b>	No

### 5.3. Summary

This chapter described the real-world tests made to assess the QoS-based admission control module proposed. First, the detailed study made to understand the network deployment environment and its characteristics, as well as the initial network deployment, were explained in detail. Then, the experiments performed to assess the QoS-based admission control modules were explained and analysed in detail. Those experiments were made in three distinct scenarios, comprising several network topologies. Finally, in view of the results obtained, significant conclusions were drawn. In particular, were identified the conditions in which the proposed QoS-based admission control method can be employed.



## **Conclusions and Future Work**

Key Findings and Promising Directions

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6.1. Conclusions

6.2. Future work

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## **6. Conclusions and Future Work**

This chapter condenses the motivation, objectives, contributions and conclusions of this thesis. It also suggests promising directions for future research.

### **6.1. Conclusions**

Wireless sensor networks combined with low-power sensor devices, have the potential to integrate the physical world with widely used computing systems. Furthermore, such networks can be used to create ubiquitous and pervasive intelligent systems with the potential to greatly impact our daily lives. Among all the application areas of the wireless sensor network, the healthcare is one of the most promising. In particular, concerning its potential to change not only the today's healthcare services provided to the citizens but also the clinical practice. The use of WSNs in healthcare brings several advantages, in particular as regards to the automation of routine processes such as periodic patient monitoring. Automatic patient monitoring systems can be used to complement the episodic measurements made by the healthcare professionals (e.g., body temperature, pulse and respiratory rates, blood pressure or oximetry), bringing out an enhancement of the quality of care, while freeing the nursing staff to provide extra attention to the patients.

Nevertheless, due to the demanding requirements of healthcare services and applications, WSNs have to fulfil high levels of quality of service (QoS) to be fully accepted by the healthcare professionals and patients. As an effort to provide healthcare professionals with a tool to manage such networks, bearing in mind the objective of maximising the QoS provided by WSNs supporting patient monitoring applications, this thesis proposes a new QoS-based network management method able to both monitor the effective QoS provided by the network and manage the admission of new nodes to the network.

The proposed QoS-based network management method consists of two modules, namely the QoS monitoring module and the QoS-based admission control module. The QoS monitoring module uses a time-domain mathematical framework to detect and classify potential QoS degradation events on its very beginning, even before they can worsen the QoS provided by the network to levels below the limits required by the applications using the WSN. To the best of our knowledge, this is a distinctive characteristic when comparing the proposed QoS monitoring

module with the ones existing on the market, in special, targeting WSNs. By detecting and classifying potential QoS degradation events on its very beginning, the QoS monitoring module is able to alert the network administrator to take the necessary measures to ensure the proper operation of the WSN.

On its turn, the QoS-based admission control module makes use of a “virtual sensor node” to verify if a new patient (i.e., a new sensor node) can be added to the network and decides which would be the best place to admit the new patient into the network. The use of a “virtual sensor node” avoids the necessity of the new patient to be physically present within the network and enables to assess the on-the-fly QoS provided by the network from a remote location. By using a “virtual sensor node”, the admission control module enables the network administrator (n.b., the figure of the network administrator must be seen in a broad sense since it could be either a person or a virtual process) to estimate the presence of a real sensor node within the network from a remote location. This characteristic gives the proposed method an innovative feel, when comparing it with other proposals. Moreover, the possibility to know in advance the best location to place a patient gives the healthcare providers an important tool to optimise their work and organizational processes.

The suggested QoS-based network management method was widely tested using both simulated and real-world environments. Due to its flexibility and facility of use (including the possibility to repeat the experiments in the exact same conditions), simulated environments were extensively used in this work, in particular during the development stage. At this point, it was necessary to choose the network simulator and operating system carefully. The choice has fallen on both the COOJA network simulator and hardware emulator, and on the Contiki OS. By choosing a network simulator and hardware emulator, the time to implement real word applications decreases dramatically since the code used within the simulator environment is the same used in the real-world applications. Such working method has proven to be effective improving outcomes. Regarding real-world deployments, they are fundamental to validate and to test the strength of new solutions. However, such deployments are very hard to manage and control. Indeed, it is necessary to have a deep knowledge about the deployment area, in particular, regarding the following aspects: what the obstacles present inside the development area are, if there are other wireless technologies inside the development area, if there are persons walking around the development area, or if there are other equipment or machinery able to cause electromagnetic

interferences. In other words, it is necessary to study the development area, before the network deployment, and identify risk factors able to decrease the QoS provided by the network.

The results obtained using both simulated and real environments, have endorsed the QoS-based proposed QoS-based network management method. In particular, the QoS monitoring module was validated based on several simulation tests. On its turn, the admission control module and particularly the concept of “virtual sensor node” were validated using both simulated and real-world deployments.

The QoS monitoring module was able to detect and classify potential QoS degradation events. Moreover, by using not only the metrics value but also its behaviour and tendency, the QoS monitoring module have proved to be able to detect and classify potential QoS degradation events even before the QoS metric in cause reaches critical values. This ability can be used to fire warning messages, providing the network administrator with valuable information to prevent the network malfunction.

Regarding the QoS-based admission control module, it is possible to outcome that the proposed method, based on the use of a “virtual sensor node” to predict the behaviour of the network when introducing the new sensor node, was successfully validated under the following conditions:

1. The “virtual sensor node” and the new real sensor node have to share the same physical space;
2. The data produced by both the “virtual sensor node” and the new real sensor node, must follow the same path to reach the sink.

In summary, the proposed QoS-based network management method was clearly presented and validated using different scenarios. Finally, the conditions necessary to its use were clearly presented.

## **6.2. Future Work**

There are some interesting directions to explore the possibility of developing and implementing innovative tools using the QoS-based network management method presented in this thesis, one of which is its implementation using multiple QoS metrics such as, the E2E delay and the delay variation (i.e., jitter), in addition to the already tested PRR. Managing the network taking into

consideration several metrics, improves the network administrator knowledge about the network behaviour and performance. Being aware of such information is vital to keep the network within the QoS limits required by the applications using it.

Regarding the concept of “virtual sensor node”, introduced by this thesis, it could be further improved. In particular, its ability to generate asynchronous data traffic from multiple sensors considering its statistic properties must be improved. Another aspect regarding the “virtual sensor node” execution that is worthy of attention is the competition for the hardware resources existing in the real sensor node, in particular the concurrent access to the radio interface.

Other important possibility to continue the work presented in this thesis towards the development of new managing tools, integrating the proposed QoS-based network management method with existing information and communication systems. Such tools must provide clear and user friendly interfaces in order to facilitate its use by the healthcare professionals.

# Appendix A

## List of Publications

### Patents, Journals, Books, Conferences

Here is a list of publications that reflects the results achieved during the development of these research work.

#### Patents

Abreu, C and Mendes, P. *Sistema de monitorização de qualidade de serviço e controlo de admissão em redes de sensores sem fios e respetivo método. Pedido provisório PT 106740.*

#### Journals

Abreu, C.; Ricardo, M.; Mendes, P. Energy-Aware Routing for Biomedical Wireless Sensor Networks. *Journal of Networking and Computer Applications*, 40(0), 270-278, 2014. (Impact Factor: 1.467).

Abreu, C.; Miranda, F.; Ricardo, M.; Mendes, P. QoS-Based Management of Biomedical Wireless Sensor Networks for Patient Monitoring. In *SpringerPlus*. 2014. (Publication fee waived!).

#### Contributions to Books

Abreu, C.; P.M. Mendes, F. Miranda, F. (Ed.). *Systems Theory: Perspectives, Applications and Developments. Providing QoS in Wireless Sensor Networks: A System Overview*. Nova Science Publishers, Inc., 2014.

#### Conferences

Abreu, C.; Miranda F.; Mendes, P. Estimating the Impact of Adding Sensor Nodes to Biomedical Wireless Sensor Networks. *International Conference of Numerical Analysis and Applied Mathematics 2014 (ICNAAM 2014)*, Rhodes, Greece, 22-28 September 2014. (Extended Abstract) (Accepted)

Abreu, C.; Mendes, P. End-to-End Quality of Service-Based Admission Control via Virtual Sensor Nodes. In the *IFMBE International Conference on Health Informatics*. Vilamoura, Algarve, Portugal, 7-9 November 2013.

Abreu, C.; Mendes, P. Deployment of Wireless Sensor Networks for Biomedical Applications – Quality of Service Improvement through Network Lifetime-Extending. In the IEEE 15<sup>th</sup> International Conference on e-Health Networking, Applications and Services (Healthcom). Lisbon, Portugal, 9-12 October 2013.

Abreu, C.; Mendes, P. Wireless Sensor Networks for Biomedical Applications - Quality of Service, Admission Control and Lifetime-Extending Challenges. In 3rd Portuguese Bioengineering Meeting. Braga, Portugal, 20-22 February 2013.

Abreu, C.; Mendes, P.; Ricardo, M. Framework for QoS Performance Assessment on Biomedical Wireless Sensor Networks. In BIODEVICES2012: International Conference on Biomedical Electronics and Devices. Vilamoura, Algarve, Portugal, 1-4 February 2012. (Short Paper)

Abreu, C.; Mendes, P.; Ricardo, M. Monitoring QoS Over Wireless Sensor Networks: For Medical Applications. In BIODEVICES2011: International Conference on Biomedical Electronics and Electronics and Devices. Rome, Italy, 26-29 January 2011. (Poster)

### **Invited Paper**

Abreu, C.; Mendes, P. Extending Lifetime of Biomedical Wireless Sensor Networks using Energy-aware Routing and Relay Nodes. Submitted to the International Journal of E-Health and Medical Communications.



# Bibliography

- [1] I.F. Akyildiz, Weilian Su, Y. Sankarasubramaniam, and E. Cayirci, "A Survey on Sensor Networks," *Communications Magazine, IEEE*, vol. 40, no. 8, pp. 102-114, August 2002.
- [2] JeongGil Ko et al., "Wireless Sensor Networks for Healthcare," *Proceedings of the IEEE*, vol. 98, no. 11, pp. 1947-1960, November 2010.
- [3] Shekhar Borkar and Andrew A. Chien, "The Future of Microprocessors," *Commun. ACM*, vol. 54, no. 5, pp. 67-77, May 2011.
- [4] Xiaofan Jiang, Joseph Polastre, and David Culler, "Perpetual environmentally powered sensor networks," in *Proceedings of the 4th international symposium on Information processing in sensor networks*, Piscataway, NJ, USA, 2005.
- [5] K.J. Vinoy and T.V. Prabhakar, "A Universal Energy Harvesting Scheme for Operating Low-Power Wireless Sensor Nodes Using Multiple Energy Resources," in *Micro and Smart Devices and Systems*, K. J. Vinoy et al., Eds.: Springer India, 2014, pp. 453-466.
- [6] Mohamed Younis, Izzet F. Senturk, Kemal Akkaya, Sookyoung Lee, and Fatih Senel, "Topology management techniques for tolerating node failures in wireless sensor networks: A survey," *Computer Networks*, vol. 58, no. 0, pp. 254-283, 2014.
- [7] M. Conti and S. Giordano, "Mobile ad hoc networking: milestones, challenges, and new research directions," *Communications Magazine, IEEE*, vol. 52, no. 1, pp. 85-96, January 2014.
- [8] Hande Alemdar and Cem Ersoy, "Wireless sensor networks for healthcare: A survey," *Computer Networks*, 2010.
- [9] Farid Touati and Rohan Tabish, "U-Healthcare System: State-of-the-Art Review and Challenges," *Journal of Medical Systems*, vol. 37, no. 3, pp. 1-20, 2013.
- [10] Pedro José Marron, Stamatis Karnouskos and Daniel Minder, and Aníbal Ollero, Eds., *The Emerging Domain of Cooperating Objects.*: Springer Berlin Heidelberg, 2011.
- [11] Jaime Chen, Manuel Díaz, Luis Llopis, Bartolomé Rubio, and José M. Troya, "A survey on quality of service support in wireless sensor and actor networks: Requirements and challenges in the context of critical infrastructure protection," *Journal of Network and Computer Applications*, vol. 34, no. 4, pp. 1225-1239, 2011, Advanced Topics in Cloud

Computing.

- [12] Nouha Baccour et al., "Radio link quality estimation in wireless sensor networks: A survey," *ACM Trans. Sen. Netw.*, vol. 8, no. 4, pp. 34:1–34:33, Sep. 2012.
- [13] S. Pakzad, G. Fenves, S. Kim, and D. Culler, "Design and Implementation of Scalable Wireless Sensor Network for Structural Monitoring," *Journal of Infrastructure Systems*, vol. 14, no. 1, pp. 89-101, 2008.
- [14] "Systems and software engineering – Vocabulary," *ISO/IEC/IEEE 24765:2010(E)*, pp. 1-418, December 2010.
- [15] Yanjun Li, Chung Shue Chen, Ye-Qiong Song, and Zhi Wang, "Real-time QoS support in wireless sensor networks: a survey," in *7th IFAC International Conference on Fieldbuses & Networks in Industrial & Embedded Systems - FeT2007*,
- [16] Yinsheng Xu et al., "Real-time Routing in Wireless Sensor Networks: A Potential Field Approach," *ACM Trans. Sen. Netw.*, vol. 9, no. 3, pp. 35:1–35:24, June 2013.
- [17] Jayavardhana Gubbi, Rajkumar Buyya, Slaven Marusic, and Marimuthu Palaniswami, "Internet of Things (IoT): A vision, architectural elements, and future directions ," *Future Generation Computer Systems* , vol. 29, no. 7, pp. 1645-1660, 2013, Including Special sections: Cyber-enabled Distributed Computing for Ubiquitous Cloud and Network Services & Cloud Computing and Scientific Applications — Big Data, Scalable Analytics, and Beyond.
- [18] J.M.L.P. Caldeira, J.J.P.C. Rodrigues, and P. Lorenz, "Toward ubiquitous mobility solutions for body sensor networks on healthcare," *Communications Magazine, IEEE*, vol. 50, no. 5, pp. 108-115, 2012.
- [19] M. Ali, T. Suleman, and Z.A. Uzmi, "MMAC: a mobility-adaptive, collision-free MAC protocol for wireless sensor networks," in *Performance, Computing, and Communications Conference, 2005. IPCCC 2005. 24th IEEE International*, 2005, pp. 401-407.
- [20] Qian Dong and W. Dargie, "A Survey on Mobility and Mobility-Aware MAC Protocols in Wireless Sensor Networks," *Communications Surveys Tutorials, IEEE*, vol. 15, no. 1, pp. 88-100, 2013.
- [21] Matthias Grossglauser and D.N.C. Tse, "Mobility increases the capacity of ad hoc wireless networks," *Networking, IEEE/ACM Transactions on*, vol. 10, no. 4, pp. 477-486, 2002.
- [22] GetsyS Sara and D. Sridharan, "Routing in mobile wireless sensor network: a survey," *Telecommunication Systems*, pp. 1-29, 2013.

- [23] Said Ould Amara, Rachid Beghdad, and Mourad Oussalah, "Securing Wireless Sensor Networks: A Survey," *EDPACS*, vol. 47, no. 2, pp. 6-29, 2013.
- [24] K. Romer and F. Mattern, "The design space of wireless sensor networks," *Wireless Communications, IEEE*, vol. 11, no. 6, pp. 54-61, 2004.
- [25] Jeonggil Ko et al., "ContikiRPL and TinyRPL: Happy Together," in *Proceedings of the workshop on Extending the Internet to Low power and Lossy Networks (IPSN 2011)*, Chicago, IL, USA, #APR# 2011.
- [26] Carlos Abreu, Manuel Ricardo, and P.M. Mendes, "Energy-aware routing for biomedical wireless sensor networks," *Journal of Network and Computer Applications*, no. 0, pp. - , 2013.
- [27] Giuseppe Anastasi, Marco Conti, Mario Di Francesco, and Andrea Passarella, "Energy conservation in wireless sensor networks: A survey," *Ad Hoc Networks*, vol. 7, no. 3, pp. 537-568, 2009.
- [28] Jennifer Yick, Biswanath Mukherjee, and Dipak Ghosal, "Wireless Sensor Network Survey," *Computer Networks*, vol. 52, no. 12, pp. 2292-2330, 2008.
- [29] Chonggang Wang, K. Sohraby, Bo Li, M. Daneshmand, and Yueming Hu, "A survey of transport protocols for wireless sensor networks," *Network, IEEE*, vol. 20, no. 3, pp. 34-40, 2006.
- [30] A. J D Rathnayaka, V.M. Potdar, A. Sharif, S. Sarencheh, and S. Kuruppu, "Wireless Sensor Network Transport Protocol - A State of the Art," in *Broadband, Wireless Computing, Communication and Applications (BWCCA), 2010 International Conference on*, 2010, pp. 812-817.
- [31] Y.G. Iyer, S. Gandham, and S. Venkatesan, "STCP: a generic transport layer protocol for wireless sensor networks," in *Computer Communications and Networks, 2005. ICCCN 2005. Proceedings. 14th International Conference on*, 2005, pp. 449-454.
- [32] Seung-Jong Park, Ramanuja Vedantham, Raghupathy Sivakumar, and Ian F. Akyildiz, "A Scalable Approach for Reliable Downstream Data Delivery in Wireless Sensor Networks," in *Proceedings of the 5th ACM International Symposium on Mobile Ad Hoc Networking and Computing*, New York, NY, USA, 2004, pp. 78-89.
- [33] V.C. Gungor and O.B. Akan, "DST: delay sensitive transport in wireless sensor networks," in *Computer Networks, 2006 International Symposium on*, 2006, pp. 116-122.
- [34] Yogesh Sankarasubramaniam, \", and Ian F. Akyildiz, "ESRT: Event-to-sink Reliable Transport in Wireless Sensor Networks," in *Proceedings of the 4th ACM International*

*Symposium on Mobile Ad Hoc Networking & Computing*, New York, NY, USA, 2003, pp. 177-188.

- [35] F.K. Shaikh, A. Khelil, A. Ali, and N. Suri, "TRCCIT: Tunable reliability with Congestion Control for Information Transport in Wireless Sensor Networks," in *Wireless Internet Conference (WICON), 2010 The 5th Annual ICST*, 2010, pp. 1-9.
- [36] Vehbi Cagri Gungor, and Ian F. Akyildiz, A Real-time and Reliable Transport (RT) 2 Protocol for Wireless Sensor and Actor Networks," *IEEE/ACM Trans. Netw.*, vol. 16, no. 2, pp. 359-370, April 2008.
- [37] Nurcan Tezcan and Wenye Wang, ART an Asymmetric and Reliable Transport Mechanism for Wireless Sensor Networks, *Int. J. Sen. Netw.*, vol. 2, no. 3/4, pp. 188-200, April 2007.
- [38] Tuan Le, Wen Hu, Peter Corke, and Sanjay Jha, "ERTP: Energy-efficient and Reliable Transport Protocol for data streaming in Wireless Sensor Networks ," *Computer Communications* , vol. 32, no. 7–10, pp. 1154-1171, 2009.
- [39] Muhammad Mostafa Monowar, Md. Obaidur Rahman, Al-Sakib Khan Pathan, and Choong Seon Hong, "Congestion Control Protocol for Wireless Sensor Networks Handling Prioritized Heterogeneous Traffic," in *Proceedings of the 5th Annual International Conference on Mobile and Ubiquitous Systems: Computing, Networking, and Services*, ICST, Brussels, Belgium, Belgium, 2008, pp. 17:1–17:8.
- [40] Cheng Tien Ee and Ruzena Bajcsy, "Congestion Control and Fairness for Many-to-one Routing in Sensor Networks," in *Proceedings of the 2Nd International Conference on Embedded Networked Sensor Systems*, New York, NY, USA, 2004, pp. 148-161.
- [41] J.W. Hui and D.E. Culler, "IPv6 in Low-Power Wireless Networks," *Proceedings of the IEEE*, vol. 98, no. 11, pp. 1865-1878, November 2010.
- [42] A.J.Dinusha Rathnayaka and Vidyasagar M. Potdar, "Wireless Sensor Network transport protocol: A critical review ," *Journal of Network and Computer Applications* , vol. 36, no. 1, pp. 134-146, 2013.
- [43] Muhammad Mahbub ALAM and Choong Seon HONG, "CRRT: Congestion-Aware and Rate-Controlled Reliable Transport in Wireless Sensor Networks," *IEICE Transactions on Communications*, vol. E92.B, no. 1, pp. 184-199, 2009.
- [44] E. Giancoli, F. Jabour, and A. Pedroza, "CTCP: Reliable Transport Control Protocol for sensor networks," in *Intelligent Sensors, Sensor Networks and Information Processing, 2008. ISSNIP 2008. International Conference on*, 2008, pp. 493-498.

- [45] Kemal Akkaya and Mohamed Younis, "A survey on routing protocols for wireless sensor networks," *Ad Hoc Networks*, vol. 3, no. 3, pp. 325-349, 2005.
- [46] Adamu Murtala Zungeru, Li-Minn Ang, and Kah Phooi Seng, "Classical and swarm intelligence based routing protocols for wireless sensor networks: A survey and comparison," *Journal of Network and Computer Applications*, vol. 35, no. 5, pp. 1508-1536, 2012, Service Delivery Management in Broadband Networks.
- [47] S. Ehsan and B. Hamdaoui, "A Survey on Energy-Efficient Routing Techniques with QoS Assurances for Wireless Multimedia Sensor Networks," *IEEE Communications Surveys & Tutorials*, no. 99, pp. 1-14, 2011, Early Access.
- [48] O. Tavallaie, H.R. Naji, M. Sabaei, and N. Arastouie, "Providing QoS guarantee of timeliness in wireless sensor networks with a new routing methodology," in *Telecommunications (IST), 2012 Sixth International Symposium on*, 2012, pp. 674-679.
- [49] JeongGil Ko, Tia Gao, R. Rothman, and A. Terzis, "Wireless Sensing Systems in Clinical Environments: Improving the Efficiency of the Patient Monitoring Process," *Engineering in Medicine and Biology Magazine, IEEE*, vol. 29, no. 2, pp. 103-109, march-april 2010.
- [50] Tao Liu, Qingrui Li, and Ping Liang, "An energy-balancing clustering approach for gradient-based routing in wireless sensor networks," *Computer Communications*, July 2012.
- [51] José Cecilio, João Costa, and Pedro Furtado, "Survey on Data Routing in Wireless Sensor Networks," in *Wireless Sensor Network Technologies for the Information Explosion Era*, Takahiro Hara, Vladimirl. Zadorozhny, and Erik Buchmann, Eds.: Springer Berlin Heidelberg, 2010, vol. 278, pp. 3-46.
- [52] Jun Zheng and Abbas Jamalipour, *Wireless Sensor Networks: A Networking Perspective*: Wiley-IEEE Press, October 2009.
- [53] Joanna Kulik, Wendi Heinzelman, and Hari Balakrishnan, "Negotiation-based Protocols for Disseminating Information in Wireless Sensor Networks," *Wirel. Netw.*, vol. 8, no. 2/3, pp. 169-185, March 2002.
- [54] Wendi Rabiner Heinzelman, Joanna Kulik, and Hari Balakrishnan, "Adaptive Protocols for Information Dissemination in Wireless Sensor Networks," in *Proceedings of the 5th Annual ACM/IEEE International Conference on Mobile Computing and Networking*, New York, NY, USA, 1999, pp. 174-185.
- [55] Chalermek Intanagonwiwat, Ramesh Govindan, Deborah Estrin, John Heidemann, and Fabio Silva, "Directed Diffusion for Wireless Sensor Networking," *IEEE/ACM Trans. Netw.*, vol. 11, no. 1, pp. 2-16, February 2003.

- [56] R.C. Shah and J.M. Rabaey, "Energy aware routing for low energy ad hoc sensor networks," in *Wireless Communications and Networking Conference, 2002. WCNC2002. 2002 IEEE*, vol. 1, mar 2002, pp. 350 - 355 vol.1.
- [57] David Braginsky and Deborah Estrin, "Rumor Routing Algorithm for Sensor Networks," in *Proceedings of the 1st ACM International Workshop on Wireless Sensor Networks and Applications*, New York, NY, USA, 2002, pp. 22-31.
- [58] Maurice Chu, Horst Haussecker, and Feng Zhao, "Scalable Information-Driven Sensor Querying and Routing for Ad Hoc Heterogeneous Sensor Networks," *International Journal of High Performance Computing Applications*, vol. 16, no. 3, pp. 293-313, 2002.
- [59] Yong Yao and Johannes Gehrke, "The Cougar Approach to In-network Query Processing in Sensor Networks," *SIGMOD Rec.*, vol. 31, no. 3, pp. 9-18, Sep. 2002.
- [60] Shio Kumar Singh, MP Singh, DK Singh, and others, "Routing protocols in wireless sensor networks—A survey," *International Journal of Computer Science & Engineering Survey (IJCSES) Vol*, vol. 1, pp. 63-83, 2010.
- [61] C. Schurgers and M.B. Srivastava, "Energy efficient routing in wireless sensor networks," in *Military Communications Conference, 2001. MILCOM 2001. Communications for Network-Centric Operations: Creating the Information Force. IEEE*, vol. 1, 2001, pp. 357-361 vol.1.
- [62] N. Sadagopan, B. Krishnamachari, and A. Helmy, "The ACQUIRE mechanism for efficient querying in sensor networks," in *Sensor Network Protocols and Applications, 2003. Proceedings of the First IEEE. 2003 IEEE International Workshop on*, 2003, pp. 149-155.
- [63] Wendi Rabiner Heinzelman, Anantha Chandrakasan, and Hari Balakrishnan, "Energy-Efficient Communication Protocol for Wireless Microsensor Networks," in *Proceedings of the 33rd Hawaii International Conference on System Sciences-Volume 8 - Volume 8*, Washington, DC, USA, 2000, pp. 8020.
- [64] L. Subramanian and R.H. Katz, "An architecture for building self-configurable systems," in *Mobile and Ad Hoc Networking and Computing, 2000. MobiHOC. 2000 First Annual Workshop on*, 2000, pp. 63-73.
- [65] Arati Manjeshwar and D.P. Agrawal, "TEEN: a routing protocol for enhanced efficiency in wireless sensor networks," in *Parallel and Distributed Processing Symposium., Proceedings 15th International*, April 2001, pp. 2009-2015.
- [66] S. Lindsey and C.S. Raghavendra, "PEGASIS: Power-efficient gathering in sensor information systems," in *Aerospace Conference Proceedings, 2002. IEEE*, vol. 3, 2002, pp. 3-1125 - 3-1130 vol.3.

- [67] A Manjeshwar and DP Agrawal, "APTEEN: a hybrid protocol for efficient routing and comprehensive information retrieval in wireless sensor networks," in *Parallel and Distributed Processing Symposium., Proceedings International, IPDPS 2002, Abstracts and CD-ROM*, 2002, pp. 195-202.
- [68] O. Younis and Sonia Fahmy, "HEED: a hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks," *Mobile Computing, IEEE Transactions on*, vol. 3, no. 4, pp. 366-379, October 2004.
- [69] M. Younis, M. Youssef, and K. Arisha, "Energy-aware routing in cluster-based sensor networks," in *Modeling, Analysis and Simulation of Computer and Telecommunications Systems, 2002. MASCOTS 2002. Proceedings. 10th IEEE International Symposium on*, 2002, pp. 129-136.
- [70] Xiaoyan Cui and Zhao Liu, "BCEE: A balanced-clustering, energy-efficient hierarchical routing protocol in Wireless Sensor Networks," in *Network Infrastructure and Digital Content, 2009. IC-NIDC 2009. IEEE International Conference on*, Nov 2009, pp. 26-30.
- [71] Haojun Huang, Guangmin Hu, and Fucui Yu, "Energy-aware geographic routing in wireless sensor networks with anchor nodes," *International Journal of Communication Systems*, vol. 26, no. 1, pp. 100-113, 2013.
- [72] Haibo Zhang and Hong Shen, "Energy-Efficient Beaconless Geographic Routing in Wireless Sensor Networks," *Parallel and Distributed Systems, IEEE Transactions on*, vol. 21, no. 6, pp. 881-896, June 2010.
- [73] Y. Yu, R. Govindan, and D. Estrin, "Geographical and Energy Aware Routing: a recursive data dissemination protocol for wireless sensor networks," *Energy*, vol. 463, 2001.
- [74] Badri Nath and Drago\c, "Routing on a Curve," *SIGCOMM Comput. Commun. Rev.*, vol. 33, no. 1, pp. 155-160, January 2003.
- [75] Adel Gaafar A.Elrahim, Hussein A.Elsayed, Salwa El Ramly, and Magdy M. Ibrahim, "An Energy Aware WSN Geographic Routing Protocol," *Universal Journal of Computer Science and Engineering Technology*, vol. 1, no. 2, pp. 105-111, November 2010.
- [76] Ya Xu, John Heidemann, and Deborah Estrin, "Geography-informed energy conservation for Ad Hoc routing," in *Proceedings of the 7th annual international conference on Mobile computing and networking*, New York, NY, USA, 2001, pp. 70-84.
- [77] Li Li and J.Y. Halpern, "Minimum-energy mobile wireless networks revisited," in *Communications, 2001. ICC 2001. IEEE International Conference on*, vol. 1, 2001, pp. 278-283 vol.1.

- [78] GM Shafiullah, Amoakoh Gyasi-Agyei, and PeterJ Wolfs, "A Survey of Energy-Efficient and QoS-Aware Routing Protocols for Wireless Sensor Networks," in *Novel Algorithms and Techniques In Telecommunications, Automation and Industrial Electronics*, Tarek Sobh et al., Eds.: Springer Netherlands, 2008, pp. 352-357.
- [79] Konstantinos Kalpakis, Koustuv Dasgupta, and Parag Namjoshi, "Maximum lifetime data gathering and aggregation in wireless sensor networks," *Proceedings of IEEE Networks*, vol. 2, pp. 685-696, 2002.
- [80] K. Sohrabi, J. Gao, V. Ailawadhi, and G.J. Pottie, "Protocols for self-organization of a wireless sensor network," *Personal Communications, IEEE*, vol. 7, no. 5, pp. 16-27, October 2000.
- [81] Jae-Hwan Chang and Leandros Tassiulas, "Maximum Lifetime Routing in Wireless Sensor Networks," *IEEE/ACM Trans. Netw.*, vol. 12, no. 4, pp. 609-619, August 2004.
- [82] Tian He, J.A. Stankovic, Chenyang Lu, and T. Abdelzaher, "SPEED: a stateless protocol for real-time communication in sensor networks," in *Distributed Computing Systems, 2003. Proceedings. 23rd International Conference on*, May 2003, pp. 46-55.
- [83] K. Akkaya and M. Younis, "An energy-aware QoS routing protocol for wireless sensor networks," in *Distributed Computing Systems Workshops, 2003. Proceedings. 23rd International Conference on*, 19-22 2003, pp. 710-715.
- [84] Ying Zhang and M. Fromherz, "Message-initiated constraint-based routing for wireless ad-hoc sensor networks," in *Consumer Communications and Networking Conference, 2004. CCNC 2004. First IEEE*, January 2004, pp. 648-650.
- [85] C. Perkins, E. Belding-Royer, and S. Das, Ad hoc On-Demand Distance Vector (AODV) Routing, July 2003.
- [86] T. Winter et al., RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks, March 2012.
- [87] E. Ancillotti, R. Bruno, and M. Conti, "The role of the RPL routing protocol for smart grid communications," *Communications Magazine, IEEE*, vol. 51, no. 1, pp. 75-83, January 2013.
- [88] Dong Han and O. Gnawali, "Performance of RPL under wireless interference," *Communications Magazine, IEEE*, vol. 51, no. 12, pp. 137-143, December 2013.
- [89] N. Accettura, L.A. Grieco, G. Boggia, and P. Camarda, "Performance analysis of the RPL Routing Protocol," in *Mechatronics (ICM), 2011 IEEE International Conference on*, April



2011, pp. 767-772.

- [90] JeongGil Ko, Stephen Dawson-Haggerty, Omprakash Gnawali, David Culler, and Andreas Terzis, "Evaluating the Performance of RPL and 6LoWPAN in TinyOS," in *Proceedings of the Workshop on Extending the Internet to Low power and Lossy Networks*, April 2011.
- [91] Omprakash Gnawali, Rodrigo Fonseca, Kyle Jamieson, David Moss, and Philip Levis, "Collection Tree Protocol," in *Proceedings of the 7th ACM Conference on Embedded Networked Sensor Systems*, New York, NY, USA, 2009, pp. 1-14.
- [92] I. Demirkol, C. Ersoy, and F. Alagoz, "MAC protocols for wireless sensor networks: a survey," *Communications Magazine, IEEE*, vol. 44, no. 4, pp. 115-121, April 2006.
- [93] Messaoud Doudou, Djamel Djenouri, Nadjib Badache, and Abdelmadjid Bouabdallah, "Synchronous contention-based MAC protocols for delay-sensitive wireless sensor networks: A review and taxonomy," *Journal of Network and Computer Applications*, vol. 38, no. 0, pp. 172-184, 2014.
- [94] Moshaddique Al Ameen, S. M. Riazul Islam, and Kyungsup Kwak, "Energy Saving Mechanisms for MAC Protocols in Wireless Sensor Networks," *International Journal of Distributed Sensor Networks*, 2010.
- [95] Wei Ye, John Heidemann, and Deborah Estrin, "Medium Access Control with Coordinated Adaptive Sleeping for Wireless Sensor Networks," *IEEE/ACM Trans. Netw.*, vol. 12, no. 3, pp. 493-506, June 2004.
- [96] A. El-Hoiydi, J.-D. Decotignie, C. Enz, and E. Le Roux, "Poster Abstract: WiseMAC, an Ultra Low Power MAC Protocol for the wiseNET Wireless Sensor Network," in *Proceedings of the 1st International Conference on Embedded Networked Sensor Systems*, New York, NY, USA, 2003, pp. 302-303.
- [97] Tijs van Dam and Koen Langendoen, "An Adaptive Energy-efficient MAC Protocol for Wireless Sensor Networks," in *Proceedings of the 1st International Conference on Embedded Networked Sensor Systems*, New York, NY, USA, 2003, pp. 171-180.
- [98] Peng Lin, Chunming Qiao, and Xin Wang, "Medium access control with a dynamic duty cycle for sensor networks," in *Wireless Communications and Networking Conference, 2004. WCNC. 2004 IEEE*, vol. 3, March 2004, pp. 1534-1539 Vol.3.
- [99] Wei Ye, Fabio Silva, and John Heidemann, "Ultra-low Duty Cycle MAC with Scheduled Channel Polling," in *Proceedings of the 4th International Conference on Embedded Networked Sensor Systems*, New York, NY, USA, 2006, pp. 321-334.

- [100] Joseph Polastre, Jason Hill, and David Culler, "Versatile Low Power Media Access for Wireless Sensor Networks," in *Proceedings of the 2Nd International Conference on Embedded Networked Sensor Systems*, New York, NY, USA, 2004, pp. 95-107.
- [101] Michael Buettner, Gary V. Yee, Eric Anderson, and Richard Han, "X-MAC: A Short Preamble MAC Protocol for Duty-cycled Wireless Sensor Networks," in *Proceedings of the 4th International Conference on Embedded Networked Sensor Systems*, New York, NY, USA, 2006, pp. 307-320.
- [102] Adam Dunkels, "The ContikiMAC Radio Duty Cycling Protocol," Swedish Institute of Computer Science, Tech. rep. December 2011.
- [103] F.M. Costa and H. Ochiai, "Energy-Efficient Physical Layer Design for Wireless Sensor Network Links," in *Communications (ICC), 2011 IEEE International Conference on*, June 2011, pp. 1-5.
- [104] Octav Chipara, Chenyang Lu, Thomas C. Bailey, and Gruia-Catalin Roman, "Reliable clinical monitoring using wireless sensor networks: experiences in a step-down hospital unit," in *Proceedings of the 8th ACM Conference on Embedded Networked Sensor Systems*, New York, NY, USA, 2010, pp. 155-168.
- [105] Jeonggil Ko et al., "MEDiSN: Medical Emergency Detection in Sensor Networks," *ACM Trans. Embed. Comput. Syst.*, vol. 10, no. 1, pp. 11:1–11:29, Aug. 2010.
- [106] Alessandro Redondi, Marco Chirico, Luca Borsani, Matteo Cesana, and Marco Tagliasacchi, "An integrated system based on wireless sensor networks for patient monitoring, localization and tracking," *Ad Hoc Networks*, vol. 11, no. 1, pp. 39-53, 2013.
- [107] Chen-Yang Cheng, Tsuo-Hung Lan, and Chin-Hong Chan, "An improved localization algorithm with wireless heartbeat monitoring system for patient safety in psychiatric wards," *Engineering Applications of Artificial Intelligence*, vol. 26, no. 2, pp. 905-912, 2013.
- [108] Abdelkrim Hadjidj, Marion Souil, Abdelmadjid Bouabdallah, Yacine Challal, and Henry Owen, "Wireless sensor networks for rehabilitation applications: Challenges and opportunities," *Journal of Network and Computer Applications*, vol. 36, no. 1, pp. 1-15, 2013.
- [109] A. Wood et al., "Context-aware wireless sensor networks for assisted living and residential monitoring," *Network, IEEE*, vol. 22, no. 4, pp. 26-33, July 2008.
- [110] Hande \ et al., "Multi-modal Fall Detection Within the WeCare Framework," in *Proceedings of the 9th ACM/IEEE International Conference on Information Processing in Sensor Networks*, New York, NY, USA, 2010, pp. 436-437.

- [111] José Carlos Castillo et al., "A multi-modal approach for activity classification and fall detection," *International Journal of Systems Science*, vol. 45, no. 4, pp. 810-824, 2014.
- [112] Xueliang Huo and M. Ghovanloo, "Tongue drive: a wireless tongue- operated means for people with severe disabilities to communicate their intentions," *Communications Magazine, IEEE*, vol. 50, no. 10, pp. 128-135, October 2012.
- [113] H. Aloulou, M. Mokhtari, T. Tiberghien, J. Biswas, and P. Yap, "An Adaptable and Flexible Framework for Assistive Living of Cognitively Impaired People," *Biomedical and Health Informatics, IEEE Journal of*, vol. 18, no. 1, pp. 353-360, January 2014.
- [114] Michele Amoretti et al., "Sensor data fusion for activity monitoring in the PERSONA ambient assisted living project," *Journal of Ambient Intelligence and Humanized Computing*, vol. 4, no. 1, pp. 67-84, 2013.
- [115] Francisco E. Martínez-Pérez, Jose Ángel González-Fraga, Juan C. Cuevas-Tello, and Marcela D. Rodríguez, "Activity Inference for Ambient Intelligence Through Handling Artifacts in a Healthcare Environment," *Sensors*, vol. 12, no. 1, pp. 1072-1099, 2012.
- [116] J. van Hoof, H.S.M. Kort, P.G.S. Rutten, and M.S.H. Duijnste, "Ageing-in-place with the use of ambient intelligence technology: Perspectives of older users ," *International Journal of Medical Informatics* , vol. 80, no. 5, pp. 310-331, 2011.
- [117] K. Lorincz et al., "Sensor networks for emergency response: challenges and opportunities," *Pervasive Computing, IEEE*, vol. 3, no. 4, pp. 16-23, Oct 2004.
- [118] Ashok-Kumar Chandra-Sekaran, Gerd Flaig, Christophe Kunze, Wilhelm Stork, and KlausD. Mueller-Glaser, "Efficient Resource Estimation During Mass Casualty Emergency Response Based on a Location Aware Disaster Aid Network," in *Wireless Sensor Networks*, Roberto Verdone, Ed.: Springer Berlin Heidelberg, 2008, vol. 4913, pp. 205-220.
- [119] FelixJonathan Oppermann, CarloAlberto Boano, and Kay Römer, "A Decade of Wireless Sensing Applications: Survey and Taxonomy," in *The Art of Wireless Sensor Networks*, Habib M. Ammari, Ed.: Springer Berlin Heidelberg, 2014, pp. 11-50.
- [120] Carrie Beth Peterson, Neeli R Prasad, and Ramjee Prasad, "The future of assistive technologies for dementia," in *Workshop ISG-ISARC*, vol. 27, 2012.
- [121] Fariba Sadri, "Ambient Intelligence: A Survey," *ACM Comput. Surv.*, vol. 43, no. 4, pp. 36:1–36:66, October 2011.
- [122] G. Acampora, D.J. Cook, P. Rashidi, and A.V. Vasilakos, "A Survey on Ambient Intelligence in Healthcare," *Proceedings of the IEEE*, vol. 101, no. 12, pp. 2470-2494, 2013.

- [123] Sokratis Kartakis, Vangelis Sakkalis, Panagiotis Tournakis, Georgios Zacharioudakis, and Constantine Stephanidis, "Enhancing Health Care Delivery through Ambient Intelligence Applications," *Sensors*, vol. 12, no. 9, pp. 11435-11450, 2012.
- [124] Julio Abascal, "Ambient Intelligence for People With Disabilities and Elderly People".
- [125] Andrew May, Val Mitchell, and John Piper, "A user centred design evaluation of the potential benefits of advanced wireless sensor networks for fire-in-tunnel emergency response ," *Fire Safety Journal* , vol. 63, no. 0, pp. 79-88, 2014.
- [126] S. Adibi, "Biomedical Sensing Analyzer (BSA) for Mobile-Health (mHealth)-LTE," *Biomedical and Health Informatics, IEEE Journal of*, vol. 18, no. 1, pp. 345-351, January 2014.
- [127] Texas Instruments, Wireless Connectivity for Medical Applications, March 2014.
- [128] S. Adibi, "Link Technologies and BlackBerry Mobile Health (mHealth) Solutions: A Review," *Information Technology in Biomedicine, IEEE Transactions on*, vol. 16, no. 4, pp. 586-597, July 2012.
- [129] Sasan Adibi, Amin Mobasher, and Tom Tofigh, "LTE networking: extending the reach for sensors in mHealth applications," *Transactions on Emerging Telecommunications Technologies*, 2013.
- [130] Benoît Latré, Bart Braem, Ingrid Moerman, Chris Blondia, and Piet Demeester, "A Survey on Wireless Body Area Networks," *Wirel. Netw.*, vol. 17, no. 1, pp. 1-18, January 2011.
- [131] T. Penzel et al., "Acquisition of biomedical signals databases," *Engineering in Medicine and Biology Magazine, IEEE*, vol. 20, no. 3, pp. 25-32, May 2001.
- [132] Priyanka Rawat, KamalDeep Singh, Hakima Chaouchi, and JeanMarie Bonnin, "Wireless sensor networks: a survey on recent developments and potential synergies," *The Journal of Supercomputing*, pp. 1-48, 2013.
- [133] Luca Mottola and Gian Pietro Picco, "Programming Wireless Sensor Networks: Fundamental Concepts and State of the Art," *ACM Comput. Surv.*, vol. 43, no. 3, pp. 19:1–19:51, April 2011.
- [134] Tony O'donovan et al., "The GINSENG System for Wireless Monitoring and Control: Design and Deployment Experiences," *ACM Trans. Sen. Netw.*, vol. 10, no. 1, pp. 4:1–4:40, December 2013.
- [135] JeongGil Ko, Tia Gao, and Andreas Terzis, "Empirical Study of a Medical Sensor Application in an Urban Emergency Department," in *Proceedings of the Fourth International Conference on Body Area Networks*, ICST, Brussels, Belgium, Belgium, 2009,

pp. 10:1–10:8.

- [136] Min Chen, Sergio Gonzalez, Athanasios Vasilakos, Huasong Cao, and Victor C. Leung, "Body Area Networks: A Survey," *Mob. Netw. Appl.*, vol. 16, no. 2, pp. 171-193, April 2011.
- [137] André Rodrigues, Tiago Camilo, Jorge Sá Silva, and Fernando Boavida, "Diagnostic Tools for Wireless Sensor Networks: A Comparative Survey," *Journal of Network and Systems Management*, vol. 21, no. 3, pp. 408-452, 2013.
- [138] Ignacio Más and Gunnar Karlsson, "Probe-based admission control for a differentiated-services internet," *Comput. Netw.*, vol. 51, no. 13, pp. 3902-3918, September 2007.
- [139] Ignacio Más and Gunnar Karlsson, "A Model for Endpoint Admission Control Based on Packet Loss," in *NETWORKING 2008 Ad Hoc and Sensor Networks, Wireless Networks, Next Generation Internet*, Amitabha Das et al., Eds.: Springer Berlin / Heidelberg, 2008, vol. 4982, pp. 506-517.
- [140] A. Dunkels, B. Gronvall, and T. Voigt, "Contiki - a lightweight and flexible operating system for tiny networked sensors," in *Local Computer Networks, 2004. 29th Annual IEEE International Conference on*, November 2004, pp. 455-462.
- [141] Li Xiao, Jun Wang, King-Shan Lui, and K. Nahrstedt, "Advertising interdomain QoS routing information," *Selected Areas in Communications, IEEE Journal on*, vol. 22, no. 10, pp. 1949-1964, 2004.
- [142] Hong linh Truong, Robert Samborski, and Thomas Fahringer, "Towards a Framework for Monitoring and Analyzing QoS Metrics of Grid Services," *Proceedings of the Second IEEE International Conference on e-Science and Grid Computing*, Society Press, 2006.
- [143] F. Osterlind, A. Dunkels, J. Eriksson, N. Finne, and T. Voigt, "Cross-Level Sensor Network Simulation with COOJA," in *Local Computer Networks, Proceedings 2006 31st IEEE Conference on*, November 2006, pp. 641-648.
- [144] Mohamed Younis and Kemal Akkaya, "Strategies and techniques for node placement in wireless sensor networks: A survey," *Ad Hoc Networks*, vol. 6, no. 4, pp. 621-655, 2008.
- [145] J. Postel, User Datagram Protocol, August 1980.
- [146] O. Gnawali and P. Levis, The Minimum Rank Objective Function with Hysteresis, RFC 6719, September 2012.
- [147] M. Zuniga and B. Krishnamachari, "Analyzing the transitional region in low power wireless links," in *Sensor and Ad Hoc Communications and Networks, 2004. IEEE SECON 2004*.

*2004 First Annual IEEE Communications Society Conference on*, October 2004, pp. 517-526.

- [148] Marco Z\ and Bhaskar Krishnamachari, "An analysis of unreliability and asymmetry in low-power wireless links," *ACM Trans. Sen. Netw.*, vol. 3, no. 2, June 2007.
- [149] Joseph Polastre, Robert Szewczyk, and David Culler, "Telos: enabling ultra-low power wireless research," in *Proceedings of the 4th international symposium on Information processing in sensor networks*, Piscataway, NJ, USA, 2005.
- [150] T. S. Rappaport, *Wireless Communications: Principles and Practice*, 2nd ed.: Prentice Hall, 2002.
- [151] JeongGil Ko, "Designing A Low-power Mobile Sensing System For Wireless Healthcare Applications," Johns Hopkins University, Baltimore, Maryland, Ph.D. dissertation April 2012.