Energy Harvesting-Aware Resource Management for Wireless Body Area Networks

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Universitat de Barcelona

Centre Tecnològic de Telecomunicacions de Catalunya

PhD Dissertation

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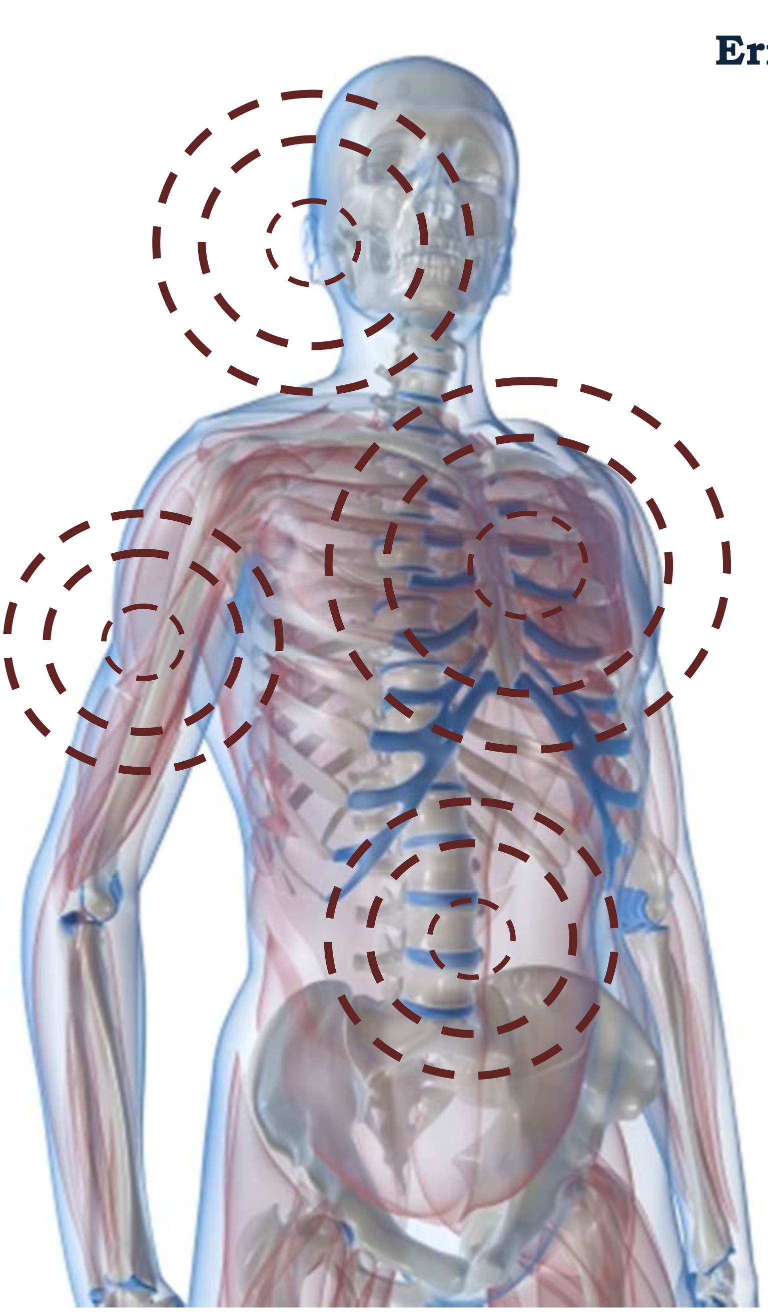

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Energy Harvesting-Aware Resource Management for Wireless Body Area Networks

PhD Thesis Dissertation

By

Ernesto Antonio Ibarra Ramirez

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Ernesto A. Ibarra R.

Quiero dedicar esta tesis doctoral a mi familia, a mi madre, a mis hermanos, pero en especial a las memorias de mi padre, y a la de mis abuelos (Tolla, Chave y Toño), gracias por ser mi modelo a seguir y enseñarme tantas cosas valiosas, que Dios me los tengan en la gloria.

"…Adelante por los sueños que aún nos quedan,

Adelante por aquellos que están por venir,

Adelante porque no importa la meta

el destino es la promesa a perseguir

…Adelante" ***Naiara***

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Ernesto A. Ibarra R.
Barcelona, Febrero 2014

Abstract

The rationale for a telemedicine system is the use of Information and Communications Technology (ICT) for the remote transmission of biomedical data and the remote control of biomedical equipment, in order to improve the provided health service. The integration of Wireless Body Area Networks (WBANs) in telemedicine systems does not only achieve significant improvements in the patient's healthcare, but also enhances their quality of life. However, the potential benefits provided by these networks are limited by the energy constraints imposed when traditional batteries are used as the power source, since the replacement or recharging of these is not always an easy task. To that end, harvesting energy from the human environment can be a promising solution to the aforementioned problems. In this context, it is important to design efficient energy-aware medium access and resource management schemes to exploit the benefits of energy harvesting while guaranteeing the Quality of Service (QoS) in the network.

This dissertation provides a contribution to the design and evaluation of novel solutions focused on energy-aware resource management for WBANs powered by human energy harvesting. In particular, our proposals are oriented to solve the problems caused by the differences in energy levels experienced by nodes due to their power supply by energy harvesting. The main thesis contributions are divided into two parts. The first part presents HEH-BMAC, an energy-aware hybrid-polling Medium Access Control (MAC) protocol for WBANs powered by human energy harvesting. HEH-BMAC is designed to provide medium access taking into account the capabilities of each node with respect to their energy profile. HEH-BMAC combines two types of access mechanisms, i.e., reserved polling access and probabilistic random access, in order to adapt the network operation to the types of human energy harvesting sources. The HEH-BMAC performance in terms of normalized throughput and energy efficiency is

assessed by means of extensive computer-based simulations, revealing a good adaptation to potential changes in the energy harvesting rate, packet inter-arrival time and network size. HEH-BMAC has been proven to outperform IEEE 802.15.6 Standard for WBANs in terms of normalized throughput and energy efficiency, as the number of nodes increases under the same conditions of energy harvesting.

The second part of the thesis is dedicated to the design and evaluation of PEH-QoS, a Power-QoS control scheme for body nodes powered by energy harvesting. PEH-QoS is designed to use efficiently the harvested energy and ensure that all transmitted packets are useful in a medical context, hence substantially improving the offered QoS. The obtained results show that this scheme efficiently manages the data queue, thus improving the node operation and optimizing the data transmission, and also provides QoS, while maintaining the node in energy neutral operation state.

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List of Acronyms

ACK	Acknowledgement
ADC	Analog-to-Digital Converter
AIAD	Additive-Increase Additive-Decrease
AIMD	Additive-Increase Multiplicative-Decrease
BE	Backoff Exponent
BER	Bit-Error-Rate
BN	Body Node
BNC	Body Node Coordinator
CCA	Clear Channel Assessment
CDMA	Code Division Multiple Access
CP	Contention Probability Control Packet
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
DC	Direct Current
DQAC	Data Queue Aware Control
ECG	Electrocardiograph
EEG	Electroencephalograph
eHealth	Electronic Health
EMIC	Energy Management Integrated Circuit
ENO	Energy Neutral Operation
FCS	Frame Check Sequence
FDMA	Frequency Division Multiple Access
GOe	Global Observatory for eHealth
GPRS	General Packet Radio Service
HEH-WBAN	WBAN powered by Human Energy Harvesting
IAT	Inter-Arrival Time
ICT	Information and Communications Technology
ID	User Identification
IEEE	Institute of Electrical and Electronic Engineers
IMEC	Interuniversity Microelectronics Centre
ITU	International Telecommunication Union

MAC	Medium Access Control
MCU	Microcontroller Unit
mHealth	Mobile Health
MIAD	Multiplicative-Increase Additive-Decrease
MIMD	Multiplicative-Increase Multiplicative-Decrease
OSI	Open Systems Interconnection
PASS	Packet Aggregator/Scheduling System
PC	Probabilistic Contention
PDA	Personal Digital Agenda
PHAM	Power-Energy Harvesting Aware Management
PHY	Physical
PLCP	Physical Layer Convergence Protocol
PM	Power Management
PPDU	Physical Layer Protocol Data Unit
PSDU	Physical Layer Service Data Unit
QoS	Quality of Service
R-out	Read-Out or Reader
TDMA	Time Division Multiple Access
Tx/Rx	Transmission/Reception
WBAN	Wireless Body Area Network
WHO	World Health Organization
WSN	Wireless Sensor Network
WSN-HEAP	WSN powered by Ambient Energy Harvesting

Notation

$\boldsymbol{i}$	Integer identifier of the node
$\mathbf{MIT}_{\mathbf{ID-BN}\boldsymbol{i}}$	Monitoring interval for ID-BN $\boldsymbol{i}$
$\mathbf{T}_{\boldsymbol{\alpha i}}$	Monitoring time (offset applied) for ID-BN $\boldsymbol{i}$
$\mathbf{T}_{\boldsymbol{\beta i}}$	Moment of completion of the communication process for BN $\boldsymbol{i}$
$\mathbf{T}_{\boldsymbol{\gamma i}}$	Duration of the data communication process for BN $\boldsymbol{i}$
$\mathbf{ID-BN}\boldsymbol{i}$	Body node $\boldsymbol{i}$ in ID-polling mode
$\mathbf{PC-BN}\boldsymbol{i}$	Body node $\boldsymbol{i}$ in PC-access mode
$\mathbf{K}_{\mathbf{EH}}$	Energy harvesting rate
$\mathbf{IAT}_{\mathbf{BN}\boldsymbol{i}}$	Packet inter-arrival time of BN $\boldsymbol{i}$
$\boldsymbol{X_i}$	Random number generated by the BN $\boldsymbol{i}$
$\boldsymbol{\alpha_{IN}}$	AIMD increase factor
$\boldsymbol{\beta_{MD}}$	AIMD decrease factor
$\boldsymbol{T_{OUT}}$	Time-out period
$\boldsymbol{T_{PCmin}}$	Minimum time to PC-access
$\boldsymbol{P_{det}}$	Detection power consumption
$\boldsymbol{P_{tx}}$	Transmission power consumption
$\boldsymbol{l_{pkt}}$	Data packet size
$\boldsymbol{E_{Tx}}$	Transmission energy consumption
$\boldsymbol{E_{det}}$	Detection energy consumption
$\boldsymbol{E_{EH}}$	Energy harvested
$\boldsymbol{D_{eff}}$	Detector efficiency
$\boldsymbol{B_{level}}$	Level of energy in the battery
$\boldsymbol{T_{EH}}$	Energy harvesting time
$\boldsymbol{D_{load}}$	Number of $\boldsymbol{l_{pkt}}$ to be transmitted
$\boldsymbol{Dly_{max}}$	Maximum allowed end-to-end delay
$\boldsymbol{SC_{max}}$	Maximum storage capacity
$\boldsymbol{T_{pkt}}$	Data packet waiting time
$\boldsymbol{DQ_{level}}$	Number of data packets stored
$\boldsymbol{T_{Qmax}}$	Maximum allowed waiting time in the data queue
$\boldsymbol{T_{TX}}$	Time needed for the data communication process

CHAPTER 1

Introduction

"Dreams can be of value even if you don't have an opportunity to turn them into reality." **Henning Mankell**

Contents

1.1 Timeliness

Nowadays, two unprecedented events in the history of humanity are taking place: i) the elderly population is greatly increasing worldwide, and ii) mobile and wireless technologies are undergoing a tremendous proliferation. With regard to the trend of global population aging, the World Health Organization (WHO) has recently foreseen [1] that the number of people over sixty-five years old will soon be greater than the number of children under five years old (Figure 1.1). According to WHO, the elderly population worldwide is growing by 2 percent every year, due to the decreasing fertility rates and the increased life expectancy, while this rate is expected to reach 2.8 percent in 2030. Based on these facts, WHO warns that the rapid growth of the elderly population in some countries will challenge their national infrastructures and, particularly, their health systems.

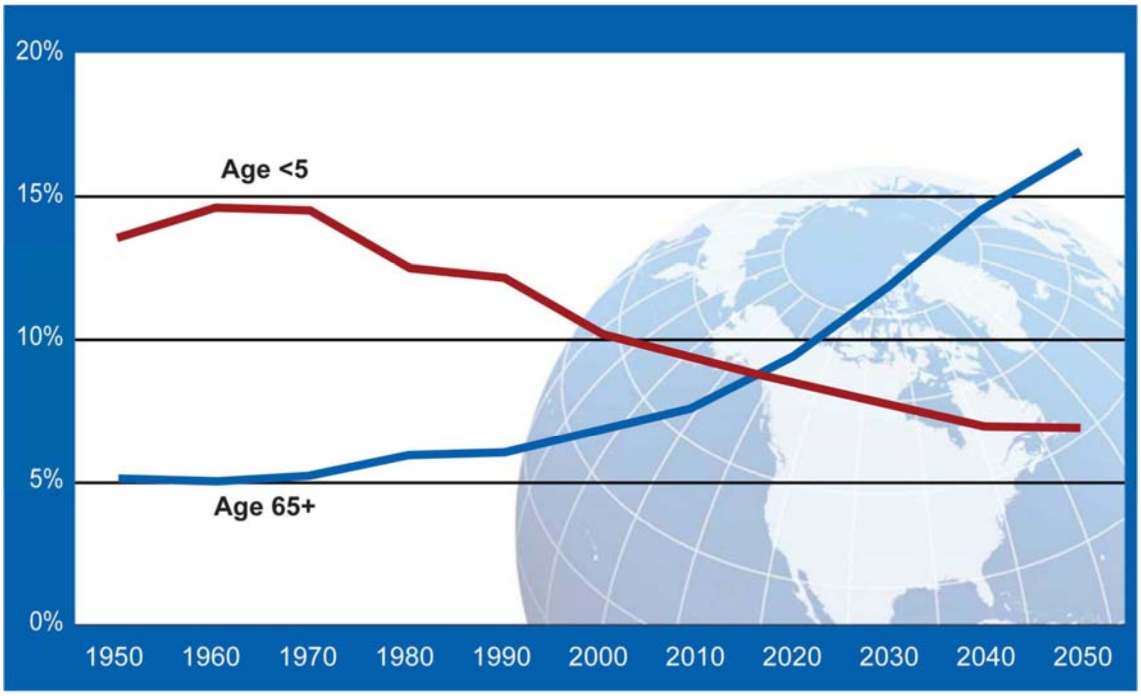


Figure 1.1 – Young Kids and Older People as a Global Population Percentage 1950-2050 [1]

Today, as a result of various factors (e.g., aging, lifestyle, diet changes, etc.), developing countries experience an increase in the incidence of chronic diseases that mainly affect adults and elderly people (Figure 1.2) [2]. Chronic diseases are characterized by long duration and generally slow recovery. Four main types of chronic are dominating: cardiovascular diseases, chronic respiratory diseases, diabetes and cancer. This kind of diseases are mainly found in developed countries and constitute a major problem for the health system, creating the need to invest more resources in medication, hospital infrastructure, health workers, etc. Often, these investments are not sufficient compared to the huge demand for services required by the population. An analysis made by WHO indicated that twenty-three countries with low and middle income levels will suffer economic losses because of chronic diseases and will have to spend around 83 billion dollars (approximately 63 billion euros) between 2006 and 2015 [1].

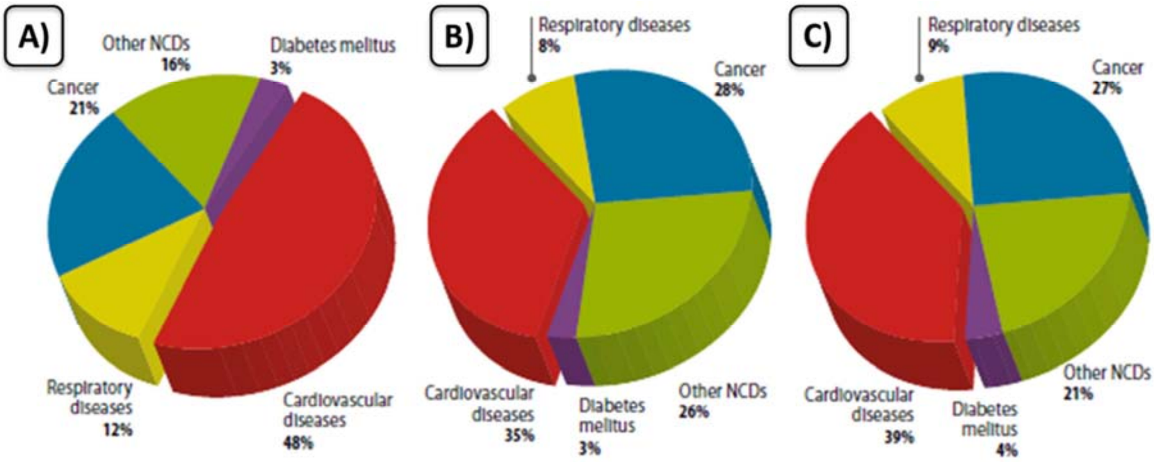


Figure 1.2 – Global Distribution of Death due to Chronic Diseases: A) Both Sexes, B) Less than 60 year old persons, and C) Less than 70 year old persons [2]

The aging population and the increase of chronic diseases are two factors that greatly affect the budget of health systems worldwide. These two factors increase the burden on the healthcare system, since people require more constant health monitoring and assistance to perform basic daily activities. On the other hand, a new concept known as "mobile health" (mHealth), which is part of the electronic health (eHealth) that includes health applications and links on mobile phones for the transfer of health resources and health care, is becoming increasingly popular. The Global Observatory for eHealth (GOe) defines mHealth as the medical and public health service carried out through mobile devices, like cellphones, patient monitoring devices, Personal Digital Assistants (PDAs), and other wireless devices [3]. According to WHO [3], mHealth is potentially able to change the trajectory of health services worldwide.

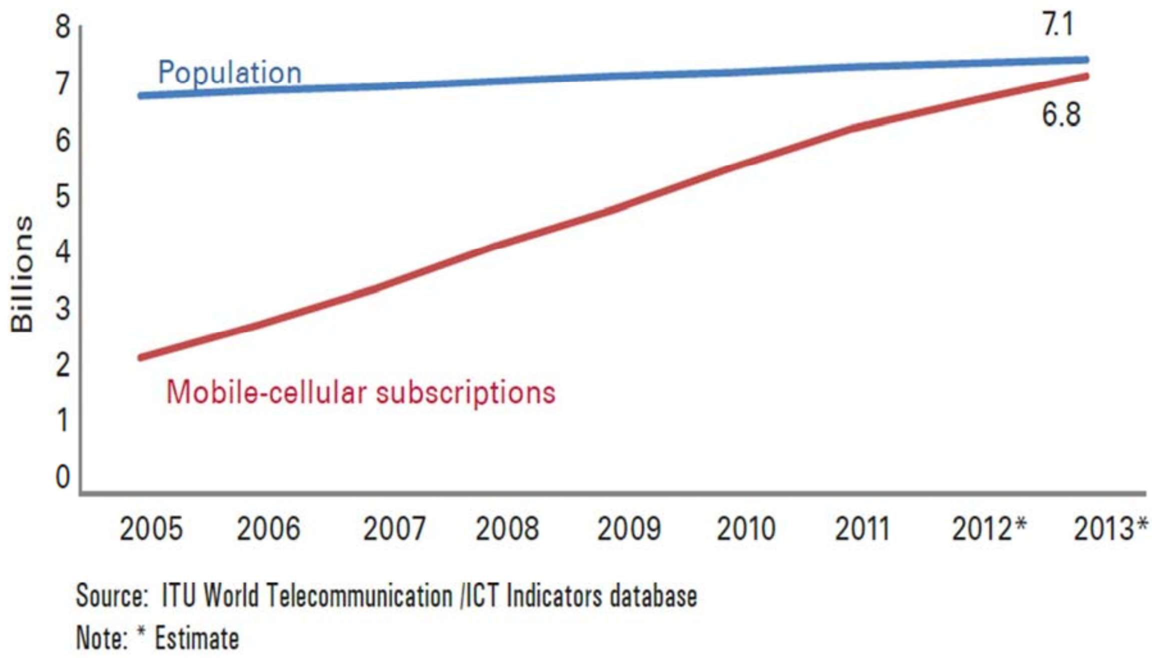


Figure 1.3 – Mobile-cellular subscriptions penetration rates [4]

According to International Telecommunication Union (ITU) statistics, in 2013, the number of mobile-cellular subscriptions has almost reached the worldwide population (Figure 1.3) [4]. Penetration rates of mobile-cellular subscriptions are estimated around 96 percent globally, 128 percent in developed countries and 89 percent in developing countries [4]. Moreover, ITU statistics have shown that more than 2.7 million people are using the internet this year, which corresponds to 39 percent of the population around the world.

The high penetration rates of mobile-cellular networks in countries of low and middle income exceeds other civil and technological projects, such as healthcare infrastructure, paved roads and drinking water systems [3, 5]. The great advances in mobile and wireless technology in both developed and developing countries are surprising. The mHealth has utilized these technology platforms to perform various tasks related to access, delivery and management of patient information. Furthermore, it is a good tool for extending the provided healthcare coverage and improving its quality. mHealth applications for cellphones are successfully tested in different scenarios in places of difficult access. Some indicative scenarios are: maternal and child healthcare, general health services and information, clinical diagnosis and treatment adherence, among others [3, 5].

Throughout the years, it has been proven that biomedical technology has greatly improved diagnosis, treatment and monitoring of patient health. Furthermore, medical technology has expanded the ways to safeguard the life of a patient (with pacemakers, insulin pumps, bionic prosthetics, among others). These types of technology are becoming more efficient by getting smaller, more robust, and more comfortable for the patient. Another trend for biomedical devices is their use with wireless technology for exchanging information, enabling the increased freedom for both patients and health workers. This technological revolution along with the raising demand for health services are the preamble to the new concept in telemedicine: the Wireless Body Area Networks (WBANs). WBANs consist of small and smart medical devices located in the vicinity of (on-body), or inside (in-body), the human body. WBANs are specified in the very recent IEEE 802.15.6 standard for short-range wireless communications in the human body [6]. The main purpose of WBANs is to efficiently manage the data communication among all the medical devices that belong to the network.

Figure 1.4 shows an mHealth system which includes a WBAN. In this example, the collected data are transmitted wirelessly to an external device such as a smartphone or a PDA. The WBANs will be the main driver in the growth of mHealth, increasing its functionalities and health benefits for the patients [7]. The potential social and economic benefits of the implementation of WBANs in the current health systems are extremely promising. WBANs will allow patient diagnosis, treatment and monitoring, independently of their location, without interrupting their daily activities. This will improve both the effectiveness of medical procedures and the quality of life of patients. Telemedicine systems based on WBANs have the potential not only to provide solutions for the care of the elderly and patients with chronic diseases, but also to reduce the financial cost of the whole health system.

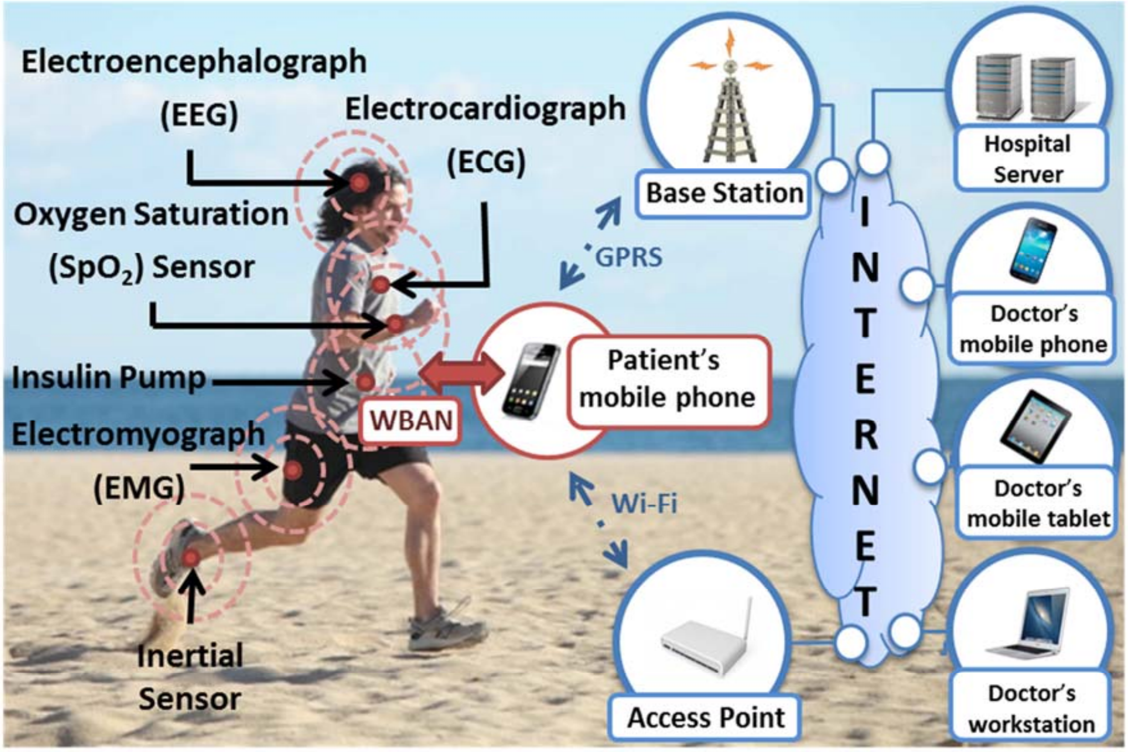


Figure 1.4 – Example of a WBAN in an mHealth system

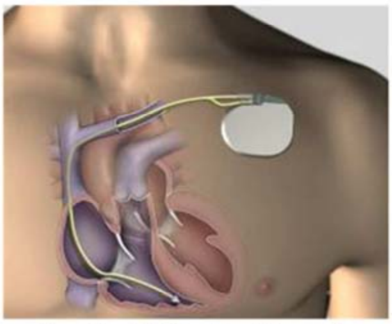
1.2 Problem Statement and Motivation

The WBANs face several challenges that should be overcome before their final implementation in telemedicine systems. The medical devices that form the network, called Body Nodes (BNs), are heterogeneous in general, since they perform different tasks, they have different Quality of Service (QoS) requirements and they need different power supply. Moreover, these networks usually face the space constraints imposed by the human body, limiting the number and the size of the nodes in the network. In WBANs, each node carries out a different important function related to diagnosis, treatment or monitoring of the patient's health. Therefore, due to the space limitations of the human body, the task performed by each node is unique. For this reason, BNs should be able to carry out their functions efficiently and interact with the human body in a discrete and undetectable way. To that end, BNs should be small and light, to adapt seamlessly to the human body. These characteristics strongly depend on the battery capacity, which is proportional to the battery's weight and size. Hence, increasing the capacity of the battery implies an increase in the weight and the size of the BN.

Apart from the physical limitations mentioned above, the limited battery capacity restricts also the lifetime of the nodes, since it is a finite power source. A battery-powered wireless node can efficiently carry out its tasks (e.g., event detection, data processing, radio reception/ transmission) as long as its battery level is sufficient to supply the required energy. However, as the battery is depleted, the node experiences a decline in its activities, before eventually becoming permanently inactive. In order for a node to start operating again, it is necessary to replace or recharge the battery as soon as possible. However, battery replacement is not always feasible, since it might jeopardize the patient's health or it could damage the BN. This problem is exacerbated even more in the case of nodes implanted inside the human body, where the replacement of the node would require surgical procedures [8, 9]. Figure 1.5 outlines the risk of complications related to the replacement of a device implanted in the human body.

The increase of the battery capacity would extend the lifetime of the node but, as we have already mentioned, it is not a viable option due to the restrictions on the size and weight of BNs. Hence, harvesting energy from other available sources [10] could permanently supply the node with the required power, providing the most promising solution to the energy problem. Using special hardware devices, known as energy harvesters, BNs can convert several types of energy present in the human environment (e.g., heat, motion, etc.) into electrical energy [11]. A node powered by energy harvesting is able to collect energy in the human environment and use it for its own operation, thus achieving higher autonomy, overcoming the problems associated with the depletion of the traditional batteries. However, the use of energy harvesting introduces an additional variable to the network, which is related to the availability and magnitude of the collected energy.

COMPLICATIONS IN THE REPLACEMENT OF IMPLANTABLE CARDIOVERTER DEFIBRILLATOR



Implantable Cardioverter Defibrillator

Patient with the device already implanted

Severity y Complications*	No. (%)**
Menor	
- Incisional infection, medically managed.	9(1.7)
- Significant site pain, medically managed.	1(0.2)
- Heart failure requiring hospitalization.	1(0.2)
- Major psychological morbidity, medically managed.	1 (0.2)
Mayor	
-Pocket infection requiring extraction.	10 (1.9)
-Death after extraction.	2 (0.4)
-Hematoma requiring a new surgery.	12 (2.3)
-System failure requiring a new surgery.	8 (1.5)
- Significant site pain requiring new surgery.	1 (0.2)

** Sample: 533 replacements of implantable cardioverter defibrillator.*
***Number of patients with the complication.*

Figure 1.5 – Complications associated with implantable cardioverter defibrillator replacements [8]

Energy harvesters in the human environment provide less amount of energy compared to the batteries, while they are more dependent on time. In many cases, the harvested energy is not sufficient for the BNs to work properly, something that motivates the use of a rechargeable storage device (e.g., a battery or a supercapacitor) until the collected energy guarantees the node's operation. The amount of energy that a harvester collects in a given period of time (i.e., harvesting rate) defines the time needed to reach the operating level. Battery-powered nodes become completely inactive once their batteries are depleted, thus interrupting all their tasks inside the network. In the case of energy harvesting, the nodes can achieve intermittent periods of inactivity, meaning that they need to momentarily suspend their tasks until reaching the required energy to resume operation. Based on the above facts, it becomes clear that the successful exploitation of the collected energy is a key factor for the smooth operation of a node. Energy is harvested from an endless power-feeding source, so nodes may be able to operate continuously. Kansal et al. [12] introduced the concept of Energy Neutral Operation (ENO), which is a method to achieve infinite lifetime, as long as there are no hardware failures. A node powered by energy harvesting is declared to be in ENO state if it consumes less or equal amount of energy compared to the energy harvested from the environment [12]. Therefore, satisfying the conditions that guarantee the ENO of a BN, we can ensure the perpetual operation of the node.

The wireless interface consumes a considerable part of the energy available during the operation of the node, while energy harvesting affects the responsiveness of a node in a given period of time, since the lack of energy may restrict the medium access of the wireless nodes. The Medium Access Control (MAC) sublayer is the most appropriate level to address the energy efficiency issues [13-16]. The MAC sublayer is part of the data link layer of the Open Systems Interconnection (OSI) architecture. The MAC layer defines the set of mechanisms and protocols through which various nodes agree to share a common transmission medium. In particular, the MAC protocols specify the tasks and procedures required for the data transfer between two or more nodes in the network, providing mechanisms to resolve potential conflicts that may arise during their attempt to access the medium. Therefore, the choice of a MAC mechanism is the main factor that determines the energy consumption of a network [14]. In addition, the energy source in different networks sets the priorities to the metrics under study. In networks operated by batteries, the main purpose of the MAC protocols is the efficient use of the stored energy in order to extend the network lifetime as much as possible. On the other hand, in networks that operate using energy harvesting, the main objective is the throughput maximization, as the energy supply is no longer a restriction.

Through energy harvesting, the life of a wireless network can be sustained, but other QoS metrics can be downgraded (throughput, delay, packet loss, etc.) [17, 18]. Generally, WBANs have more stringent QoS requirements with respect to the traditional Wireless Sensor Networks (WSNs) [19]. In WBANs, throughput maximization, delay minimization and lifetime extension of the network operation are some of the main goals to be achieved [20]. In addition, the measurement accuracy of the wireless nodes is another major challenge that WBANs should face. Unlike WSNs, where a large number of nodes can compensate for the lack of accuracy in the measurements, in WBANs, each node should be robust and accurate [21]. At the present time, most of the WBAN-oriented MAC protocols have been designed taking into account battery-powered BNs, thus not being compatible with energy harvesting oriented networks. Hence, it is of great importance to propose and design mechanisms that guarantee an acceptable QoS level in WBANs powered by Human Energy Harvesting (HEH-WBANs).

Despite the great benefits that HEH-WBANs can bring to the quality of life, they require new protocols and algorithms to make optimal use of the limited energy collected in the human environment. The MAC design for HEH-WBANs should take into account the particular types and features of the power sources to be harvested in the human environment. It should also provide the nodes with medium access according to their priority and their available energy. In this context, taking into account recent developments in WBANs and in the energy harvesting field, this thesis is focused on the study and design of efficient energy harvesting-aware resource management techniques that aim at a better QoS in HEH-WBANs. To the best of our knowledge, this work is the first contribution to MAC protocol design for WBANs powered by energy harvesting in the human environment.

1.3 Objectives

The planning, development and realization of this PhD thesis pursued the following objective:

- ***Design and development of efficient energy harvesting-aware resource management solutions that guarantee the QoS requirements of the medical applications in WBANs.***

By achieving the aforementioned goal, this thesis constitutes a contribution to the advancement of WBANs powered by human energy harvesting in terms of efficient management of their energy towards a better QoS.

To successfully meet the general objective, the following partial objectives had to be also fulfilled:

1. To provide a comprehensive review of the state of the art in the areas of MAC protocols for WBANs and energy harvesting in the human environment.

2. To propose and evaluate an energy-aware MAC protocol, able to adapt the operation of a WBAN to the random, time-varying nature of the human energy harvesting sources.

3. To design and develop a control scheme that allows the optimal use of scarce energy collected by a node powered by human energy harvesting, in order to improve the provided QoS.

4. To evaluate the results of our proposals and compare with reference standard systems using different QoS metrics.

1.4 Methodology

The first step carried out in our research was the complete review of the issues related to the application of energy harvesting techniques in WBANs. The literature review was focused on identifying the main problems in a WBAN powered by human energy harvesting. Having identified the issues that should be addressed, we proceeded to analyze their characteristics and, subsequently, we proposed possible ways to cope with them.

Based on the analysis of the current state of the art, we have classified the problems addressed in this thesis into two categories (Figure 1.6):

i) WBAN-level problems: At this level, we have grouped all the problems faced by a WBAN due to the power supply by energy harvesting. These issues affect the operation of all nodes in the network. In particular, the problems that we address in this level are: energy efficiency, throughput, network flexibility, access priorities and optimal use of the shared wireless channel.

ii) BN-level problems: At this level, we have included all the problems due to the energy harvesting sources that affect the performance of the nodes individually. These problems arise at each node due to their particular conditions of provision and consumption of energy. These problems affect the performance of the node, resulting in the degradation of QoS. The problems that we address in this level are: optimal management of the collected energy, events detection and data storage efficiency.

Due to the nature of the topics covered in this thesis, we have chosen to employ computer-aided Monte Carlo simulations. For this task, we have chosen the MATLAB software, since it is a powerful computing high-level language used for algorithm development, data visualization, data analysis, and numerical computation. In our research, we adopt a network star topology (Figure 1.6), where the head (sink) is the Body Node Coordinator (BNC) responsible for setting up the network and collecting all the information transmitted by the BNs. We assume that the BNC has an external power supply and higher processing capabilities than BNs. The BNC may be a mobile device like a smartphone or a PDA, thus serving as a personal server and gateway to other mHealth services. In our research, we are focusing on the study of energy efficiency of the BNs powered by energy harvesting, so that the energy consumption of the BNC is not taken into account in the calculations. We have developed two event-driven simulators, for WBAN-level and BN-level experiments, respectively. These simulation tools assisted us in the design, test, analysis and evaluation of the systems under study, while they also allowed us to compare our results with reference standard systems.

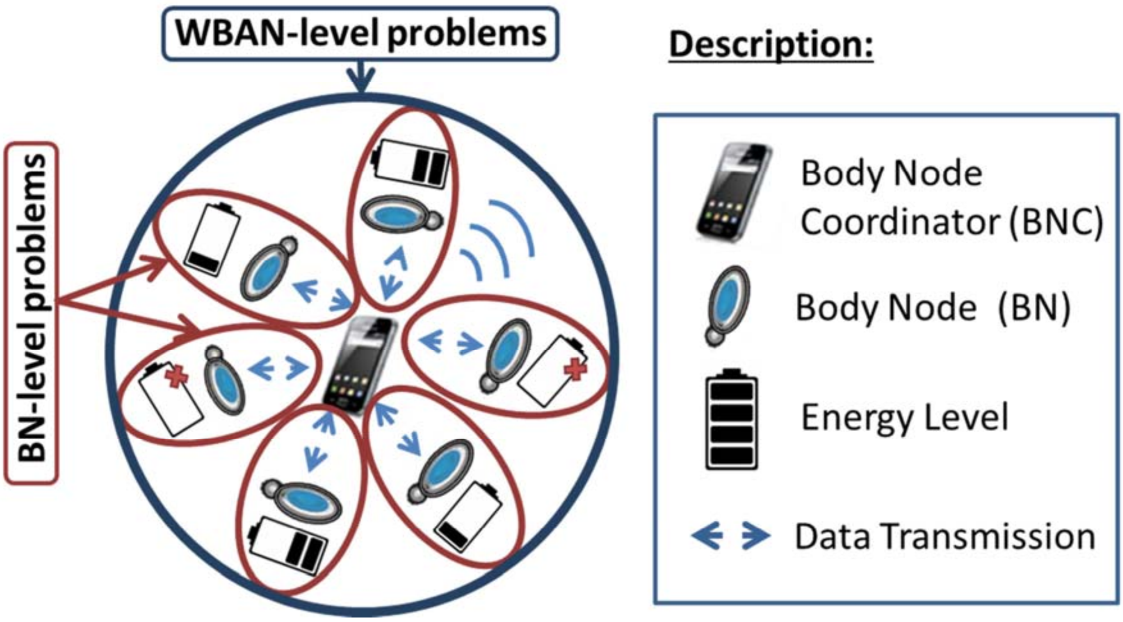


Figure 1.6 – Illustration of WBAN in star topology and the two levels of problems under study in a particular case

1.5 Structure of the Dissertation and Main Contributions

The goal of this thesis is to improve both the QoS of each node (BN-level) as well as the overall QoS of the network (WBAN-level), making efficient use of the energy collected in the human environment. As a result of our research, we have designed, developed and evaluated two novel solutions to the abovementioned issues. The contribution of this PhD thesis is twofold:

I. The first contribution is contained in Chapter 3, where we introduce a hybrid MAC protocol, called HEH-BMAC, which has been designed and developed for HEH-WBANs. HEH-BMAC uses a dynamic scheduling algorithm to combine User Identification (ID) polling and Probabilistic Contention (PC) random access, adapting the network operation to the random, time-varying nature of the human energy harvesting sources. Moreover, it offers different levels of node priorities (high and normal), energy awareness and network flexibility.

II. The second contribution of this research is included in Chapter 4, where we propose a Power-QoS control scheme for BNs powered by human energy harvesting. This scheme was designed to achieve the optimal use of collected energy and substantial improvement of QoS. The proposed scheme intends to ensure that a node can both capture/detect the medical events and transmit the respective data packets efficiently. One of the main features of our mechanism is that only useful data sequences are transmitted, discarding data packets that have lost their clinical validity (i.e., out of date data).

The remainder of this thesis consists of four chapters, where the contents and the contributions of each chapter are described in detail as follows:

- **Chapter 2.** The second chapter provides the reader with the basic knowledge needed to understand the context and the main concepts of this thesis. First, we explain the basic parts that compose a BN powered by energy harvesting, with particular emphasis on the types of energy sources available in the human environment. Next, we explain topics related to the characteristics of the BNs. We will focus on power consumption, data traffic, and the QoS requirements, giving the preamble to properly introduce the concept of energy efficiency. Sequentially, we provide a comprehensive state of the art of MAC protocols designed for WBANs. We briefly describe the main advantages and disadvantages of the main types of MAC protocols in WBANs. The protocols designed for WSNs powered by energy harvesting are also analyzed. In this way, we set the parameters to be followed in the design and development of our protocol for HEH-WBANs.

- **Chapter 3.** This chapter contains our first major contribution, the HEH-BMAC: a hybrid-polling MAC protocol with Human Energy Harvesting capabilities designed for WBANs. HEH-BMAC is energy-aware, since it has been designed to address the variation in the human energy harvesting sources. In this chapter, we present the structure, the operation modes, and the performance evaluation of the protocol. First, we explain in detail the two modes of operation (i.e., ID-polling and PC-access) executed by our protocol and the algorithm that combines them (i.e., the Dynamic Scheduling Algorithm). To facilitate the understanding of the protocol operation, we explain its overall functioning through a comprehensive operational example. In addition, extensive simulations have been conducted in order to evaluate the performance of the protocol and study the performance/energy tradeoffs. Finally, we evaluate the energy efficiency and throughput of our scheme compared to the IEEE 802.15.6 standard in energy harvesting conditions.

The findings outlined in this chapter have been published/accepted in part in one scientific journal and one international conference:

- **E. Ibarra**, A. Antonopoulos, E. Kartsakli and C. Verikoukis, "HEH-BMAC: Hybrid Polling MAC Protocol for Wireless Body Area Networks Operated by Human Energy Harvesting", *Springer Telecommunications Systems Journal (Special Issue on Research Advances in Energy-Efficient MAC Protocols for WBANs)* (accepted, December 2012).

- **E. Ibarra**, A. Antonopoulos, E. Kartsakli and C. Verikoukis, "Energy Harvesting Aware Hybrid MAC Protocol for WBANs", IEEE HEALTHCOM 2013, October 2013, Lisbon, Portugal.

- **Chapter 4.** This chapter introduces our second contribution, a novel Power-QoS control Scheme for BNs powered by energy harvesting, called PEH-QoS. PEH-QoS is an ENO-inspired algorithm developed for providing the best possible QoS under energy harvesting conditions. It achieves a balance between the proper operation of the node and the QoS requirements, taking into account the energy harvesting rate in the human environment. PEH-QoS attains three key achievements, which are: efficient management of the available energy, control of the data queue, and optimization of the data transmissions. To achieve these goals, our mechanism combines three sub-modules: i) the Power-Energy Harvesting Aware Management

(PHAM), ii) the Data Queue Aware Control (DQAC), and iii) the Packet Aggregator/Scheduling System (PASS). In this chapter, each sub-module and the interaction between them are described in detail. One of the most important tasks performed by the proposed control scheme is the maintenance of the clinical validity of the information stored by discarding old packets and updating the data queue. In addition, we evaluate via extensive simulations the throughput and other important QoS metrics in a typical BN with PEH-QoS, and we compare them with a baseline scenario under the same EH conditions, where the PEH-QoS is not applied.

The contribution of this chapter has been accepted to one international conference:

- **E. Ibarra**, A. Antonopoulos, E. Kartsakli and C. Verikoukis, "Joint Power-QoS Control Scheme for Energy Harvesting Body Sensor Nodes", *IEEE ICC 2014*, June 2014, Sydney, Australia.

- **Chapter 5.** This chapter concludes the dissertation by providing a summary of our contributions, together with some potential routes for future investigation.

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CHAPTER 2

Background

"Life is like riding a bicycle. To keep your balance, you must keep moving." **Albert Einstein**

Contents

The second chapter of this thesis is divided into two sections. The first section contains the required information to understand the concept of BNs operated by human energy harvesting. We address issues related to the energy harvesting sources available in the human environment, the typical architecture (harvesters and energy storage units), and some characteristics of medical BNs in the WBANs. In the final part of this section, we focus on the BN's energy consumption, while we discuss the concept of ENO state and its importance in a BN operated by energy harvesting.

In the second section of this chapter, we address the issue of MAC protocols for WBANs. We present a brief classification of MAC protocols that can be applied in a typical WBAN and we compare them with groups of MAC protocols supported by energy harvesting. At the end of this section, we explain in more detail four groups of MAC protocols specifically adapted for operation with energy harvesting. The main idea is to show how the protocol behavior and the wireless network performance are affected by energy harvesting. Even though these protocols employ ambient energy harvesting, they will be used as a reference for our proposal based on human energy harvesting sources, presented in chapter 3.

2.1 BNs Powered by Energy Harvesting

In recent years, the interest of the scientific community and electronic industry in energy harvesting as a power source in low-power wireless devices has significantly increased [1], since it is projected to be an ideal solution for eliminating the energy dependence of electronic devices on batteries. The harvesting process is carried out through a device called energy harvester. This device transforms a physical or a chemical source present in the environment into electrical energy. A complex tradeoff must be considered when designing energy harvesters for wireless nodes [2]. This tradeoff is derived from the interaction of various factors, including the characteristics of the sources to be harvested, the energy storage devices, the power management of the nodes, the employed communication protocols, and the application requirements. Figure 2.1 shows a basic block diagram of the structure of a BN powered by energy harvesting.

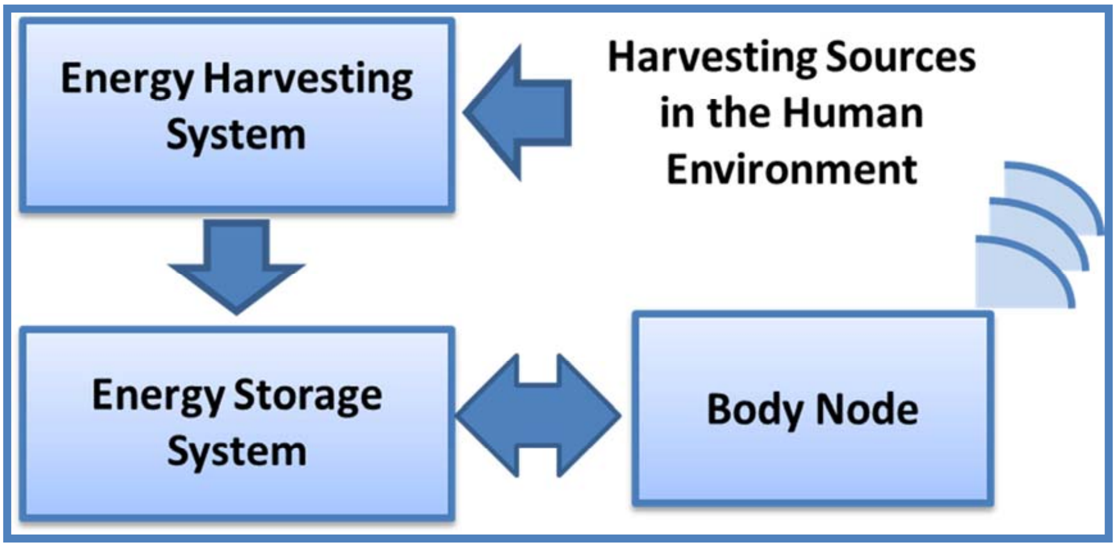

Figure 2.1 – Block diagram of a BN powered by energy harvesting

In Figure 2.1, three main parts can be identified in a BN powered by energy harvesting:

- **Energy Harvesting System:** Its function includes the capture of the source energy and its conversion into electrical energy. The collected energy is sent to the storage system.

- **Energy Storage System:** Its task is to store the energy collected by the energy harvesting system in order to power the node later. This type of system also deals with possible changes in the harvesting source in order to protect the BN from possible damages.

- **Body Node:** It is the device that is powered by the available energy in the storage system. Aiming to always provide proper operation, the BN should adapt its operation to the available energy supply and the rate of energy collection (i.e., energy harvesting rate).

2.1.1 Energy Harvesting System in the Human Environment

The energy harvesters that can be used in WBANs differ from those used in traditional WSNs. In WSNs, nodes can use various sources available in the environment, which are often called ambient energy harvesting sources. Currently, the most frequently used energy harvesting sources in WSNs are: solar, mechanical, thermal and electromagnetic [3, 4]. However, the harvesting sources that power BNs in WBANs (Figure 2.2) may come from multiple sources of energy inside or on the human body [5], including mechanical [6, 7], thermal [8, 9], and biochemical energy [10, 11]. Sources related to movement (vibration) and thermal temperature (body heat) are the main candidate power sources in WBANs [12]. Energy harvesting sources are not uniformly distributed in the human environment, i.e., the magnitude and availability of a given source varies depending on its characteristics. In this way, certain phenomena are more prevalent in some parts of the body than in others. A harvester device may be designed to capture energy by two or more sources, in order to increase both the availability and the amount of harvested energy per time unit. For example, hybrid generators could capture from: thermal/mechanical sources [13], mechanical/biochemical sources [10], photovoltaic/thermal sources [14], and mechanical/electromagnetic sources [15], among others. To exploit the energy harvesting sources, the nodes must have an efficient architecture for multi-input energy harvesters. Bandyopadhyay and Chandrakasan [16] have designed a circuit that allows a node to switch between three energy harvesting sources (i.e., solar, thermal, and vibration sources) quickly, optimizing the energy production. Thus, the system can be powered from the three energy sources simultaneously, in order to achieve higher reliability without the need to increase the number of system components.

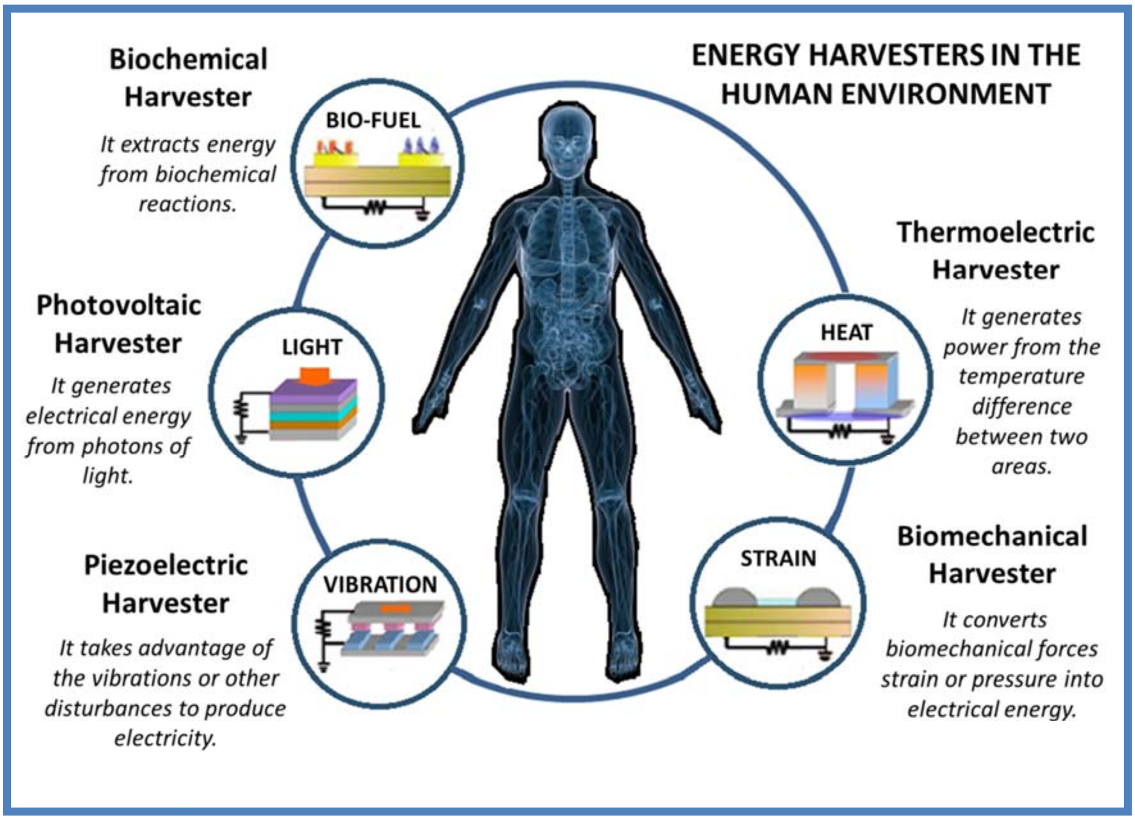

Figure 2.2 – Energy harvesters in the human environment

The availability of energy harvesting sources on the human body differs from those available within it. The human body has regulatory mechanisms to keep the conditions of its internal environment constant and resistant to the changes experienced due to the external environment. Therefore, the body keeps stable internal conditions (homeostasis) through self-regulatory actions in dynamic control parameters such as temperature, amount of water, salts, etc. On the other hand, the external environment cannot be controlled by these mechanisms. Based on the classification used in [17], it is possible to classify the energy harvesting sources present in the human environment into two groups:

a) **Predictable sources:** Those energy sources that come from phenomena that can be accurately modeled and/or predicted with small margin of error. Two such examples are the piezoelectric harvester that uses mechanical energy produced from heartbeats and the biochemical harvester that uses glucose oxidation to produce electrical energy within the human body (Figure 2.3). Both examples are uncontrollable harvesting sources, but deliver a given amount of energy per unit of time quite constantly. Hence, the amount of collected energy can be well estimated (predicted), since we basically know that the heart normally beats 60 to 100 times per minute and that the normal glucose level in the cerebrospinal fluid is between 50 to 80 mg/100 ml.

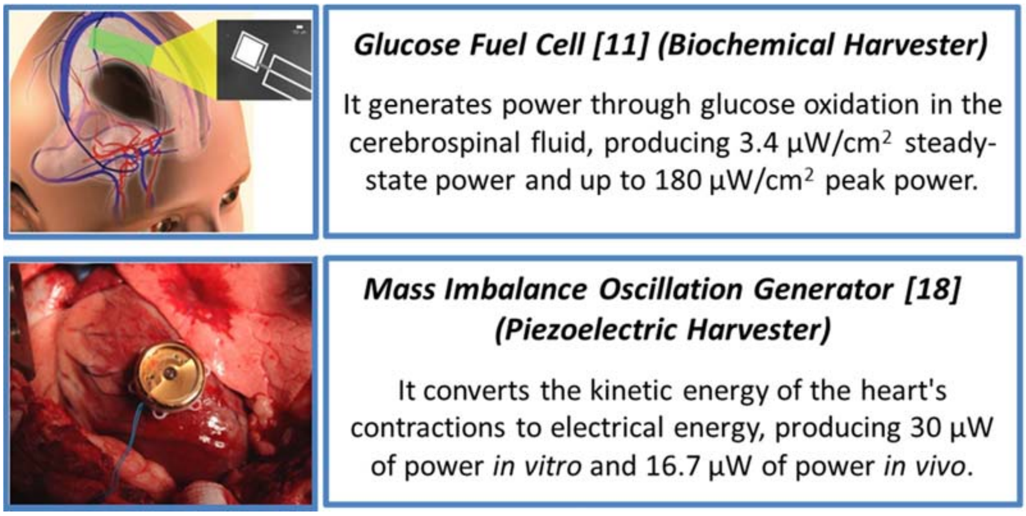

Figure 2.3 – Examples of predictable energy harvesting sources

b) **Unpredictable sources**: This group covers the random energy harvesting sources in which the predictive modeling becomes complex or impossible to apply in WBANs. Examples include a piezoelectric harvester that takes advantage of the movement of human locomotion, or a thermoelectric harvester that uses the temperature difference between the human body and the environment to produce electrical energy (Figure 2.4). In the first example, the human walk can be considered as a random process difficult to be predicted with accuracy, since it depends on several variables (duration, speed, breaks, etc.). Therefore, the amount of energy that is collected by the harvester in a given period of time cannot be known in advance. Similarly, regarding a thermoelectric harvester located on the body, the collected energy cannot be predicted because the changes in the environmental temperature are usually uncontrollable. Although thermoregulatory mechanisms tend to keep the body temperature at 37°C, changes in the external environment mean that the temperature difference between the two mediums may vary, thus causing changes in the amount of the collected energy.

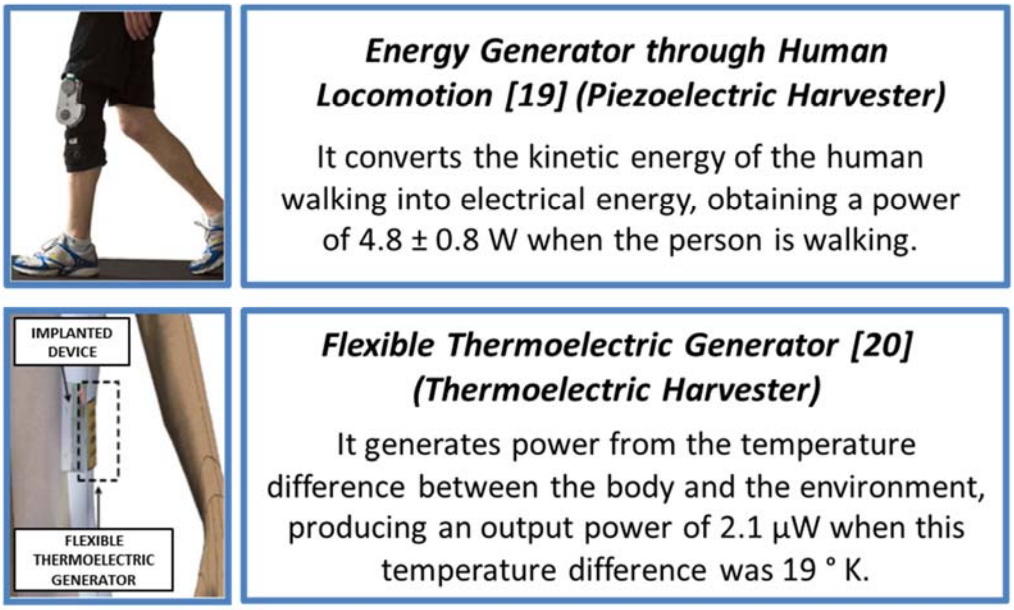

Figure 2.4 – Examples of unpredictable energy harvesting sources

The artificial energy harvesting is another type of source that can be used to supply power to the nodes. Such sources usually do not exist in the human environment, but they are located in a suitable manner for supplying power to the nodes when necessary. An example of these sources is the transcutaneous energy transfer systems [21, 22] (Figure 2.5). These systems transfer power from a transmitter to a receiver implanted in the human body through the materials that are placed between them, i.e., clothes, skin, fat, blood, etc. Energy is transferred through unbroken skin by an alternating magnetic field which induces electric current flow in the receiver. These systems deliver much more power compared to the energy harvesting sources available naturally in the human environment, enabling the power supply of energy-hungry implantable devices (e.g., artificial hearts).

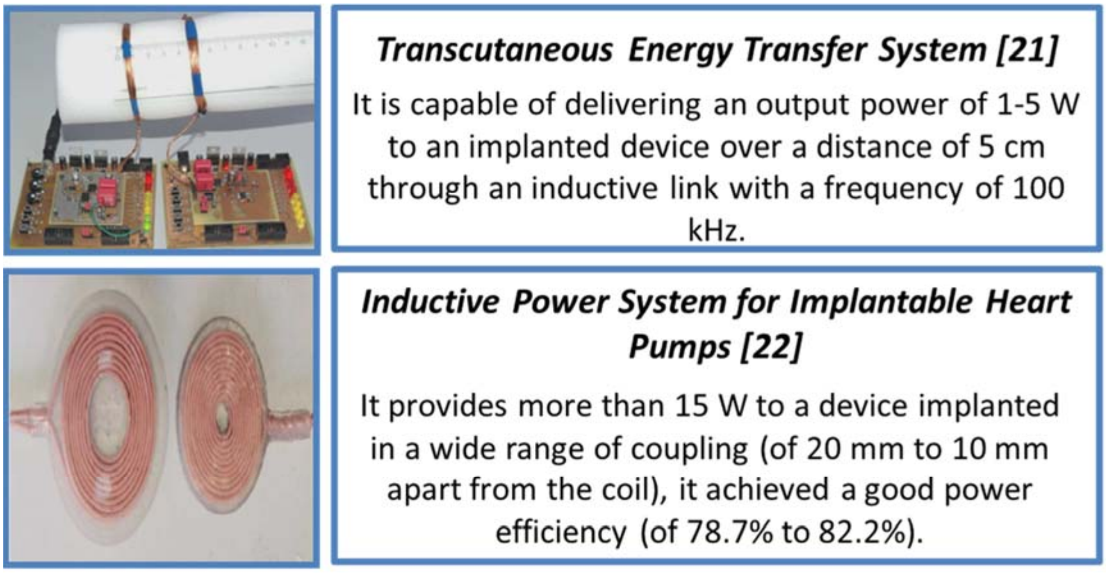

Figure 2.5 – Examples artificial energy harvesting sources

2.1.2 Energy Storage System for BNs

Wireless sensors powered by energy harvesting mainly classified into two basic architectural types depending on the way in which the collected energy is used [17, 23]. If the energy is captured and immediately used, the Harvest-Use architecture is utilized. On the other hand, if the energy is stored before use, a Harvest-Store-Use architecture is employed. Figure 2.6 shows the main characteristics of these two architectures.

Figure 2.6a shows the Harvest-Use architecture, whose main characteristics are:

- The energy harvesting system supplies power directly to the node.
- This type of architecture is very effective when the energy harvesting source delivers big amounts of energy.
- The output power of the energy harvesting system must be continuously above the minimum required power, in order to ensure the successful operation of the node.

- Failure to reach the minimum required power causes the node to turn off automatically.
- Abrupt variations in the output power near the threshold (minimum power) cause an intermittent operation of the node (i.e., fluctuation between active and inactive states).

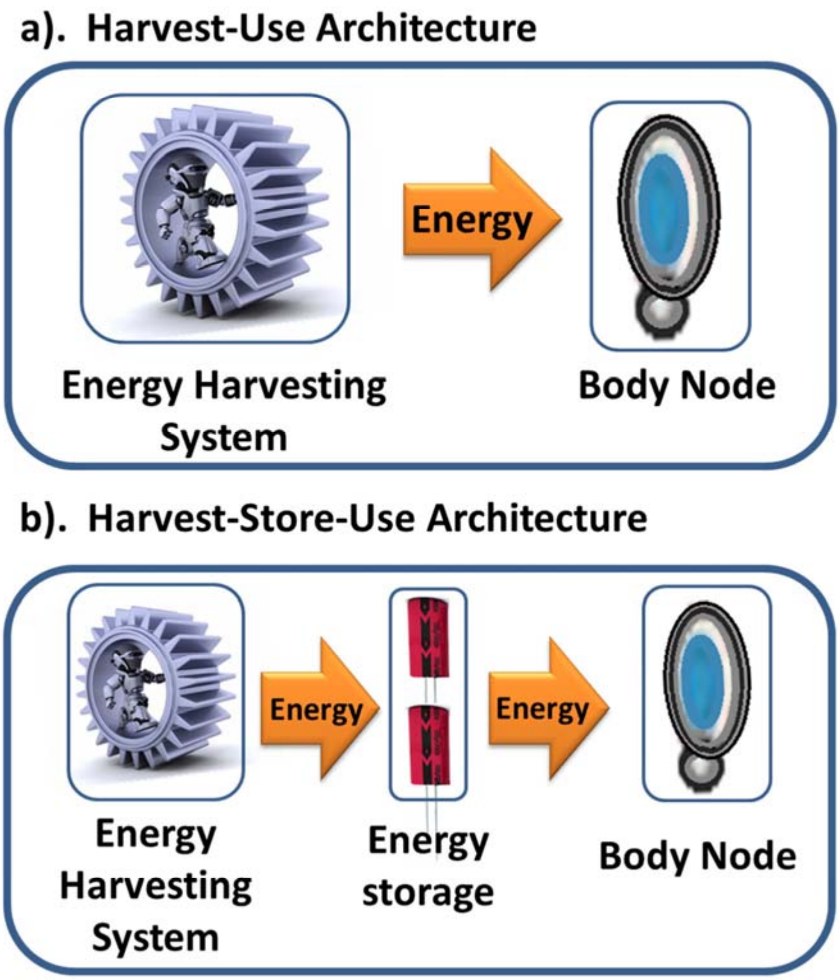

Figure 2.6 – Architectures of systems powered by energy harvesting: a) Harvest-Use Architecture, and b) Harvest-Store-Use Architecture

With regard to the Harvest-Store-Use architecture, shown in 2.6b, the main characteristics are:

- The node is powered through devices that store and deliver the collected energy.

- This type of architecture is also very effective when the energy harvesting source delivers more power than required, so the node can be kept operational and the excess energy is stored for later use.
- If the power delivered by the energy harvesting source is less than the required amount, the available energy can be stored until it reaches the necessary level to make the node operational.
- Through the energy storage device we can address the issues related to the abrupt changes in the power supply.

The energy collected in the human environment is usually not enough for the direct operation of the node and, hence, the energy must be stored before use (i.e., Harvest-Store-Use architecture). The collected energy must be deposited in a rechargeable device, usually a battery or supercapacitor, until it reaches the level required for the node to function properly. The supercapacitor is the most suitable device for this task, because of its small size, its light weight, and its almost infinite charge and discharge cycles [23, 24]. Figure 2.7 shows the main characteristics of the energy storage devices used in wireless nodes [24, 25] and biomedical devices [26].

Due to their advantages as energy storage devices, supercapacitors are considered as an extremely attractive option for implantable medical devices [27]. For reference, 100 mV in a supercapacitor in Farad (1F) results in 100 mJ; this energy should be enough to power an implanted device for at least 3 hours [28]. The design of a reconfigurable capacitor bank for maximizing the energy use is presented in [28]. In particular, exploiting more than 98% of the stored energy, supercapacitors outperform significantly the conventional technology based on batteries.

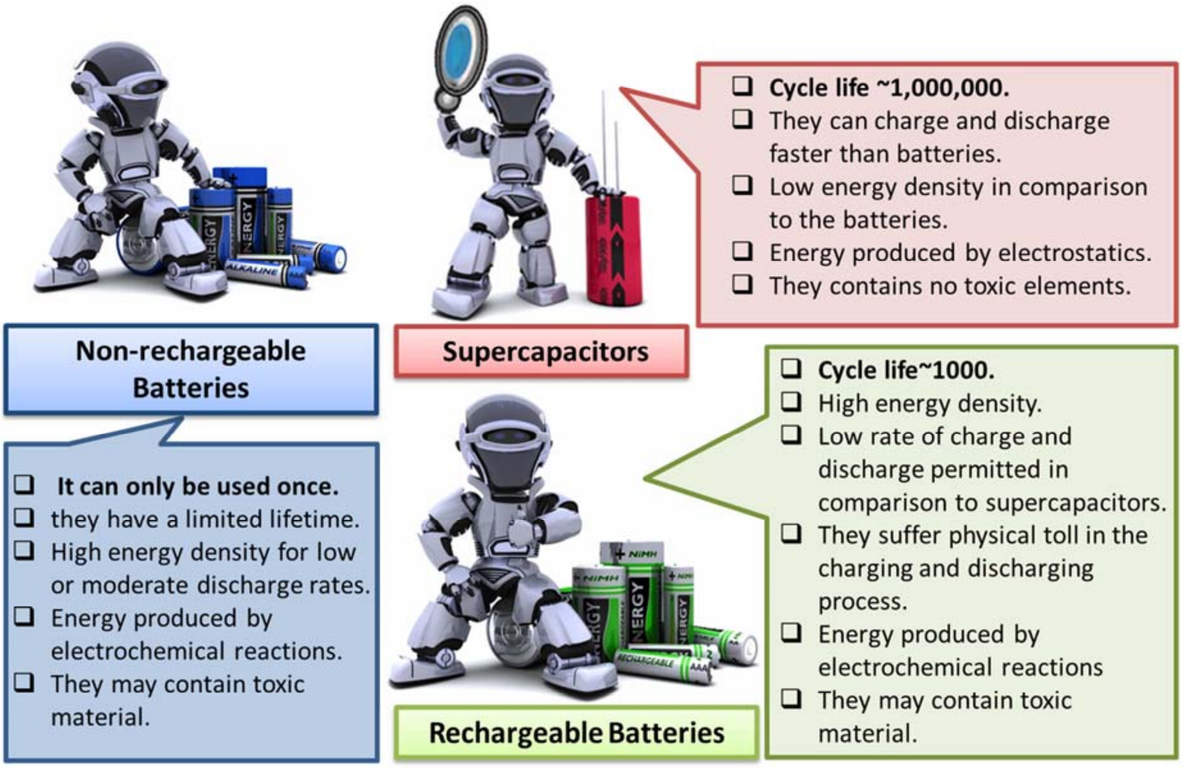

Figure 2.7 – Main characteristics of energy storage units

2.1.3 BNs in the Wireless Body Area Networks

The WBANs are specified in the IEEE 802.15.6 standard for short-range wireless communication in the proximity or inside the human body (but not limited to humans) [29]. Figure 2.8 shows the relationship between IEEE 802.15.6 and the other IEEE standards for wireless networks.

WBANs consist of small, smart medical devices with sensing, processing and wireless communication capabilities. These BNs have the ability to act on their own without assistance from other devices. The nodes that belong to the WBANs may execute one or more actions related to either physiological signal monitoring, diagnosis or treatment of diseases. As seen in Figure 2.9, the BNs are a very heterogeneous group of devices with regard to their tasks (applications), hardware type, location in the human body, and propagation mediums of the radio wave (e.g., biological tissues, air, etc.).

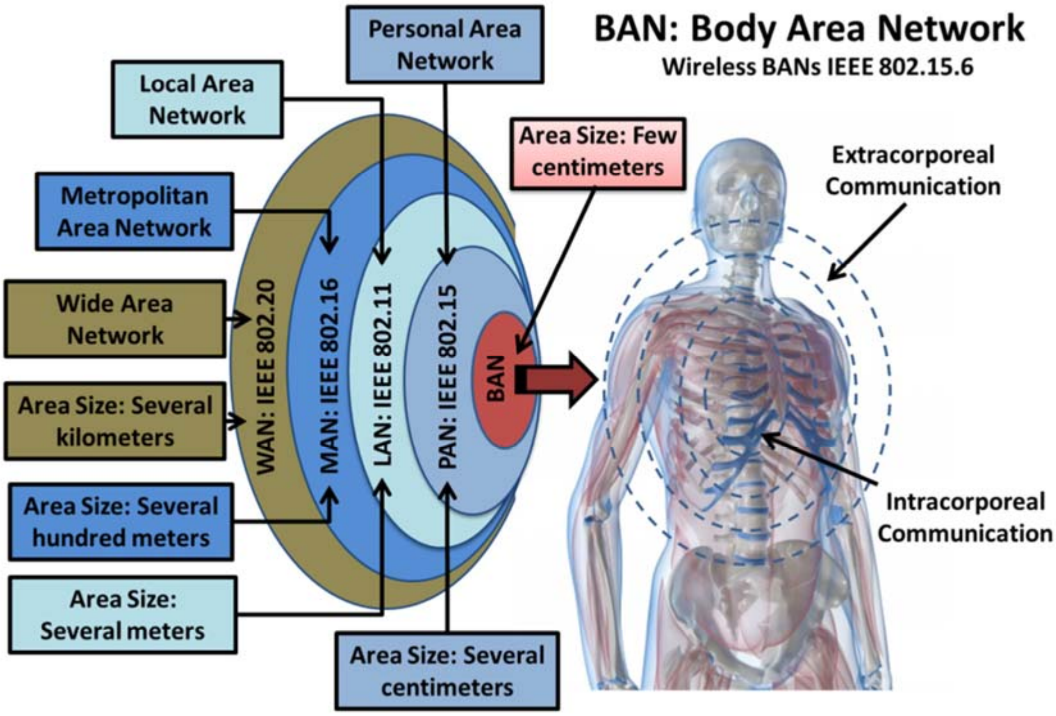

Figure 2.8 – Relation between IEEE 802.15.6 and the others types of wireless networks

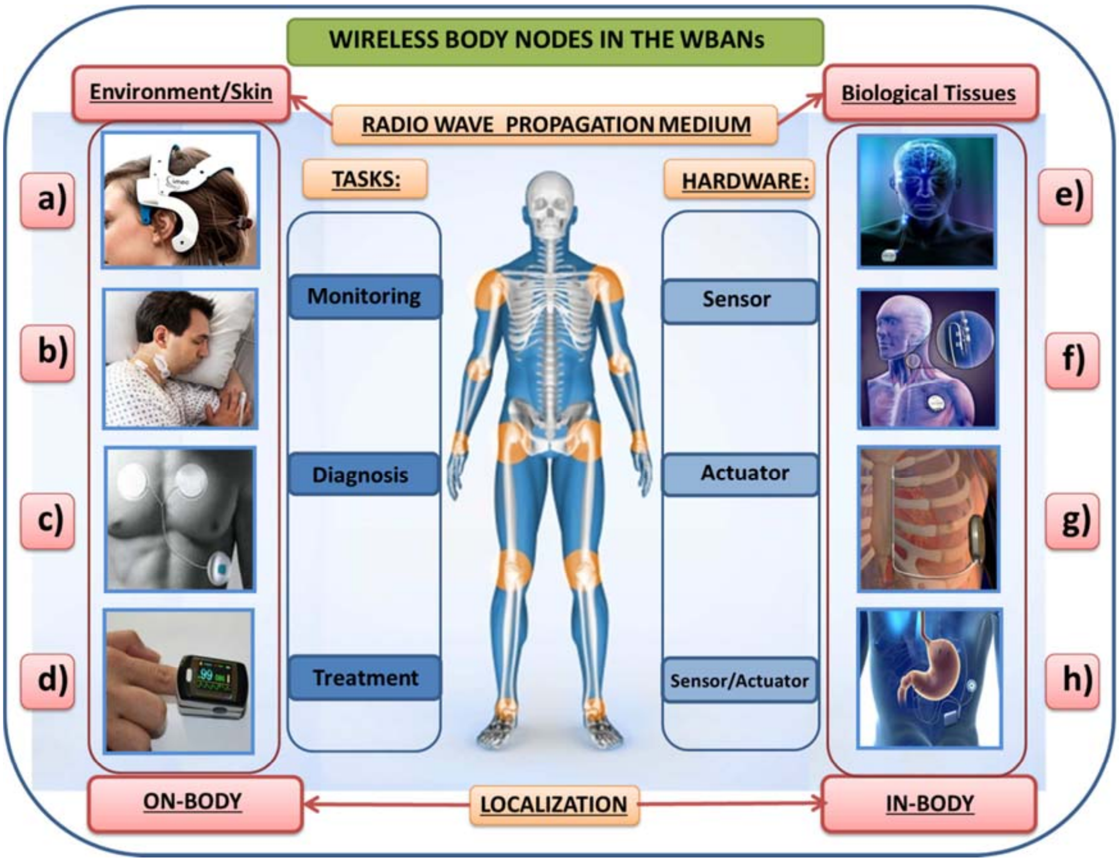

Figure 2.9 – Illustration of the heterogeneity of the BNs in the WBANs

Figure 2.9 shows some examples of BNs located:

• **On the Human Body:** (a) Electroencephalograph (EEG) (e.g., EEG Imec / Holst Centre), (b) Respiratory rate sensor (e.g., Masimo Rainbow SET Acoustic Monitoring), (c) Electrocardiograph (ECG) (e.g, ECG V-Patch), and (d) Pulse Oximeter (e.g, OEM Fingertip Pulse Oximeter).

• **Inside the human body**: (e) Deep brain stimulator (e.g., LibraXP deep brain stimulator), (f) Vagus nerve stimulator (e.g., Cyberonics VNS Inc), (g) Subcutaneous implantable cardioverter-defibrillator (e.g., Cameron Health S-ICD System) and (h) Gastric stimulation system (e.g., DIAMOND System).

Due to the great heterogeneity of BNs and their respective characteristics, the nodes can be easily distinguished according to:

• **Priority:** The level of importance of each node. Since the clinical environment is extremely random, a node's priority will be also volatile, since it depends on the current health status of the patient and the parameters studied in a given period of time.

• **Quality of Service (QoS)**: This concept is related to the requirements in the treatment of specific data traffic. The parameters handled in QoS (e.g., packet loss, delay, throughput, etc.) depend on the particular requirements of the executed application.

• **Data Packet Size**: Group of bits into which the information is broken down and then transmitted.

• **Inter-arrival Packet Time**: Corresponds to the time delay between two packet generations.

• **Power Consumption**: The energy consumption of each node per unit of time.

• **Duty Cycle**: Percentage of usage of each component of the node (e.g., radio, CPU, sensor, etc.) in certain periods of time. In a sensor node, we can define duty cycle as the ratio of the active period and the full active / inactive period [30].

• **Battery Lifetime**: The time of power supply provided by batteries before they run out, directly impacting the node autonomy.

2.1.4 BNs Energy Consumption

Energy consumption is a key factor in WBANs, due to restrictions in the power supply, the operation of the nodes, and their delicate functions which may be affected or interrupted. In Figure 2.10 (based on information from Texas Instruments), it can observed that the medical WBANs are designed to handle data rates ranging from a few kb/s up to several Mb/s , while consuming small amounts of energy (in the order of a few mJ/s).

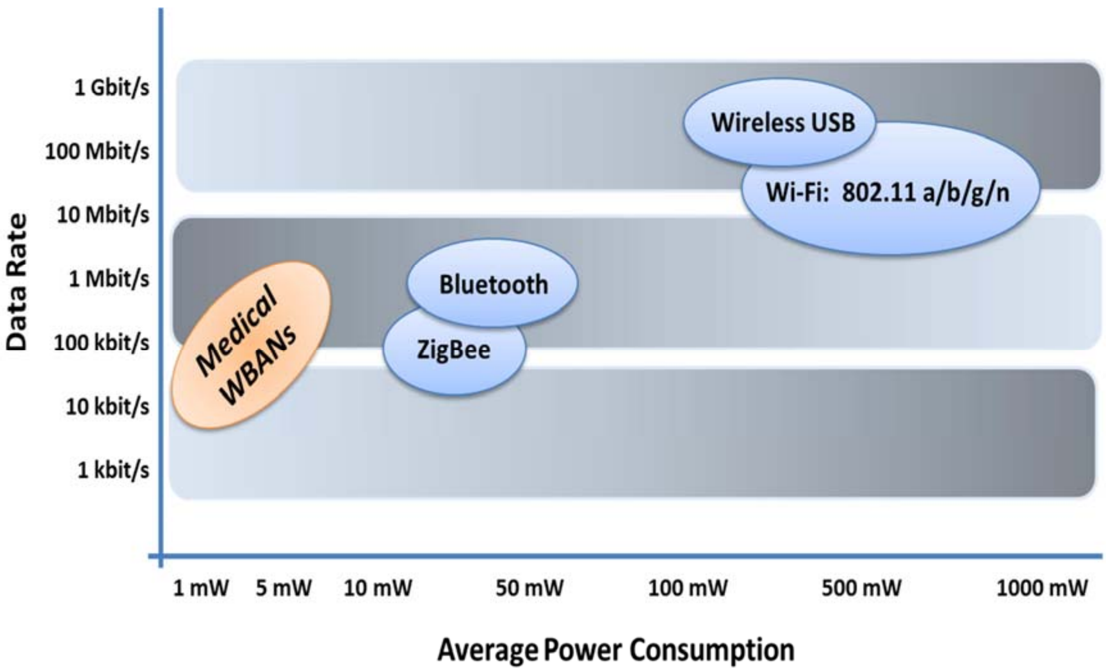

Figure 2.10 – Medical WBANs: data transmission rates and average power consumption, compared to other wireless technologies

As seen in Figure 2.11, the highest amount of energy of an ECG node is consumed by the radio interface. In this example, the radio uses 50% of the total energy consumed per unit of time, followed by the power management system (PM) (25%), the sensor and reader (R-out) (19%), the microcontroller unit (MCU) (5%), and, finally, the analog to digital converter (ADC) (1%).

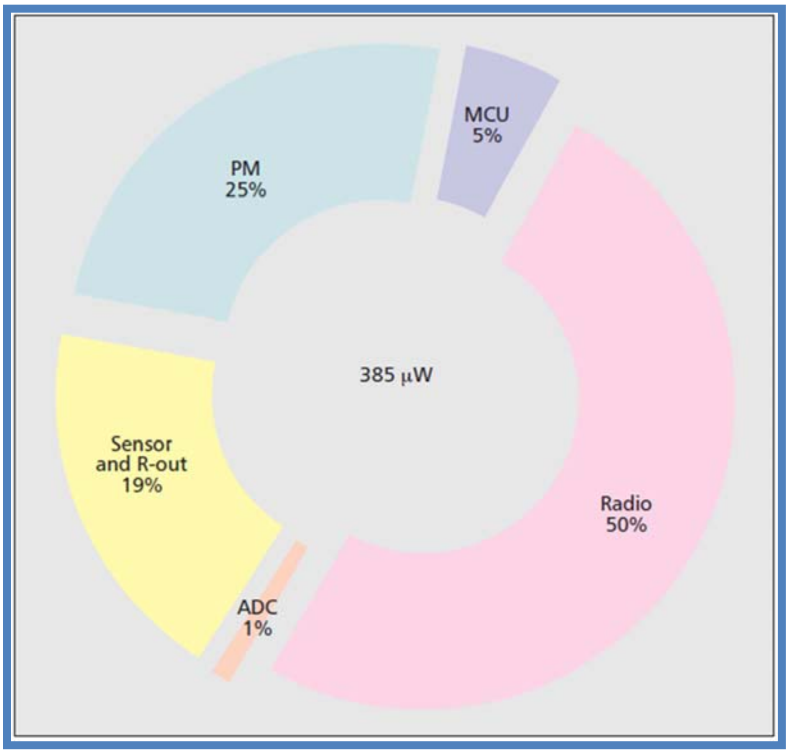

Figure 2.11 – Distribution of power consumption when a sampled signal is transmitted by an ECG [31]

The efficient energy management is the key to extend the lifetime of the node as much as possible before it becomes necessary to change or recharge their batteries. Most wireless nodes have several modes of operation supported by the MCU. These modes are characterized by different power consumption, due to internal switches that allow the system to turn on or off parts of the hardware of the node, depending on the task it is performing, thus increasing or decreasing, respectively, the energy consumption per unit of time. Figure 2.12 shows an example of the operation modes of a wireless sensor [32]. There are four modes, namely active (Active Mode), sleep (Sleep Mode), reception (RF Receive) and transmission (RF Transmit). The transmission and reception modes are more power consuming. The time that a node spends in a particular mode, as well as the number of transitions, greatly affects its duty cycle and energy consumption. The duty cycle of each node depends on the type of application and the tasks to develop, which is why operating modes conform to these requirements.

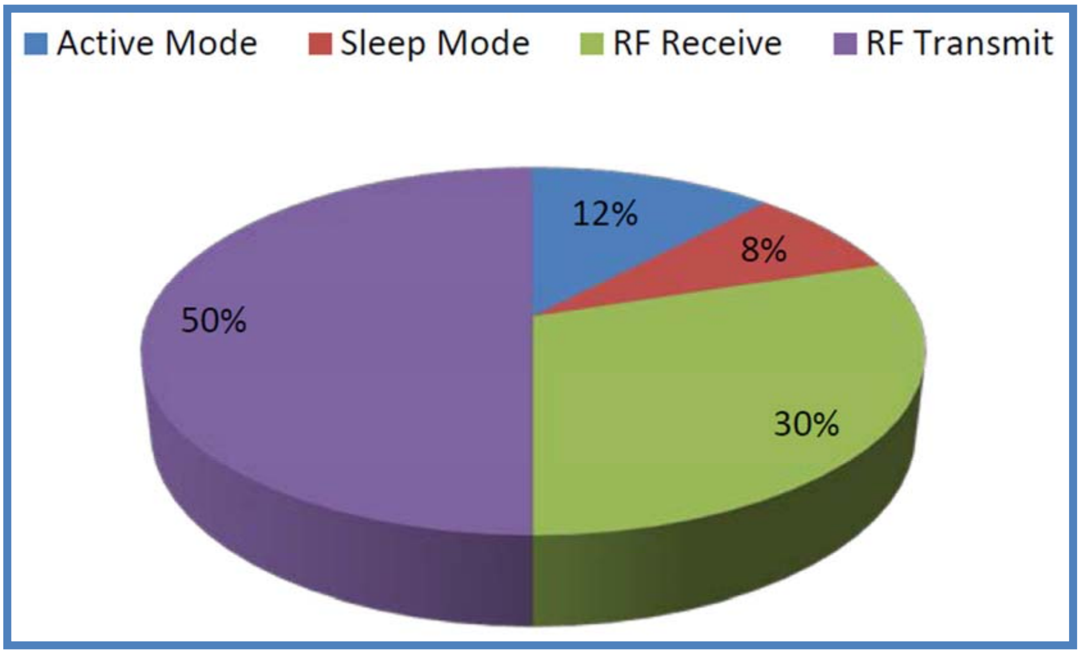

Figure 2.12 – Power consumption of some operation modes in a wireless sensor [32]

2.1.5 BNs Powered by Human Energy Harvesting

Generally, the BNs within a WBAN have differences in their features, their power consumption and their energy harvesters. Their performance is conditioned by their power consumption and the energy supply of their harvesting system.

The positioning of a BN on or inside the human body is determined by the particular medical application. In addition, the proximity to the condition that is being treated, the availability of a physiological signal that is monitored and the performance of the diagnostic process, among others, must be considered. The location of the node, the nature of the source to be harvested, as well as the characteristics and dimensions of the employed harvester, are parameters that determine the amount of energy that can be collected from the human environment. For this reason, the choice of the best harvester source for each node is an important task in these networks, since the harvester performance directly affects the performance of the node and not vice versa. Taking into account the fact that the scope of the BNs is always the human body, a node located in a respective area may be attached to a number of given energy harvesters (Figure 2.13).

In this point, let us briefly explain the subfigures in Figure 2.13:

- Figure 2.13a shows a piezoelectric harvester that takes advantage of the heart contractions (predictable source) to power a pacemaker. This harvester was designed and clinically tested by the consortium Zarlink Semiconductor and the company Perpetuum.
- Figure 2.13b shows a photovoltaic/thermal hybrid harvester based on environmental light and the temperature difference between the body and the environment (unpredictable sources) to power a wireless EEG. The depicted EEG node is a prototype designed and implemented by the Belgian research center, in nano-electronics and nanotechnology, IMEC (Interuniversity Microelectronics Centre).
- Figure 2.13c shows an artificial heart which is powered by a transcutaneous wireless transfer system (artificial source). This figure shows the AbioCor artificial heart system designed and developed by the U.S. Abiomed Company.

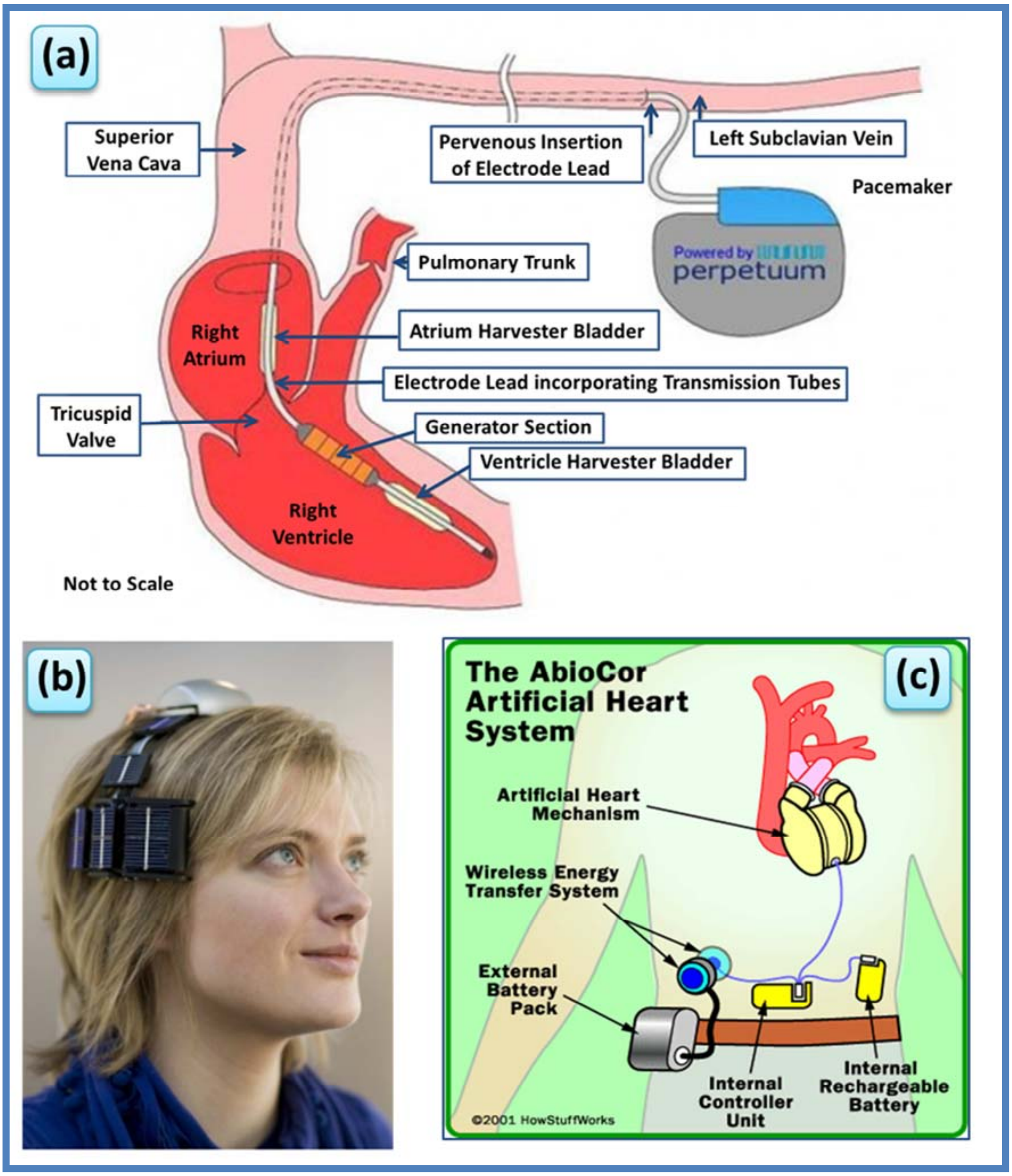

Figure 2.13 – BNs connected to various energy harvesters in the human body: (a) heartbeats (predictable source), (b) environmental light and temperature difference (unpredictable sources) and (c) transcutaneous energy transfer (artificial source)

2.1.5.1 Energy Neutral Operation (ENO)

A node powered by energy harvesting is in ENO mode if it is able to support a desired performance without interruptions, as long as there are no hardware failures [17]. In the ENO state, the node consumes less or equal amount of energy compared to the energy harvested from the environment, allowing it to operate continuously. The availability of the harvesting source in time and space, as well as the way that the harvested energy is used, are the two key factors that determine whether a system operates in ENO state. Kansal et al. [17] explain that the maximum achievable performance by a BN depends on how the harvested energy is distributed through the components that comprise it. Vigorito et al. in [33] emphasize and demonstrate that by implementing control mechanisms for the duty cycle of nodes powered by energy harvesting, they can achieve performance maximization, maintain ENO state, and duty cycle stability. The authors define as ENO-MAX the condition in which a node reaches a maximum performance while maintaining the ENO state [33]. ENO and ENO-MAX are based on the assumption that the node's energy consumption and system performance are strongly related [17, 33]. Figure 2.14 shows a graphical representation of the relationship between system performance and the energy consumption of the nodes [34]. In order to reach the ENO-MAX state, the duty cycle of the node should be adapted to the changes in energy supply due to the harvesting process. In this way, the node can enhance its performance by increasing its duty cycle when there is an excess of harvested energy, or otherwise decrease its duty cycle to reduce power consumption when the collected energy level is low.

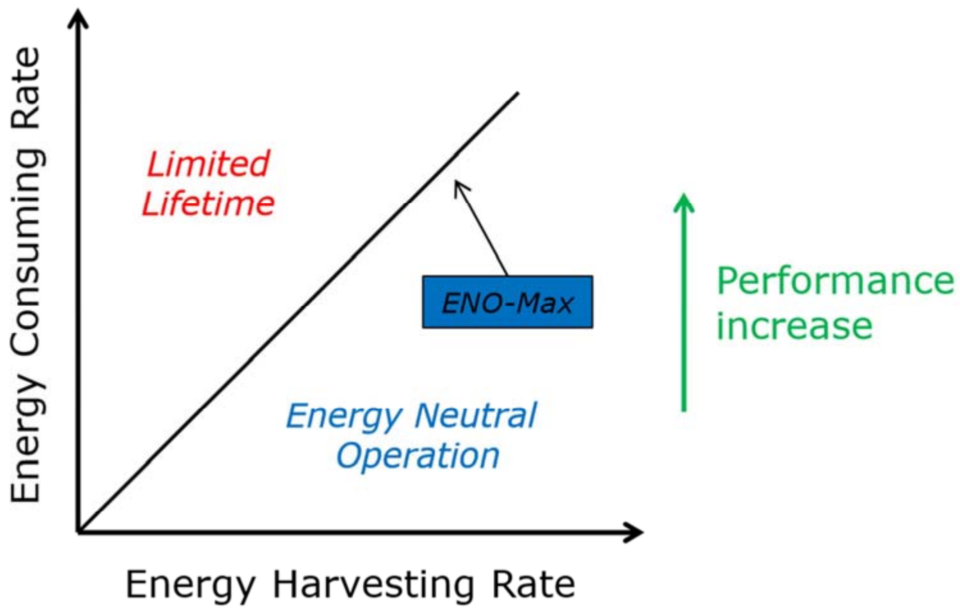

Figure 2.14 – System performance and energy consumption correlation in ENO and ENO-MAX states [34]

2.2 Medium Access Control Protocols

In wireless networks, sharing the medium implied various cases that increase the power consumption and, therefore, reduce the lifetime of the network. The main situations that increase the energy wastage in wireless networks are [35]:

- **Packet Collision**: Occurs when more than one packet is transmitted at the same time. The retransmissions of packets that have collided require additional energy consumption.

- **Idle Listening**: Happens when a node listens to an idle channel to receive data.

- **Overhearing**: Occurs when a node listens to the channel to receive packets that are destined for other nodes.

- **Packet Overhead**: Refers to the control packets and the information added to the payload (headers). The number of control packets used to carry out the data communication process also increases the power consumption.

Wireless communication consumes a considerable portion of the energy available in the nodes. Therefore, the MAC layer is probably the most appropriate level to address the energy efficiency issues [36]; it carries out functions related to channel access control, scheduling of the transmissions, data framing, error handling, and energy management, among others. An efficient MAC protocol maximizes the data throughput and the energy efficiency of the network, thereby achieving optimum use of the wireless channel and extending the lifetime of the batteries. MAC protocols can be divided into two general types (Figure 2.15): contention-free and contention-based access schemes.

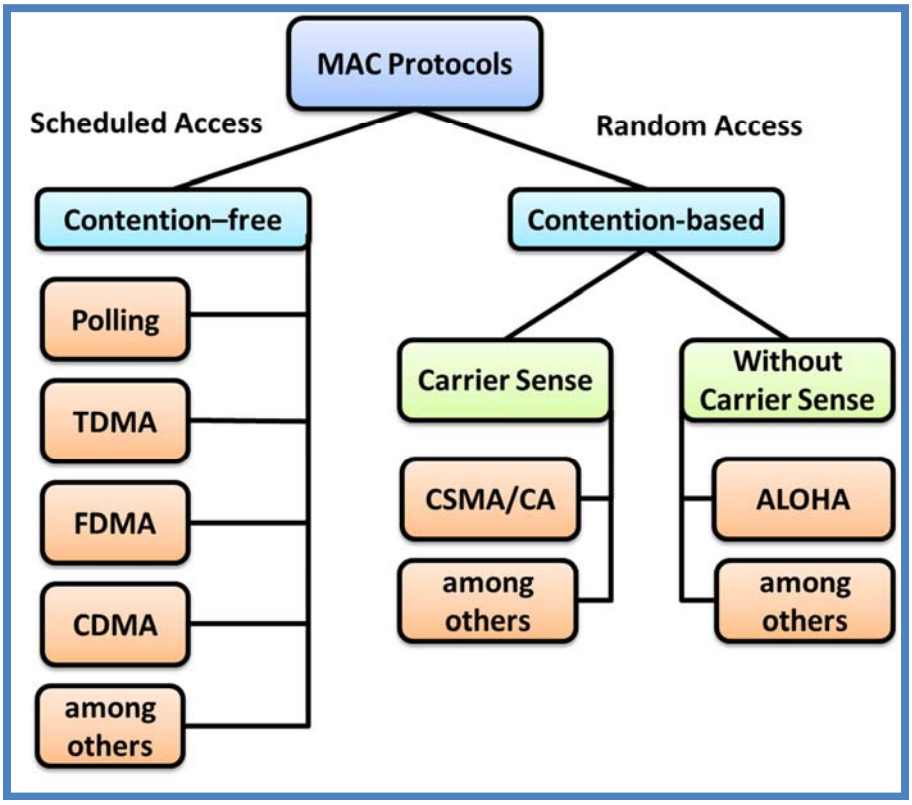

Figure 2.15 – Classification of MAC protocols

In contention-free MAC protocols, medium access is scheduled, so that each node can access the medium without interfering with other nodes. This can be done either by direct assignment by the central controller through a polling request (Polling-based schemes) or by assigning different time slots (TDMA: Time Division Multiple Access), different frequency channels (FDMA: Frequency Division Multiple Access) or different unique codes (CDMA: Code Division Multiple Access). Figure 2.16 illustrates TDMA, FDMA and CDMA contention-free methods. In TDMA, the nodes transmit in different time slots using the whole frequency bandwidth. Regarding FDMA, the nodes transmit at the same time but in different frequencies within the available bandwidth. In the case of CDMA, the nodes are distinguished with their own unique codes that allow them to transmit at the same time and through the same channel. Due to energy efficiency requirements, medium access schemes based on FDMA and CDMA are not a feasible application in WBANs. Although such mechanisms offer collision-free access, they require complex hardware circuitry and high computational power [37, 38].

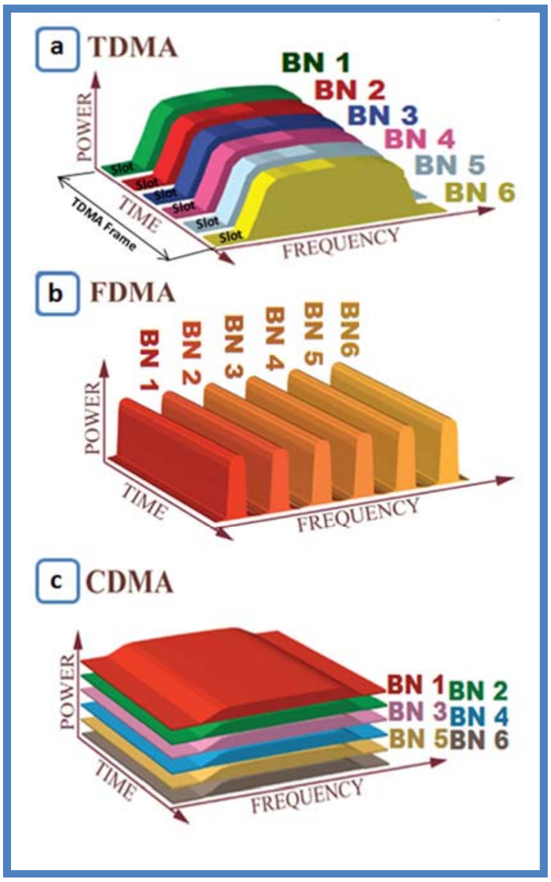

Figure 2.16 – Contention-free multiple-access methods: (a) TDMA, (b) FDMA, and (c) CDMA. Each BN in the network is represented by a different color and number (based on [39])

On the other hand, contention-based protocols provide random access to the medium and the nodes must compete to gain the channel resources. In turn, these protocols can be divided into two sub-categories depending on whether they include mechanisms for checking channel availability (e.g., CSMA/CA: Carrier Sense Multiple Access/Collision Avoidance) or not (e.g., ALOHA), before making their data transmissions. In CSMA/CA, the nodes perform Clear Channel Assessment (CCA), i.e., listening to the wireless channel, and transmitting only if the medium is perceived as idle. If the channel is busy, the node postpones its transmission until the channel becomes idle. If the transmission is successful, the receiver sends an acknowledgment (ACK) to the transmitter. In the case of ALOHA, nodes attempt transmissions as soon as they have packets in their buffers. If a data collision occurs, each node retransmits the packet after a random time interval, in order to reduce the probability of further collisions. The slotted ALOHA version is more suitable for WBANs. In slotted ALOHA, data packets are transmitted only within the time slots. In this way, slotted ALOHA enhances the system performance and the medium utilization efficiency (see Figure 2.17).

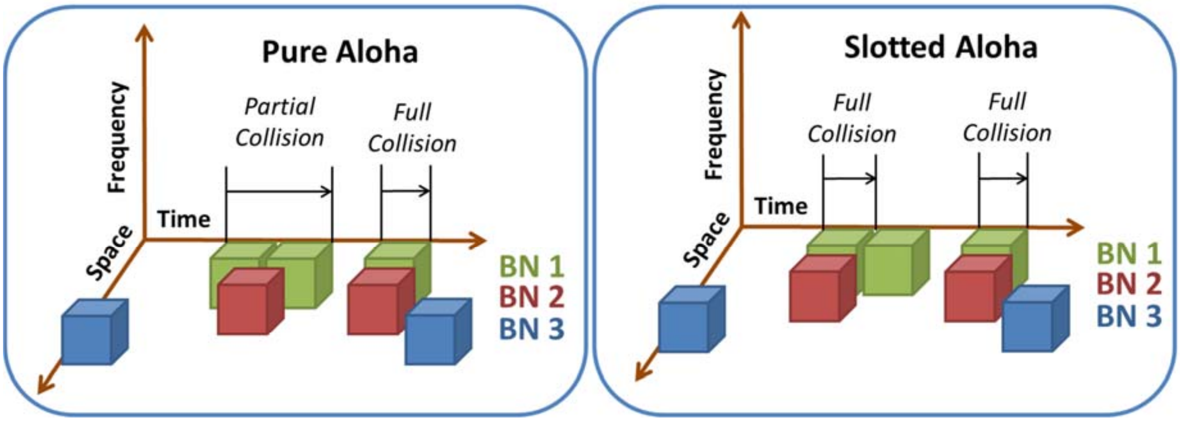

Figure 2.17 – Timing diagram of Aloha pure and slotted (based on [40])

In protocols that use time slots, time is divided into discrete intervals (slots) and actions (transmissions or receptions of packets) are initiated exactly at the beginning of each slot. Hence, packet collisions are reduced significantly and the network performance is increased. Nodes plan and use the time slots depending on the duty cycle of the radio, i.e., if it is in reception mode, transmission mode, or whether it is turned off. The slots must be synchronized on all the nodes, allowing them to turn on their radios only when needed, thereby greatly reducing idle listening.

2.2.1 MAC protocols for WBANs

The design of energy efficient MAC protocols for WBANs is a research topic that is gaining much interest and significant importance in the last years. WBANs have captured the attention of research centers and companies worldwide. This has led to the development of numerous MAC protocols for WBANs. MAC protocols that aim to improve the energy efficiency of the network can be used as a strategic tool for extending the battery life of BNs. With the aid of the scientific and industrial community, the IEEE Task Group 6 published on February 29, 2012 the IEEE 802.15.6 standard for WBANs. The protocol provides specifications and recommendations for the physical (PHY) and the MAC layer for WBANs. In IEEE 802.15.6, time is divided into superframes. This structure allows three types of access mechanisms: i) random access (contention-based), which uses either CSMA/CA or slotted ALOHA for resource allocation, ii) improvised and unscheduled access, which uses unscheduled polling/posting for resource allocation, and iii) scheduled access, which schedules the allocation of slots in one (1-periodic) or multiple (m-periodic) time allocations.

In the current literature, we can find various surveys of proposed MAC protocols for WBANs [35-38, 40, 41]. In the contention-based MAC schemes the main advantages are: good scalability, adaptation to traffic load fluctuations, low complexity, lower delay, and reliable transmission of packets. However, their transmission efficiency is reduced due to packet retransmissions, while the power consumption is relatively high due to overhearing, idle listening and packet collisions. The data packet collisions are the main source of energy inefficiency [37]. Additionally, an analytical study of MAC protocols for WBANs by Ullah et al. [35] shows that the CSMA/CA-based protocols, besides having a high number of collisions, they also have problems with unreliable CCA. With respect to pure and slotted ALOHA, Javaid et al. [40] explain that these techniques are not widely used in WBANs due to their high packet drop rates and low energy efficiency due to data collisions. On the other hand, the TDMA-based protocols have high transmission efficiency, no overhearing problems, no packet collision, low power consumption and maximum bandwidth utilization. In the analytical studies [40] and [41], the authors considered the TDMA-based protocols as the most energy-efficient and reliable MAC protocols for WBANs. The main disadvantage of the TDMA-based protocols is that they are not adaptive, flexible, and scalable, while they require precise synchronization, whereas in the case of the CSMA/CA and pure ALOHA, synchronization is not required. In addition, Rahim et al. [38] claim that the CSMA/CA approach has better adaptation than the TDMA in dynamic environments, thereby providing good mobility to the wireless network. On the other hand, the TDMA approach is well-suited for static WBANs, as it provides good support for high traffic level but poor adaptation in dynamic environments [38]. In addition, Zhen et al. [42] demonstrate experimentally that CSMA/CA cannot be adopted in WBANs in-body due to the unreliable CCA, aggravated with the rapid attenuation of electromagnetic wave through biological tissues.

Boulis and Tselishchev [43] provide a study about the variation of performance and energy consumption in WBANs, when using the contention-based access and polling-based access under different traffic loads. The results obtained [43] indicate that polling-based access offers significant energy gains compared to contention-based access.

Regarding the latency (end-to-end delay), the combination of short contention periods with long polling periods provides the most stable performance with respect to packet transmissions. Khan and Yuce in [44] explain that the polling-based MAC protocols can support traffic sources with different data inter-arrival rates, providing higher network flexibility than the TDMA-based protocols. The same authors [44] claim that the combination of polling-based and CSMA/CA-based access protocols could be a good mechanism for power saving and for the reliable communication of critical medical data.

2.2.2 MAC protocols for WSNs Powered by Ambient Energy Harvesting (WSNs-HEAP)

Significant research in the field of WSNs Powered by Ambient Energy Harvesting (WSNs-HEAP) has been conducted by Eu et al. [45-49]. These works are very relevant to the contributions of this thesis, since they propose MAC protocols designed for energy harvesting, even though the focus is put on ambient energy harvesting (and not human energy harvesting).

In [45], Eu et al. perform an empirical characterization of a WSN-HEAP of commercially available thermal and solar energy harvesting sensor nodes. The results in this study show that the transmission range of the nodes is highly dependent on the environment in which they are deployed, and that the energy charging times vary in different scenarios even in the absence of mobility [45]. In [46], the authors provide a comprehensive survey of the WSNs-HEAP that includes the main challenges to be faced. As part of this study, the authors have provided a summary of the key aspects of WSN and WSNs-HEAP (see Table 2.1), and through this compilation and analysis they have concluded that current technology in energy harvesting does not provide a sustained energy supply to enable WSNs to work continuously [46].

Table 2.1: – Summary of Key Aspects of WSN and WSN-HEAP [46]

Aspect	Battery-operated WSNs	Battery-operated WSNs helped by energy harvesters	WSN-HEAP
Goal	Throughput and latency are usually traded off for longer network lifetime	Longer lifetime achieved by supplementing battery power with harvested energy	Maximize throughput and minimize delay since energy is renewable & there is no concept of lifetime
Protocol Design	Sleep-and-wakeup schedules can be determined precisely	Sleep-and-wakeup schedules can be determined if future energy availability is correctly predicted	Sleep-and-wakeup schedules cannot be predicted
Energy model	Energy model is well understood	Energy model can be predicted with high accuracy	Energy harvesting rate varies across time, space, as well as with the type of energy harvester.

The same authors have developed analytical studies on the design and performance of MAC schemes for WSNs-HEAP [47-49]. MAC protocols using time slots, like TDMA, slotted ALOHA and the slotted version of CSMA/CA, are difficult to apply to the WSNs-HEAP because they require time synchronization. The energy harvesting sources for WSNs are usually unpredictable, complicating the exchange of time schedules between nodes, since the nodes do not know the future availability of energy [47]. In [48] and [49], the authors conducted a performance study of four different MAC protocols based on CSMA-based and polling-based techniques for WSNs-HEAP. The authors analyzed the following protocols: slotted CSMA/CA, unslotted

CSMA/CA, ID-polling and probabilistic polling. The four protocols contain adaptations introduced by the authors, in order to make them functional in energy harvesting conditions. In all these studies, supercapacitors were used for energy storage because of the advantages they offer (see Section 2.1.2). In [47] and [48] a single-hop wireless network composed of a sink and nodes has been considered. In [49], the study focused on the implementation of the probabilistic polling protocol in multi-hop networks. In the following sections, a description of the aforementioned four MAC protocols is given.

2.2.2.1 Slotted CSMA/CA MAC protocol

Slotted CSMA/CA MAC protocol for WSN-HEAP [48,49] is a modified version of the slotted CSMA/CA protocol specified in the standards IEEE 802.11 [50] and IEEE 802.15.4 [51]. In this protocol, the nodes can be in one of the following modes (see Figure 2.18):

- **Charging State**: In this state, both the processor and the transceiver are off. The node is mainly engaged in collecting energy from the environment.
- **Carrier Sensing State**: In this state, both the processor and the transceiver are on. The transceiver is in reception mode in order to detect whether the channel is idle by performing the CCA procedure.
- **Transmit State**: In this state, the processor and the transceiver are on. The transceiver is in transmission mode in order to transmit its data packet.

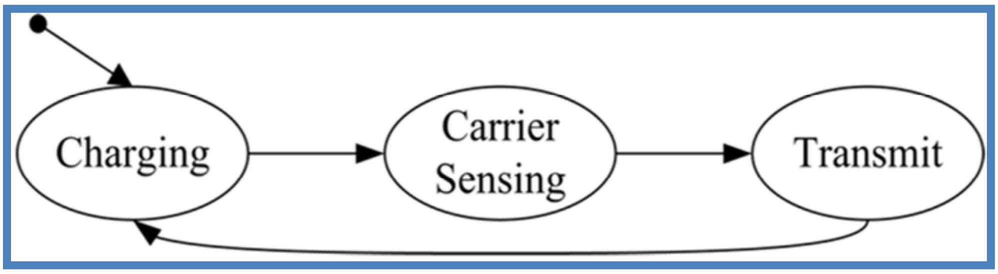

Figure 2.18 – Slotted CSMA, state transition diagram [43]

As seen in Figure 2.18, the default state of the node is the charging state. When the node has collected a predetermined amount of energy (threshold), it wakes up, leaving the charging state, and goes to the carrier sensing state to wait for the start of the next time slot. If the channel has been detected idle, the node goes into the transmission state in the next time slot, where it transmits its data packet to the sink. Subsequently, the node returns to the charging state in order to reach the energy threshold level again. The time the node remains in the charging state depends on the energy harvesting rate that, in turn, depends on the characteristics of the harvesting source. Figure 2.19 shows an example of the transmission timings in slotted CSMA/CA.

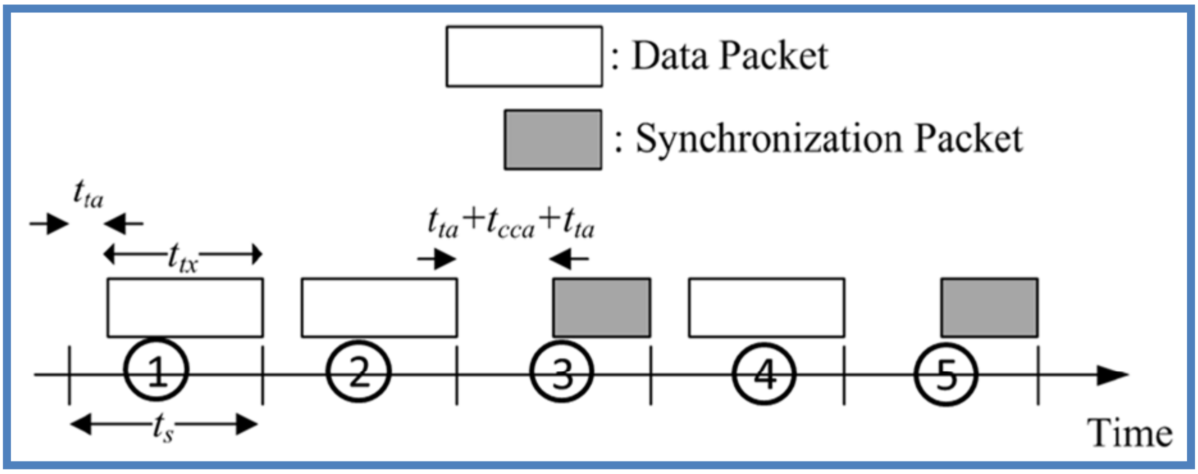

Figure 2.19 – Slotted CSMA, transmission timings [48]

In the example of Figure 2.19 we depict five time slots of duration t_s. The parameter t_{tx} is the time to send a data packet, t_{ta} is the hardware turnaround time from the receiving state to the transmission state or vice versa, and t_{cca} represents the time of the CCA procedure in order to determine if the channel is idle or not. In time slots 1, 2 and 4, the nodes transmit data packets to the sink. In time slots 3 and 5, the sink transmits a synchronization packet once it detects that no sensor has transmitted in that slot.

2.2.2.2 Unslotted CSMA/CA MAC protocol

The unslotted CSMA/CA is another version of the CSMA/CA protocol that does not employ time slots. The unslotted CSMA/CA includes two additional states with respect to the slotted CSMA/CA version: the receiving state and the idle state (see Figure 2.20).

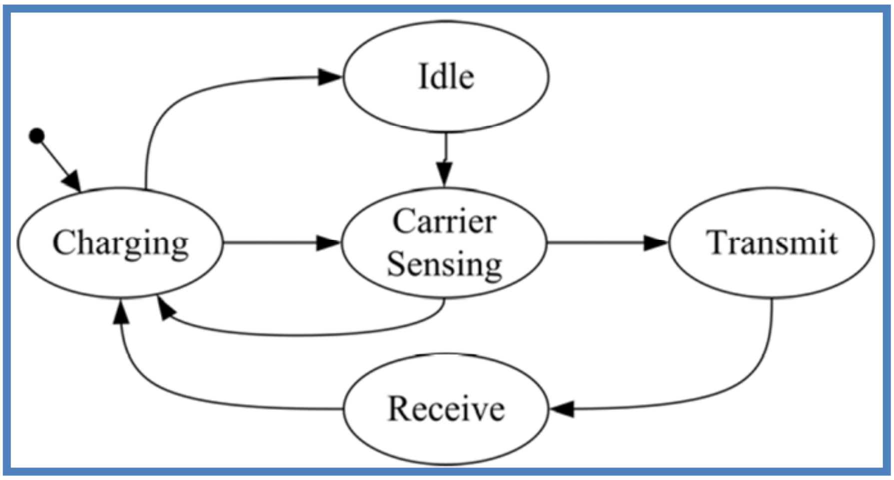

Figure 2.20 – Unslotted CSMA, state transition diagram [48]

In the example seen in Figure 2.20, we can observe the five states of the unslotted CSMA/CA state transition diagram. The initial state is the charging state. The node remains in the charging state until its supercapacitor is full. When the supercapacitor is full, the node changes to the carrier sensing state in order to determine if the channel is free. If it is detected that the channel is clear, the node proceeds to transmit its data packet. After sending the data packet, the node changes to the receiving state in order to receive the ACK packet from the sink. Upon receiving the packet, the node switches back to the charging state again. On the other hand, if the channel is sensed busy, then the node performs a backoff and returns to the charging state. Figure 2.21 illustrates the backoff mechanism of the unslotted CSMA/CA.

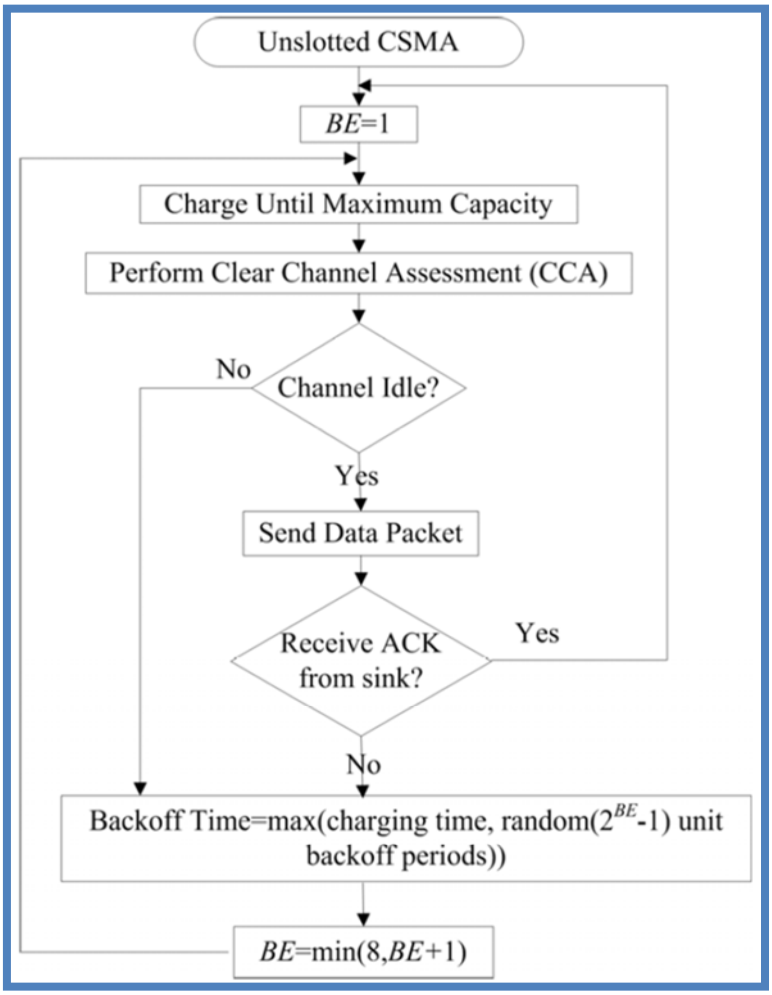

Figure 2.21 – Unslotted CSMA, flowchart of the backoff mechanism [48]

If the supercapacitor is filled before the backoff period is complete, then the node switches to the idle state for the remaining of the backoff period. As seen in Figure 2.21, the backoff period is doubled in two cases: i) if the channel is detected busy, and ii) if the ACK packet is not received after a transmission. The backoff exponent (BE) is doubled after every backoff attempt in order to double the average backoff time. The maximum value that this BE can achieve is *maxBE*. The minimum duration of a backoff is one unit, and the maximum duration is 2^{maxBE} backoff units.

2.2.2.3 ID-polling MAC protocol

In order to carry out identity (ID) polling, the sink must be able to predict the energy level of the nodes. The prediction of energy levels in nodes powered by ambient energy harvesting is very complicated, since the charging times may have large fluctuations and are uncorrelated in time and space [46]. Each node has a unique ID which identifies and distinguishes it from the other nodes. The state transition diagram of this protocol is shown in Figure 2.22.

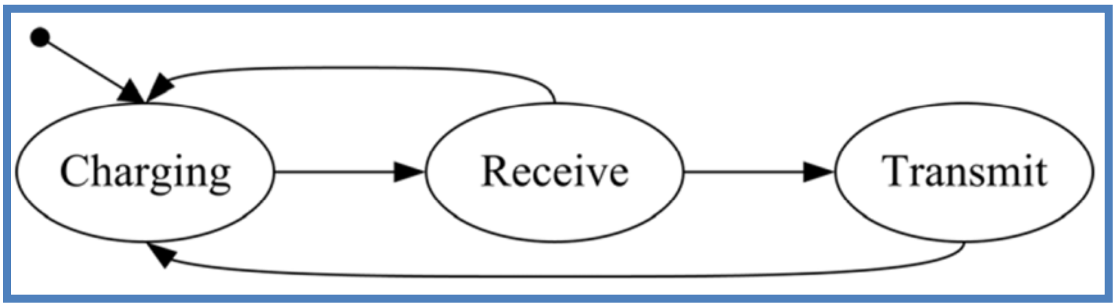

Figure 2.22 – ID-polling, state transition diagram [45]

As seen in Figure 2.22, the node remains in the charging state until it has collected the sufficient amount of energy needed to operate. Upon reaching the threshold energy, the node switches to the receiving state to wait for the polling packet from the sink. The polling packet contains the ID of the node to be polled. If the node receives the polling packet with a matching ID, then it proceeds to transmit its data packet. On the other hand, if the ID does not match, then the node turns back to the charging state. The transmission timing is shown in Figure 2.23.

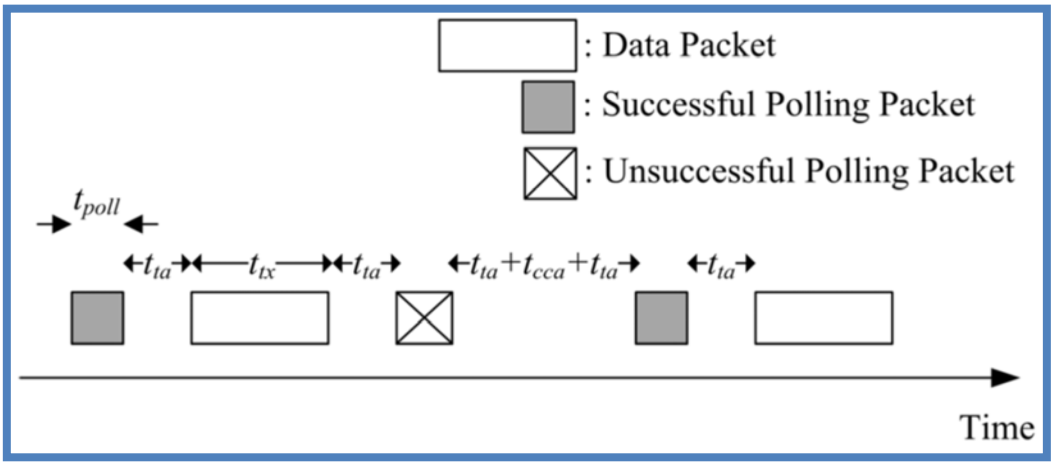

Figure 2.23 – ID-polling, transmission timings [48]

In Figure 2.23, the reception time of the polling packet is t_{poll}. The node may receive the polling packet only if it is in receiving mode when the coordinator is sending it. If the node being polled is in the charging state, it cannot receive the polling packet and, therefore, cannot transmit its data packet (i.e., unsuccessful polling packet). When an unsuccessful polling packet occurs, the nodes must wait for the sink to become aware that the node polled did not respond before another polling packet is received. Figure 2.23 shows the minimum time separation between two successive polling packets as the sum of $2t_{ta}$ and t_{cca}. The probability of a successful poll is very low, since nodes spend much more time in the charging state compared with the time they remain in the receive state [48].

2.2.2.4 Probabilistic polling protocol

Eu et. al. designed and proposed the probabilistic polling protocol in order to achieve high throughput, fairness and scalability in WSN-HEAP[47-49]. In probabilistic polling, unlike ID-polling that uses a unique identifier for each node, the sink broadcasts a control packet that includes a threshold value with a contention probability (p_c). When a node receives the polling packet, it generates a random number x, where $x \epsilon [0,1]$. If the value of x is less than p_c, then the node transmits its data packet; otherwise, the node transits to the idle state, waiting for the next polling packet. It is worth noting that p_c is dynamically adjusted at the sink according to an updating algorithm that takes into account the response of the nodes to the polling. In Figure 2.24, the p_c updating algorithm is shown.

1: Send a polling packet with contention probability p_c.
2: **if** no sensor responds to the polling packet **then**
3: increase p_c
4: **else if** a data packet is successfully received from one of the sensor nodes or there is a packet loss due to a weak signal received from a single node **then**
5: maintain p_c at current value
6: **else if** there is a collision between two or more sensor nodes as indicated by a corrupted data packet **then**
7: decrease p_c
8: **end if**
9: Repeat step 1.

Figure 2.24 – Probabilistic polling, p_c updating algorithm [48]

As seen in Figure 2.24, the value of p_c is updated in two cases: i) if no node responds to the polling packet, the sink increases the value of the p_c threshold to increase the transmission probability of the nodes, and ii) when there is a collision between two or more nodes, the sink decreases the value of the threshold to reduce the probability of collision. In the case of successful transmissions, the current value of the threshold is maintained in the next polling packet. Some techniques that can be used to increase or decrease the value of the p_c are [49]: additive-increase multiplicative-decrease (AIMD), multiplicative-increase multiplicative-decrease (MIMD), additive-increase additive-decrease (AIAD) and multiplicative-increase additive-decrease (MIAD). Thus, the sink, depending on the technique selected, can gradually increase p_c (additive-increase), gradually decrease p_c (additive-decrease), increase p_c by a large amount (multiplicative-increase), or decrease p_c by a large amount (multiplicative-decrease). Figure 2.25 shows the mathematical representation of such techniques, where p_{inc} is the factor that increases p_c, p_{dec} is the factor for decreasing p_c, p_{lin} is a lineal factor, p_{mi} ($p_{mi} > 1$) is a multiplicative-increase factor, p_{md} ($p_{md} < 1$) is a multiplicative-decrease factor, and p_i is the contention probability for the ith polling packet that has been sent by the sink.

$$p_{inc} = \begin{cases} p_{lin} & \text{for AIMD and AIAD} \\ (p_{mi} - 1)p_i & \text{for MIMD and MIAD} \end{cases}$$

$$p_{dec} = \begin{cases} p_{lin} & \text{for AIAD and MIAD,} \\ (1 - p_{md})p_i & \text{for AIMD and MIMD.} \end{cases}$$

Figure 2.25 – Mathematical representation AIMD, MIMD, AIAD, and MIAD techniques for probabilistic polling protocol [49].

Eu et. al. [47] applied these p_c updating techniques for the probabilistic polling protocol in a single-hop wireless network. The results showed that the AIMD technique is the best choice for this type of network topology powered by energy harvesting, since it gradually increases the value of p_c in the case of an unsuccessful polling packet and greatly decreases the value of p_c when data collisions occur. In addition, AIMD has been shown to outperform in throughput, in comparison to the other techniques (Figure 2.26).

As seen in Figure 2.26, AIMD provides better adaptation to changes in the number of nodes (n) in the network (e.g., due to additions, removals, or failures of the nodes) and changes in the energy harvesting rate (K_{EH}). The main advantage of the probabilistic polling protocol in WSN-HEAP is that it solves the problem of data collisions in a dynamic way, while offering good flexibility and scalability [48]. For example, if more nodes are added to the network or if the K_{EH} increases, then the contention probability p_c will increase in order to reduce the number of packet collisions. Furthermore, if there are failures/removals of nodes or if the K_{EH} is reduced, then the contention probability p_c is decreased in order to facilitate the active nodes to transmit their data packets.

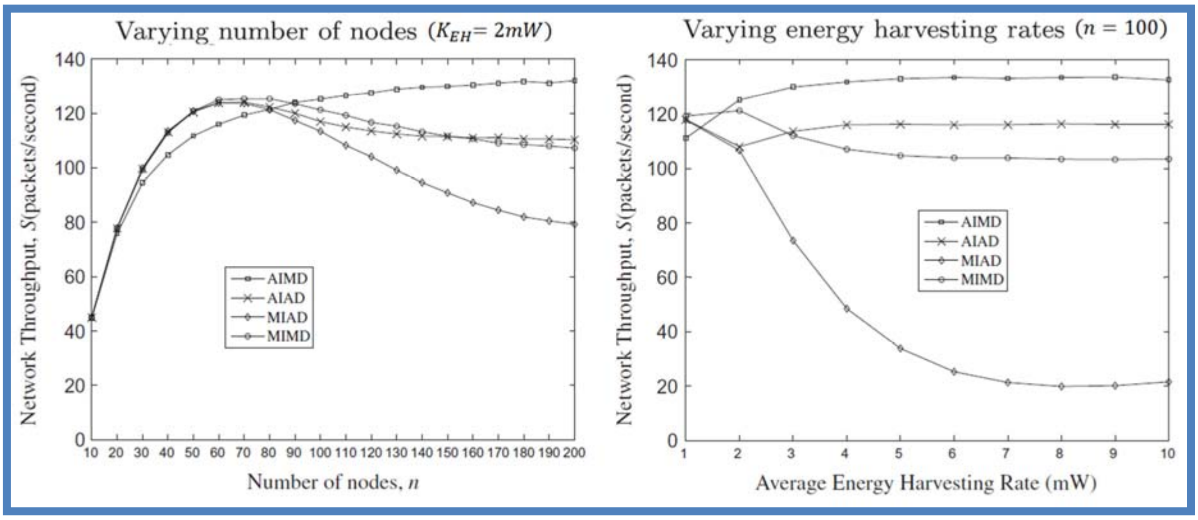

Figure 2.26 – Comparison of AIMD, MIMD, AIAD, and MIAD techniques for probabilistic polling ($p_{lin} = 0.01$, $p_{mi} = 2$, and $p_{md} = 0.5$) [47]

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CHAPTER 3

HEH-BMAC: Hybrid Polling MAC Protocol for WBANs Operated by Human Energy Harvesting

"Strength Lies in Differences, Not in Similarities."

Stephen Covey

Contents

3.1 Introduction

In the previous chapter, we have discussed some of the characteristics of the different types of MAC protocols, highlighting their main advantages. A key goal in WBANs is to extend the lifetime of BNs through an efficient management of the available energy. Hence, many authors have proposed MAC protocols for WBANs that aim to achieve the most energy efficient way of sharing the medium. Many proposals adopt TDMA for WBANs, due to its increased energy efficiency. Timmons and Scanlon [1] introduced the Medical Medium Access Control (MedMac) protocol. MedMac is a TDMA-based MAC protocol, which does not require any synchronization overhead. In MedMac, the synchronization of the nodes is maintained through a combination of timestamp scavenging and an innovative adaptive guard band algorithm. In [2], Fang and Dutkiewicz proposed another TDMA-based MAC protocol (BodyMAC) that uses flexible and efficient bandwidth allocation schemes and sleep mode to be able to work in dynamic applications in WBANs. Li and Tan [3] proposed a Heartbeat-Driven MAC (H-MAC) protocol. H-MAC is also based on TDMA, but it uses the heartbeat rhythm to perform time synchronization, eliminating the energy expenditure of the synchronization to prolong the network's life significantly. Moreover, Ameen et al. [4] designed a MAC protocol using TDMA combined with out of band (on-demand) wakeup radio through a centralized and coordinated external wakeup mechanism. In their work, the communication process takes places in two stages: i) a wakeup radio is used to activate the node and ii) a main radio is used for control and data packet exchange. In their protocol, the coordinator maintains a table with the wakeup scheduling of every node in the network. This table is constructed according to the traffic of every particular node, while the wakeup intervals are calculated by the packet inter arrival time. The authors proved through extensive simulations that their method outperforms well-known low-power MAC protocols for WSNs, including B-MAC [5], X-MAC [6], WiseMAC [7] and ZigBee (power saving mode) [8], in terms of energy efficiency and delay. Besides, this MAC protocol depends on a fixed, predetermined schedule over table, which has two side effects: i) the state changes of the nodes from active to inactive mode may cause idle slots in the system and ii) the flexibility is restricted, since it is cumbersome to add/remove nodes in the network.

Since WBANs can support a wide range of applications with different requirements, it is important to design MAC protocols that can provide QoS guarantees. Otal et al. [9] proposed the Distributed Queuing Body Area Network (DQBAN) MAC protocol. DQBAN divides TDMA slots into smaller units of time (called minislots) for serving access requests, while the data packets use the normal slots. In order to satisfy the stringent QoS demands in WBANs, DQBAN introduces a novel cross-layer fuzzy-logic scheduling mechanism and employs energy-aware radio activation policies to achieve a reliable system performance. The On-Demand MAC (OD-MAC) protocol is another interesting approach, proposed by Yun et al. [10]. OD-MAC is based on IEEE 802.15.4 with some modifications to support WBANs requirements such as real-time transmission, collision avoidance and energy efficiency. It uses guaranteed time slots to satisfy the real-time transmissions and collision avoidance, while it adjusts the duration of the super-frames to provide higher energy efficiency.

Currently, the majority of MAC protocols proposed for WBANs aim to optimize power consumption through efficient battery management and improve QoS. However, the effects introduced by power sources based on energy harvesting are not effectively addressed. In the literature, there are papers that model and analyze energy harvesting in WBANs using probabilistic models based on Markov chains [11,12], optimal numerical solutions for energy efficient transmission strategies [13] and resource allocation [14,15]. In none of the aforementioned works, though, a MAC protocol that supports energy harvesting techniques is proposed. The main challenge in energy harvesting-based WBANs is to design protocols that provide access depending on the BN's priorities, taking into consideration its particular energy supply condition. As mentioned in the previous chapter, in [16, 17] Eu et al. conducted studies about the design, performance and comparative analysis of MAC schemes for WSN-HEAP. These authors proposed a MAC protocol especially designed for WSN-HEAP, known as probabilistic polling (see section 2.2.2.4), for both single-hop [16, 17] and multi-hop [18] networks. The obtained results show that the protocol is able to adapt to different factors such as changes in the energy harvesting rates and the number of nodes. Furthermore, due to this dynamic adaptation, some metrics like throughput, fairness and scalability can be substantially improved.

At this point, it should be noted that the clinical environment is extremely volatile. The importance of each node depends on the current health condition of the patient and the studied parameters at any given time. For this reason, adding and removing nodes in a fast and easy way is a desirable feature in WBANs. This flexibility is supported by polling schemes, which, in general, have two main advantages: i) deterministic and bounded transmission delay, and ii) scalable network architecture [19]. In a typical polling network, when a node is willing to enter the network, it sends a JOIN message to the coordinator. Upon receiving this message, the coordinator verifies the request, and creates a new polling slot and data slot for the new node. In the case that a node has to be removed, the coordinator receives the DEPART request by the node that wants to leave, and then proceeds to remove the allocated resources. This simple process of adaptation to a variable number of nodes is much more complicated in the case of networks powered by energy harvesting due to the difference in energy levels of the nodes. As we mentioned above, probabilistic polling MAC has the ability to adapt the network's operation to fluctuations in both energy supply and number of nodes. However, the application of this protocol to WBANs operated by energy harvesting is not straightforward, since the access for all nodes is probabilistic, thus not assigning different level of priorities to the nodes. In WBANs, the early detection of crucial events is of vital importance, since it provides information about the patient's health. In typical WSNs, the data loss in a node can be compensated by the other nodes in the network, but in WBANs is not possible mainly due to the reduced number of nodes and the specialized tasks of each node.

In this chapter, taking into account the latest developments in WBANs, we propose a hybrid polling MAC protocol, so called HEH-BMAC, to address the effects of human energy harvesting. In particular, the main contribution of this chapter is summarized in the following:

1) To our knowledge, HEH-BMAC is the first MAC protocol designed to adapt to different energy conditions introduced by the human energy harvesting sources in WBANs. In particular:

   a) The proposed protocol offers service differentiation by combining two different access methods: reserved polling access (ID-polling) for nodes of high priority and probabilistic random access (PC) for nodes of normal priority.

   b) The ID/PC periods are dynamically adjusted according to the energy levels of the wireless nodes.

   c) HEH-BMAC facilitates the network's flexibility by allowing the dynamic addition/removal of wireless sensor nodes.

2) We evaluate the performance of HEH-BMAC for different numbers of nodes in order to study the scalability of the protocol, while we elaborate on the network parameter tuning, i.e., transmission data rate and energy harvesting rate, to achieve the best possible performance for the protocol.

3) We compare the performance and energy efficiency of HEH-BMAC with the IEEE 802.15.6 standard under the same energy harvesting conditions.

The remainder of the chapter is organized as follows. In Section 3.2, we describe our system model and the network topology. In Section 3.3, we introduce the HEH-BMAC along with its frame structure and the protocol rules. In Section 3.4, we explain how our protocol is energy-aware when the network is powered by energy harvesting. In Section 3.5 we evaluate the performance of HEH-BMAC by extensive simulations. In this section are also shown the results of the comparison of the performance and the energy efficiency between our protocol and IEEE 802.15.6 standard. Finally, Section 3.6 concludes the chapter.

3.2 System Model

In our system model, we adopt a star topology, where the head (sink) is the BNC responsible for setting up the network and collecting all the information transmitted by a number of lightweight and portable BNs. The BNs have different functionalities and, consequently, different traffic load (i.e., packet inter-arrival time and packet payload). Figure 3.1 illustrates the considered WBANs topology.

The events detected by the BNs can be either signals carrying sensitive and vital information (e.g., ECG, EEG, etc.) or signals with random characteristics (e.g., motion, position, temperature, etc.). In order to model a realistic scenario based on the above arguments, we adopt the same inter-arrival times (IAT_{BN}) as in [20] for the event generation.

In HEH-WBAN, each sensor is connected to an energy harvester. We assume that the BNC has an external power supply and higher processing capabilities than BNs, while the BNs have a constant energy harvesting rate (K_{EH}). The energy harvester must be able to harness the available energy at all times and for all states of the node (i.e., sleep state, idle state, T_X state, R_X reception state, and inactive state), as shown in Figure 3.2. Hence, the performance of the energy harvester directly affects the operation of the node, but not vice versa.

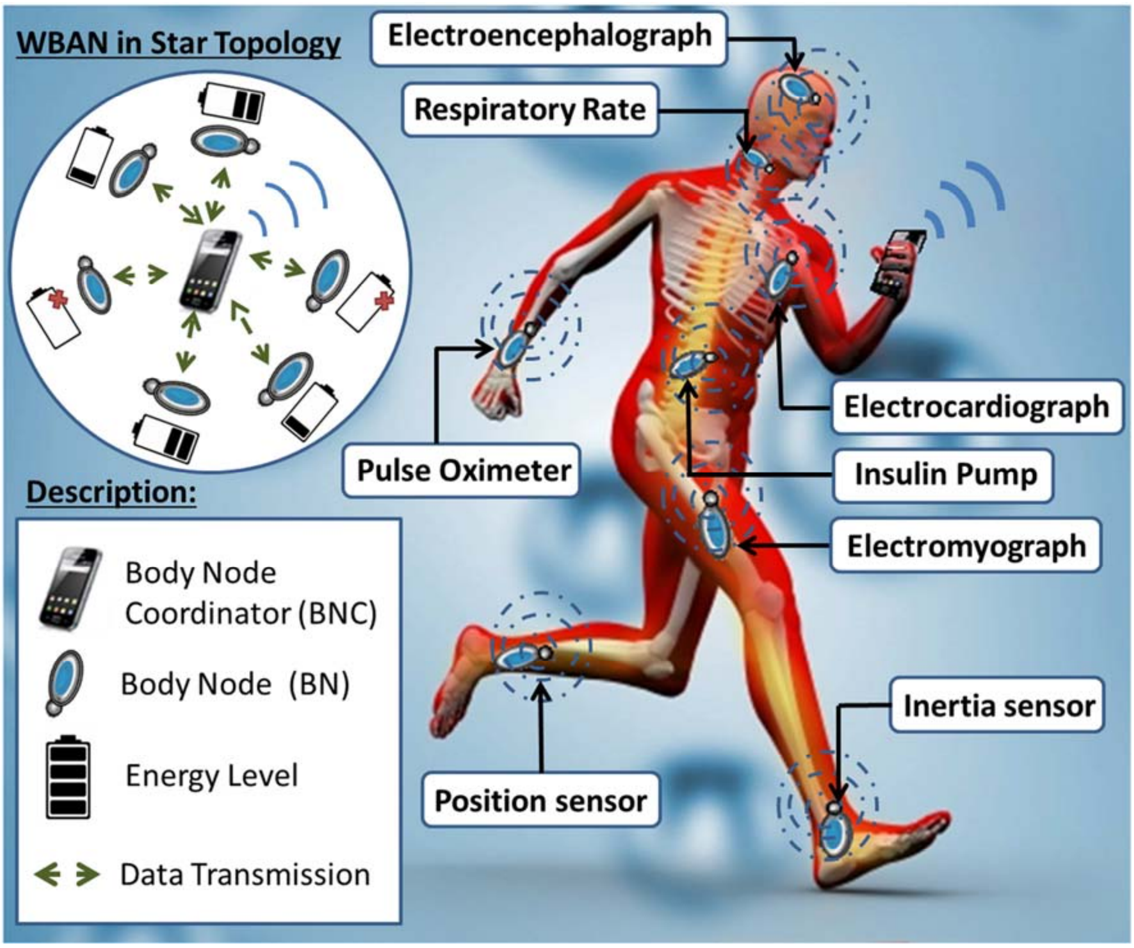

Figure 3.1 – HEH-WBAN, System Model and Network Topology

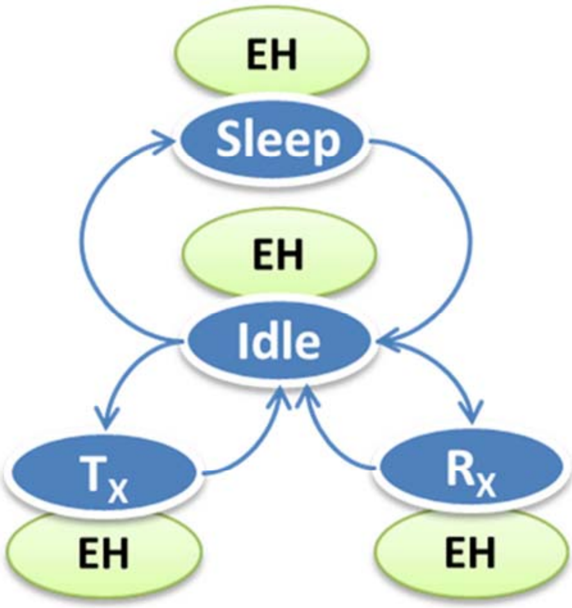

Figure 3.2 – BNs state transition diagram with energy harvesting

3.3 Proposed Hybrid Polling MAC protocol Operated by Human Energy Harvesting (HEH-BMAC)

HEH-BMAC protocol has two operation modes: i) contention-free ID-polling, and ii) probabilistic contention (PC) channel access. Hence, our protocol offers two levels of priority depending on the BN type. The use of contention-free ID-polling access is provisioned for nodes with predictable energy sources or nodes with high priority (ID-BNs). On the other hand, the use of contention-based PC-access applies to nodes with unpredictable energy sources or nodes with normal priority (PC-BNs). The base of our protocol resides in an algorithm that performs time allocation in a dynamic way. The goal of the dynamic scheduling is to assign time periods for both ID-polling and PC-access. Due to the combination of these two access modes and the dynamic scheduling algorithm, the HEH-BMAC protocol is able to adapt to changes in the network size and the energy harvesting rate K_{EH}. In the following subsections we describe in detail the operation and the different modes of our protocol.

3.3.1 ID-polling access mode

In ID-polling, the BNC assigns a monitoring interval (MIT_{ID-BN}) to each node in this mode (ID-BN). Such monitoring intervals are stored and updated in a dynamic table. The MIT_{ID-BN} for each node is calculated using its respective IAT_{BN} and K_{EH} information. In this way, the BNC can estimate the energy level of each sensor node and determine the polling periods based on a predictable scheduling.

The BNC can apply an offset to the initial value of MIT_{ID-BN} (advance or delay) for each BN, to prevent that its IAT_{BN} coincides in time with other nodes (Figure 3.3). For the allocation of this offset, the IAT_{BN} and the K_{EH} are also taken into account, in order to ensure the quality and quantity of the collected clinical information. The BNC maintains the present values of MIT_{ID-BN} in the dynamic table, which is updated after every transmission.

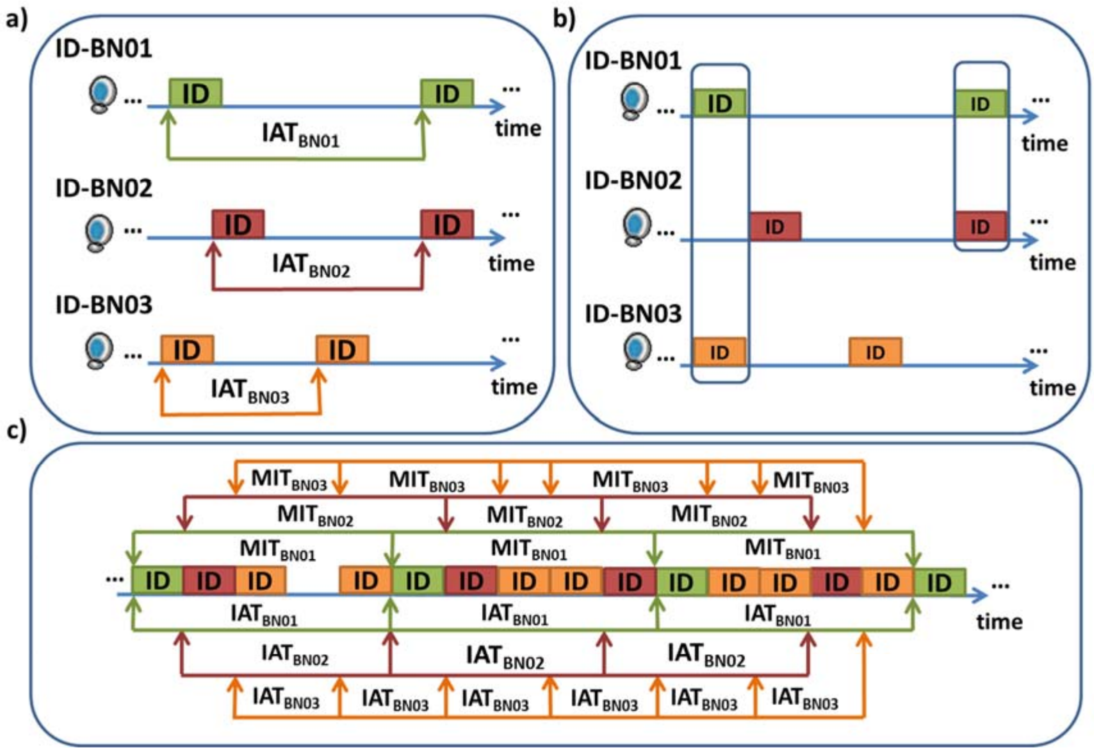

Figure 3.3 – Example of ID-polling access mode (a) IAT_{BN} of the ID-BNs (b) Overlap of the IAT_{BN} of the ID-BNs (c) MIT_{ID-BN} of the ID-BNs using the offset

All nodes in the HEH-WBAN are assigned a unique ID for data security, data control and medical application. Figure 3.4a illustrates the communication process in ID-polling mode which consists of three steps: i) the BNC transmits a polling packet containing the ID of the BN to be polled, ii) the polled BN responds with a data packet transmission, and iii) the BNC sends an ACK packet that confirms the successful reception of the data packet. As shown in Figure 3.4b, the ID-BN remains into the sleep state until its turn to transmit. Upon its turn, it wakes up and goes into the R_x state to receive the ID-polling from the BNC. Once the communication is completed, the ID-BN turns again its radio off until the next round of polling.

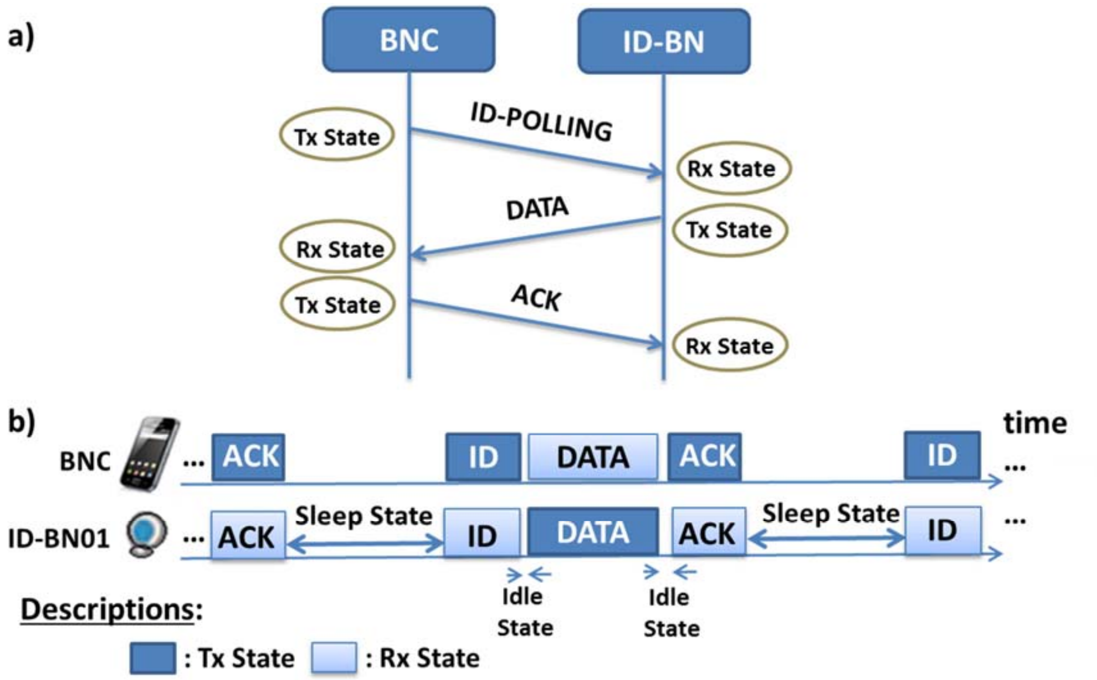

Figure 3.4 – ID-polling access mode (a) Data communication process (b) ID-BN states and transmission

3.3.2 Probabilistic contention (PC) access mode

The PC-access mode deals effectively with contention, achieving high throughput and maintaining fairness for single-hop networks. In addition, this mode offers the advantage of adaptation to the changes in the energy harvesting rates, node failures or additions/removals of nodes. In PC-access [16-18], instead of ID-polling, the BNC broadcasts a control packet (CP-packet) that includes the value of the contention probability (CP). When a PC-BN (node in PC-access mode) receives the CP-packet, it generates a random number X_i, where $X_i \in [0, 1]$ and i is an integer identifier of the node. If the value of X_i is less than CP, then the PC-BN transmits its data packet (Figure 3.5a); otherwise, the node transits to the idle state, waiting for the next CP-packet (Figure 3.5b).

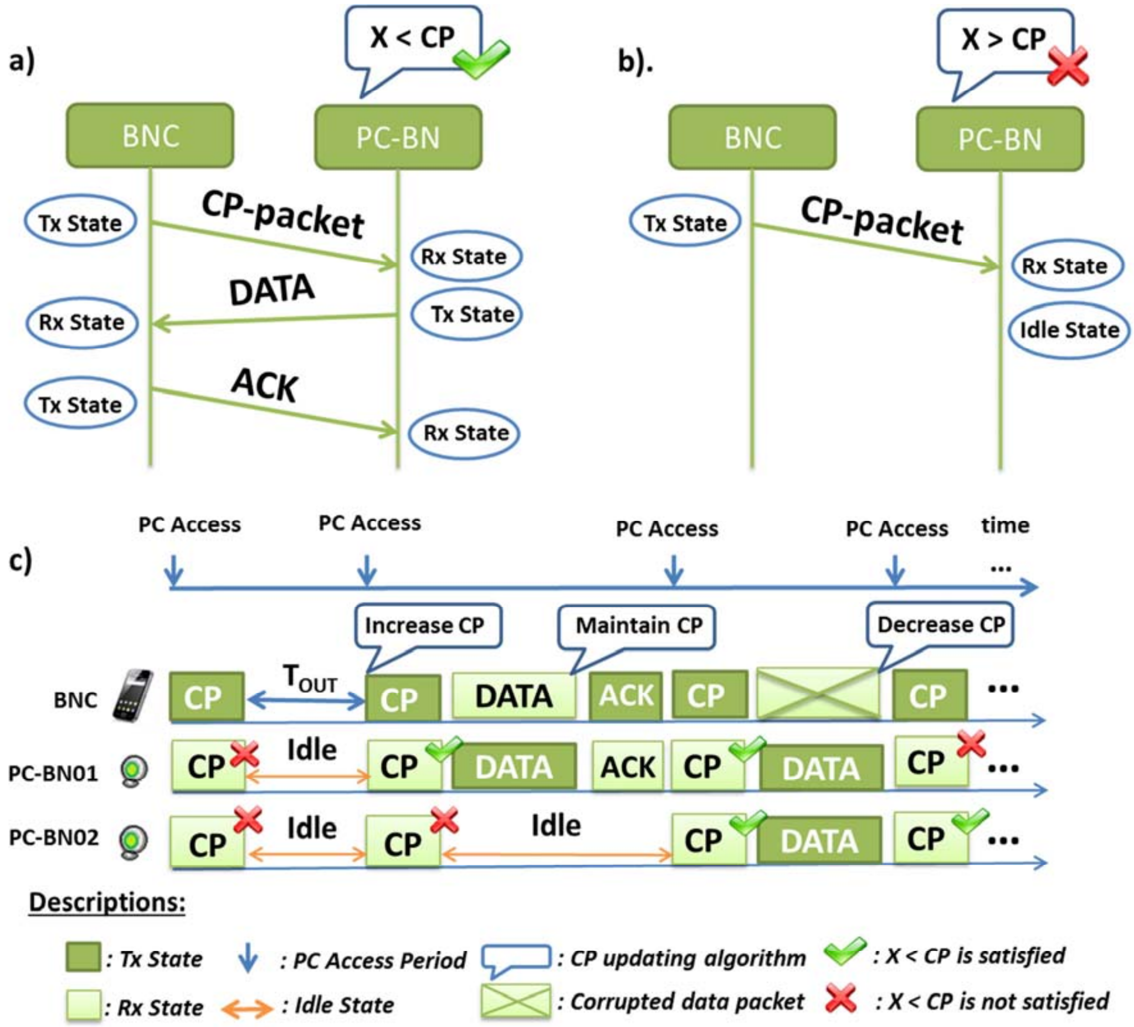

Figure 3.5 – PC-access mode (a) Data communication process when X<CP is satisfied (b) Data communication process when X<CP is not satisfied (c) CP updating algorithm and transmission process

It is worth noting that CP is dynamically adjusted at the BNC according to an updating algorithm that takes into account the network load (in terms of traffic load and addition/removals of nodes) and the K_{EH}. The value of CP is updated in two cases: i) if no PC-BN responds to the CP-packet, the BNC increases the value of the CP threshold to increase the transmission probability of the PC-BNs, and ii) when there is a collision between two or more PC-BNs, the BNC decreases the value of the threshold to reduce the probability of collision. In case of successful transmissions, the current value of the threshold is maintained in the next CP-packet.

Some techniques that can be used to increase or decrease the value of the CP-packet are: AIMD, MIMD, AIAD and MIAD [17]. In our model we use the AIMD technique because it provides higher throughput than the other schemes for single-hop scenarios (see Section 2.2.2.4) [16, 17]. The AIMD is a mechanism to increase the CP gradually by an increase factor α_{IN} $(0 < \alpha_{IN} < 1)$ when polling is unsuccessful because of idle slots (i.e., $CP_{(t+1)} = CP_{(t)} + \alpha_{IN}$), or to decrease the CP by a larger decrease factor β_{MD} $(0 < \beta_{MD} < 1)$ in case of collisions in the network (i.e., $CP_{(t+1)} = CP_{(t)} * \beta_{MD}$).

An example is shown in Figure 3.5c. The BNC broadcasts a CP-packet containing the contention probability that determines whether the PC-BN should transmit its data packet. In case of no packet reception, the BNC waits for a predefined time-out period (T_{OUT}), updates the CP-packet with the increased threshold and broadcasts the new value in the next PC round. The PC-BN transmits its data packet if $X_i < CP$. If only one node transmits in the current PC round, the BNC sends the ACK packet to the polled PC-BN (successful transmission). In case of packet loss (unsuccessful transmission) due to collision between two or more PC-BNs, the BNC updates the CP-packet with the decreased threshold and the nodes are prepared to retransmit their data in the following PC round. All PC-BNs maintain a buffer to store the data to be retransmitted.

3.3.3 Dynamic Schedule Algorithm

The BNC is responsible for allocating the ID-polling periods and the PC-access periods as illustrated the flow chart in Figure 3.6. The boundaries of these time periods are defined by the Dynamic Schedule Algorithm.

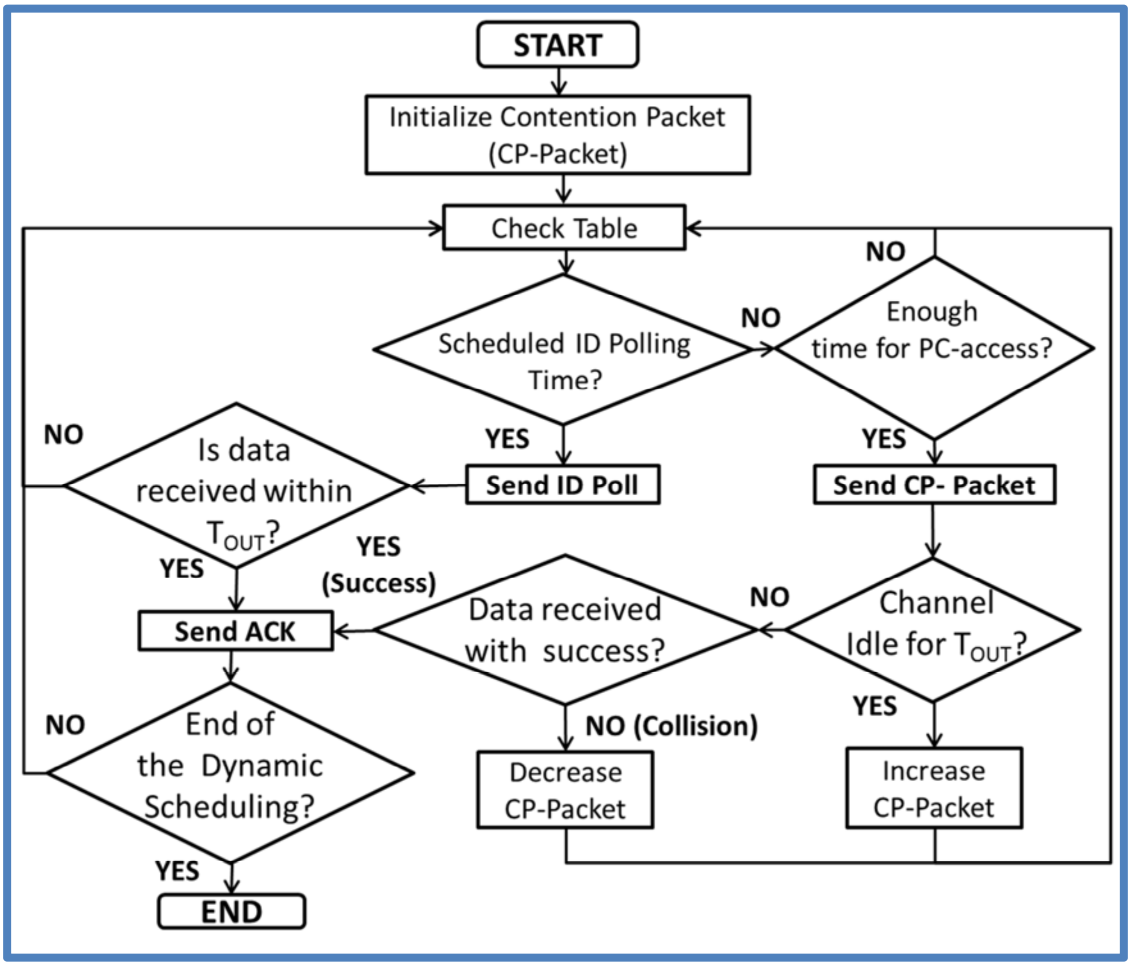

Figure 3.6 – HEH-BMAC flow chart for time allocation of the ID-polling periods and PC-access periods

The operation of the Dynamic Schedule Algorithm is illustrated in Figure 3.7. The algorithm performs two main tasks. The first task is to assign a monitoring time ($T_{\alpha i(n)}$) and calculate the duration of the data communication process ($T_{\gamma i(n)}$) for each ID-BN i during the nth access period. The value of $T_{\alpha i(n)}$ for an ID-BN i must be greater or equal to the minimum time required to obtain enough energy to send its data packet. BNC calculates the $T_{\alpha i(n)}$ for each ID-BN using the K_{EH} of the respective harvester and the IAT_{BN} of the sampled sensor data. Thus, the BNC can estimate when each ID-BN has data to transmit and whether its energy level is sufficient, in order to select an appropriate value for $T_{\alpha i(n)}$. On the other hand, $T_{\gamma i(n)}$ is defined as the time required for ID-BN i to perform a successful transmission. We also define $T_{\beta i(n)}$ as the moment of completion of the current communication process, i.e., $T_{\beta i(n)} = T_{\alpha i(n)} + T_{\gamma i(n)}$.

The current values of $T_{\alpha i(n)}$ and $T_{\beta i(n)}$ for all ID-BNs are stored in a dynamic table and are employed by the BNC to coordinate the ID-polling process. When the BNC proceeds to an ID-polling, then the dynamic table is updated with the next values of $T_{\alpha(n+1)}$ and $T_{\beta(n+1)}$ for the next ID-BN to be polled. In this way, we can predict the responsiveness to an ID-polling for a given node, and make the decision to poll it or not (thus improving the scalability of the system, since the dynamic table is constantly updated). Figure 3.7a presents an example of dynamic calculation of ID-polling and PC-access periods operating together.

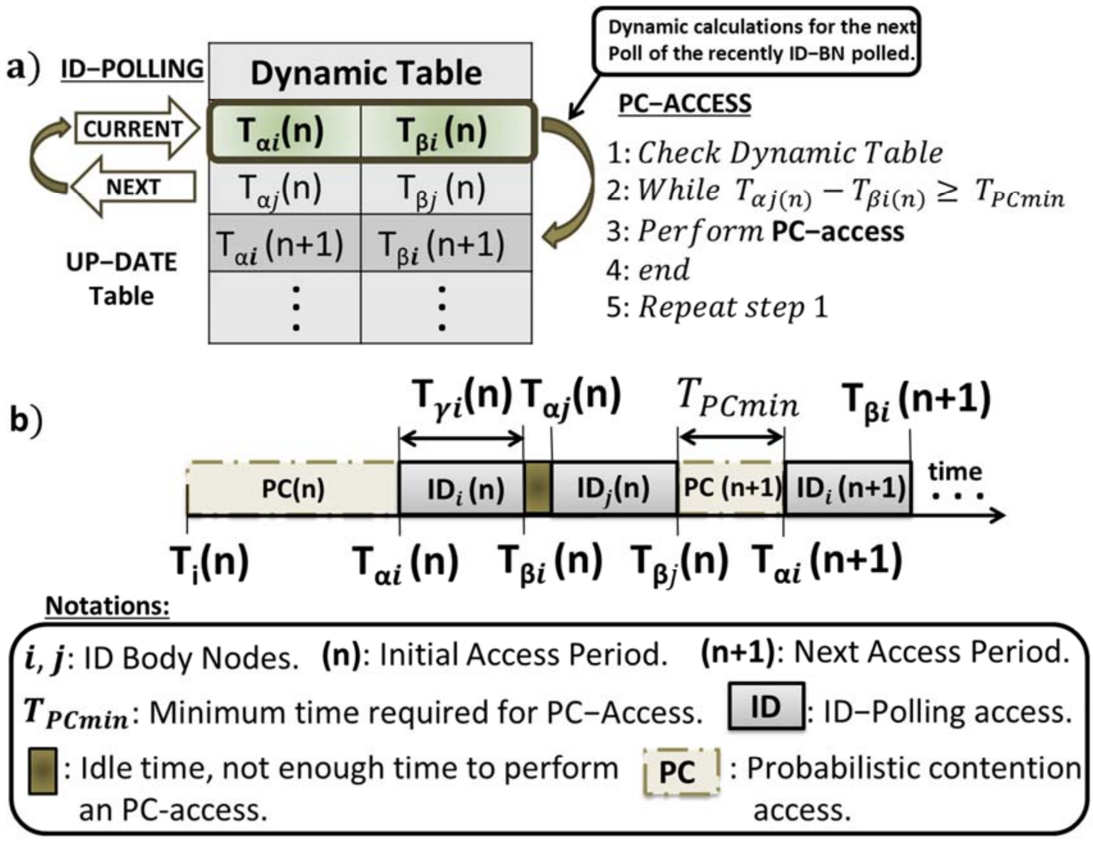

Figure 3.7 – Dynamic Schedule Algorithm for ID-polling/PC periods access in HEH-BMAC protocol

The second task of the Dynamic Schedule Algorithm is to calculate the interval between two adjacent ID-polling periods, for example (Figure 3.7b) the $T_{\beta i(n)}$ of the node $ID_{i(n)}$ and the $T_{\alpha j(n)}$ of the next node $ID_{j(n)}$. The BNC performs the calculation of this interval using the data provided in the dynamic table. If the time between two consecutive ID-polling periods is sufficient for a successful data transmission of a PC-BN in PC access mode ($t \geq T_{PCmin}$), then this time is exploited for probabilistic contention (PC period). Otherwise, if this time is not sufficient ($t < T_{PCmin}$), the BNC remains idle waiting for the next ID-polling period.

3.3.4 HEH-BMAC operation example

Figure 3.8 shows an illustrative example of the HEH-BMAC protocol running on a network with four nodes, where two nodes are in ID-polling mode and two nodes are in PC-access mode.

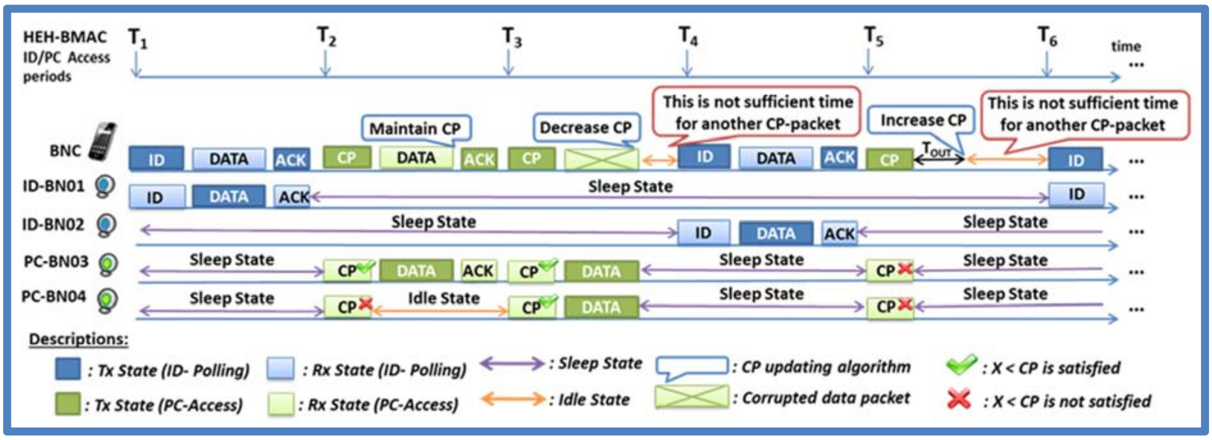

Figure 3.8 – Frame exchange in HEH-BMAC protocol

In detail, the protocol works as follows:

1. The BNC performs the configuration and time calculations for the ID-BNs. Then, the BNC stores the values $T_{\beta(ID-BN)}$ and the current values of $T_{\alpha(ID-BN)}$ for ID-BN01 and ID-BN02 in a dynamic table.

2. At instant T_1, BNC initiates ID-polling access for ID-BN01. Once the communication process has been completed, BNC updates the dynamic table with the next value of $T_{\alpha(ID-BN01)}$. ID-BN01 turns into sleep mode until its next ID-polling period. ID-BN02 remains in sleep state waiting its ID-polling period. The PC-BNs remain in sleep state, since they do not have packets for transmission.

3. BNC uses the dynamic list to calculate the interval between two adjacent ID-polling accesses (T_1 and T_4 in this example). In this example, the interval is sufficient for two successful data transmissions in PC-access.

4. At instant T_2, BNC sends the CP-packet (starting PC-access) to all PC-BNs (i.e., PC-BN03 and PC-BN04). In this example, PC-BN03 randomly selects $X_3 < CP$ whereas PC-BN04 selects $X_4 > CP$. Hence, PC-BN03 gains access to the medium and starts its data transmission, whereas PC-BN04 remains in idle state waiting the next PC-access period. The CP updating algorithm maintains the current threshold value.

5. At instant T_3, BNC sends the next CP-packet to all PC-BNs. In this example, the condition $X_i < CP$ is satisfied for both PC-BN03 and PC-BN04. Hence, both nodes transmit their data packets, resulting in a collision. According to the CP update algorithm, the BNC must decrease the CP threshold and include the updated value in the next CP-packet. In this example, the remaining interval (after the packet collision) is not sufficient for another PC-access. Therefore, the BNC remains idle until the next ID-polling period (which starts at T_4).

6. At instant T_4, the BNC starts ID-polling access for ID-BN02. Once the data transmission has been completed, the BNC updates the dynamic table with the next value of $T_{\alpha(ID-BN02)}$. Meanwhile, ID-BN01 is in sleep state waiting its ID-polling period. The table is

used to calculate the next interval between T_4 and T_6 and determine if there is enough time for PC-access (in this example, the interval is sufficient for one successful data transmission in PC-access).

7. At instant T_5, BNC broadcasts the CP-packet containing the new threshold value to all PC-BNs. In this example, neither PC-BN03 nor PC-BN04 selects a X_i that satisfies the condition $X_i < CP$. Hence, neither node transmits in the current PC-access.

The BNC waits for a predefined T_{OUT} and then increases the CP threshold value. In this case, since the remaining interval is not sufficient for another PC-access, the BNC remains idle until the next ID-polling period (T_6).

3.4 HEH-BMAC with Energy Harvesting

As we have already mentioned, HEH-BMAC is energy-aware, since it has been mainly designed to operate in energy harvesting conditions. In particular, the behavior of each BN dynamically adapts to its energy level. The energy level of a node at a given moment can be defined as the energy stored in the battery plus the harvested energy minus the energy consumed by the radio interface. The modifications that energy-awareness brings to our protocol are explained in the following subsections.

3.4.1 ID-polling Energy-Aware:

a) *Dynamic schedule:* The BNC calculates the $T_{\alpha(ID-BN)}$ using the information of K_{EH} and IAT_{BN} of each ID-BN. The $T_{\alpha(ID-BN)}$ does not have a fixed value, since this time interval is continuously updated in the dynamic table, in order to know in advance the energy state of a node at any given time. In this way, we can predict the responsiveness to an ID-polling for a given node, and take the decision whether to poll it or not.

b) _Polling-awareness:_ When a node receives an ID-poll packet, it checks its energy level. If the level is not sufficient the node does not respond to the poll but enters a sleep mode. In this case, the BNC assigns the time reserved for this ID-polling to the PC-access users.

3.4.2 PC-access Energy-Aware:

a) _Energy-awareness:_ The PC-BNs check both their energy level and their data packet buffers in order to decide whether to participate in the PC-access. If their energy is below a certain level or their buffers are empty, they enter into sleep mode. All PC-BNs will be in sleep state during the ID-polling.

b) _Polling-awareness:_ The PC-access mode is employed if there is enough time between successive ID-pollings. The BNC dynamically adjusts the CP-packet according to the response of the PC-BNs (through the CP updating algorithm).

3.5 HEH-BMAC Performance Evaluation

In order to analyze, evaluate and compare the performance of HEH-BMAC, we have developed an event-driven MATLAB simulator that executes the rules of our protocol. In the following subsections, we present the simulation setup along with the results of our experiments.

3.5.1 Simulation Consideration and Setup

In our simulation model, we assume a star topology for a network consisting of a BNC, K nodes in ID-polling mode and L nodes in PC-access mode. The simulation scenario is depicted in Figure 3.9.

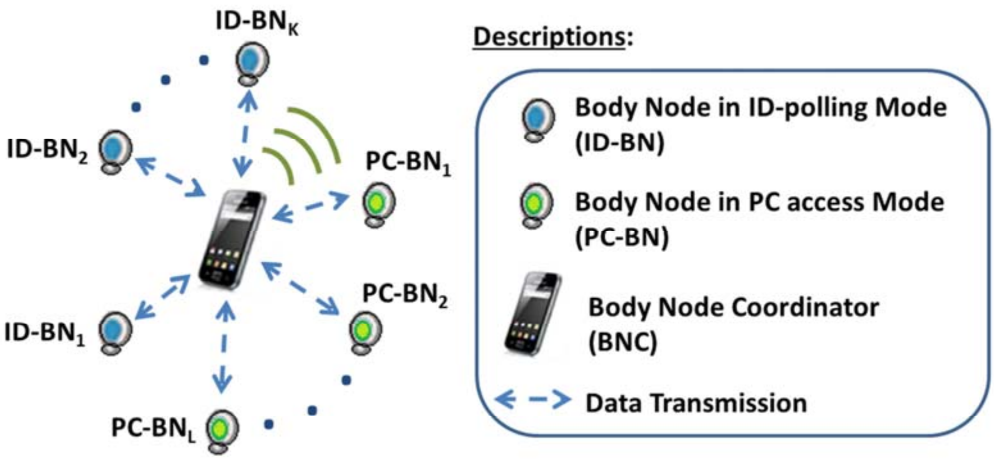

Figure 3.9 – Simulation scenario

The nodes in our simulations are typical medical sensors, whose traffic characteristics and priorities are shown in Table 3.1. Let us recall that the high and normal priorities correspond to ID-polling and PC-access mode, respectively. The characteristics of the selected nodes in our experiments can be found in [20]. However, in the case of the ECG and Blood Pressure nodes, we adopt a slightly different aggregate traffic model which results in sample size of 120 bits and 96 bits, respectively. For this process, it was taken into account the bit rate and the delay requirements of healthcare data [21, 22].

Table 3.1 – BNs used in the simulation

Physiological Signal	IAT_{BN} (ms)	Sample Size (bits)	Data rate (kb/s)	Priority	Access Method HEH-BMAC
ECG signal (**ECG**)	20	120	6.0	High	ID-Polling
Respiratory Rate (**RR**)	50	12	0.24	High	ID-Polling
Blood Pressure (**BP**)	80	96	1.2	High	ID-Polling
Blood pH (**BpH**)	250	12	0.048	Normal	PC-Access
Blood Flow (**BF**)	25	12	0.48	Normal	PC-Access

The configuration parameters of the network have been selected according to the IEEE 802.15.6 PHY-MAC specification [23]. The physical layer frame structures used (based on IEEE 802.15.6) is shown in Figure 3.10.

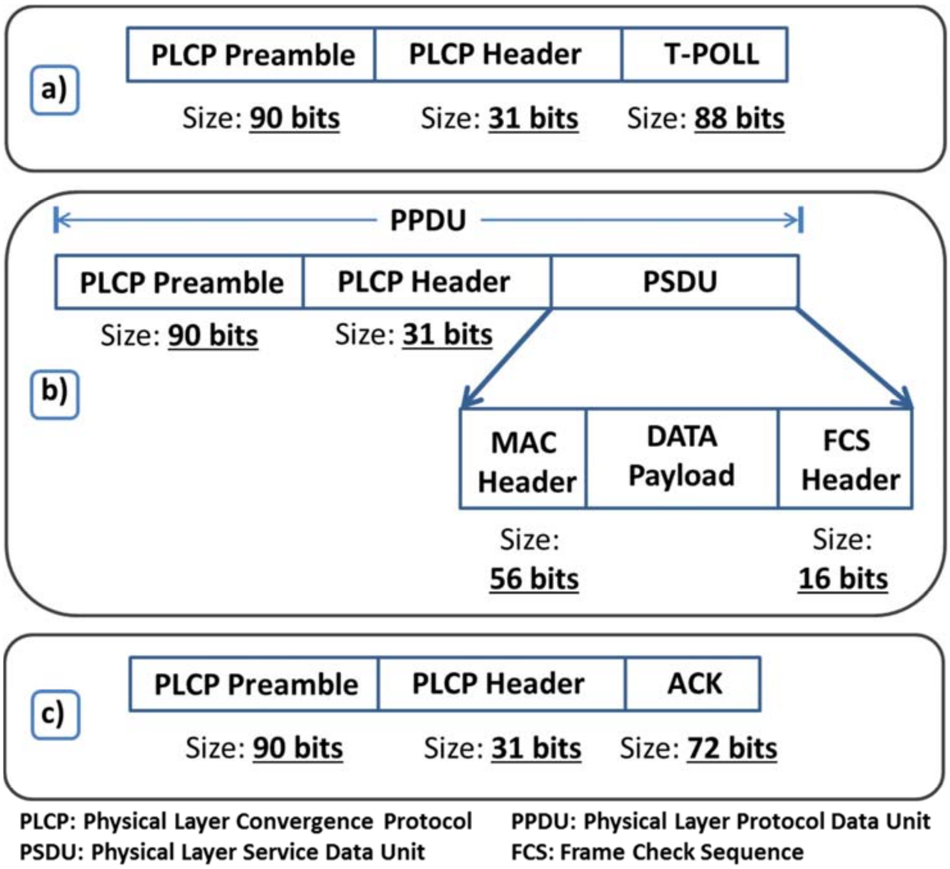

Figure 3.10 – Physical layer fame structures: a) Polling Packet, b) Data Packet, and c) ACK Packet

We assume that the ID-BNs perform data transmission in real time (no packet retransmissions and no packets are stored in the buffer). In the PC-BNs retransmissions may take place when a collision occurs (packets are stored in the buffer). However, when the energy level of a node is very low (almost zero), the node cannot proceed to the transmission or retransmission of packets and packet loss may occur. Data packets that remain in the buffer after the simulation are considered lost packets. Moreover, the BNC maximum waiting time (T_{OUT}) for a response from the nodes (ID-BNs or PC-BNs) is assumed to be equal to the value of the Short Inter Frame Space period (pSIFS) 0.05 ms. For the AIMD CP updating algorithm, we use $\alpha_{IN} = 0.01$ and $\beta_{MD} = 0.5$, since these values give high throughput for single-hop scenarios [17]. Simulation parameters are summarized in Table 3.2.

Table 3.2 – HEH-BMAC/IEEE 802.15.6: System parameters

Parameter	Value	Parameter	Value	Parameter	Value
MAC Header	56 bits	Data T_x Rate	121.4 kb/s	P_{TX}	27 mW
FCS	16 bits		242.9 kb/s	P_{RX}	1.8 mW
PLCP Preamble	90 bits		485.7 kb/s	P_{SLEEP}	0.004 mW
				P_{IDLE}	0.712 mW
PLCP Header	31 bits		971.4 kb/s	T_{OUT}	0.05 ms
ACK	72 bits	Control T_x Rate	121.4 kb/s	pSIFS	0.05 ms
T-poll	88 bits	PLCP T_x Rate	91.9 kb/s	pCSMA Slot	0.125 ms

Regarding the power supply, we assume that each node has incorporated an energy harvester that supplies power at a constant rate K_{EH}. In the beginning of our experiments, the nodes have empty batteries and, consequently, not sufficient energy for transmissions. We refer to this condition as the inactive state, which is the default state when the node has not sufficient energy level. In the inactive state, one node can only harvest energy but cannot perform any energy consuming operations. Through the energy harvesting process, the node collects energy in order to recover and start transmitting packets.

The energy consumed (E_{CON}) in a given state (apart from the inactive state) is determined by multiplying the power consumed (P_{STATE}) with the time spent in this state (T_{STATE}). On the other hand, the harvested energy (E_H) is calculated as the energy harvesting rate (K_{EH}) multiplied by the energy harvesting time (T_{EH}).

In order to evaluate the behavior of the HEH-BMAC protocol in energy harvesting conditions, we have conducted tests with different values of K_{EH}. The metric that is used to evaluate the performance of our protocol is the network throughput. Moreover, in order to evaluate the energy performance of our proposed protocol we use the energy efficiency metric [24].

3.5.2 HEH-BMAC: Performance results.

Figure 3.11 presents the HEH-BMAC normalized throughput performance in the scenario described above versus the four IEEE 802.15.6 data transmission rates, for different values of K_{EH}. The normalized throughput of the network is defined as the percentage of successfully transmitted data packets divided by the total amount of generated data packets. In the same figure, we observe that for different data rates there is a specific value of K_{EH} that achieves the maximum throughput. For example, in case of 485.7 kb/s and 971.4 kb/s, the maximum throughput is reached for a harvester with a harvesting rate of $K_{EH} = 1.2$ mJ/s. However, for the same K_{EH} but for transmission rates of 121.4 kb/s and 242.9 kb/s we can achieve only up to 54 % and 74 %, respectively. It is also worth noticing the similar behavior of 485.7 kb/s and 971.4 kb/s despite their great difference. This fact can be rationally explained if we consider that the protocol performance is dominated by the control transmission rate and the Physical Layer Convergence Protocol (PLCP) transmission rate. In this figure, we can also see the changes in the curve slopes which result from the interaction of two different channel access modes (ID-polling and PC-access). Figure 3.12 shows the normalized throughput performance per node versus the K_{EH}, for the data transmission of 485.7 kb/s. In this specific scenario, it can be observed that the nodes achieve improved performance in different threshold values of K_{EH}. As it can be seen for both ID-BNs and PC-BNs, a small/large IAT_{BN} (see Table 3.1) value will require a longer/smaller K_{EH} value in order to achieve the optimal performance.

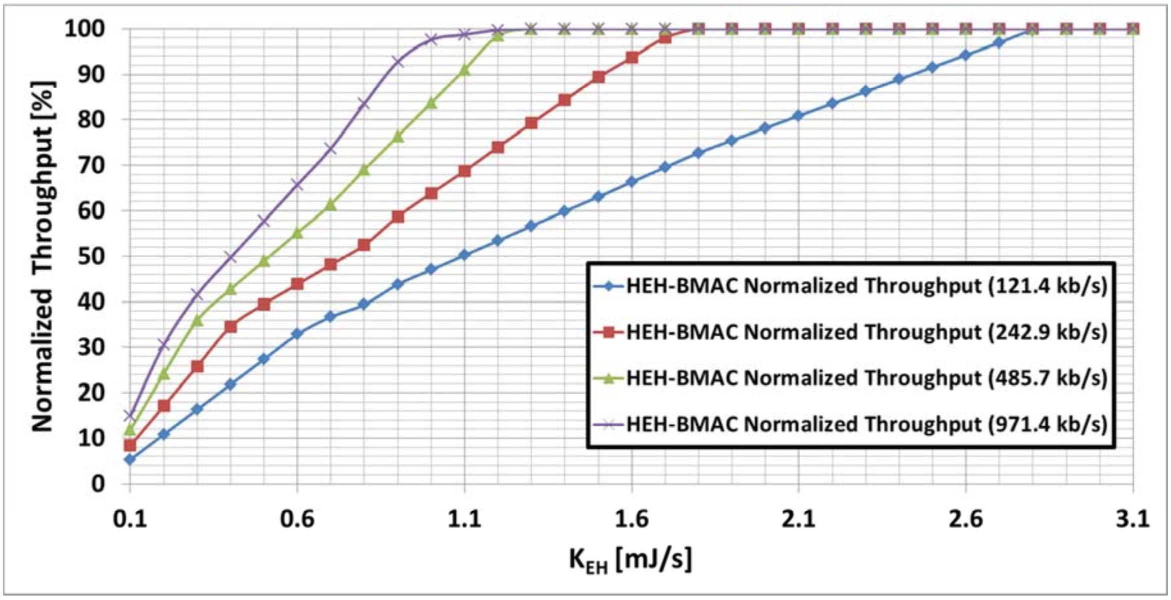

Figure 3.11 – Total normalized system throughput versus the energy harvesting rate, for the four data transmission rate (K = 3, L =2)

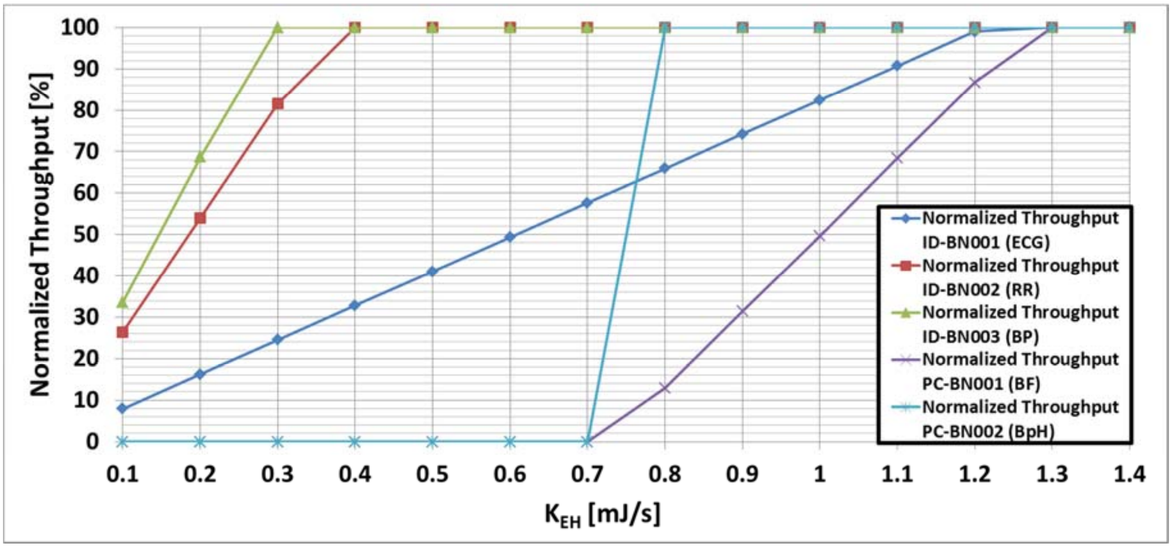

Figure 3.12 – Normalized throughput per node versus the energy harvesting rate (data rate= 485.7 kb/s, K = 3, L =2)

Figure 3.13 presents the energy efficiency of a network composed of K= 3 and L =2. The energy efficiency metric is defined as the total amount of useful data delivered to the sink over the total energy consumption. Energy efficiency increases when throughput is increased and when energy consumption is reduced. In this specific case, it can be seen that the energy efficiency is improving as the K_{EH} increases. This is because as K_{EH} increases, more energy is harvested in less time, allowing more data packets to be transmitted. The maximum energy efficiency achieved is 0.99 Mb/J ($K_{EH} = 2.8$ mJ/s), 1.49 Mb/J ($K_{EH} = 1.8$ mJ/s), 2.12 Mb/J ($K_{EH} = 1.2$ mJ/s) and 2.34 Mb/J ($K_{EH} = 1.2$ mJ/s) for data rates of 121.4 kb/s, 242.9 kb/s, 485.7 kb/s and 971.4 kb/s, respectively. To have a more complete picture for the energy performance, Figure 3.14 depicts the total harvested energy and the remaining energy versus the energy harvesting rate, for the four data transmission rates. Both the collected and the remaining energy increase as the K_{EH} increases. This occurs because the collected energy higher compared to the energy used by the nodes and, consequently, this extra energy can be stored.

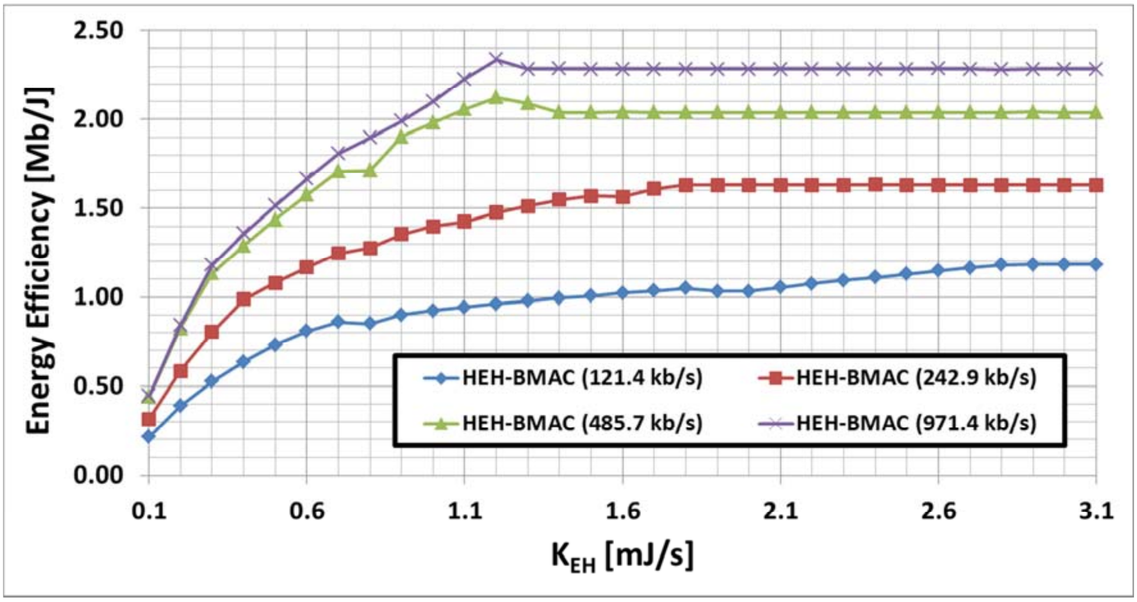

Figure 3.13 – Energy efficiency versus the energy harvesting rate, for the four data transmission rate (K = 3, L =2)

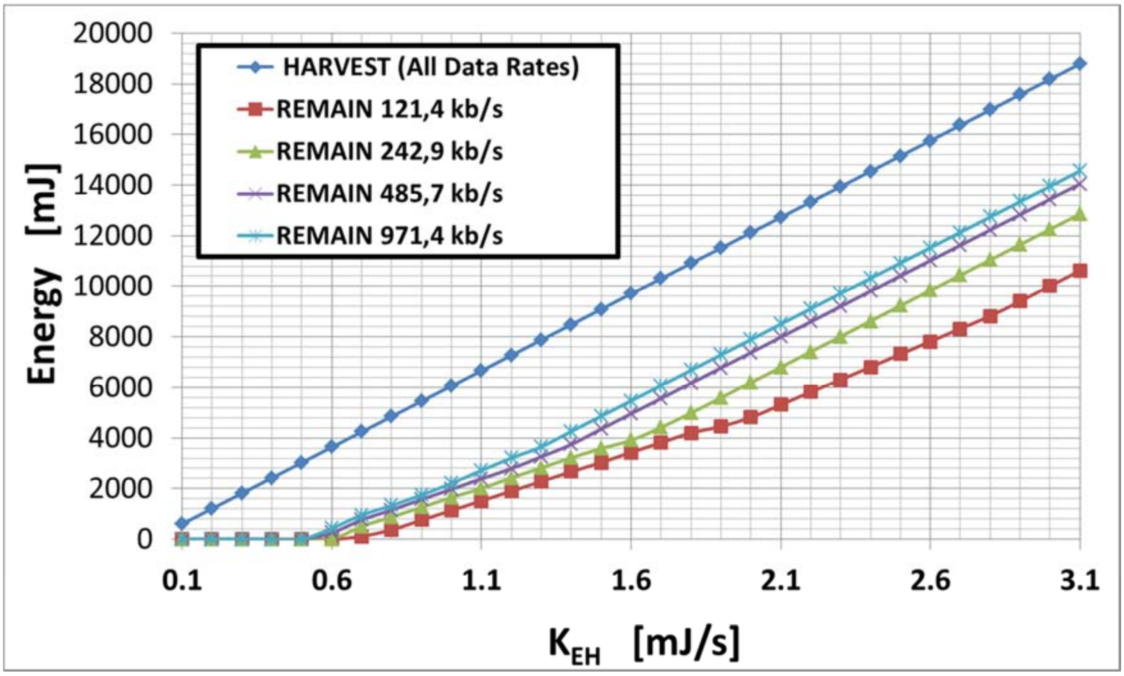

Figure 3.14 – Total system energy harvest and energy remain versus the energy harvesting rate, for the four data transmission rate (K = 3, L =2)

Figure 3.15 presents the normalized throughput performance of a network composed of K=3 ID-BNs and L=17 PC-BNs. The packet inter-arrival time IAT_{BN} of ID-BNs is given by Table 3.1, as before, however, different values of IAT_{BN} are applied to the PC-BNs. The throughput of the network is defined by the amount of data packets successfully transmitted within a certain period of time. If we increase the IAT_{BN}, fewer packets will be generated in a node, since the time interval between the generation of consecutive packets increases. In this specific case (data rate= 485.7 kb/s, K_{EH} =1.3 mJ/s), it can be seen that the system performance is improving as the IAT_{BN} is reaching the value of 250 ms (throughput ≈ 100%), while after this value the performance remains almost stable. The increase of the IAT_{BN} implies a decrease of the number of packets to be transmitted, hence reducing the energy consumption of the node.

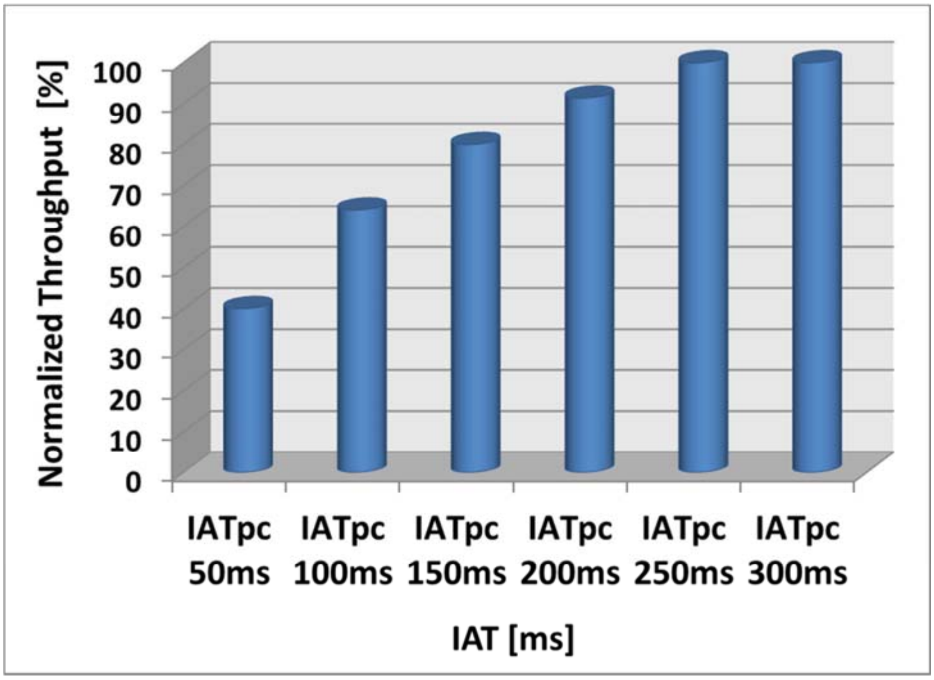

Figure 3.15 – Total normalized system throughput versus IAT of PC-BNs (data rate= 485.7 kb/s, K= 3, L =17, $K_{EH} = 1.3$ mJ/s)

Figure 3.16 shows the normalized system throughput versus the number of PC-BNs (ranging from 2 to 10), using a fixed data rate of 485.7 kb/s, 3 ID-BNs and $K_{EH} = 1.3$ mJ/s. As it can be observed, the HEH-BMAC protocol can maintain an almost stable system performance, since the total system throughput is not significantly affected when the number of PC-BNs increases. Similar results have been obtained by changing the number of ID-BNs, keeping constant the number of PC-BNs. This can be explained by the fact that the time intervals for the ID-Polling and the PC-access are constantly updated through the dynamic list, and packet collisions of the PC-BNs are dynamically resolved through the CP updating algorithm.

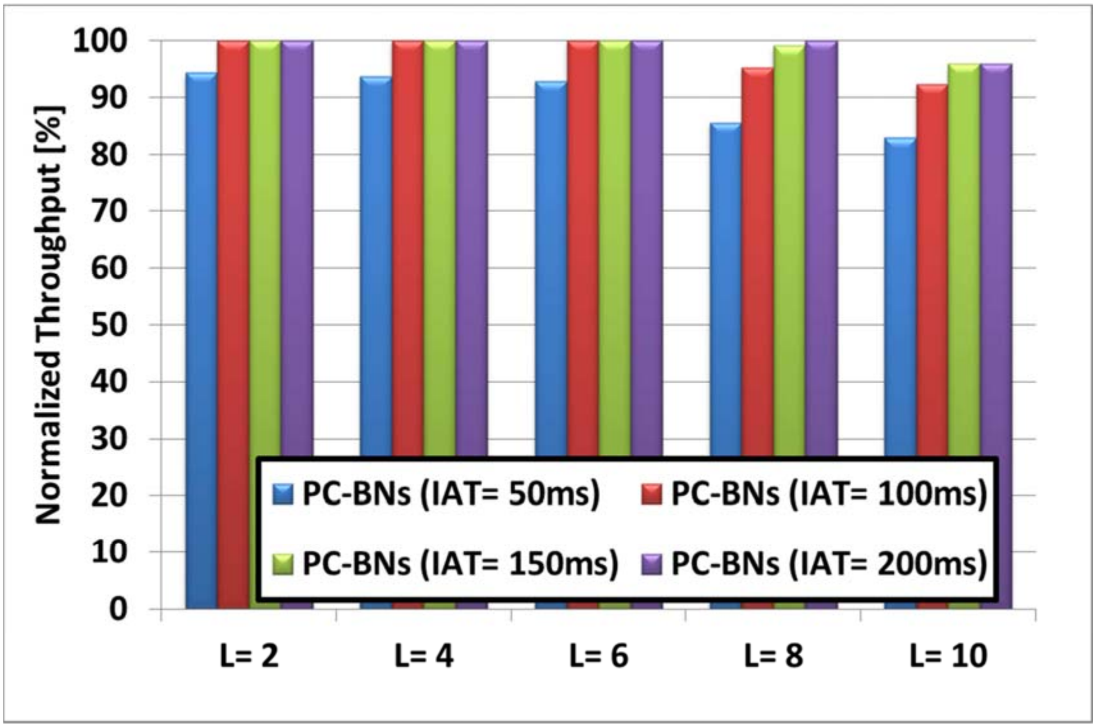

Figure 3.16 – Total normalized system throughput versus number of PC-BNs for different IAT (data rate= 485.7 kb/s, K= 3, $K_{EH} = 1.3$ mJ/s)

3.5.3 HEH-BMAC vs. IEEE 802.15.6: Performances Comparison

To evaluate our approach, we compare the performance of HEH-BMAC with the IEEE 802.15.6 Standard protocol. For comparison, we use the data transmission rate of 485 kb/s, and adopt the non-beacon mode without superframes of the IEEE standard [23]. We chose this configuration because it offers random and prioritized access through the contention window (CW) bounds of CSMA/CA. For the normal priority BNs we will use the CW values that correspond to the user priority (UP) 0 of the IEEE 802.15.6. As for the high priority BNs we examine two different cases, in order to evaluate the IEEE 802.15.6 performance for different CW values and provide a fair comparison with HEH-BMAC. In the first case (Case 1), the CW values of the UP 6 are employed, whereas in the second case (Case 2) the CW values of the UP 3 are selected. Initially, the considered setup consists of 4 BNs in high priority and 3 BNs in normal priority. The number of normal priority BNs is gradually increased up to 18 nodes. The system setup used to compare the performance of our protocol with the standard is shown in Table 3.3.

Table 3.3 – HEH-BMAC/IEEE 802.15.6 System Setup

№	BN	IAT (ms)	Payload (bits)	Priority Type	HEH. BMAC	IEEE 802.15.6
1	ECG SIGNAL	20	120	HIGH	ID. Polling	CSMA/CA
2	RESPIRATORY RATE	50	12	HIGH	ID. Polling	CSMA/CA
3	BLOOD PRESSURE	80	96	HIGH	ID. Polling	CSMA/CA
4	BLOOD FLOW	25	12	HIGH	ID. Polling	CSMA/CA
L	Normal Priority BNs	65	12	NORMAL	PC. Access	CSMA/CA

IEEE 802.15.6				HEH-BMAC	
USER PRIORITY		CW_{min}	CW_{max}	**CP UPDATING ALGORITHM**	
HIGH	UP 3	8	16	Method:	AIMD
HIGH	UP 6	2	8	δ_{add}	0.01
NORMAL	UP 0	16	64	δ_{md}	0.5

We assume that each BN possesses an energy harvester that supplies power at a constant rate K_{EH} = 1.3 mJ/s. This particular value of K_{EH} allows our protocol to reach 100% throughput in the initial setup of the network. The metrics for the evaluation of the performance of our protocol are energy efficiency and normalized throughput. Simulation results for the energy efficiency for both protocols, HEH-BMAC and IEEE 802.15.6, are shown in Figure 3.17. Energy efficiency for both schemes decreases as the number of low-priority BNs L grows. For L=3, the energy efficiency for the IEEE 802.15.6 protocol reaches 2.36 Mb/J for Case 1 (low CW values) and 1.85 Mb/J for Case 2 (high CW values). This difference is observed because of the higher number of data collisions in Case 1, caused by the smaller values of CW bounds compared to Case 2. In Figure 3.17, we can also see how the HEH-BMAC protocol initially (L=3) has similar energy efficiency (1.89 Mb/J) to IEEE 802.15.6 Case 1, but lower energy efficiency than IEEE 802.15.6 Case 2. However, as L increases, our protocol gradually outperforms IEEE 802.15.6, regardless of the CW selection. For L =18 (see Figure 3.17), it can be seen HEH-BMAC achieves a gain of approximately 20% in energy efficiency with respect to IEEE 802.15.6.

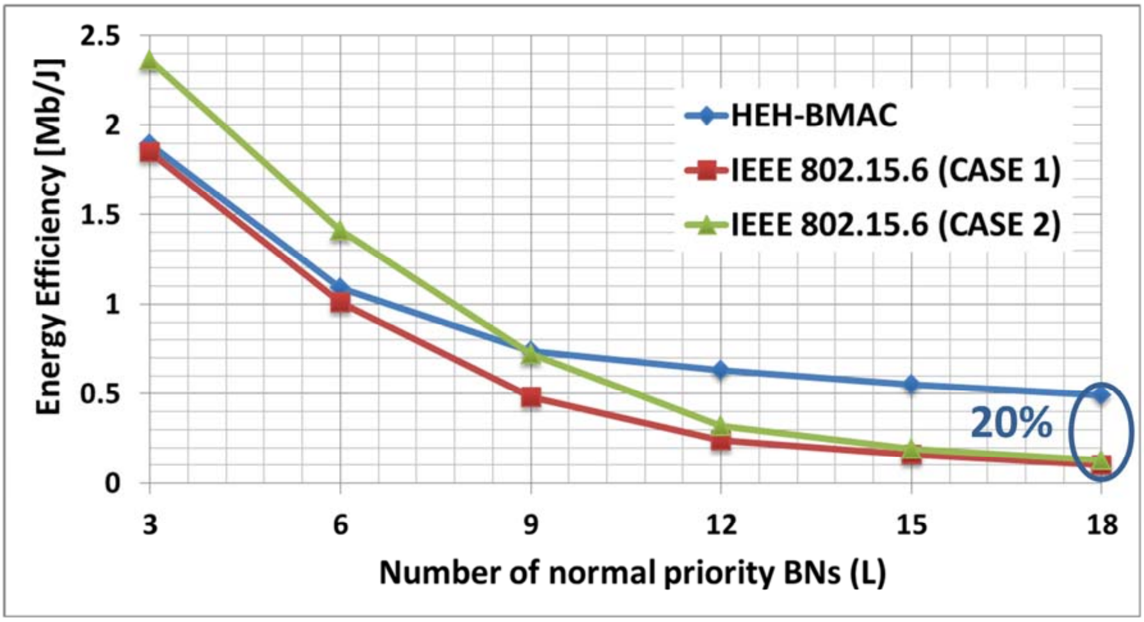

Figure 3.17 – HEH-BMAC vs. IEEE 802.15.6: Energy Efficiency

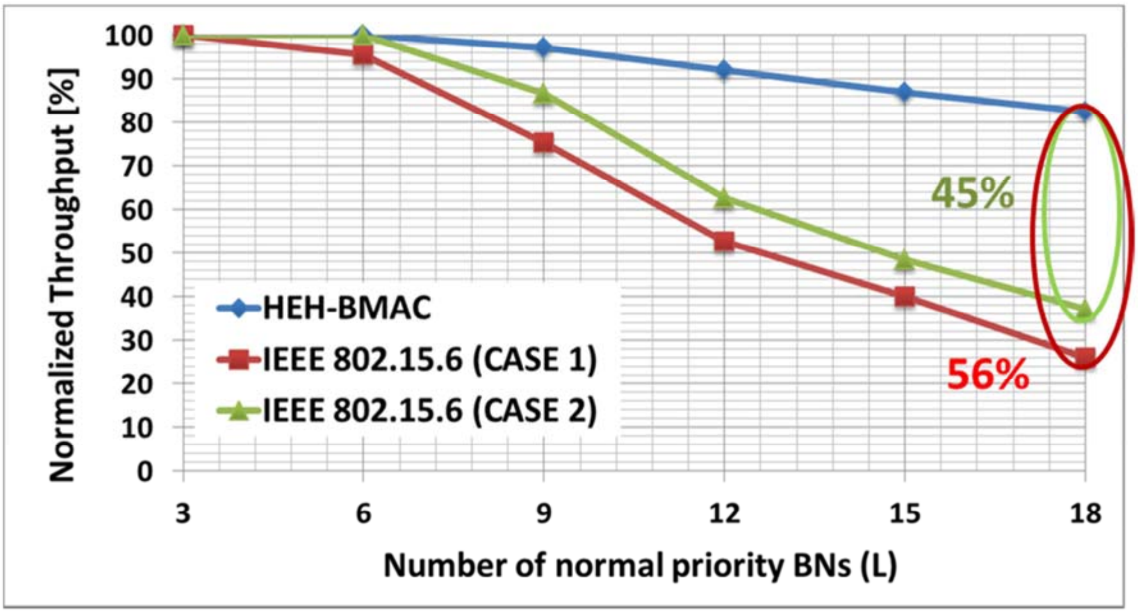

Figure 3.18 – HEH-BMAC vs. IEEE 802.15.6: Normalized Throughputs

Figure 3.18 shows the normalized throughput for the two MAC protocols. We can observe how HEH-BMAC achieves higher throughput as the number of BNs is increasing, compared to the two cases of the IEEE 802.15.6. Looking at L= 18, we can see that the normalized throughput of the HEH-BMAC protocol overcomes the Case 1 and Case 2 of the IEEE 802.15.6 by 56% and 45 % respectively.

This performance enhancement is explained next. In IEEE 802.15.6, even though high priority nodes have a higher chance to access the medium, they may still suffer collisions with other normal or high priority BNs. On the contrary, in HEH-BMAC, the high priority BNs do not experience packet collisions, since the dynamic scheduling algorithm provides them with contention-free medium access. Packet collisions may only take place among the L normal priority BNs, but they are resolved in a dynamic way through the CP updating algorithm in the PC-access.

In order to highlight the benefits of the dynamic scheduling algorithm of the HEH-BMAC, we compare the normalized throughput per BN of our protocol with Case 1 of the IEEE 802.15.6. Figure 3.19 shows the normalized throughput of the 4 high priority BNs and the average normalized throughput for L=6, 12 and 18 BNs in normal priority for both HEH-BMAC and IEEE 802.15.6. We can see how through the dynamic schedule algorithm in the HEH-BMAC the normalized throughput of the high priority BNs is maintained to 100%. On the contrary, in IEEE 802.15.6, the normalized throughput of the high priority BNs is gradually reduced because of the increased number of collisions as L increases. The average normalized throughput of the normal priority BNs is decreased for both protocols. However HEH-BMAC obtains a better performance with respect to the standard.

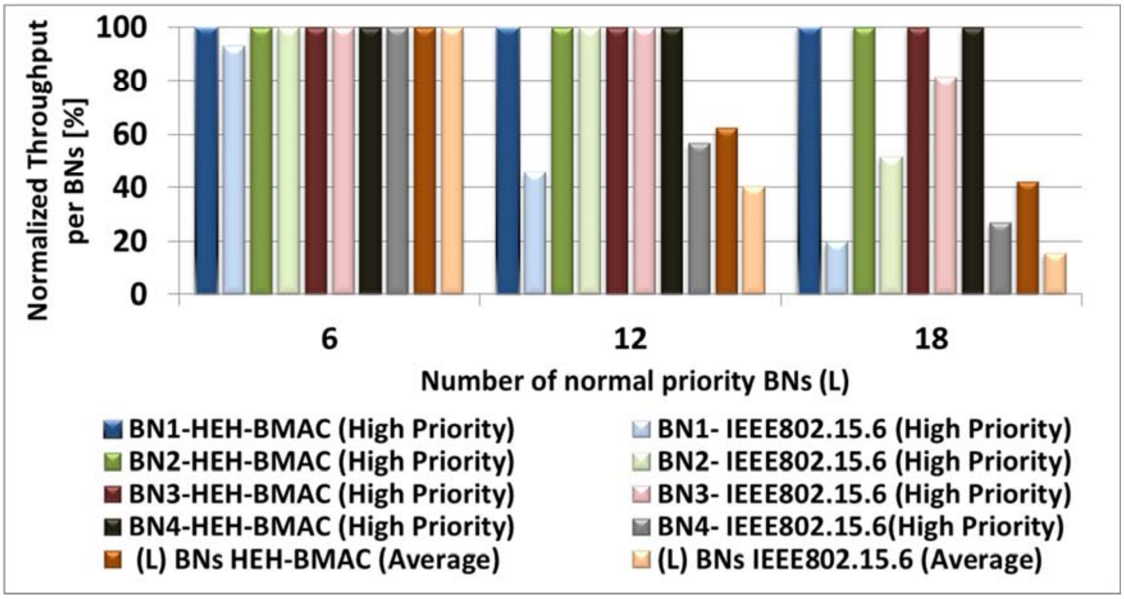

Figure 3.19 – HEH-BMAC vs. IEEE 802.15.6: Normalized Throughputs per BNs

3.6 Chapter Summary and Conclusion

In this chapter, which constitutes the first main part of the thesis, a novel hybrid polling MAC for WBANs powered by human energy harvesting (HEH-BMAC) has been presented. The novelty of the proposed scheme is that it is the first MAC protocol, to our knowledge, designed for WBANs in energy harvesting conditions. HEH-BMAC adopts two modes of operation, in order to provide priority differentiation to the sensor nodes and flexibility to the network. Moreover, HEH-BMAC is energy-aware, adapting its operation to changes in the energy supply of the nodes. Through a performance evaluation of our protocol for different energy harvesting rates, packet inter-arrival times and network size, we observe that HEH-BMAC dynamically adapts its operation to potential changes of these parameters. In this chapter, we have also presented a performance comparison of the HEH-BMAC protocol to the IEEE 802.15.6 standard. In this context, our protocol has been proven to outperform the IEEE 802.15.6 standard in terms of normalized throughput under the same conditions of energy harvesting. In addition, HEH-BMAC achieves higher energy efficiency when the number of nodes is increasing.

Concluding, this chapter has presented an innovative and energy efficient MAC scheme in WBANs powered by energy harvesting. The next chapter presents the second main contribution of this thesis, which is the study of a control scheme to improve the QoS and performance of BNs powered by energy harvesting.

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CHAPTER 4

PEH-QoS: Joint Power-QoS Control Scheme for Energy Harvesting BNs

"One should seek good balance in motion and not in stillness."

Bruce Lee

Contents

4.1 Introduction

The idea of a WBAN that works in synergy with the human body is indeed promising. However, certain considerations must be taken into account to maintain an acceptable level of QoS in HEH-WBANs. Hortos [1, 2] conducted studies about the effect of energy harvesting on the QoS in real-time WSNs incorporating solar and wind energy harvesting techniques at the sensor nodes. The obtained results revealed that the network's lifetime can be extended through the use of energy harvesting, but this may come at the cost of QoS (e.g., throughput, delay, packet loss, etc) degradation. Prashanth et al. [3] performed stability measurements in the data queues of nodes powered by solar energy harvesting in indoor environments. The author pointed out that the degradation in the throughput in WSNs powered by energy harvesting is primarily due to increased waiting time of the data in the queue, as a result of the energy variation. Regarding the stability of the data queue, the author highlighted that it depends on the data arrival rate, the service time and the waiting time. In the same study, some other interesting facts were shown, such as: i) the energy per byte is lower for higher data rates compared to lower data rates, ii) the queue stability is the highest possible when data and energy arrive following an exponential distribution. Joseph et al. [4] focused on increasing throughput and stabilizing the data queue through the development and implementation of optimal sleep-wake policies for energy harvesting sensor nodes. Via their policy, these goals are fulfilled by allowing the node to sleep in some slots and drop some generated packets. Yang and Ulukus [5] developed optimal off-line scheduling policies to minimize the time by which all packets are delivered to the sink, in a single-user WSN under causality constraints on both data and energy arrivals. To achieve this goal, the transmission rate is adapted to the traffic load and available energy. Adapting the operation of the nodes to the variations of their energy level provides important benefits in energy harvesting systems. Khairnar and Mehta [6] proposed a transmission scheme for an energy harvesting node that achieves an average throughput close to the optimal achievable value. In their proposed scheme, the node can only switch between a pre-specified set of discrete data rates and adjusts its power depending on its channel gain and its energy level. Murthy [7] developed an optimum transmission scheme, focused on power management and data rate maximization for WSN-HEAP. Via their transmission scheme, applied to power-controlled nodes that transmit data using a fixed modulation and coding scheme, a particular data throughput can be guaranteed. Ozel et al. [8] proposed adaptive transmission policies in order to maximize the average number of bits transmitted by a given node within a specific time. This energy management approach is able to adapt to the random energy arrivals and to random channel fluctuations.

The papers cited above reveal how some authors address the problems introduced by energy harvesting in WSNs. In the current literature, we can find various interesting approaches, e.g., the application of game theory to perform an energy-aware transmission control in WSN-HEAP [9], and a power manager with a Proportional Integral Derivative (PID) controller that enables the node to operate in ENO state [10]. However, the QoS requirements are more stringent on the WBANs compared to traditional WSNs [11, 12]. From a QoS point of view, Kateretse et al. [13] explained that the WBANs principally have stringent delay and packet loss requirements. In order to provide QoS guarantees in WBAN, the authors in [13] proposed a differentiated traffic and scheduling scheme based on patients' data classification and prioritization according to their current status and diseases. Razzaque et al. [14] proposed a data-centric multi-objective QoS-aware routing (DMQoS) protocol for WBANs. The protocol is based on modular design architecture and consists of five modules: the dynamic packet classifier, delay control, reliability control, energy-aware geographic routing, and QoS-aware queuing and scheduling modules. DMQoS addresses QoS issues for multihop WBANs, focusing on the enhanced delay and reliability. Liang and Balasingham [15] proposed a novel QoS-aware routing service framework for WBANs. The routing service provides prioritized routing service and user specific QoS support. In general, the QoS and the working requirements of a BN depend on the patient's health conditions, the clinical application, as well as the characteristics of the collected data. In order to meet the stringent QoS requirements in WBANs, many authors have designed and implemented new techniques. Hassanpour et al. [16] proposed a new method for routing using a genetic algorithm in order to improve the reliability and the delay in WBANs. Tsouri et al. [17] proposed a global routing with a novel link cost function, designed to balance energy consumption across the WBAN in order to increase the network's lifetime. Otal et al. [18] designed and implemented a novel QoS fuzzy-rule-based cross-layer scheduling algorithm for WBANs. The objective of the specific scheduling algorithm is to guarantee that all packets are served with a specific Bit-Error-Rate (BER) and within particular latency limits, without endangering the battery life.

As we have previously seen, the current literature has several works that address issues related to QoS guarantees in WBANs. However, the literature lacks papers that address issues related to the guarantee of QoS in HEH-WBANs. Seyedi and Sikdar [19] conducted a modeling and analysis of BN powered by energy harvesting in WBANs. In their paper, the authors provide a discrete time model based on a two-state Markov chain, that integrates models for energy harvesting and traffic generation. The aforementioned study is focused on finding the average probability that an event is not detected or transmitted (i.e., lost event), due to the lack of sufficient energy in the BN. The obtained results showed the close relationship between the average harvested power, the average traffic rate and the maximum battery capacity. In [20], the same authors addressed the problem of developing energy efficient transmission strategies in HEH-WBANs. In particular, the authors formulated the problem and proposed a transmission strategy based on a Markov decision process, while they also propose two other strategies based on an energy balancing and aggressive policies. In order to lose the least amount of possible events, the decisions taken by those strategies are based on the current energy level of the BN, the recharging states, as well as the event generation process. Ventura and Chowdhury [21] extended the research carried out by Seyedi and Sikdar [19, 20] by proposing a multiple board Markov model for energy harvesting sensors (MAKERS) that allows us to analyze the overall HEH-WBAN to obtain values for important performance metrics. He et al. also extended the above research based on Markov model, by proposin analytical solutions for the optimal source rate [22] and resource allocation [23] to provide QoS guarantee to data delivery through the HEH-WBANs. The main goal of the proposed optimization schemes is to provide a sustainable QoS that guarantees low delay and low packet loss to subscribers. All these cited works show the operation degradation at the nodes due to the energy harvesting, not only in packet transmission but also in the event detection. The time required to store the amount of energy needed to detect or report (transmit) an event depends on the amount of the collected energy in a given period of time. Based on the above, the main challenge to be faced by a BN powered by human energy harvesting is to maintain its functionality of detecting and transmitting correctly.

In the same context, this chapter introduces a Power-QoS control scheme (PEH-QoS), designed for BNs operated by human energy harvesting. PEH-QoS is an ENO inspired algorithm, developed for providing the best possible QoS under energy harvesting conditions. Our contribution is summarized in the following:

1. PEH-QoS balances the proper BN's operation and the QoS requirements according to the energy harvesting rate in the human environment. Specifically, the proposed algorithm has the following traits: i) it promotes the BN's ability to detect events (normal or emergency) through power-aware

management based on ENO, ii) it prevents the saturation of the data packet queue and maintains the clinical validity of the information stored by discarding old packets and updating the data queue, and iii) it makes an optimum use of the energy dedicated for data communication through a packet aggregation system in order to maximize the throughput under energy harvesting conditions.

2. We evaluate via extensive simulations the throughput and other QoS metrics in a typical BN with PEH-QoS and we compare them with a baseline scenario under the same energy harvesting conditions, where the PEH-QoS is not applied.

The remainder of the chapter is organized as follows. In Section 4.2, we present the system model. Section 4.3 introduces the PEH-QoS control scheme. In Section 4.4, we evaluate the performance of PEH-QoS by extensive simulations. Finally, Section 4.5 concludes the chapter.

4.2 System Model

The BN's architecture and the considered WBAN topology are depicted in Figure 4.1. We adopt a Harvest-Store-Use architecture (see section 2.1.2), and the WBAN is configured in star topology, assuming a single BN. In order to achieve a realistic model, we have chosen the characteristics based on current technological trends in low-power [24, 25] and ultra-low power [26] wireless node designs for WBANs. We have chosen the supercapacitors as energy storage units due to the benefits they provide to the system (see section 2.1.2), e.g., they can charge and discharge with faster rate than batteries. It becomes clear that the collected energy exploitation is a key factor that will determine the smooth operation of a node. For this reason, we assume the energy management architecture proposed in [27] for biomedical devices using supercapacitor for energy storage. This energy management integrated circuit (EMIC) consists of a switched-capacitor DC-DC converter (which converts a source of direct current (DC) from one voltage level to another), a 4 nW bandgap voltage reference, a high-efficiency rectifier (to allow recharging of the capacitor bank), and a switch matrix and digital control circuitry (to govern the stacking and unstacking of the supercapacitors) [27]. Through the use of EMIC, more than 98% of the stored energy may be available for use. Regarding the transceiver, the sensor and the reader, the transceiver is modeled as a 1.9 nJ/b 2.4 GHz Multi-standard (Bluetooth Low Energy/Zigbee/IEEE802.15.6) transceiver for Personal/Body-Area Networks [28], while the sensor and the reader are modeled based on a 30 μW analog signal processor integrated circuit for biomedical signal monitoring [29]. These components were chosen because of their low power consumption and good reliability for WBANs.

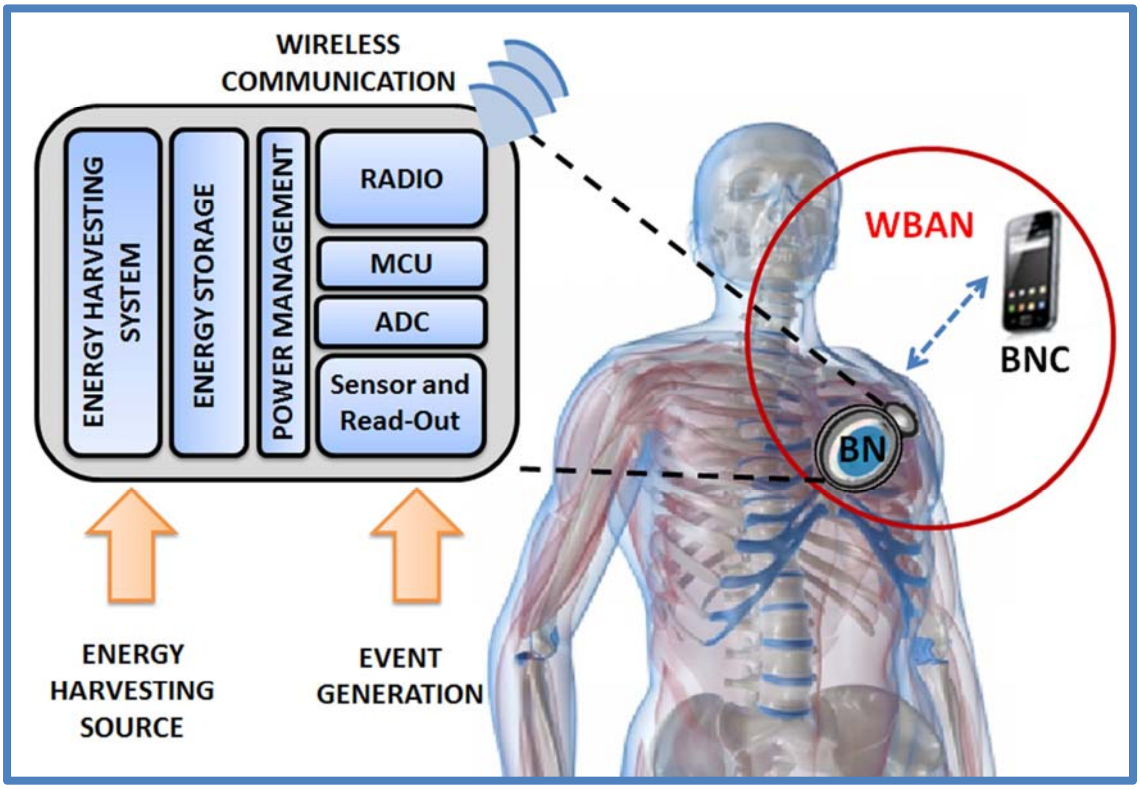

Figure 4.1 – BN's architecture and WBAN topology: System model

In our model, the BNC is the sink responsible for setting up the WBAN and collecting all information transmitted by the BN. We assume that the BNC is a smartphone that has higher processing capabilities than the BN. The data communication between the BNC and the BN takes place via the ID-polling access mode of the HEH-BMAC protocol (see section 3.3.1). We consider that our BNC has an external power supply, and the BN has an energy harvester able to harvest in a constant rate K_{EH} the energy available in the human body. In order to model a more realistic scenario, we will adopt the same IAT_{BN} and packet size (l_{pkt}) as in [30] for the event generation. In our study, we consider that the BN's power consumption is divided into two main parts: the detection power consumption (P_{det}) and the transmission power consumption (P_{tx}). The term P_{det} includes the power consumption related to the correct BN's operation (i.e., MCU, ADC, sensor and read-out). On the other hand, the term P_{tx} includes the power consumption related to the duty cycle of the transceiver (i.e., data communication process).

4.3 Power-QoS Aware Management Algorithm

The PEH-QoS is executed at each node in the WBAN. The main goal of our scheme is to adapt the BN's performance considering its particular features, power supply and QoS requirements. To achieve this goal, our mechanism combines three main sub-modules: i) the Power-EH Aware Management (PHAM), ii) the Data Queue Aware Control (DQAC) and iii) the Packet Aggregator/Scheduling System (PASS). Figure 4.2 shows the interrelationship of these three sub-algorithms in the BN's operation. As it can be seen, the BN's operation is adapted according to the characteristics and requirements of each node, as well as on the respective medical application.

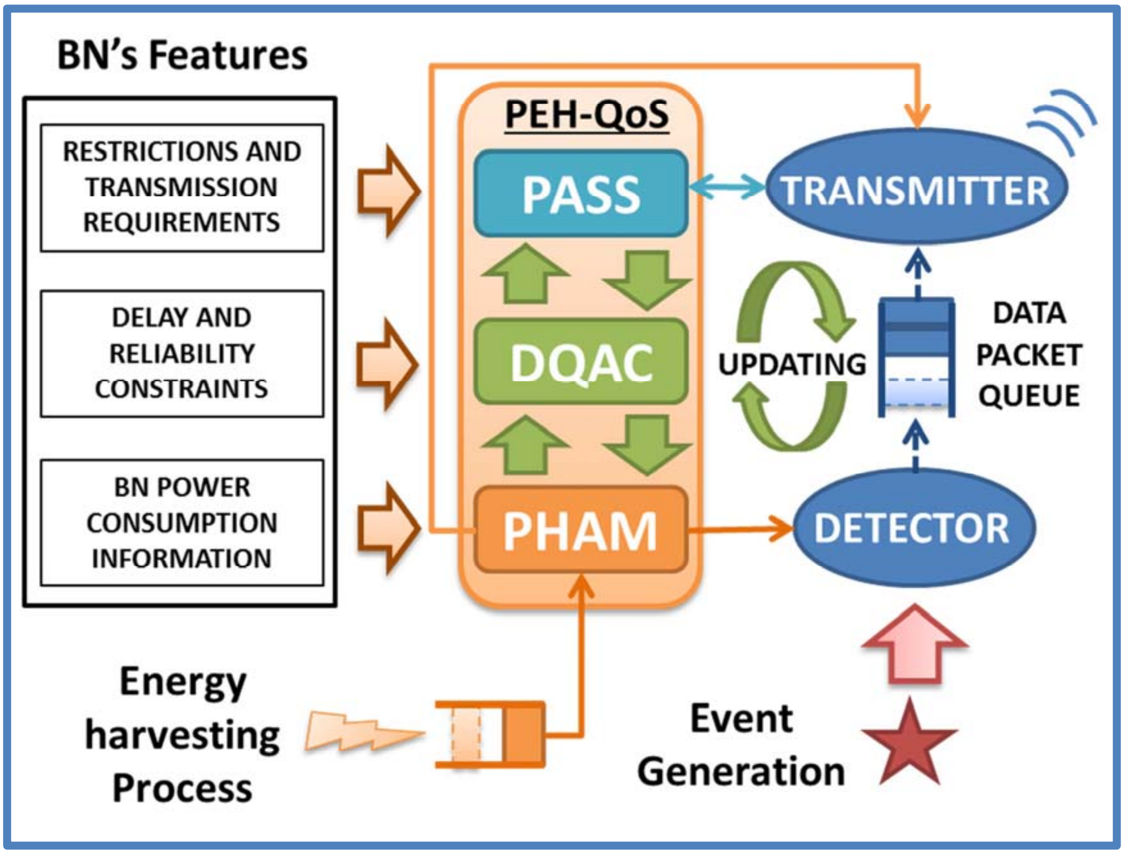

Figure 4.2 – Illustration of the PEH-QoS operation

In the PEH-QoS control scheme, the PHAM sub-module uses, calculates, and manages the energy required to carry out each task that must be performed, thus keeping the node in ENO state and control the overall energy consumption of the system. DQAC sub-module uses the information about the delay and reliability requirements of the node in order to transmit only useful data sequences, discarding data packets that have lost their clinical validity (i.e., out of date data). Finally, the PASS sub-module uses the amount of power available for transmission (information from the PHAM sub-module) and the amount of data stored in the queue (information from the DQAC sub-module) to transmit the maximum number of possible packet for each data communication process. In the following sections, we provide the details of each sub-module and their respective operations.

4.3.1 PHAM: Power-EH Aware Management

This sub-module handles the distribution and guarantees the optimal use of energy collected from the human environment. The energy management is a key to achieve acceptable performance in energy harvesting conditions. PHAM performs power management using the BN's power consumption information. The operation of a BN mainly consists of two tasks: detection and transmission. BN's radio consumes much more energy compared to the detector ($E_{Tx} >> E_{det}$). The energy harvesting process affects these two tasks, since the node must harvest enough energy to carry out its work properly. In WBANs, the BN's ability to detect events is the same important as the transmission function. If an event is not detected, it is not possible to know whether this is a normal or abnormal event (i.e., alarm or critical event). The purpose of PHAM sub-module is to try to keep the node in ENO state and maintain good detection efficiency. The detector efficiency (D_{eff}) is given by:

$$D_{eff} = \frac{Total\ number\ of\ events\ detected(t)}{Total\ number\ of\ events\ occurred(t)} \tag{4.1}$$

In our control scheme, the power management is carried out by the PHAM sub-module depending on the energy harvesting conditions. In PHAM sub-module (see Figure 4.3), we use the principles of ENO (see Section 2.1.5.1) to try to maintain a good performance of the detector (BN's main function).

The level of energy stored in the battery (B_{level}) depends on the energy harvested (E_{EH}) from the human environment, so we have:

$$\mathrm{B}_{level}(t) = \mathrm{B}_{level}(t-1) + E_{EH} \tag{4.2}$$

In turn, E_{EH} depends on the $\mathrm{K_{EH}}$ and the time (T_{EH}), which can be expressed as follows:

$$E_{EH} = \int_0^{T_{EH}} \mathrm{K_{EH}} = \mathrm{K_{EH}} * T_{EH} \qquad \forall\, T_{EH} \in [0, \infty) \tag{4.3}$$

ALGORITHM 1: *Power-EH Aware Management*

if $B_{level} \geq E_{det} + E_{Tx}$ **then**
    Keep BN's detector ***ON***
    if $D_{Queue} \geq D_{Load}$ **then**
        Keep BN's transceiver ***ON***
        Make communication process of D_{Load}
    else
        Keep BN's transceiver ***SLEEP mode***
elseif $B_{level} < E_{det} + E_{Tx}$ ***do***:
    if $B_{level} \geq E_{det}$ **then**
        Keep BN's detector ***ON***
        Keep BN's transceiver ***OFF***
    else
        Keep BN's detector ***OFF***
        Keep BN's transceiver ***OFF***
end
Repeat step 1

Figure 4.3 – PHAM sub-module algorithm

In PHAM, energy harvested is intended to keep the detector operating properly (i.e., BN's detector ON, when $B_{level} \geq E_{det}$). To achieve this goal, the algorithm controls the BN's power consumption based on the stored energy level. The transmission may be performed when the battery's energy level reaches $B_{level} \geq E_{det} + E_{Tx}$ (BN's transceiver ON), where E_{det} is the amount of energy required to maintain the function of detection at time t and E_{Tx} is the amount of energy required to perform the data communication process of D_{Load}. D_{Load} is the number of $\boldsymbol{l_{pkt}}$ to be transmitted for every data communication process. D_{Load} is calculated with the help of DQAC and PASS sub-modules. Moreover, E_{TX} is calculated with the help of PASS sub-module.

4.3.2 DQAC: Data Queue Aware Control

Since the amount of the harvested energy depends on the magnitude and the availability of the energy harvesting source, data packets can remain stored for a long time before their transmission. This raises two major issues; the first is related to the saturation of the data queue, since the node has a finite storage capacity. Once the node has reached its maximum capacity of data storage, it may not be able to store the next events detected and, consequently, these packets are lost. The second problem is related to the loss of validity of the data stored. In this condition, the stored data may lose their clinical importance because of the waiting time (e.g., in monitoring vital signs, in some cases, old data lose their value in the presence of most recent data). DQAC is a sub-module designed to control the data queue and deal with these problems. DQAC sub-module performs two main tasks: i) prevents the saturation (overflow) of the queue with unimportant data, and ii) allows all detected events to be stored.

The sub-module performs the packet discard and update of the data queue (see Figure 4.4) using the information of maximum allowed end-to-end delay (Dly_{max}) and maximum storage capacity (SC_{max}). Dly_{max} depends on the BN's application requirements and SC_{max} is a physical restriction of the BN's hardware. DQAC constantly monitors the waiting times of each data packet (T_{pkt}) and the number of packets stored (DQ_{level}). The value of T_{pkt} must not exceed the maximum waiting time in the queue (T_{Qmax}), otherwise the data packet is deleted to release space in the queue. Deleted packets are data packets that either have lost their importance or have been deleted to make space for recent data packets. T_{Qmax} is calculated as:

$$T_{Qmax} = Dly_{max} - T_{TX} , \qquad (4.4)$$

where T_{TX} is the time needed for the data communication process and it is calculated in PASS sub-module.

ALGORITHM 2: *Data Queue Aware Control*

1: **if** $DQ_{level} > 0$ **then**
2:     ***Check*** T_{pkt} *of all packets stored.*
3:     **if** $T_{pkt} \geq T_{Qmax}$
4:         **Delete** Data *packet.*
5:     **end**
6: **end**
7: **if** $DQ_{level} < SC_{max}$ **then**
8:     **if** event is detected **then**
9:         **Save** Data packet in the Queue
10:     **end**
11: **elseif** $DQ_{level} == SC_{max}$ **then**
12:     **if** event is detected **then**
13:         **Delete** packet with longer waiting time.
14:         **Save** new Data packet in the Queue
15:     **end**
16: **end**
17: *Repeat step* 1

Figure 4.4 – DQAC sub-module algorithm

4.3.3 PASS: Packet Aggregator/Scheduling System

In BNs operated by battery, the data packets can be transmitted as soon as they are generated. On the other hand, in BNs operated by energy harvesting, data transmission can be realized when the node accumulates enough energy to do it. *PASS* is a sub-module that has been designed to optimize the data transmission in energy harvesting conditions (see Figure 4.5). The main objective of this algorithm is to send the maximum number of data packets (among the BN's transmission possibilities) for every transmission. *PASS* uses the MAC protocol information for the calculation of E_{Tx} .

ALGORITHM 3: *Packet Aggregator/Scheduling System*

1: **Calculate** E_{Tx} *required to send a single packet.*
2: **Check** B_{level} *and* DQ_{level} *status*
3: **if** $\mathrm{DQ}_{level} = 1$ *and* $\mathrm{B}_{level} \geq E_{Tx} + E_{det}$ **then**
4:     **Make** $D_{Load} = 1$
5:     **Perform** *data communication process.*
6: **elseif** $\mathrm{DQ}_{level} > 1$ **then**
7:     **Determine** D_{Load}
8:     **Calculate** E_{Tx} *required to send* D_{Load}
9:     **if** $\mathrm{DQ}_{level} \geq D_{Load}$ *and* $\mathrm{B}_{level} \geq E_{Tx} + E_{det}$ **then**
10:         **Make** packet aggregation D_{Load}
11:         **Perform** *data communication process.*
12:     **elseif** $\mathrm{DQ}_{level} < D_{Load}$ *and* $\mathrm{B}_{level} \geq E_{Tx} + E_{det}$ **then**
13:         **Recalculate** D_{Load}
14:         **Calculate** E_{Tx} *required to send* D_{Load}
15:         **Make** packet aggregation D_{Load}
16:         **Perform** *data communication process.*
17:     **else** *wait to accumulate* $\mathrm{B}_{level} \geq E_{Tx} + E_{det}$
18:         **Perform** *from Line 13 to Line 16*
19:     **end**
20: **end**
21: *Repeat step 1*

Figure 4.5 – PASS sub-module algorithm

Figure 4.6 shows the structure of the IEEE 802.15.6 data frame [31]. In this way, several packets can be transmitted using the same control frames (depending on the applied protocol). The aggregation packet number is variable (D_{Load}). An increase of the size of D_{Load} implies an increase of the amount of required E_{Tx}. D_{Load} depends on the BN's energetic conditions (i.e., B_{level}) and the status of the data queue (i.e., DQ_{level}). Thus, the value of D_{Load} is indirectly adapted to the K_{EH} and data arrival time in the node.

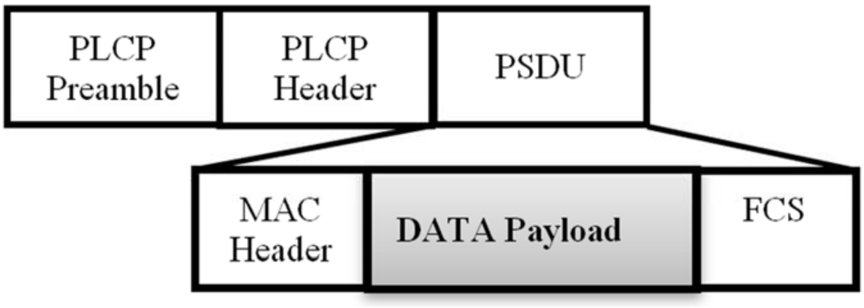

Figure 4.6 – Illustration of IEEE 802.15.6 data frame structure

4.4 PEH-QoS Performance Evaluation

4.4.1 Simulation Consideration and Setup

We have developed an event-driven MATLAB simulator that implements our algorithm in a simple HEH-WBAN. We consider a HEH-WBAN formed by one BNC and one BN. We assume that the BNC has no energy shortage problems (it has an external power supply), while the BN is connected to an energy harvester. Energy harvester supplies energy to the node at a constant rate K_{EH}. The BN stores the harvested energy in a rechargeable supercapacitor. The node we have chosen for our simulation is the ECG node. Events detected by the ECG are converted into packets and then stored in a data buffer. The characteristics [24, 28-30] and the QoS requirements [14] of the ECG are summarized in Table 4.1.

We assume that the communication between the ECG and the BNC can take place directly without interference. The BNC provides medium access through the execution of the ID polling access of the HEH-BMAC (see Section 3.3.1). The network parameters have been selected according to the IEEE 802.15.6 PHY-MAC specifications [31]. The system parameters used in the simulation are summarized in Table 4.2.

Table 4.1 – ECG BN: Characteristics

<table>
<tr><td rowspan="3">Data and Trafic Features</td><td colspan="2">DATA ARRIVAL TIME</td><td>2 ms</td></tr>
<tr><td colspan="2">BUFFER SIZE</td><td>200 packets</td></tr>
<tr><td colspan="2">PACKET SIZE</td><td>12 bits</td></tr>
<tr><td rowspan="6">Power Consumption Distribution</td><td colspan="2">SENSOR, READ − OUT AND ADC</td><td>30 μW</td></tr>
<tr><td colspan="2">MCU</td><td>19.25 μW</td></tr>
<tr><td rowspan="4">TRANSCEIVER</td><td>Reception</td><td>3.8 mW</td></tr>
<tr><td>Transmission</td><td>4.6 mW</td></tr>
<tr><td>Sleep</td><td>4 μW</td></tr>
<tr><td>Idle</td><td>0.712 mW</td></tr>
<tr><td rowspan="2">QoS Requirements</td><td colspan="2">DELAY CONSTRAINT</td><td>250 ms</td></tr>
<tr><td colspan="2">PACKET LOSS CONSTRAINT</td><td>10 %</td></tr>
</table>

Table 4.2 – ECG BN: System Parameters

PARAMETER	**VALUE**	**PARAMETER**	**VALUE**
SIMULATION TIME	60000 ms	MAC HEADER	56 bits
pSIFS	0.05 ms	FCS	16 bits
pCSMA Slot	0.125 ms	PLCP PREAMBLE	90 bits
PLCP Tx RATE	91.9 kbps	PLCP HEADER	31 bits
DATA T_X RATE	485.7 kbps	ACK	72 bits
CONTROL T_X RATE	121.4 kbps	T. POLL	88 bits

To evaluate our approach, we study the performance of an ECG with and without PEH-QoS, respectively. In our simulation scenario, we consider only the packet loss due to saturation of the data buffer, the non-detection of the events, and the non-transmission of the stored packets. For delay calculation, we use the average packet end–to-end delay of all data packets sent. The delay experienced by each data packet is calculated as the time the packet is generated until it is received by the BNC. In addition, we also measure the data storage efficiency, the normalized throughput and the energy efficiency of the BN. We calculate the efficiency of data storage as the total number of events stored divided by the total number of events detected. Energy efficiency is defined as the total amount of useful data delivered over the total energy consumption [32]. Finally, normalized throughput is defined as the number of bits successfully transmitted over the total number of generated bits, within the same period of time.

4.4.2 Simulation Results

Simulation results for the detection efficiency of ECG with and without PEH-QoS are shown in Figure 4.7. In this figure, we can see how the PEH-QoS improves the performance of the ECG in terms of detection efficiency. We observe that for very small values of K_{EH} (i.e., $K_{EH} < \frac{E_{det}}{T}$), the ECG without the PEH-QoS cannot detect any event. This is because the node is not aware of the available energy and it keeps trying to detect events, although there is not enough energy for the detection, hence wasting the collected energy. In this range, our scheme enhances the performance by a 12.8% and 93.4% for $K_{EH} = 0.01$ mJ/s and $K_{EH} = 0.05$ mJ/s, respectively. In the case of $K_{EH} = 0.06$ mJ/s ($K_{EH} \geq \frac{E_{det}}{T}$), we can see that both systems achieve a detection efficiency of 100%, since there is sufficient energy for the detection of all the events.

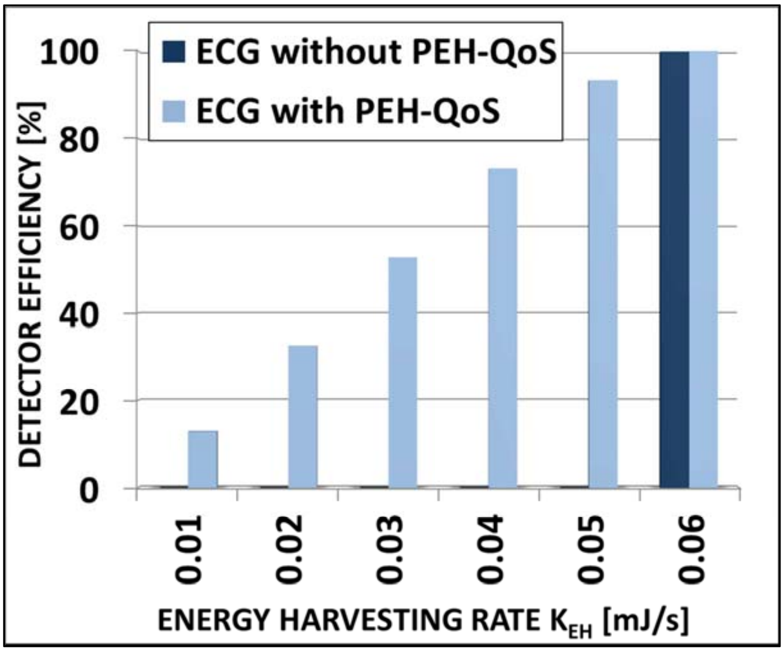

Figure 4.7 – Detection Efficiency

Figure 4.8 shows the behavior of the data queue for the two systems when $K_{EH} = 0.06$ mJ/s. In this graph, we can observe that the packets are continuously accumulated because the nodes do not have sufficient energy for the transmission. In these conditions, our algorithm manages to stabilize the data queue, unlike the baseline scenario, where the data queue saturates. In Figure 4.8, it can be also seen that the level of the queue is stabilized in 124 data packets (i.e., in this case $D_{Load} = 124$), where 100% of the stored information is valid, unlike the case that the algorithm is not applied and the queue is saturated with information that is no longer valid.

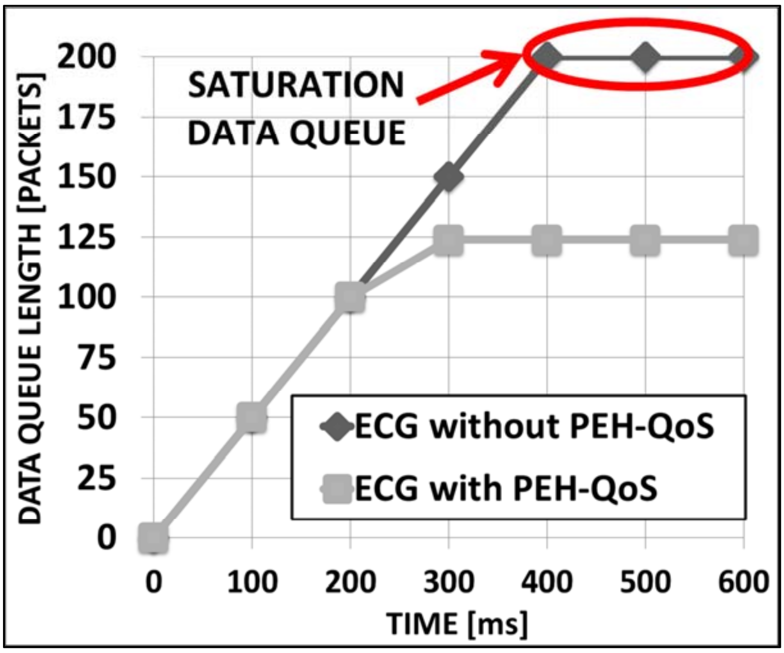

Figure 4.8 – Data Queue Behavior

Figure 4.9 demonstrates that PEH-QoS is able to maintain the efficiency of data storage at 100%, which allows all sensory data to be stored until they are transmitted or have lost their clinical validity. In order for the node without PEH-QoS to reach good storage efficiency, a larger K_{EH} should be used but, unfortunately, high values of K_{EH} cannot be achieved with energy harvesting current technologies.

Figure 4.10 presents the system throughput behavior for different values of K_{EH} for both schemes. In this figure, we can see that our scheme, with data aggregation $D_{Load} = 124$, significantly outperforms the baseline system. Our system in $K_{EH} = 0.16$ mJ/s reaches 100% of the normalized throughput while the other system is only reached 2.06%. This is justified by the fact that our scheme sends 124 data packets for transmission, unlike of the baseline that transmits only a single packet.

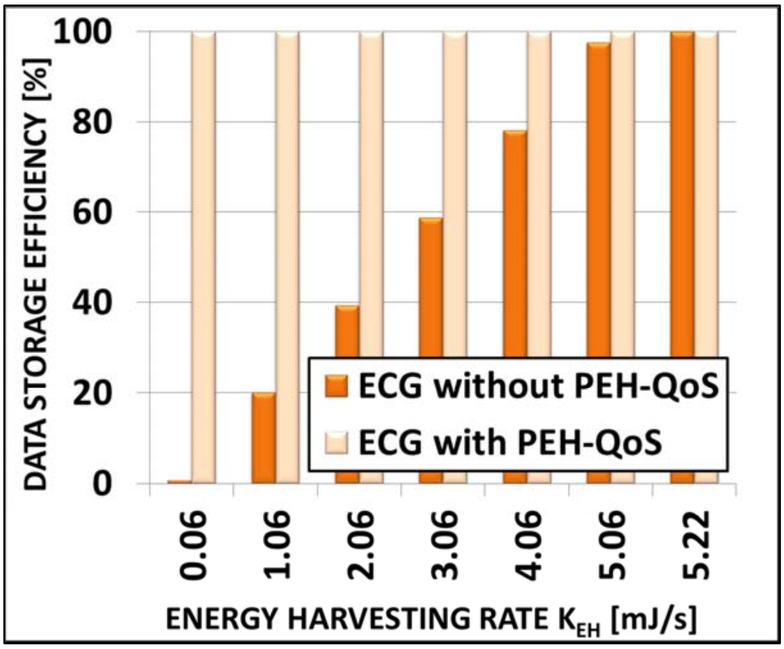

Figure 4.9 – Storage Efficiency

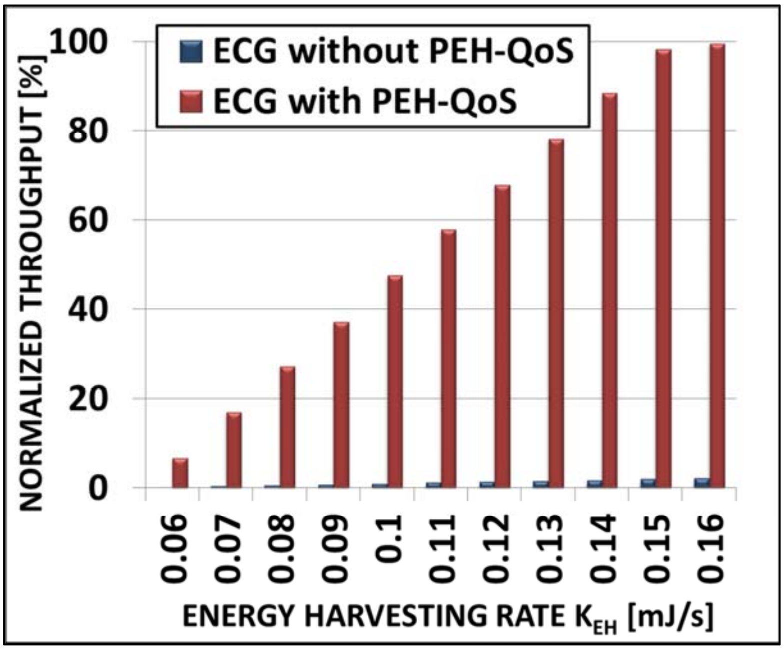

Figure 4.10 – Normalized Throughput

Figure 4.11 shows the variation in the normalized throughput in our scheme when applying different D_{Load} when $\mathrm{K_{EH}} = 0.16\,\mathrm{mJ}/s$. For the same conditions, Figure 4.12 and Figure 4.13 show the relationship between D_{Load} and the restrictions of reliability and delay respectively. As can be corroborated in these two figures, the value of D_{Load} =124 data packets achieves the best delay value and reliability.

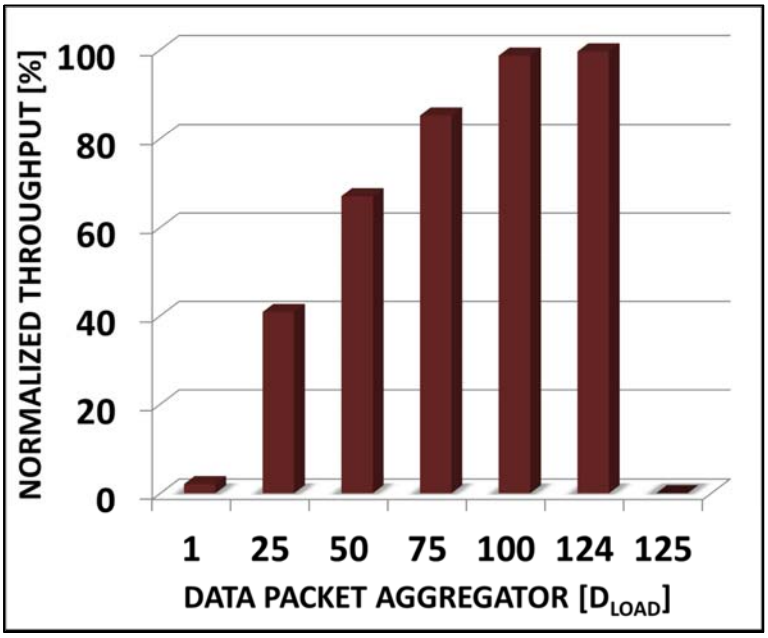

Figure 4.11 – Normalized Throughput vs. D_{Load}

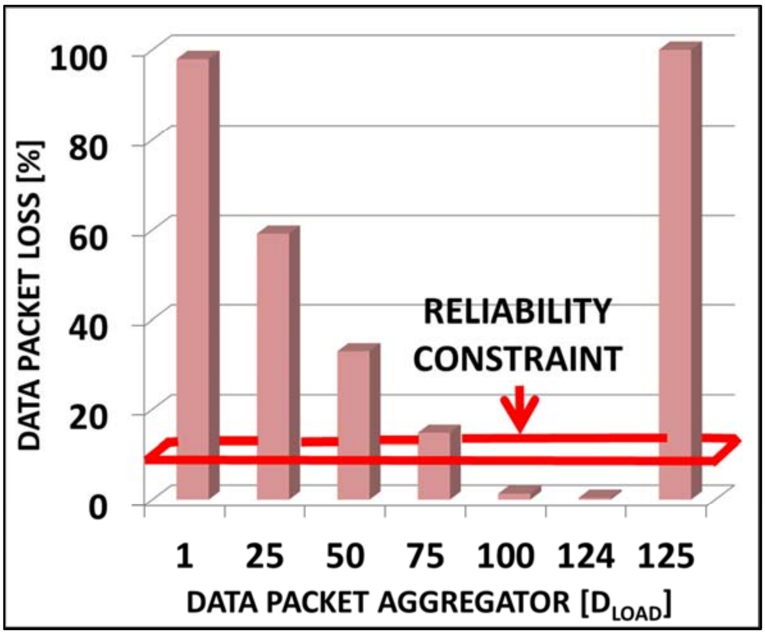

Figure 4.12 – Data Packet Loss

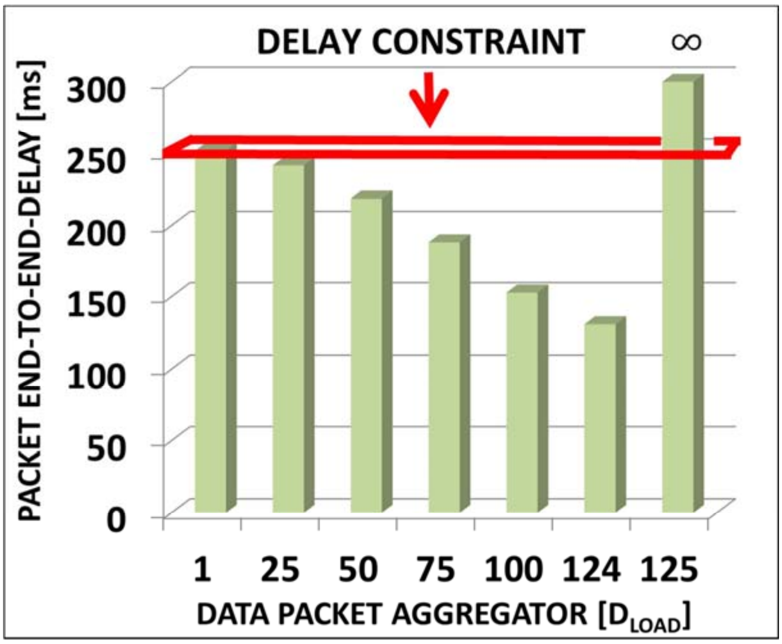

Figure 4.13 – Average Packet End-To-End Delay

Furthermore, Figure 4.14 shows that the energy needed to perform the transmission in both systems with and without PEH-QoS. In the case of ECG with PEH-QoS, for the transmission of a sequence of 124 data packets of 12 bits, the node spends only $E_{Tx} = 24.3\,\mu J$. On the contrary, in the case of ECG without PEH-QoS, where no aggregation is applied (i.e., L=1), the node needs $E_{Tx} = 10.3\,\mu J$ for the transmission of a single data packet of 12 bits.

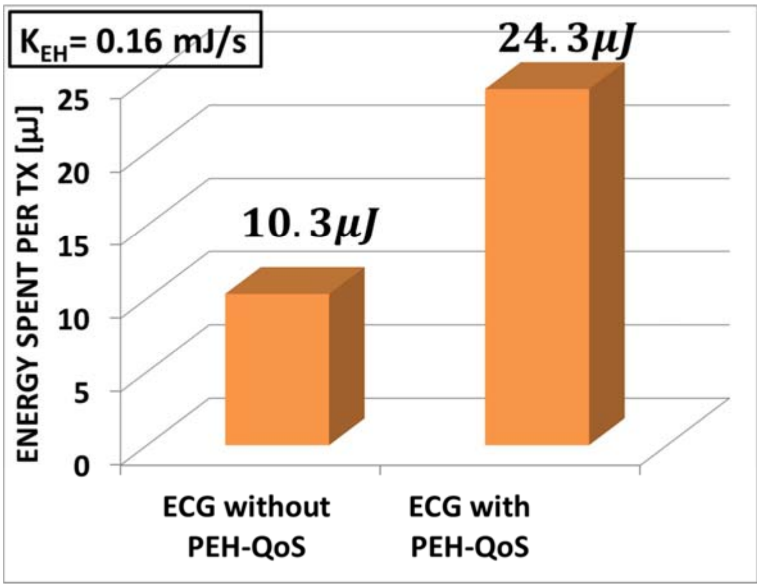

Figure 4.14 – Energy Spend per Data Transmission.

In Figure 4.15, we can see that our system is 50 times more energy efficient than the benchmark. In terms of packet loss, our scheme fulfilled the reliability required by the application (i.e., maximum packet loss 10%), unlike the basic system which exceeded this threshold. In particular, our system achieved 0.39% packet loss, while the baseline reaches 97.94% (see Figure 4.16).

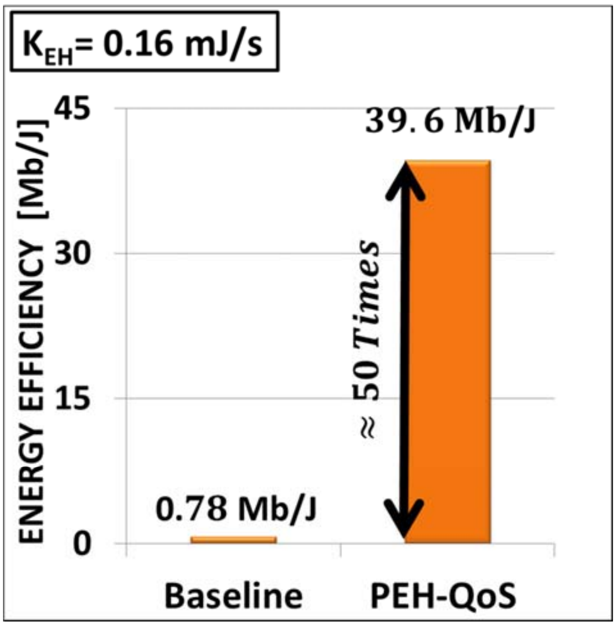

Figure 4.15 – Energy Efficiency

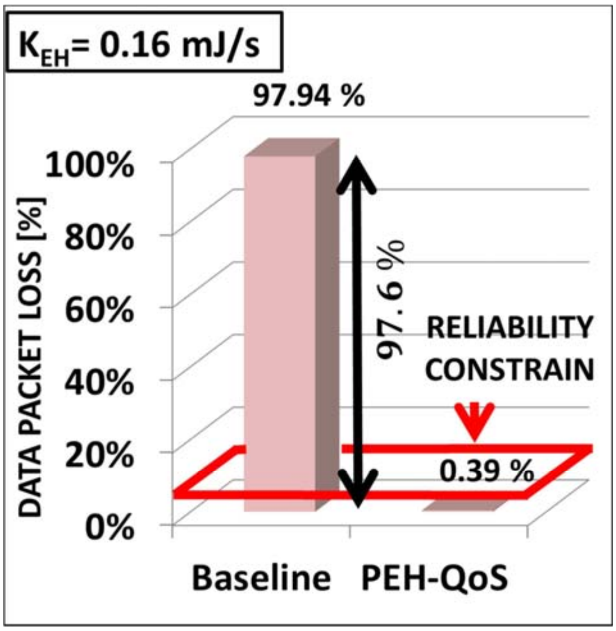

Figure 4.16 – Packet Loss

Finally, in Figure 4.17, we can see that the average packet end-to-end delay experienced in our system is 130 ms (maximum delay permitted 250 ms), contrary to the baseline which obtained a much higher value (16.18s).

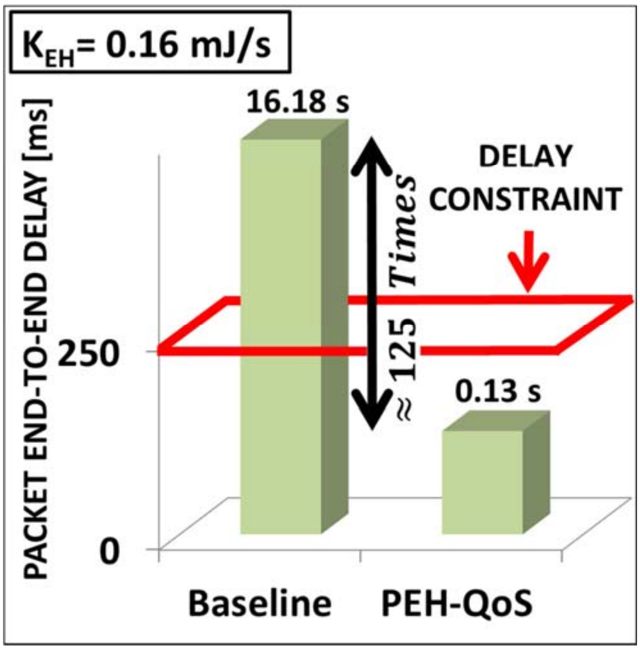

Figure 4.17 – Average Packet End-To-End Delay

4.5 Chapter Summary and Conclusions

This chapter introduced the second main part of the thesis, dedicated to improve and resolve problems that individually affect the performance of the nodes, due to the energy harvesting sources, i.e., problems at the BN-Level. In particular, we proposed PEH-QoS, a novel and highly efficient control scheme for BNs powered by energy harvesting. This control scheme has a modular architecture focused at the optimal use of the energy collected in the human environment, in order to improve the provided QoS. PEH-QoS consisting of three sub-modules which are: PHAM (it provides stability to the node, keeping it in ENO state), DQAC (controls and manages the data queue, keeping it updated with valid packets), and PASS (optimizes data transmission, enabling the transmission of a greater number of bits with less energy).

The control scheme is designed to be executed on each node, under its particular energy harvesting conditions, achieving tailor not only in issues related to the role of data transmission, but also ensures the proper functioning of the detection of events. The most substantial conclusions can be summarized as follows:

- The application of our control scheme in the node achieves significant performance improvements in both the data transmission function and the event detection function, attaining optimal management of the energy collected in the human environment. In this way, PEH-QoS can ensure that a BN can both capture/detect the medical events and transmit the respective data packets efficiently.

- Extensive simulations have been conducted in order to evaluate the behavior of PEH-QoS in a typical medical node under energy harvesting conditions. Our algorithm has been proven to outperform the BN without PEH-QoS in terms of normalized throughput, energy efficiency, packet loss and average packet end-to-end delay.

- BN with PEH-QoS has higher detection and storage efficiency than the baseline scheme under the same energy harvesting conditions. This feature enables our node to detect all events, while all events can be stored as we avoid the data buffer saturation.

With this chapter we have completed our main scientific contributions. The last chapter of the thesis contains the main conclusions, drawing the road map for the future work.

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CHAPTER 5

Thesis Conclusions and Future Work

"The future is not a gift.
It is an achievement." **Robert F. Kennedy**

Contents

This chapter concludes the PhD thesis that has been focused on the application of energy harvesting techniques in WBANs, considering the union of these two trends (i.e., energy harvesting and WBANs) as a good alternative for creating autonomous and self-sufficient mHealth platforms, comfortable for the patient healthcare. The chapter is divided into two sections: the first one contains the concluding remarks, and the second section discusses some open issues related to the contributions of the thesis.

5.1 Concluding Remarks

The nodes that comprise the WBANs are biomedical devices that perform their tasks on or inside the patient's body. However, since the traditional batteries are a finite source of energy that, in the case of WBANs, is often difficult to recharge or replace, the nodes may permanently lose their functionality when the stored energy is depleted, thus restricting the wireless network autonomy. In this context, our research was aimed at proposing energy-aware solutions, able to support and create autonomous, reliable and energy efficient HEH-WBANs. Our system has been designed to operate in a star topology, where the BNC (e.g., smartphone or PDA) provides medium access through the execution of the HEH-BMAC protocol rules. As a result of the research in this area, two innovative approaches were developed: the HEH-BMAC protocol that is responsible for sharing the medium and solve problems in the WBAN-level, and the PEH-QoS control scheme, which is responsible for solving the problems in the BN-level and improve the QoS provided. These major contributions of the thesis are presented in Chapter 3 and Chapter 4, respectively. The detailed contributions of each chapter are summarized in the following:

Chapter 3: In this chapter, we introduced HEH-BMAC, a hybrid polling MAC protocol designed for HEH-WBANs. The main feature of the HEH-BMAC is the energy-awareness in energy harvesting conditions, allowing each node to access the medium according to its energy level. Depending on the characteristics and needs of each node, the protocol assigns the most appropriate access mechanism (ID-polling mode or PC-access mode) to provide energy-aware priority-based scheduling.

The ID-polling mode allows nodes with high priority to access the medium through a contention-free mechanism, guaranteeing an exclusive period of time to carry out their data transmissions without packet collisions. The ID-polling scheduling decisions are made by the BNC that maintains a table that is dynamically updated depending on the energy level of the nodes. The ID-polling is performed taking into account the data inter-arrival time and the energy harvesting rate, in order to predict the best time interval between successive transmissions. It has been demonstrated, through extensive simulation tests, that this mode significantly improves the normalized throughput of the nodes, while reducing energy consumption. Furthermore, the energy-awareness of ID-polling enables its quick adaptation to changes in the variations of the energy levels of the nodes.

On the other hand, the PC-access mode is used for nodes with normal priority. This method provides the nodes with random access through a threshold value, selected and transmitted by the BNC. This threshold determines the data transmission probability of the active PC-access nodes and is modified (increased or decreased) depending on the nodes' responses. Incorporating this access method to our system allowed us to reduce the number of data packets collisions, improving both the energy efficiency and the normalized throughput, while effectively coping with the energy changes experienced by the nodes due to the energy harvesting process.

HEH-BMAC assigns time periods for both ID-polling and PC-access, through a dynamic scheduling algorithm. The time allocations are performed in a dynamic way, achieving optimum use of the medium. All nodes in the WBAN are energy-aware, i.e., they try to access the medium only if they have data packets to transmit and if they have sufficient energy to successfully complete a transmission sequence. The combination of these two access modes and the dynamic scheduling algorithm, not only improves the normalized throughput and the energy efficiency of the system, but also enables the network adaptation to changes in the number of nodes, the data inter-arrival time and the energy harvesting rate.

Finally to complete our research study, we compared the normalized throughput and energy efficiency of our protocol with the IEEE 802.15.6 standard protocol. In comparison with IEEE 802.15.6, HEH-BMAC achieves a gain up to 20% in energy efficiency and up to 56% in normalized throughput. In addition, the results showed that our protocol can better adapt to a potential increase in the number of nodes in the network, compared to the standard under the same energy harvesting conditions.

Chapter 4: This chapter introduced PEH-QoS, a Power-QoS control scheme for BNs powered by energy harvesting. The energy harvesting process introduces variations in the energy levels of BNs (mainly due to the characteristics and availability of the sources to be harvested) that directly affect their operation, reducing their performance and efficiency on the performed tasks. Small amounts of energy that can be harvested from the human body should be used in an optimal and efficient way to prevent it from being wasted. PEH-QoS efficiently addresses these problems in order to improve the provided QoS.

The obtained results showed that when PEH-QoS is applied, the energy efficiency of the node is increased from 0.78 MB/J up to 39.6 MB/J ($\approx$ 50 times), while reducing the packet loss (up to 0.39%) and the average end-to-end delay (up to 130 ms). Our approach substantially improves the provided QoS, while it also achieves higher detection and storage efficiency, demonstrating that the techniques based on energy-awareness are excellent tool for improve BN's performances.

Concluding, the two proposed schemes, HEH-BMAC and PEH-QoS, have introduced significant improvements in the system performance for both the HEH-WBAN and the BNs.

5.2 Future Work

The main contributions presented in this thesis can be further extended, thus opening new research lines for future investigation, summarized next.

- Introduce accurate channel models in order to evaluate the performance of the proposed schemes under more realistic scenarios. These models should take into account variations, such as motion and other disturbances present not only on the human body but also within it. The effect of the channel conditions on the energy harvesting process and the system performance may provide new interesting challenges to study.

- Employ more complex models to discover or to correlate the performance of our HEH-WBANs in different human scenarios, for example scenarios involving elderly adults, or children, to name a few. Evaluation under these scenarios may reveal whether the behavior of energy harvesting systems is affected by the change of various anatomical or physiological conditions.

- Conduct studies in HEH-WBANs using new technological trends as for example cloud computing, network coding, among others, in order to further increase energy efficiency and QoS. The progress of ICT and biomedical technology is surprising, providing many tools to explore various ways to efficiently solve problems.

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Abstract

The rationale for a telemedicine system is the use of Information and Communications Technology (ICT) for the remote transmission of biomedical data and the remote control of biomedical equipment, in order to improve the provided health service. The integration of Wireless Body Area Networks (WBANs) in telemedicine systems does not only achieve significant improvements in the patient's healthcare, but also enhances their quality of life. However, the potential benefits provided by these networks are limited by the energy constraints imposed when traditional batteries are used as the power source, since the replacement or recharging of these is not always an easy task. To that end, harvesting energy from the human environment can be a promising solution to the aforementioned problems. In this context, it is important to design efficient energy-aware medium access and resource management schemes to exploit the benefits of energy harvesting while guaranteeing the Quality of Service (QoS) in the network.

This dissertation provides a contribution to the design and evaluation of novel solutions focused on energy-aware resource management for WBANs powered by human energy harvesting. In particular, our proposals are oriented to solve the problems caused by the differences in energy levels experienced by nodes due to their power supply by energy harvesting. The main thesis contributions are divided into two parts. The first part presents HEH-BMAC, an energy-aware hybrid-polling Medium Access Control (MAC) protocol for WBANs powered by human energy harvesting. HEH-BMAC is designed to provide medium access taking into account the capabilities of each node with respect to their energy profile. HEH-BMAC combines two types of access mechanisms, i.e., reserved polling access and probabilistic random access, in order to adapt the network operation to the types of human energy harvesting sources. The HEH-BMAC performance in terms of normalized throughput and energy efficiency is assessed by means of extensive computer-based simulations, revealing a good adaptation to potential changes in the energy harvesting rate, packet inter-arrival time and network size. HEH-BMAC has been proven to outperform IEEE 802.15.6 Standard for WBANs in terms of normalized throughput and energy efficiency, as the number of nodes increases under the same conditions of energy harvesting.

The second part of the thesis is dedicated to the design and evaluation of PEH-QoS, a Power-QoS control scheme for body nodes powered by energy harvesting. PEH-QoS is designed to use efficiently the harvested energy and ensure that all transmitted packets are useful in a medical context, hence substantially improving the offered QoS. The obtained results show that this scheme efficiently manages the data queue, thus improving the node operation and optimizing the data transmission, and also provides QoS, while maintaining the node in energy neutral operation state.

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