Design and performances evaluation of a wban monitoring system for mobile people in a cooperative environment

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2016
UB, École Nationale d’Ingénieurs de Sfax
https://repository.ub.edu.bi/handle/123456789/1213

République Tunisienne
Ministère de l'Enseignement Supérieur, de la Recherche Scientifique

Université de Sfax
École Nationale d'Ingénieurs de Sfax

Ecole Doctorale
Sciences et Technologies

Thèse de *DOCTORAT*

Ingénierie des Systèmes Informatiques

N° d'ordre: 690/15

THESE

Présentée à

L'École Nationale d'Ingénieurs de Sfax

En vue de l'obtention du

DOCTORAT

Dans la discipline
Ingénierie des Systèmes Informatiques

Par

Audace MANIRABONA

(Mastère en Informatique et multimédia)

DESIGN AND PERFORMANCES EVALUATION OF A WBAN MONITORING SYSTEM FOR MOBILE PEOPLE IN A COOPERATIVE ENVIRONMENT

Soutenu le 20 Avril 2016, devant le jury composé de :

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Republic of Tunisia
Ministry of High Education and Scientific Research

University of Sfax
National School of Engineers of Sfax

Doctoral School
Sciences and Technologies

DOCTORAL Thesis

Computer Systems Engineering
Sequence No: 690/15

THESIS

Presented at

National School of Engineers of Sfax

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Defended on 20 April 2016, in presence a board including:

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Résumé

En général, les gens vivent en communauté et travaillent souvent en groupe et les WBANs doivent s'adapter à ce mode de vie pour l'améliorer. Les sujets WBANs étant des personnes, leurs interactions peuvent améliorer la qualité de service offert et la cooperation rend ces interactions possibles par la redondance de l'information, la couverture réseau, etc. Comme les sujets WBANs sont en libre movement, la localisation devient important pour la détection de chute, les urgences, l'orientation, le secourisme, etc. L'objectif de cette thèse est d'offrir à l'utilisateur un système de qualité, qui guarantit la qualité des liens intra et inter WBANs, le moins consommateur d'energie possible et qui s'adapte aux éventuels changements de l'environnement. Pour satisfaire ces exigences, des mécanismes de coopération ont été choisis et la localisation a été étudiée suite à la mobilité.

A part l'étude sur la technologie WBAN, ses applications et services ainsi que les systèmes de surveillance et projets y relatifs, cette thèse englobe trois principales parties:
La première propose une architecture à 4 niveaux pour les WBAN-MS afin de leur permettre de mieux supporter la mobilité. C'est une amélioration d'un WABN-MS 3 niveaux qui est plus utilisé pour les systèmes de santé. Comme il n'ya pas jusque là des mécanismes proposés pour gérer les traffics sortant du WBAN, il est ici proposé d'implémenter au niveau du coordinateur une technique d'ordonnancement, Priority Weighted Round Robin, pour des traffics sensibles au retard.

La seconde traite la coopération intra et inter-WBANs. A cette fin, un mécanisme de coopération MAC intra WBAN, Decode and Merge, a été proposé et un NetBAN qui est un réseau de WBANs a été conçu pour la coopération inter WBANs avec un protocole de routage pour optimiser la consommation d'énergie.

La troisième et la dernière traite le problème de localisation dans les WBANs. Ainsi, après un état de l'art sur les mécanismes de localisation, un mécanisme coopératif basé sur la détection de posture a été proposé suivi d'un mécanisme de localisation indoor, kridged fingerprinting ainsi qu'une méthode de localisation coopérative outdoor qui utilise le filtre de kalman sur les données récoltées dans la nature.

Enfin, des perspectives offertes par cette thèse sont alors données.

Abstract

People normally live in community and often work in group, and the WBAN applications intends to reinforce this way of living. WBAN subjects as persons should interact cooperatively each other by providing information redundancy, better coverage, etc. and so improve the WBAN's quality of service. As WBAN subjects are likely to move, the localization service is important for emergency, guidance, securing etc. The main goal of this thesis is to offer to a user a system with a high quality, that should ensure the quality of intra/inter-WBANs transmissions, be less energy consumer and adaptable to changes of environment. To fulfill these requirements, cooperation mechanisms are a chosen as solution and localization service is studied due to mobility effects.

Apart from a survey on WBAN technology, applications and services, and WBAN based monitoring systems projects, this thesis encompasses three main parts:
The first part proposes a 4-tiers architecture for WBAN-MS to sustain mobility. It is a really improvement of a 3-tiers architecture mostly used for healthcare monitoring systems. Noticing that there is so far no mechanisms proposed for traffics going out of WBAN, it is proposed to implement at the coordinator a Priority Weighted Round Robin (PWRR) scheduling technique to bridge sensitive data from WBAN to peer-networks.

The second part deals with the intra-WBAN and inter-WBANs cooperation. For this end, a Decode and Merge cooperative MAC mechanism is defined for intra WBAN and a NetBAN, a concept of network of BANs, is designed for inter-WBANs cooperation with a routing protocol to optimize energy consumption.

The third part undergoes the localization problem in WBAN. Thus, from a survey on WBAN localization mechanisms, a comparative study was done fallowed by a cooperative technique based on body posture detection is given. It is also proposed a kridged fingerprinting mechanism for WBAN indoor localization and a localization technique based on Kalman filter and kriging using environmental data for WBAN outdoor localization.

Finally, new horizons are described as open issues.

Acknowledgements

First and foremost, I want to thank my thesis director and supervisor Lamia CHAARI FOURATI. It has been an honor for me to be among her first Ph.D. students. I appreciate all her contributions in time and ideas.

I gratefully thank Saadi BOUDJIT for his co-supervisory and financially support especially for my stay at L2TI lab. I am very grateful for that and also thank all the L2TI team members for their attitude of working in interdisciplinary and multi-cultural environment.

My acknowledgments also go to the ENIS staff especially to Prof Mohamed ABID (the former Director of the EDST doctoral school) for his fruitful and kind interventions in many of administrative processes. I also thank the Head and all the members of the LETI lab for their direct or indirect support in working together.

I particularly think of Noureddine BOUDRIGA and Joël RODRIGUES for their precious time to review this manuscript and provide helpful comments.

I gratefully acknowledge the funding sources that made this Ph.D. possible. It is the case of the BURUNDI government who provided a financial support, as small as it is. This thesis would not be done without its funds.

I can not forget the support of any kind from my family especially my grand brother Emile NIYONDIKO. I also think of Hassan KIBEYA with whom I shared many troubles relating to this thesis.

Lastly, I would like to thank all my friends, acquaintances and encounters for any conscious or unconscious contribution.

Thank you all.

Dedication

To

my family,

my home country Burundi,

all my friends, . . .

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Abbreviations

AAP	**A**tmospheric **A**ir **P**ressure
A-GPS	**A**ssisted-**GPS**
ALE	**A**verage **L**ocalization **E**rror
AoA	**A**ngle of **A**rrival
AODV	**A**d-hoc **O**nDemand **D**istance **V**ector
AP	**A**ccess **P**oint
APIT	**A**pproximate **P**oint **I**n **T**riangle
BFA	**B**acterial **F**oraging **A**lgorithm
BTS	**B**ase **T**ransceiver **S**tation
CCA	**C**lear **C**hannel **A**ssessment
CFP	**C**ontention **F**ree **P**eriod
CSMA-CA	**C**arrier **S**ense **M**ultiple **A**ccess with **C**ollision **A**voidance
DE	**D**ifferential **E**volution
DSR	**D**ynamic **S**ource **R**outing
ECG	electrocardiogram
EEG	electroencephalogram
EE-OLSR	**E**nergy **E**fficient **O**ptimized **L**ink **S**tate **R**outing
EFC	**E**lectrostatic **F**ield **C**ommunication
EKF	**E**xtended **K**alman **F**ilter
EMG	electromyogram
FCS	**F**rame **C**heck **S**equence

FE	**F**unctional **E**nergy
FIFO	**F**irst **I**n **F**irst **O**ut
FOV	**F**itness **O**ptimal **V**alue
GA	**G**enetic **A**lgorithm
GME	**G**eometric **M**ean **E**rror
GPS	**G**lobal **P**ositioning **S**ystem
GRA	**G**ray **R**elational **A**nalysis
GSM	**G**lobal **S**ystem **M**obile
GTS	**G**uaranteed **T**ime **S**lot
HBC	**H**uman **B**ody **C**ommunication
HHO	**H**orizontal **H**andoff
HMM	**H**idden **M**arkov **M**odel
ISM	**I**ndustrial **S**cientific **M**edical
KF	**K**alman **F**ilter
KKF	**K**riged **K**alman **F**ilter
LAI	**L**ocal **A**rea **I**dentifier
LETI	**L**aboratory of **E**lectronics and **I**nformation **T**echnologies
LQI	**L**ink **Q**uality **I**ndicator
LQI	**L**ink **Q**uality **I**ndicator
LS	**L**east **S**quare
MAC	**M**edium **A**ccess **C**ontrol
MANET	**M**obile **A**d-Hoc **NET**work
MDS	**M**ultidimensional **S**caling
MEN	**M**erged **F**rames **N**umber
MICS	**M**edical **I**mplant **C**ommunication **S**ervice
MLE	**M**aximum **L**ikelihood **E**stimation
MMBCR	**M**inimum **Ma**ximum **B**attery **C**ost **R**outing
MPRs	**M**ultipoint **R**elays
MS	**M**obile **S**tation

NetBAN	**N**etwork of **BAN**s
NLoS	**N**on-**L**ines **of** **S**ight
OLSR	**O**ptimized **L**ink **S**tate **R**outing
PEER	**P**rogressive **E**nergy **E**fficient **R**outing
PF	**P**article **F**ilter
PHR	**P**HY layer **H**eader
POS	**P**ersonal **O**perating **S**pace
PPDU	**P**HY layer **P**rotocol **D**ata **U**nit
PS	**P**riority **S**cheduling
PSDU	**P**hysical layer **S**ervice **D**ata **U**nit
PSO	**P**article **S**warm **O**ptimization
PWRR	**P**riority **W**eighted **R**ound **R**obin
QoS	**Q**uality **of** **S**ervice
RE	**R**esidual **E**nergy
RLT	**R**emaining **L**ifetime
RMS	**R**emote **M**onitoring **S**ystem
RMSE	**R**oot **M**ean **S**quare **E**rror
ROCRSSI	**R**ing **O**verlapping based on **C**omparison **RSSI**
RSSI	**R**eceived **S**ignal **S**trength **I**ndicator
SAR	**S**pecific **A**bsorption **R**ate
SHR	**S**ynchronization **H**eader
SLAM	**S**imultaneous **L**ocalization **A**nd **M**apping
SMS	**S**hort **M**essage **S**ervice
SNR	**S**ignal to **N**oise
TC	**T**opology **C**ontrol
TDoA	**T**ime **D**ifference of **A**rrival
ToA	**T**ime of **A**rrival
TW-ToF	**T**wo-**W**ay **T**ime of **F**light
UKF	**U**nscented **K**alman **F**ilter

UP	**U**ser **P**riority
UWB	**U**ltra **W**ideband
VHO	**V**ertical **H**and- **o**ff
WBAN	**W**ireless **B**ody **A**rea **N**etwork
WLAN	**W**ireless **L**ocal **A**rea **N**etworks
WMTS	**W**ireless **M**edical **T**elemetry **S**ystem
WSN	**W**ireless **S**ensor **N**etwork

Chapter 1

Introduction

1.1 Thesis framework description

This thesis project falls within the framework of the promotion of Wireless Body Area Network (WBAN) applications and services, and related systems as well as helping the IEEE 802.15.6 standard reach its matureness. In fact, the rise of information and communication technologies and the progress achieved in telecommunications have brought out other types of communicating tools and objects and also changed the way people live. The very illustrative example is a mobile phone that is now used by more than three quarters of world's population [1], thus changing completely the way people communicate and interact each other. Here are some other examples among many others. Homes are experiencing spectacular improvement by the integrated smart devices and furniture, that offer comfort and other services such as communication and security. Hospitals are using sophisticated tools to treat diseases more efficiently and assist patients properly. Industries use these technologies to produce more in small time with minimum number of persons. Armies also use these technologies to detect and defend against enemies. More specifically, with the technology revolution on image and signal processing there has been a growth interest in systems for security and surveillance. It is the case of home monitoring with camera, industry production and terrain surveillance with sensors, etc. In general, the devices used for these systems are static and placed in a target zone or on a unity to monitor. Recently, the interest of using new technology of information to improve human life has increased leading to utilizing sensors on/in human body to monitor physiological activities. In 2012, a specific standard [2] to these kinds of communication has been released with WBAN as a common use name.

The WBAN is an emerging technology likely to respond to new markets expectations in varied fields such as security, emergency, health, gaming, smart clothing, etc. As a WBAN is a set of sensor nodes and actuators with BAN coordinator playing the role of gateway, many wireless communication technologies can be used to link the WBAN at a remote monitoring station to form a monitoring system. In this context, new forms of wireless communication, named "cooperative" are candidate to be employed and involved in at different levels of interaction i.e between nodes within the same WBAN and /or between different WBANs as WBAN subjects in a group.

The monitoring system based on WBAN is however complicated in design given that the user (a WBAN subject) is likely to sometimes move and thus creating the need of tracking and localization. The signal passing through the human tissue imposes many constraints of transmission quality and energy optimization especially for implants. In addition, the WBAN must be linked to a processing station via an other transmission technology forming a heterogeneous network with other constraints relating to connection, data convey and scheduling.

1.2 Motivations

People normally live in community and often work in group with free mobility, and the WBAN applications do not change this way of living but reinforce it and try to make it easier. WBAN subjects as persons should interact and so improve the WBAN's quality of service. The cooperation makes it possible to provide an information redundancy, better coverage, and increased accuracy of location service as we know the importance of knowing the subject's location in some types of application. So it seems now appropriate to consider jointly cooperative functions of wireless communication and radio location in mobile personal networking groups. Typically, distance measurements can thus be made between mobile, in order to position the nodes of a network of ad hoc sensors or track mobile users of heterogeneous access networks. The knowledge of the users preferences (in terms of distance or location) would be interesting for innovative applications based on WBANs (coordinated group of browsing, capturing the collective gesture for sport or game, nomadic geo-referenced social networks ...).

The [2] standard is very recent and not mature enough to fulfill application requirements. Therefore the systems based on it need much improvement. Furthermore, there are so far no devices working on this standard to help systems building and applications development. It is then important to help in making it more intelligible to the public and highlight the potentialities of the applications and systems based on it. Cooperation and localization mechanisms are not yet defined specifically in the field of WBAN.

1.3 Goals

As the title implies, the WBAN subject is likely to move and this mobility implies the need of localization and tracking; the WBAN Monitoring System comprises communication based on IEEE 802.15.6 standard on the one hand, and an other communication technology on the other hand, what creates a heterogeneous environment and allowing WBAN subjects grouping and cooperating so as to increase performances. The main goal of this thesis is to offer to a user as a WBAN subject a system with a high quality of service. Therefore the system should ensure communication links for intra/inter-WBANs with less data errors. It should also be less energy consumer, adaptable to changes of environment. To fulfill these requirements, cooperation mechanisms are a chosen solution. For mobility, localization algorithms and mechanisms shall be defined.

For this end, this thesis mainly focuses on the architecture of a monitoring system for mobile persons with cooperation and localization service. As part of the work of this thesis, we study and develop innovative features for communication and radio location built on cooperative radio links inter / intra-WBANs to ensure QoS on criteria of energy consumption optimization and delivery and latency rate. On one hand, this is to provide solutions to precisely position the nodes scattered in mobile WBAN groups, and the networks themselves. Secondly, we seek to ensure proper management of the quality of service (QoS) communication links (at the protocol level, mainly), while keeping compatibility with standard IEEE 802.15.6. We will evaluate the impact on QoS of WBAN when cooperative mechanisms are defined.

1.4 Contributions

Throughout this thesis, several technical contributions have been made and set in three main groups:

1. *System design and mobility:*
   • This thesis presents a survey on WBAN technology, applications and services, and WBAN based monitoring systems projects;
   • It proposes a 4-tiers architecture for WBAN-MS as an improvement of 3-tiers architecture to sustain mobility and much facilitate the system design;
   • A Priority Weighted Round Robin (PWRR) scheduling technique is proposed to bridge sensitive data from WBAN to peer-networks;

2. *Cooperation:*
   - For intra WBAN communication, a Decode and Merge cooperative MAC mechanism is defined;
   - For inter-WBANs cooperation, a network of BANs (NetBAN) is designed with a routing protocol for energy optimization;
3. *Localization:*
   - A survey on likely techniques for WBAN localization is presented with a comparative study;
   - A cooperative mechanism based on posture detection is proposed to improve the cooperative trilateration;
   - A kridged fingerprinting mechanism for WBAN indoor localization is proposed;
   - A technique for WBAN outdoor localization based on Kalman filter and kriging using environmental data is also defined.

1.5 Thesis outline

The rest of this thesis is organized as follows: Chap. 2 presents an overview on WBAN technology. It focuses on different related standards, devices and applications and services. This chapter helps well understand the next chapters as they stand on features described in it. Chap. 3 relies on the WBAN technology presented in Chap. 2 especially IEEE 802.15.6 to design a WBAN-MS. It defines a new architecture based on the existing ones, defines the way tiers should interact and proposes a data bridging structure. In short, this chapter sets up functional features of a WBAN-MS. With the needs come out in Chap. 3, Chap. 4 focuses on cooperation between sensors within a WBAN and cooperation between WBANs themselves in group. The major concern here is to minimize energy consumption, to offer an improved QoS especially for time-sensitive and loss-sensitive data. Therefore some techniques to decode and merge data and energy saver routing protocols are defined. Chap. 5 forth deals with the localization mechanisms for WBAN subject in indoor and outdoor environment to respond to the need of mobility and rescue. Chap. 6 finally concludes this manuscript on a thesis summary, some open issues and perspectives offered by this work.

Chapter 2

Wireless Body Area Network

2.1 Introduction

A WBAN is a collection of miniaturized wireless sensor nodes deployed on the body or implanted in the body to supervise the human body functions and its environment and a BAN coordinator mostly playing the role of gateway. These nodes include sensors that sense physiological parameters values and actuators that execute commands such as injection for diabetes patients. They communicate then their sensed data to the BAN coordinator and this latter can convey the data to a remote station via so called peer networks (WLAN, WIMAX, LTE, UMTS, etc.) for processing and analysis. In such a world, networking and computing technologies coexist with people in a ubiquitous and pervasive way. WBANs meet many needs for the market in a variety of innovating and interesting applications, it is a promising technology to revolutionize many domains such as ubiquitous healthcare applications [3, 4], military and aerospace [5], safety, interactive gaming, entertainment, animal managements and urgency [6]. Furthermore, nodes for medical applications can be wearable [7] and/or implanted [8]. Wearable WBANs are considered for both medical and non-medical applications; however implanted WBANs are mainly considered for medical and healthcare applications. Wearable devices are those that can be used on a human body surface. The implantable medical devices are those inserted inside human body. Non-medical application service includes real-time audio/video streaming, data wave, stream delivery, etc.

A WBAN [2] is a wireless sensor network (WSN) with some particularities such as a small number of sensor nodes that are deployed around or on the body or else implanted in the body and a small transmission range of sensor nodes as shown in Figure 2.1. As the WBAN is designed to monitor a person equipped with it by a remote station, its usefulness is getting increasingly important due to its function of sensing vital parameters to ensure human well-being while being more costless. Then, the WBAN subject can be still going about his activities in his environment even in group or alone.

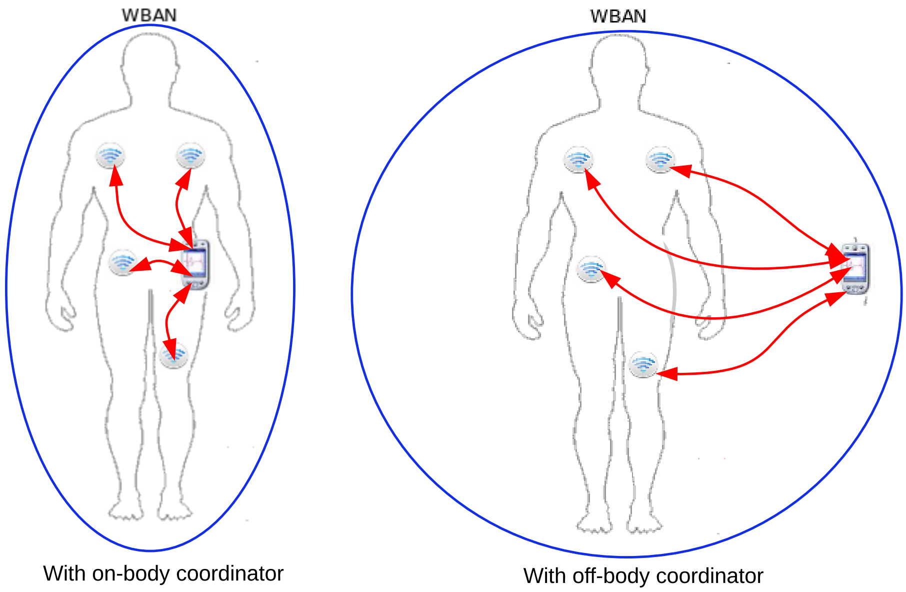

FIGURE 2.1: A WBAN architecture

The main key applications include first the healthcare by supplying assistance to elderly population or patients at hospital or at home [7, 9]. They include secondly the entertainment where people, for instance, can play game in group or exchange some data such as visit cards though handshake [10]. They comprise also the sport where athletes or other sportsmen in workout can be monitored to increase their performance [10]. Finally, there is military area where soldiers can be assisted and share data like in sport area [7].

2.2 WBAN standards overview

The IEEE 802.15 standards family defines the PHY and MAC specifications of communications for Wireless Personal Area Networks (WPANs). The WBAN standard is a particular case of WPAN specifically defined with low rate transmissions and dedicated to human body environments. Two standards are studied: IEEE 802.15.6 is fully dedicated for WBANs and IEEE 802.15.4 is suggested by authors to be considered as WBAN standard due to its characteristics.

2.2.1 IEEE 802.15.6

This standard [2] is for short-range (3m) and wireless communications around or inside a human body (but not limited to humans) what makes it a dedicated standard for WBANs. It uses ISM (Industrial, Scientific and Medical) bands and other bands as well as low radio frequency emission in compliance with healthcare requirements and communication regulatory authorities. It also defines mechanisms to help transmissions resist to interferences what gives a better coexistence with other wireless networks. It allows devices to operate on very low transmit power for safety to minimize the specific absorption rate (SAR) into the body and increase the battery life. It supports quality of service (QoS), for example, to provide for emergency messaging. Since some communications can carry sensitive information, it also provides for strong security by authentication, encryption, and decryption mechanisms using strong security keys system.

2.2.1.1 PHY Layer Specifications

The 802.15.6 standard defines three physical layers: Narrowband (NB), Ultra Wideband (UWB) and Human Body Communications (HBC). The main features of the different PHY layers are the following:

1) Narrowband PHY: The NB PHY is an optional physical layer, which is responsible for the following tasks:

- Activation and deactivation of the radio transceiver
- Clear channel assessment (CCA)
- Data transmission and reception.

This PHY layer supports different frequency bands: 402-405 MHz, 420-450 MHz, 863-870 MHz, 902-928 MHz, 950-958 MHz, 2360 to 2400 MHz, and 2400-2483.5 MHz.

2) Ultra Wideband PHY: The Ultra Wideband (UWB) PHY is used to provide a data interface to the MAC layer under the control of Physical Layer Convergence Protocol (PLCP). Its main functions are:

- Activation and deactivation of the radio transceiver.
- The PLCP constructs the PHY layer protocol data unit (PPDU) by concatenating the synchronization header (SHR), physical layer header (PHR) and physical layer service data unit (PSDU), respectively.
- It may provide CCA indication to the MAC.

The UWB PHY operates into two bands: Low Band and High Band. Each band is divided into channels which each one is characterized by a bandwidth of 499.2 MHz. The Low Band includes three channels numbered from 1 to 3 where number 2 is mandatory and centered at a frequency of 3993.6 MHz. The High Band comprises seven channels (4-11) where number 7 is mandatory and centered at a frequency of 7987.2 MHz. Other channels are optional what means that a UWB device has to support at least a mandatory channel.

3) Human Body Communications PHY: Human Body Communication (HBC) PHY supports two modes of operation: default mode and high Quality of Service (QoS) mode, depending on the application. HBC PHY operates in two frequency bands centered 16

MHz and 27 MHz with the bandwidth of 4 MHz. The main operation of HBC is to provide Electrostatic Field Communication (EFC) specification for the whole WBAN. According to the standard, a maximum of 64 nodes may be connected to a hub or LDPU simultaneously. Also, it is mentioned that a WBAN operating according to the IEEE 802.15.6 communication guidelines, can operate in one of the three access modes.

2.2.1.2 MAC Layer Specifications

Regarding the MAC layer specifications, let us focus on the way the nodes access to medium, the network topology and the MAC frame structure. In fact, a WBAN is composed of one and only one hub as a coordinator and up to 64 nodes deployed in one-hop star topology or in two-hop extended topology. Exchanged frames over the network are classified into three categories: Management, Control and Data frames. Management type frames include beacon, Security association and Disassociation, Connection Request and Assignment, Pairwise and Group Temporal Key, Disconnection and Command. Control type frames are all kind of acknowledgment and polling message and wakeup command. Finally, Data type frames are sensed data or emergency.

The medium access is controlled according to user priorities defined as follows: Background (UP0), Best effort (UP1), Excellent effort (UP2), Controlled load (UP3), Video (UP4), Voice (UP5), Media data or network control (UP6) and Emergency or medical event report (UP7). The standard supports three communication modes. The first is beacon mode with superframe boundaries where the hub and nodes have to set a time reference base whose time axis is divided by the hub into beacon periods (superframes). A superframe is equally divided into allocation slots numbered from 0 up to 255 and includes Exclusive Access Phases (EAP1 and EAP2), Random Access Phases (RAP1 and RAP2), type-I/II, Access Phases and Contention Access Phase (CAP) as illustrated in Figure 2.2.

Allocation slots may only be contended allocations in EAP1, EAP2, RAP1, RAP2 and CAP and obtaining the contended allocation access methods CSMA/CA and Slotted

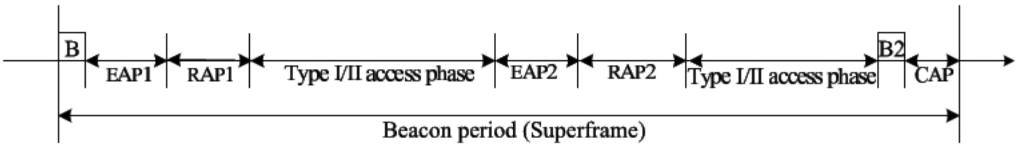

FIGURE 2.2: Layout of access phases in a beacon period (superframe) for beacon mode

Aloha are used. User priorities and access methods for contended allocations are mapped following the minimum and maximum contention windows, (CWmin, CWmax): (16,64), (16,32), (8,32), (8,16), (4,16), (4,8), (2,8), and (1,4), respectively for CSMA/CA and maximum and minimum contention probability (CPmax, CPmin): (1/8,1/16), (1/8,3/32), (1/4,3/32), (1/4,1/8), (3/8,1/8), (3/8,3/16), (1/2,3/16), (1,1/4) respectively. The second is non-beacon mode with superframe boundaries where the hub uses superframe with managed access phase (MAP) and does not send beacon to let nodes upload their data . The last is non-beacon mode without boundaries where the hub provides bilink allocations and nodes can use EAP1 or RAP1 with CSMA/CA as access mode. The EAPs are only accessed for transmitting the emergency frames (UP7) and the RAPs are used by other frames (UP0-UP6) to access the medium.

2.2.2 IEEE 802.15.4

This standard [11] defines the physical layer (PHY) and medium access control (MAC) sublayer specifications for moving and stationary devices operating in low-data-rate wireless connectivity with a very limited battery consumption (multi-month to multi-year battery life)and very low complexity requirements. The personal operating space (POS) does not typically exceed 10 m. The devices are simply deployed in a one-hop star network topology or when lines of communication exceed 10 meters, the network is self-configured into multi-hop network. Two addressing modes are defined: a device can use either a 64-bit IEEE address or a 16-bit short address., and a single 802.15.4 network can accommodate up to 64k (2^{16}) devices. The standard defines 27 channels numbered 0 to 26 set across three frequency bands: 16 channels in the 2.4GHz ISM band, 10 channels in the 915 MHz I and one channel in the 868 MHz band. Wireless links under 802.15.4 can operate in three license free industrial scientific medical (ISM) frequency bands. These accommodate over air data rates of 250 kb/sec (or expressed in symbols, 62.5 ksym/sec) in the 2.4 GHz band, 40 kb/sec (40 ksym/sec) in the 915 MHz band, and 20 kb/sec (20 ksym/sec) in the 868 MHz.

2.2.2.1 PHY Layer Specifications

The standard (IEEE Std 802.15.4, 2006) defines four PHYs as follows:
• An 868/915 MHz direct sequence spread spectrum (DSSS) PHY using binary phase-shift keying (BPSK) modulation
• An 868/915 MHz DSSS PHY using offset quadrature phase-shift keying (O-QPSK) Modulation
• An 868/915 MHz parallel sequence spread spectrum (PSSS) PHY using BPSK and amplitude shift keying (ASK) modulation
• An 2450 MHz DSSS PHY employing O-QPSK modulation

The PHY is responsible for:
• activation and deactivation of the radio transceiver what turns it into one of the three states: transmitting, receiving or sleeping;
• Energy detection (ED) within the current channel to estimate the received signal power;
• Link quality indicator (LQI) for received packets which is performed using ED or signal to noise (SNR) ratio for each received packet;
• Clear channel assessment (CCA) for carrier sense multiple access with collision avoidance (CSMA-CA);
• Channel frequency selection that intends to select one channel from 27 channels to respond to the MAC request;
• Data transmission and reception that permits sending and receiving signals.

2.2.2.2 MAC Layer Specifications

The MAC sublayer is responsible for the following tasks:

• Generating network beacons if the device is a coordinator: A coordinator can optionally decide to work in a beacon enabled mode by bounding its channel time using a superframe structure whose bounds are made by a beacon frame transmission. To synchronize the attached devices, a coordinator transmits the beacons periodically. A superframe can have an active portion and an inactive portion. The coordinator may enter a low-power (sleep) mode during the inactive portion

• Synchronizing to the beacons: When the coordinator is working in a beacon enabled mode, a device attached to it can track the beacons to synchronize with the coordinator.

• Supporting personal area network (PAN) association and disassociation: 802.15.4 embeds association and disassociation functions in its MAC sublayer for the network self-configuration: to enable the star topology to be setup automatically and the creation of a peer-to-peer network when the line of communication exceeds the coverage range.

• Employing the carrier sense multiple access with collision avoidance (CSMA-CA) mechanism for channel access: 802.15.4 uses CSMA-CA mechanism for channel access.

• Handling and maintaining the guaranteed time slot (GTS) mechanism: When working in a beacon enabled mode, a coordinator can allocate portions of the active superframe to a device. These portions are called GTSs, and comprise the contention free period (CFP) of the superframe.

• Providing a reliable link between two peer MAC entities: The MAC sublayer employs various mechanisms to enhance the reliability of the link between two peers, among them are the frame acknowledgment and retransmission, data verification by using a 16-bit CRC field.

• Supporting device security: For incoming and outgoing frames the security is assured by offering data confidentiality, data authenticity and replay protection services.

2.3 Sensors

A WBAN can include a large number of physiological sensors, which can be used as a bridge between the human body and electronic systems, in order to generate all the information regarding the human under observation and control. Nowadays, many kinds of sensors and actuators are already commercially available such as:

• *ECG (electrocardiogram)* sensor used for monitoring heart activity. In order to obtain an ECG signal, several electrodes are attached at specific sites on the skin (e.g., arms, and chest), and the potential differences between these electrodes are measured;

• *EEG (electroencephalogram)* sensor used for monitoring brain electrical activity by attaching small electrodes to the human's scalp at multiple locations. Then information of the brain's electrical activities sensed by the electrodes forwarded to an amplifier for producing a pattern of tracings.

• *EMG (electromyogram)* sensor used for monitoring muscle activity during contractions or at rest. Nerve conduction studies are often done together while measuring the electrical activity in muscles, since nerves control the muscles in the body by electrical signals (impulses), and these impulses make the muscles react in specific ways. Nerve and muscle disorders cause the muscles to react in abnormal ways.

• *Glucose sensor* is an optical meter (glucometer) which used to analyze the blood sample and gives a numerical glucose reading.

• *The blood pressure sensor* designed to measure systolic and diastolic blood pressure.

• *Gyroscope and accelerometer* for monitoring trunk position and movement: the accelerometer is used to recognize and monitor body posture, such as sitting, kneeling, crawling, laying, standing, walking and running. The gyroscope used for measuring or maintaining orientation, based on the principle of conservation of angular momentum. Gyroscopes can be used with accelerometers for physical movement monitoring.

• *Breathing sensor* for monitoring respiration;

• *Infrared or diode-based sensors* for monitoring temperature;

• *Pulse oximeter* used for cardio-respiratory monitoring. It measures oxygen saturation;

• *Humidity and temperature sensors* used for measuring the temperature of the human body and/or the humidity of the immediate environment around a person. An alarm signal can be issued if a certain amount of changes is measured;

• *Gas sensor* used to monitor oxygen concentration during human respiration. In table 2.1, we have specified sensors and actuators that could be used for Wearable BAN and those that could be used for Implanted BAN. Table 2.2 highlights WBAN services and applications.

• *Implantable Neural Stimulator* that send electrical impulses into the brain or spinal cord to treat for instance Parkinson's disease, intractable epilepsy and chronic pain. Authors in [12] gave an example of such a device.

Table 2.1: Sensors and actuators for wearable and implanted BANs

Category	**Sensors and actuators**
Wearable BAN [7, 13, 14]	EEG, ECG, EMG, Vital signals monitoring, temperature, respiration monitor, SpO2, Blood pressure monitor, pH monitor, Glucose sensor, Hearing etc. A deep review related to smart wearable systems providing a survey of recent implementations of wearable health-care systems was conducted in [14]
Implanted BAN [8]	Glucose sensor, Cardiac arrhythmia monitor/recorder, Brain liquid pressure sensor, Endoscope capsule, Drug delivery capsule, Deep brain stimulator (e.g. Epilepsy, Parkinson's therapy), Cortical stimulator, Visual neuro-stimulator, Audio neuro-stimulator, Brain computer interface

2.4 WBAN Applications and Services

WBAN applications and services can be considered according to the sensor types (wearable and implanted sensors), functionality (medical and non-medical) and frequency band categorized into MICS (Medical Implant Communication Service), ISM (Industrial Scientific Medical) and WMTS(Wireless Medical Telemetry System). As described in previous sections, medical applications cover all wearable and implanted sensors while non-medical include only wearable sensors. The main application domains of WBANs are Healthcare, Sport, Entertainment and Military [15].

Healthcare: These applications are to be revolutionary in terms of assistance they can give to elderly population, to patients at the hospital and to home living patients. Some diseases have been considered for these WBAN cares: Cardio diseases, Cancer, Glucose, Asthma, Medical accidents, Alzheimer, etc. Related services are Caregiver, Physician, Emergency, Clinic [16]. Discouraging bad motional habits and behaviors to insure good health are also involved.

Sport: WBAN applications for sport are designed to monitor body efforts provided during physical exercises. These applications can help to assist athletics and other sportsmen to increase their performance. For instance, Figure 2.3 [17] illustrates the variation of muscle efforts (EMG) with different thresholds. Authors in [18] developed a quantitative WBAN model for golf swing training to train and evaluate the quality of movements.

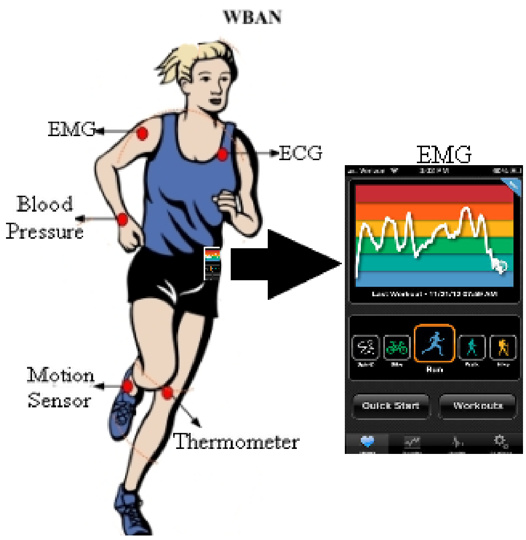

FIGURE 2.3: WBAN application for Sport

Entertainment: When people play desktop games, listen to music, command remote devices, etc., WBAN entertainment applications take their usefulness. It is the case when one can display the content of his mobile device on the home HD screen or play music from his MP3 device in the home music player. We can also take the example of fighting or driving game where a player can perform actual actions trough his body and these actions interact automatically with the game. This makes the game more enjoyable. Furthermore, in social networking, people could exchange visit cards through handshake, data stored in WBAN could be used in shopping and banking for authentication more secured by physiological data [16]. Other related applications could include monitoring forgotten things.

Military: Applications related to military environment are for surveillance, battlefield communication and survivability. Soldiers on battlefield [19] would benefit from this WBAN applications good assistance: they can be located, guided and secured; those with low awakening or tired could be replaced. However, a secure channel must be allocated for communication to prevent ambushes [20].

So far, worldwide WBAN projects have been conducted to design and implement various WBAN applications. Developed systems are for example CodeBlue, MobHealth, Artificial Retina, eWatch, UbiMon, Hip guard system [15]. Table 2.2 shows some WBAN applications with related services.

Table 2.2: WBANs services and applications

Category	**Services**
Continuous Health Monitoring [13]	Using body sensor networks for monitoring physiological measures [21]
Disability assistance	Disability assistance Muscle tension monitor, Muscle tension stimulation, Weighing scale, Fall detection...
Continuous Behavioral Monitoring [22]	Using sensor for monitoring human behaviors in order to motivate them to lead a healthier life style (Eating,Sleeping, Sitting, etc.)
Remote control of medical devices	Pacemaker, Implantable cardio-verterdefibrallitor ICD, Implanted actuator, Insulin pump, Hearing aid, Retina implants....
Human performance management [22]	Assessing emergency service personnel performance, Assessing soldier fatigue and battle readiness...
Therapy and Rehabilitation [23, 24]	Supporting people who require rehabilitation services with remote and autonomous system
Assisted Living [21]	Creating smart environments for supporting patients and elderly during their daily activities

2.5 WBAN challenges and requirements

There are still many tasks to do to see the WBAN fully operating. As this thesis intends to promote the WBAN based systems and related applications, we only focus on energy and mobility implying localization. However many other challenges are out of the thesis scope and need deep study.

2.5.1 Routing

WBAN standards define PHY and MAC layers features but routing mechanisms are not defined. However, they are needed especially when network topology changes. Crosby et al.[25] talk about network partitioning resulting in postural mobility of the body, high propagation loss through human body, low transmission power of WBAN, that makes routing needed. Some authors have dealt with the definition of routing algorithms and protocols with different purposes: optimize energy consumption and so increase network lifetime [26, 27], deliver data in consideration of mobility [28], etc. Authors in [29] classified routing strategies into five categories: thermal-aware routing protocols, cluster-based routing protocols, cross layer-based routing protocols, QoS-used earlier-aware routing protocols, and delay-tolerant-aware routing protocols. Javed et al. [30] adopted the same classification but with other formulation and more details: QoS-aware, temperature-aware , cluster-based, postural-movement-based and cross-layered routing protocols.

2.5.2 Security

The WBAN and supporting infrastructure must implement security operations that guarantee the security, data integrity, privacy and confidentiality of the patients' medical records. The following security requirements should be attained [25]:
Authentication: This is necessary to enable the WBAN to validate network nodes and

thus prevent network compromise and/or node impersonation.

Data Integrity: this is needed to prevent the altering of data traversing the communication paths between nodes, and to prevent replay attacks.

Confidentiality: the network should be able to guarantee the secrecy of message exchange among nodes.

Availability: Since this network carries highly sensitive, important and potentially life-saving information, it is important that the network resources are always available.

Privacy: The patients' data should not be disclosed to unauthorized users. Medical information is one of the most sensitive forms of personal data. The system must employ mechanisms able to adequately address current and potential laws in the future, governing the privacy of medical data.

2.5.3 QoS requirements

The QoS is a wide used expression to say how great a service shall satisfy the users. In the case of WBAN we have many requirements such as maximum throughput, minimum delay, buffer size limitation, removal of redundancy, and maximum network lifetime [31]. Table 2.3 reports some medical application requirements.

TABLE 2.3: Functional requirements for WBAN application

Application	**Data rate**	**Bandwidth**	**Latency**	**Accuracy**	**Reliability**
ECG (12 leads)	144 Kbps	100–1,000 Hz	< 250 ms	12 bits	10^{-10}
EMG	320 Kbps	0–10,000Hz	$< 250ms$	16 bits	10^{-10}
EEG (12 leads)	43.2 Kbps	0–150 Hz	$< 250ms$	12 bits	10^{-10}
Blood saturation	16 bps	0–1Hz	—	8 bits	10^{-10}
Glucose monitor	1,600 bps	0-50Hz	$< 20ms$	16 bits	10^{-10}
Temperature	120 bps	0–1Hz	—	8 bits	10^{-10}
Motion sensor	35 Kbps	0–500Hz	—	12 bits	10^{-3}
Audio, medical imaging,video	10 Mbps	—	$< 100ms$	—	10^{-3}
Voice	50–100 Kbps	—	$< 10ms$	—	10^{-3}
Capsule endoscope	1 Mbps	—	—	—	10^{-10}
Artificial retina	50–700 Kbps	—	—	—	—
Cochlear implant	100 Kbps	—	—	—	—

2.5.4 Localization, tracking and motion detection

Localization, tracking and motion detection are WBAN required services due to WBAN applications. In fact, for military/firefighting applications [19], it is important to implement localization and tracking features due to the mobility of the WBAN subjects. It is the case for people in forest adventure or exploration. For medical healthcare [32–34] or sport [10] applications, motion detection is more required. However, one application can implement all these services depending on the needs. In this thesis, we will be interested on the localization and more less on the tracking.

2.5.5 Energy consumption optimization

Energy consumption optimization is the main key issue for nowadays wireless devices and comes down to the world policy for green earth. Particularly for WBANs where implant devices for example are required to last some tens of years, the energy consumption optimization is more important for a long network lifetime (see Chapter 4, section 4.2.1). Our proposed system in this thesis will be partly evaluated in terms of energy consumption.

2.6 Conclusion

This chapter is a comprehensive overview on the main features of the WBAN. It summarizes the key points of PHY and MAC layers according to the IEEE 802.15.6 and IEEE 802.15.4 standards, the characteristics of the sensors involved in communication, and the routing protocols and algorithms. It is clear that we can talk much more on WBAN but the focus here is on the understanding of the features interesting the implementation of the system in the next chapters.

Thus, with this global view on the related applications and services, this chapter opens a path to the next chapter focusing on the monitoring system based on the WBAN.

Chapter 3

WBAN Monitoring Systems

3.1 Introduction

Nowadays, there is an emergence of applications on wireless sensors that are invading many sectors of human life. It is for instance the case of healthcare, terrain surveillance, industrial production monitoring, security, military, etc. Thanks to the internet, these applications are remotely monitored what grants many advantages such as in case of non-accessibility when a place to monitor is unreachable, in the case of mobility when a patient is not still at hospital, etc. For healthcare and other applications that include the human being as a subject to monitor, a specific wireless communication standard for WBANs was defined [2]. Building a WBAN monitoring system (WBAN-MS) especially for healthcare or other applications where WBAN subjects are mobile is an interdisciplinary task that includes communication, designing, programming, operating systems, etc. There are so far many monitoring systems (MS) defined for healthcare with 3-tiers architecture: motion and heart activity [35], motor impairments sufferance, physical health monitoring for diabetes patients, etc. However, all those designed architectures put the storage unit and the monitor unit together and these architectures are defined differently as related applications are different each other. Moreover, there is no study on the way the WBAN accesses the peer networks as the WBAN is an emerging network that requires access mapping mechanisms. The WBAN-MS shall offer some facilities in mobility, scalability and adaptability to any application in the field. Therefore a 4-tiers architecture that separates storage unit from monitor unit to help this latter to access data wherever it is and facilitate users mobility is further proposed in this chapter. On the one hand, it includes a traffic classes mapping function between WBAN and peer-networks. On the other hand it proposes the implementation of a Priority Weighted Round Robin (PWRR) scheduling technique at the coordinator for emergency and medical data, what is so far the first suggestion according to our knowledge. Results of analysis and simulations show the impact of this architecture on the system in terms of mobility, end-to-end delay in peer-networks and waiting time especially for time-sensitive data flows.

As WBAN based applications handle sensitive physiological data, the implementation of PWRR scheduling is proposed to reduce the waiting time of the high priority data and avoid low priority data from starvation. In this way, delay and packets loss are taken into account.

There are some proposed scheduling techniques [36, 37] but in the case of WBAN-MS, our proposal provides good results and seem to meet related requirements. Analytical and simulation results show how the designed system achieves the related application requirements in terms of waiting time and data loss mitigation and flexibility for mobility.

3.2 Some related projects and applications

Some years ago, researchers have been working on these new ubiquitous technologies and proposing diverse remote monitoring systems. A MS is designed according to the targeted application what leads to many kind of system with the 3-tier architecture though. For instance, health monitoring, ambulatory monitoring, etc. have different MS. Health monitoring system attracted much attention of authors than other applications. In [14]

WBAN key applications were presented and in [38] a survey on different architectures used in WBANs for ubiquitous healthcare monitoring was provided. Authors in [39] proposed a hardware and software architecture for monitoring motion and heart activity of a patient recovering at home. In the same way a system to monitor patients suffering from motor impairments caused by neurological diseases was proposed in [35]. In [40] a three-tier network architecture to facilitate physical health monitoring for diabetes patients automatically was proposed while in [41] was proposed smartphone-based system for remote real-time tele-monitoring of physical activity in patients with chronic heart-failure (CHF). In [42] was proposed and developed a WBAN prototype aiming for ambulatory monitoring of user activity and other physiological parameters and in [43] was proposed an Android mobile application for calories burned during running exercise. As for scheduling, authors in [44] introduced priority scheduling and data compression into the system to increase transmission rate of physiological critical signals which improve the bandwidth.

3.2.1 Projects and systems

Many projects have been developed to promote WBAN applications and here are some of them:

• **WSN4QoL**: Wireless Sensor Networks for Quality of Life is a project focused on wireless communication technologies for m-Health applications [45]. The main goals of the project are: (2) to provide a protocol stack architecture which can accommodate a variety of protocols, algorithms and sensor devices for healthcare applications; (2) to develop reliable, energy efficient, interference-robust communication protocols and algorithms; (3) to develop distributed localization protocols that meet the constraints imposed by WBANs in health care scenarios; and (4) to propose effective and efficient security solutions for the proposed communication protocols. The project aims to integrate proposed protocols and algorithms in healthcare commercial devices in order to evaluate the performance improvements in realistic environments.

• **UbiHeld:** Ubiquitous Healthcare Monitoring System analyzes patient data (from smart phone Kinect camera and online social network) to detect abnormal situation or behavior [46]. The Kinect platform armed with Infra-Red sensors is used for people identification, location and activity detection. The social sensing acts as a soft-sensor network where the user has to allow the application to access his or her posts and transfers the posts to back-end for computing and analysis. The smart phone sends to the Back-end vital signs, patient location and activity. The Back-end performs fusion of the long term data from the smart phone, Kinects and Social Network to get acknowledges on the individuals behavioral patterns (normal and abnormal). This system is useful for elderly supervision and assisting living and individual behavior analysis.

• **Capsule endoscope:** This is a novel application of wireless technology into in-body patient monitoring [47]. It is a result of collaboration of universities and industries and can be used to monitor digestive organs by video and images transmitted from inside body to the outside over WBAN.

• **CARA:** Context-Aware Real-time Assistant is a pervasive web-based healthcare architecture [48]. It includes four subsystems: 1) Wireless Monitoring Device (WMD) that corresponds to the WBAN including medical sensors such as ECG, SpO2 meter, temperature sensor and mobility sensor. 2) Home Monitoring System: dedicated to improve elderly person daily living at home. It is based on the live web broadcasting which let the caregiver to have a direct real-time view of the patient and its surroundings and to communicate remotely with him when it is required. 3) Remote Clinical Monitoring System whose basic role is to monitor continuously patients' physiological signals and obtain real-time data from WBAN and record them on the server for further reviewing and analyzing. 4) Healthcare Reasoning System perform three tasks: (i) continuous contextualization of the physical state of a person, (ii) notification of possible emergency situations and (iii) prediction of possibly risky situations.

• **HELP:** Home-based Empowered Living for Parkinson Disease Patients targets at designing a health monitoring system able to control disease progression and to mitigate Parkinson Disease symptoms, thus improving the quality of life of affected elderly people [49]. The aim of the project is to design a control system for a subcutaneous infusion pump that administers the exact required drug dose according to the patients level of activity without focusing in communication issues. This system is composed of the following components: (i) an intra-oral electronic drug delivery device with miniaturized, non-invasive and removable design; (ii) an external pump that delivers higher amounts of drug; (iii) a WBAN to gather information on the user environment to detect blockades; (iv) a telecommunication and services infrastructure to analyze and transfer data exchanged between the user and the automated system; and (v) a remote care unit for patient supervision.

• **Help4Mood** project aims to build an end-to-end system to help the recovery of people with major depression [50]. The system is designed to be used together with other forms of therapy such as self-help, counseling or medication. The sensor devices communicate by using a proprietary low-power RF network protocol named SimpliciTI [51] over Bluetooth.

• **HEALTH@HOME** project aims to provide an end-to-end solution for the remote monitoring of cardiovascular and respiratory patient parameters [52]. The most significant measured signals are ECG, SpO2, weight, blood pressure, chest impedance, respiration and body posture. The measured data are sent through the gateway to a server located at the health service facilities that is integrated with the Hospital Information System. The gateway communicates with the server through ADSL as the primary transmission channel, or mobile broadband (i.e., GSM/GPRS/UMTS) as the secondary (backup) data channel. Alarms are sent by Short Message Service (SMS) directly to the physicians, the patients relatives and their caregivers.

• **CAALYX-MV**: Complete Ambient Assisted Living Experiment Market Validation [53] whose goal is to provide an end to end solution to improve the elders quality of life, all sensors in the WBAN are wearable. The sensory data are sent using Bluetooth links with a mobile phone and through standard low-cost networking equipment to a GPS-enabled smart phone (3G/UMTS) that runs a completely autonomous software application. The application continuously analyzes sensor data in order to identify problematic conditions and promptly alert the care system.

- **CodeBlue** is the project of Harvard University trying to develop novel applications of wireless sensor network technology to medical applications [54].
- **BOHM:** The Wireless BOHM Center is used for self-monitoring and management of vital signs by patients [55]. The system consists of five healthcare devices with integrated Bluetooth and cellular communications. The Wireless BOHM Center can be used to monitor 5 patients vital signs simultaneously, including heart rate, body temperature, blood glucose levels, body fat and 1-Lead ECG Mobile Cloud-Computing-Based Healthcare Service by Non-contact ECG Monitoring [56] employs a non-contact biomedical signal measurement technique applied on different chairs (car, office, home, etc.) to track the patient health status at multiple locations for multiple users. Acquired biomedical data can be processed to identify and recognize the user whose ECG is being measured to ensure that his medical record is stored correctly, using a mobile device that acts as healthcare assistant for the patient and monitor seamlessly and in real time the patients bio-signals. The system provides feedback to the user when an abnormal situation detected. The mobile device integrates a medication reminder to provide personal dosage assistance useful for elderly patients. A Web server healthcare cloud computing system is employed for health status remote monitoring.

3.2.2 Existing HMS smartphone based applications

Several prospective wireless smartphone-based devices such as a body analysis scale, digital scale, blood pressure wrist monitor and blood pressure monitor, besides an integrated mobile application named iHealth My Vitals app, are provided by iHealth Lab Inc.[57]. The Bluetooth wireless protocol is used to scale measures, stores, monitors and shares the weight and body mass index. GENTAG [58] is another company that offers low-cost and disposable wireless sensors with a proprietary near-field communication (NFC), a Bluetooth like technology. The devices can be managed by any NFC-capable smartphones, tablets or PC for many applications such as healthcare or diagnostics. Regarding management, AliveCor, Inc. [59] allows medical professionals to manage single-channel ECG rhythms and heart rates. In the same way of patients' management, CellScope [60] focuses on personalizing healthcare tools for home diagnostic applications. It has also developed two optical attachments to modify a smartphone into a diagnostic-quality imaging system for healthcare and consumer skincare. One of them is CellScope Oto that takes visual images of the middle ear to probe ear infection. Nonin Medical, Inc,[61] manufactures pulse oximeters such as Onyx® II Model 9560 Finger Pulse Oximeter, a wireless device to measure the SpO2 and the pulse rate of perfused patients with COPD, congestive heart failure and asthma. Artificial Life, Inc. [62] is another manufacturer that has developed GluCoMo, an electronic diary and a reminder system for diabetics targeted towards diabetic monitoring and coaching. It is compatible with various platforms such as iOS, Android, etc. Holomic LLC [63] is another company specialized in smartphone based HMS and whose the main product is a smartphone-based Holomic Rapid Diagnostic Test Reader (HRDR-200) to perform lateral flow immunoassay tests for telemedicine, public health monitoring, etc. More details can be found in the study of Vashist et al. [64].

3.3 WBAN monitoring system design

The WBAN-MS design requires some important and essential factors as a WBAN itself has other specific requirements related to sensors. Hence, the design involves the devices themselves and the connection to the user. Here are some factors requiring optimization for a good system:

• *Data sensitivity:* some WBAN applications if not all, are time-sensitive and loss-sensitive. It is the case of medical and sport related applications. The multiplication of access points and a well-designed MAC layer shall respond to this requirement.

• *Mobility:* one of the most advantages of the WBAN applications is to allow the WBAN subject to move and go about his activities if possible. However this mobility could lead to the disconnection or the signal weakness due to the distance and signal reflection. It is then important to think how to maintain connection and take advantage of available networks when designing a WBAN-MS.

• *Scalability:* it is important to design a system capable of adaptation to any change such as adding or removing a sensor to/from a WBAN or a WBAN to/from the system.

• *Quality of Service:* this requirement involves many parameters such as delay, jitter, data loss, data rate [9].

3.3.1 3-tiers Architecture

As explained previously, the very commonly used architecture encompasses three tiers and the most health monitoring systems as example, follow this model: a set of individual wearable sensors, the personal server and a medical server [40, 65] as illustrated by Figure 3.1 [23].

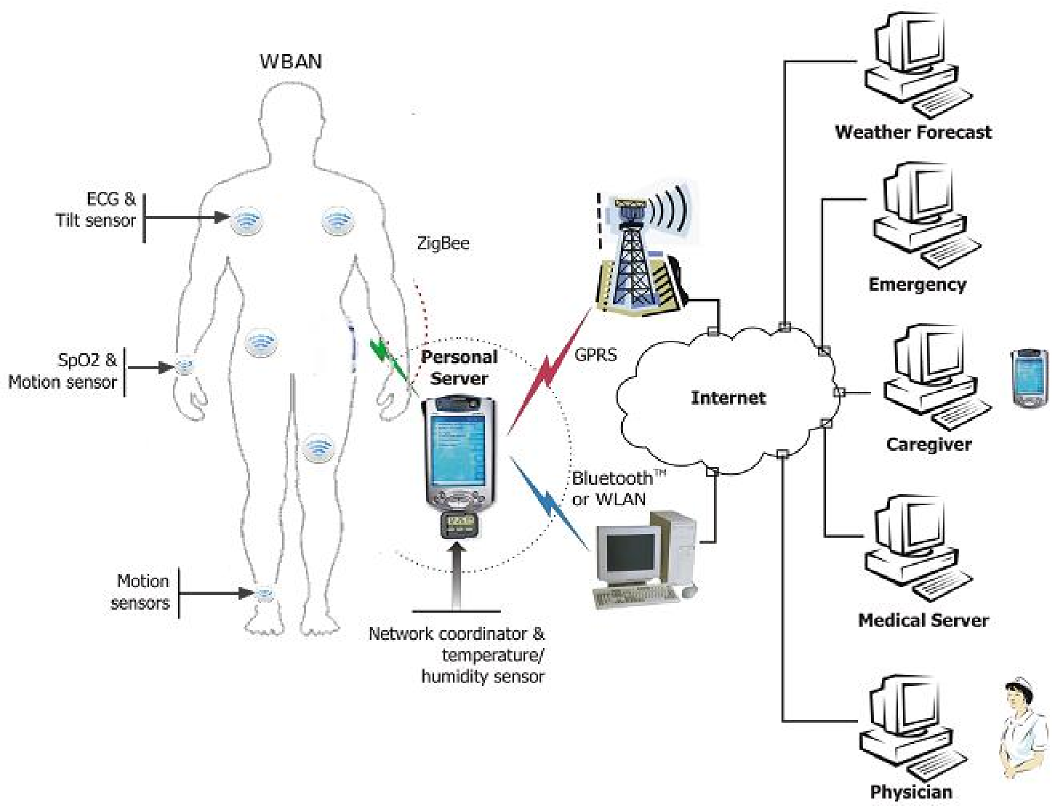

FIGURE 3.1: 3-tiers architecture

The MS relies on the tier 1 which is essential part as it is the source of the data. It comprises a set of sensor nodes with skills of sensing, sampling, processing and transmitting of physiological signals. These sensor nodes can be for instance an ECG sensor for monitoring heart activity, an EMG sensor for monitoring muscle activity, an EEG sensor for monitoring brain electrical activity, a blood pressure sensor for monitoring blood pressure, a tilt sensor for monitoring trunk position, and a breathing sensor for monitoring respiration, while the motion sensors can be used to discriminate the user's status and estimate her or his level of activity.

The second tier which is the personal server interfaces sensor nodes with services at the medical server, the tier 3. This personal server is generally implemented on a PDA or a smartphone or else on a home personal computer particularly for personal private monitoring of elderly patients [38].

The personal server holds patient authentication information and is configured with the medical server IP address in order to interface the medical services. The communication between the personal server and the medical server is performed with IP networking via WIFI, LTE, 3G, etc. In the case when a link between the personal server and the medical server is not available, the personal server should be able to store the data locally and upload them later.

The medical server as tier 3 is implemented to serve numerous registered users. The medical server behaves as a database and keeps electronic physiological records of registered users and provides in return various services to the users, medical personnel, and informal caregivers. It also implements mechanisms of security and sessions management.

Note that a 2-tiers WBAN MS is also possible: it is simply a WBAN and the data analysis can be performed at the coordinator for self-monitoring cases such as workout or disease monitoring.

As it is impossible to talk about WBAN with only sensor nodes without coordinator implementing the personal server and as the users and the medical server are set in the same entity, this leads us to split entities and consider the information as a backbone of the system and define a 4-tiers architecture described in the following section.

3.3.2 4-tiers Architecture

In the WBAN-MS, data or piece of information is a backbone of the system as all other parts rely on it. In fact, the information generated by a WBAN is expected to be used by the final user as a monitor or the WBAN subject himself. Generally, this information does not get to the user directly, it needs to be saved and processed or simply saved for future use. However, for real time applications the information is displayed to the user before it is saved or displayed and saved at the same time. Figure 3.2 illustrates different parts of the system.

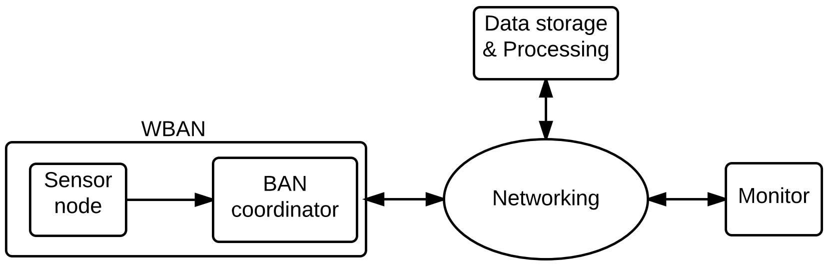

FIGURE 3.2: 4-tiers architecture modules

3.3.2.1 Tier 1: A sensor node

This part of the MS constitutes a very important module as the all system is based on it. In fact, the sensor node is the source of information from either a patient with a particular disease or an athlete on workout or a military/firefighter on battlefield.

3.3.2.2 Tier 2: The BAN coordinator

The BAN coordinator that can be a smartphone, a PDA (personal digital assistant) or a laptop, collects sensed data from implantable and/or wearable sensors and uploads them to the remote station via one of the available networks (WIFI, WIMAX, LTE-A, etc.) for storage and future processing. Furthermore, the WBAN module can receive commands or instructions from a monitor to subject actuators for prompt actions or advise in some critical situations. Besides that, the patient can send requests to consult remote data.

3.3.2.3 Tier 3: Data storage and processing

The data storage and processing part of the system serves as database and can be a cloud, a dedicated server, a web server or a local server.

• The cloud computing [40] gets its importance in its conception as an infinite computing resources often paid according to service consumption [66]. In a RMS, subjects data increase indefinitely what leads to the lack of data storage and so require much complex tools of processing and management. The cloud computing seems to be a great solution to overcome this drawback by providing extensible, flexible, robust and huge data storage. The main concerns for cloud computing are specially security and privacy, connectivity and rapidity [67]. However, this is insured and regularly maintained by the provider. A cloud computing platform could consist of four layers: service interaction and presentation layer, cloud engine layer, data processing and analysis layer and distributed cloud storage layer.

The first layer is the service interaction and presentation layer that provides inter-operation between client (subjects and monitors or user) application on mobile phone or browser on a computer, to upload and collect data also to download the analysis results from the cloud servers. Furthermore it provides various services to the authenticated users.The second layer is the cloud engine layer that makes the cloud running by using message-driven mode through message queue and provides access control. As for the third layer as the data processing and analysis layer it is clusters of computing, including data pre-processing and analysis and data mining, it can treat the collected data and store the results back to database. Data analysis can be performed autonomously, without human intervention by comparing the subjects vital signs against pre-existing knowledge as well as any recommendations prescribed by the subjects monitor. Finally, the cloud storage layer keeps electronic records of all registered subjects' data including user information, vital signs, status, and graphic data for processing.

• Dedicated server: that may be required for users developing a considerable amount of traffic, can usually be configured and operated remotely from the client. The use of dedicated server is likely to save router, internet connection, security system, and network administration costs.

3.3.2.4 Tier 4: Monitor

This part is related to the monitor or final user and the monitoring module includes: doctors who look after patients' physiological parameters and emit prescriptions, emergency staff that intervene in case of patients accident, pharmacists and drugstores that receives prescriptions and deliver medicines, patient relatives or the WBAN subject himself, monitor personnel in case of sport or battle, any other monitor. This monitor module gets access to the data stored in a remote database for viewing or analyzing or else editing some related recommendations. In other words, a monitor interact with a database.

This 4-tiers architecture (see Figure 3.3) is an information driven architecture, i.e. it follows the whole precess of information, from its creation to its use. Thus, the heterogeneity of networks and the system allows the mobility of the WBAN and the remote storage allows the mobility of the monitor unlike the existing architectures. It also makes easy interactions between different modules and allows the implementation abstraction. This is more beneficial given that all WBAN based system can be designed using this architecture disregarding the target application.

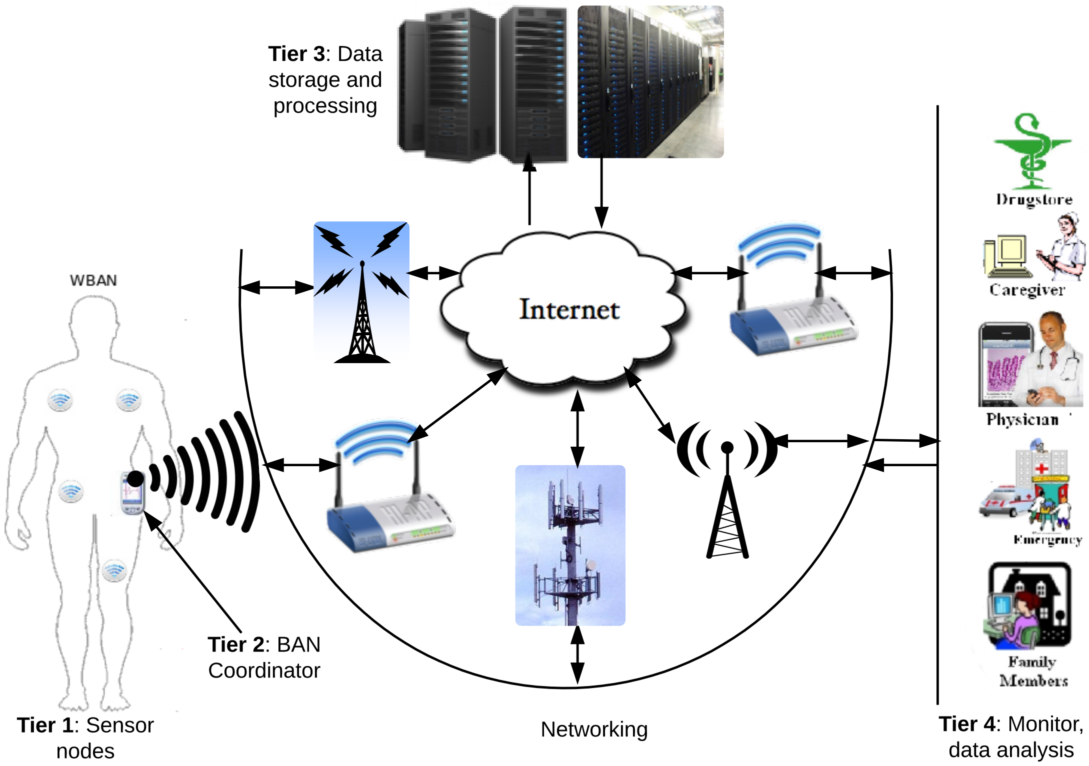

FIGURE 3.3: 4-tiers architecture modules

3.3.3 Tiers interactions: WBAN-peer networks bridging

Tier 1 - tier 2: These two tiers form a WBAN and related transmissions are based on IEEE 802.15.6 standard.

Tier 2 - tier 3: The BAN coordinator periodically uploads data to the storage tier part. This latter shall save the data and implement some triggers and processing modules: for a certain monitored parameter if the value exceeds a fixed threshold, the related data source subject and/or the monitor should be alerted or a fixed task should be performed accordingly.

Tier 4 - tier 3: The monitor accesses the data in the database via the monitor interface using a smartphone, a laptop or any web access device. This is beneficial in making the client application of the system more portable and access non-dependent of the device. He can also write messages, prescriptions and recommendations or command remote actuators if any. However, the main challenge in tiers interactions concerns the link tier2-tier3. This link is a bridge between the WBAN and peer networks where a BAN coordinator has to deal with the communication bridging between the IEEE 802.15.6 interface and the other wireless networks interfaces. As illustrated by Figure 3.4, there are some relevant tasks to be performed by this bridge: QoS mapping, scheduling and peer-network election, for instance.

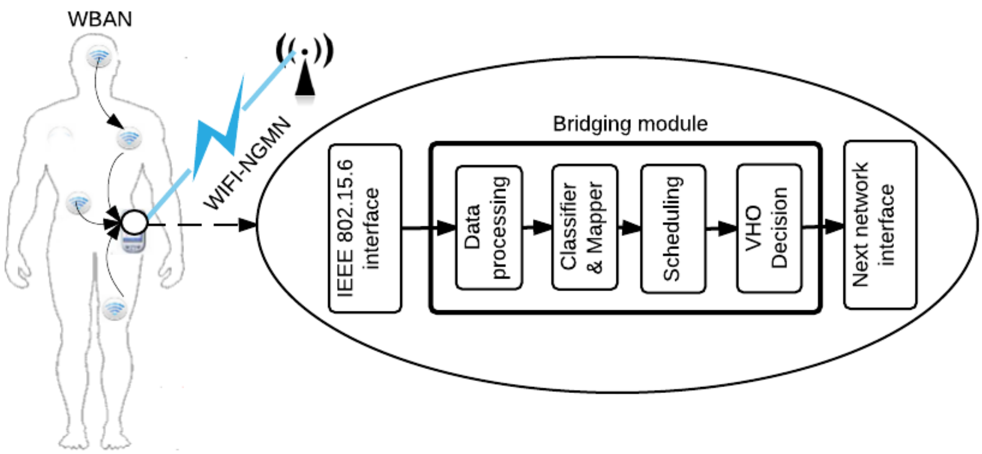

FIGURE 3.4: A bridge model for a heterogeneous WBAN system

- Processing module: this module is responsible for refining data received from a sensor by filtering and packing. For data with low priority, it can be decided to wait for other data so as to aggregate them into one packet as per the available network packet size.

-Classifier, mapping module: this module buffers and puts data into queues according to their priorities after QoS mapping mechanism.

-Scheduling module: this module applies scheduling technique and conveys packets in the queue.

-VHO Decision module: this vertical hand-off decision maker decides which network to choose when multiple ones are available, using combination of many network parameters.

3.4 Scheduling

In the WBAN [2], data traffic from sensor nodes to the coordinator access the medium according to the priority model following Equation 3.1. In that, for a node with a user priority UP_i, the value of the backoff counter is initialized to a random integer from $[1, W_0^i]$, where $[W_0^i]$ denotes the minimum value of the backoff counter. For every number of retry k, the value of the contention window is computed depending on whether k is odd or even.

$$W_k^i = \begin{cases} W_0^i, \text{when } k = 0 \\ W_{k-1}^i, \text{when } k \quad is \quad odd, 1 \leq k \leq m \\ min(2W_{k-1}^i, W_{max}^i), \text{when } k \quad is \quad even, 2 \leq k \leq m \end{cases} \tag{3.1}$$

Where k stands for the number of retries of transmission that a data packet has undergone.

When data get to the coordinator, they are put into buffers and scheduled in the way to provide for a minimum waiting time for service to time-sensitive data and for real-time applications. As data arriving at the coordinator from sensor nodes are classified into eight traffic classes as user priorities (UPs) and given that some traffic classes are for WBAN management and do not need to go out of the coordinator, they are then mapped into only four priority classes Ps following Equation 3.15.

$$P_i = \begin{cases} \frac{UP_i}{2} \times 2 + 1, \text{when } UP_i \geq 5 \\ \frac{UP_i - 2}{2} \times 2 + 1, \text{when } UP_i < 5 \end{cases} \tag{3.2}$$

Where $UP_i, P_i \in \mathbb{N}$

In this way, data crossing the coordinator should be classified into Emergency (EM), Medical (MD), Audio-Video (AV) and non-Medical (nMD). The mapping function between data class and data priority is as follows:

$(P_1, P_2, P_3, P_4) = (EM, MD, AV, nMD)$ with $(P_1, P_2, P_3, P_4) = (7, 5, 3, 1)$

The incoming data will then be sent to four different buffers after the mapping stage and each buffer has the same weight as the priority of the traffic class it receives, i.e. Q_1 with weight 7 contains EM, Q_2 with weight 5 contains MD, Q_3 with weight 3 contains AV, and Q_4 with weight 1 contains nMD.

The traffic from Q_1 and the WRR outgoing traffic are scheduled using priority scheduling while those from Q_2, Q_3 and Q_4 are scheduled using WRR.

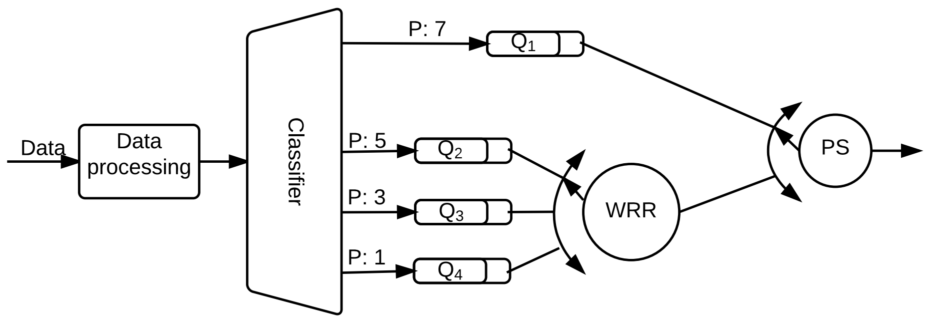

Figure 3.5: A PWRR architecture for a WBAN based HMS

The architecture illustrated in Figure 3.5 offers advantages to EM traffic classes to keep their priority in PS and then do not have to wait. MD traffic classes are managed in separated queue from the one of EM traffic classes what gives them high priority over other traffic classes and they are not penalized in PS if EM data arrive while they are under service because the PS runs in non-preemptive mode. The architecture finally prevents other data traffic classes from starvation.

3.4.1 Priority Weighted Round Robin (PWRR)

The WRR scheduling algorithm is simply RR with weights assigned to each queue. Unlike the RR whose transmission service cycles through queues taking equal amount of packets (one packet) from each, the WRR service takes amount of packets as per the weight assigned to each queue. Hence, the WRR uses the priority as weights. It also ensures that lower priority queues never starved for long time for buffer space and output link bandwidth. The WRR scheduling is based on assigning fraction weight φ_i to each service queue such that the sum of weight of all service queues is equal to one.

$$\sum_{i=1}^{n} \varphi_i = 1 \tag{3.3}$$

As it is already stated in the introduction section and illustrated in Figure 3.5, the PWRR scheduling is a combination of priority scheduling (PS) and WRR strategies. In this case of WBAN based HMS, we have two stages: in the first stage, the EM data are scheduled by non-preemptive PS with the WRR output data. In the second stage, other data including MD data are scheduled by WRR and pass through PS afterwards.

As the main goal here is to guarantee the minimum waiting time and also the delay for EM and MD data, the evaluation is done by comparing PWRR with FIFO strategy. Considering that different traffic classes from the sensors arrive to the coordinator in a random way and the coordinator which is only one server conveys data with independent service time from their arrival rate but according the WBAN peer-network availability, the problem can be modeled by M/G/1 queuing system.

By applying the queuing theory of a M/G/1 system with n priorities, i.e. with multiple classes of data, let us assume that the data traffics arrive according to the Poisson process with rate λ_i (i=1, 2,.., n), that to say that the inter-arrival times are independent and exponentially distributed random variables with parameter λ. The service times are also assumed to be independent and exponentially distributed with parameter μ. Furthermore, all the involved random variables are supposed to be independent of each other.

3.4.1.1 First stage: PS

As illustrated by Figure 3.5 and stated before, we have two scheduling techniques WRR and non-preemptive PS. For the PS we consider two traffic classes: the EM class (the highest priority) and the traffic class from the second stage.

The system stability is given by

$$\sum_{i=1}^{n} \rho_i < 1 \tag{3.4}$$

Where $\rho_i = ^{\lambda_i} /_{\mu_i}, i = 1, 2, ...$ and n is the number of queues.

Let $E(W_i)$, $E(D_i)$, $E(N_i)$ and $E(R)$ be the mean response time, the mean delay, the mean number of class i in the system and the mean residual service time, respectively. The delay of a data traffic class i is the simply the time it spends waiting for the server to be free if it is being used and the time of its own service. As the service times are exponentially distributed with parameter μ, the delay is given by:

$$E(D_i) = E(W_i) + \frac{1}{\mu_i} \tag{3.5}$$

Assuming that the priority i is higher than $i + 1$, we get by the Pollaczek Khintchine Formula for the high priority class: $E(W_1) = E(R) + \frac{(E(N_1))}{\mu_1}$ what gives, by Little's law

$$E(W_1) = \frac{E(R)}{(1 - \rho_1)} \tag{3.6}$$

Given that,

$$\sum_{i=1}^{n} N_i = \frac{\sum_{i=1}^{n} \rho_i}{1 - \sum_{i=1}^{n} \rho_i} \tag{3.7}$$

By generalization and using the Little's law, we get

$$E(W_i) = \frac{E(N_i)}{\lambda_i} = \frac{E(R)}{(1 - \sum_{j=1}^{i-1} \rho_j)(1 - \sum_{j=1}^{i} \rho_1)} \tag{3.8}$$

$E(R) = \frac{1}{1}\sum_{i=1}^{n}\lambda_i E(S_i^2)$
$\Leftrightarrow E(R) = \frac{1}{2}\sum_{i=1}^{n}\lambda_i \frac{1}{\mu_i^2}$, with $E(S_i) = \frac{1}{\mu_i}$
$\Leftrightarrow E(R) = \frac{1}{2}\sum_{i=1}^{n}\frac{\rho_i}{\mu_i}$, with $\rho_i = \frac{\lambda_i}{\mu_i}$

$$\Rightarrow E(W_i) = \frac{\frac{1}{2}\sum_{j=1}^{n}\frac{\rho_j}{\mu_j}}{(1-\sum_{j=1}^{i-1}\rho_j)(1-\sum_{j=1}^{i}\rho_i)} \tag{3.9}$$

When using FIFO strategy, $E(W) = \frac{E(N)}{\sum_{i=1}^{n}\lambda_i}$
$\Rightarrow E(W) = \frac{\sum_{i=1}^{n}\rho_i}{(1-\sum_{i=1}^{n}\rho_i)(\sum_{i=1}^{n}\lambda_i)}$

With relations (3.4) and $\rho_i = ^{\lambda_i}/_{\mu_i}$, we get

$$E(W) = \frac{1}{1-\sum_{i=1}^{n}\rho_i} \tag{3.10}$$

Relations (3.6) and (3.10) are such that $E_{PS}(W_1) < E_{FIFO}(W_i)$

3.4.1.2 Second stage: WRR+PS

In the second stage of PWRR architecture the data of buffer i wait for $1-\varphi_i$ units of time before their service as buffers are served in cycle way in respect of assigned weights. In this way Equation 3.9 becomes:

$$\Rightarrow E(W_i) = \frac{\frac{1}{2}\sum_{j=1}^{n}\frac{\rho_j}{\mu_j}}{(1-\sum_{j=1}^{i-1}\rho_j)(1-\sum_{j=1}^{i}\rho_j)}(1-\varphi_i) \tag{3.11}$$

In addition, the output of WRR becomes the second priority in PS with the probability B_{em} by which the EM data as first priority can be in the server. The second priority in PS is given by

$$E(W_2) = \frac{\frac{1}{2}\sum_{j=1}^{n}\frac{\rho_j}{\mu_j}}{(1-\rho_1)(1-\sum_{j=1}^{2}\rho_j)} \tag{3.12}$$

Finally, the waiting time and delay become respectively:

$$E(W_i) = \frac{\frac{1}{2}\sum_{j=1}^{n}\frac{\rho_j}{\mu_j}}{(1-\sum_{j=1}^{i-1}\rho_j)(1-\sum_{j=1}^{i}\rho_j)}(1-\varphi_i) + \frac{\frac{1}{2}\sum_{j=1}^{n}\frac{\rho_j}{\mu_j}}{(1-\rho_1)(1-\sum_{j=1}^{2}\rho_j)}B_{em} \tag{3.13}$$

$$E(D_i) = \frac{\frac{1}{2}\sum_{j=1}^{n}\frac{\rho_j}{\mu_j}}{(1-\sum_{j=1}^{i-1}\rho_j)(1-\sum_{j=1}^{i}\rho_j)}(1-\varphi_i) + \frac{\frac{1}{2}\sum_{j=1}^{n}\frac{\rho_j}{\mu_j}}{(1-\rho_1)(1-\sum_{j=1}^{2}\rho_j)}B_{em} + \frac{1}{\mu_i} \tag{3.14}$$

Assuming that all types of data in the WBAN have the same probability to occur, the EM data would be generated with the probability of $B_{em} = 1/\sum_i^n P_i$, where $\sum_i^n P_i$ represent the different data traffic classes.

3.4.1.3 Performance evaluation

In reality, EM data traffic classes are not frequently generated what could lead to assume that the high priority has low arrival rate; however here we take the worst case where EM traffic classes have as important arrival rate as other traffic classes and then assume that all sensor nodes have the same transmission rate and the same service rate $\mu = 1$ as the coordinator is the same server for all nodes. Thence, we vary the arrival rate of EM traffic classes, then one of the second priority traffic classes and finally those of both traffic classes: from $\sum_{i=1}^{n}\lambda = 0.15$ to $\sum_{i=1}^{n}\frac{\lambda_i}{\mu_i} < 1$ is still respected; this requirement is stated in condition 3.4. For PS, the waiting time depends only on priority and arrival rate.

Figure 3.6 illustrates the impact of the arrival rate on the EM traffic classes with PS in terms of waiting time. We first vary the arrival rate of the EM traffic classes, and then vary the one of the traffic classes of second priority and finally all both arrival rates. It is clear that the waiting time increases with the increase of the arrival rate given that the service rate does not change what impacts on the waiting time. It is noticed that the EM traffic class does not suffer from the increase of arrival rate of the traffic classes of the

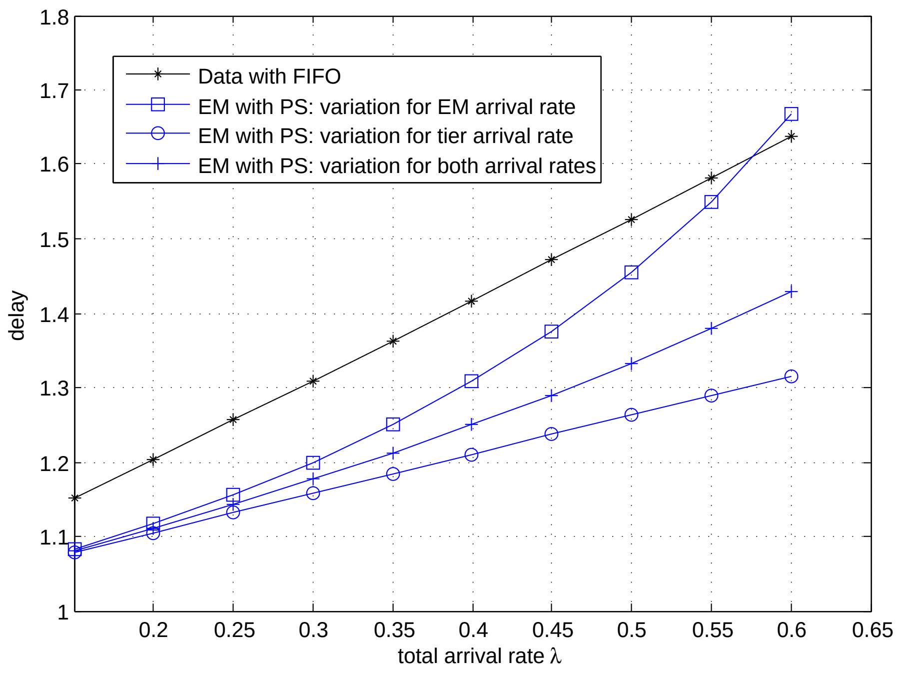

FIGURE 3.6: Average Delay vs. EM arrival rate in PS

second priority, however, the arrival rate of EM traffic class impacts on its own waiting time. In all these three cases, the proposed solution outperforms the FIFO scheme with the arrival rate not exceeding 0.55.

For PWRR, each class j has normally to wait $1 - \varphi_j$ normalized time for each service round. The evaluation is focused on the medical flow and the impact of the arrival rates of involved flows as in previous tests. As depicted in Figure 3.7 it is noticed that the more MD arrival rate (λ_{MD}) increases, the more the MD delay increases too like in PS. However, the any variation in arrival rate of the remainder of the flows has the same impact on the delay of MD flow. One can also notice that the delay of MD flow is much lower than in FIFO for all studied situations.

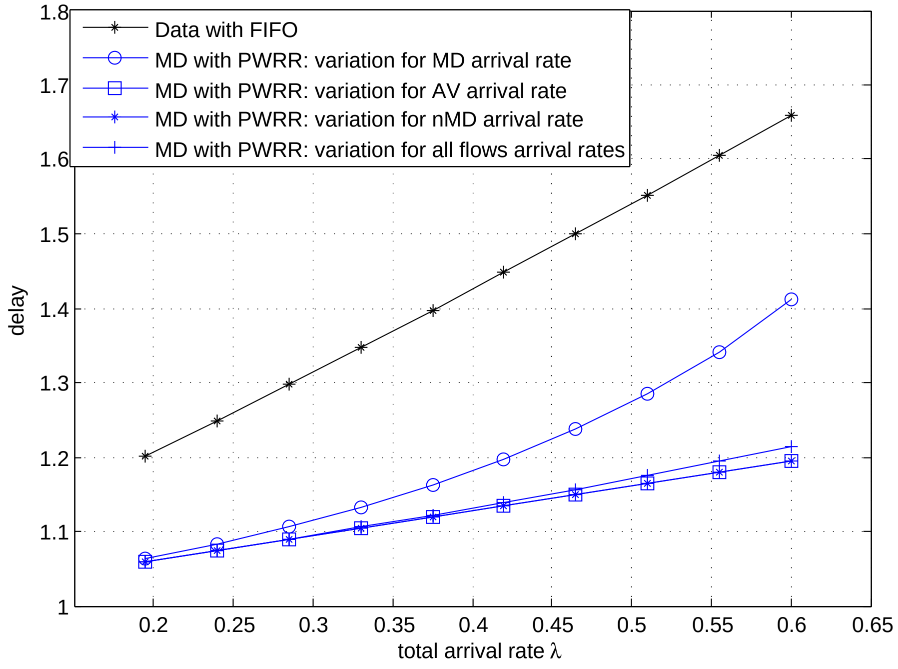

Figure 3.7: Average Delay of MD vs. all arrival rates in PWRR

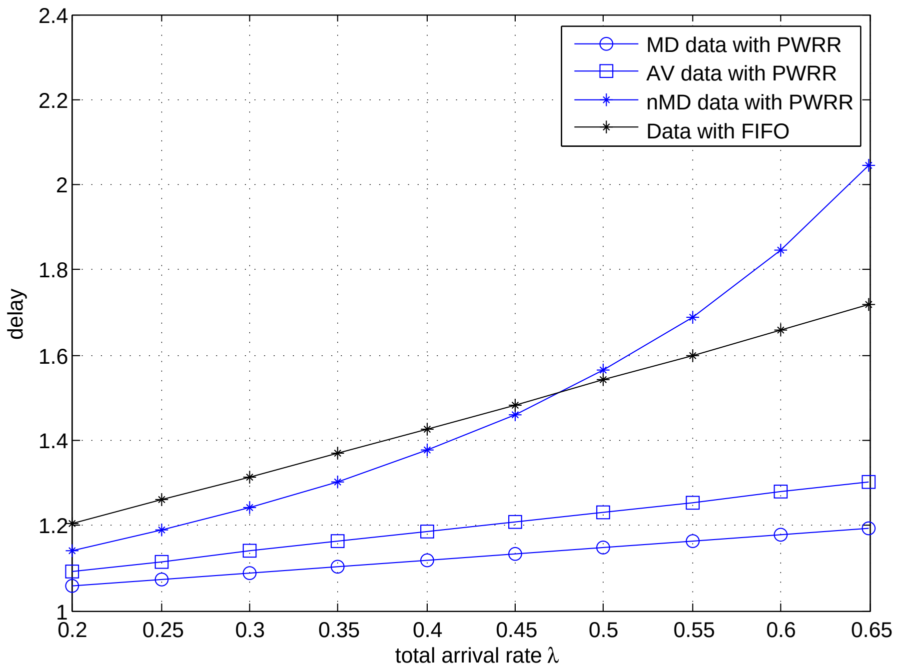

Figure 3.8: Average Delay of all data flows in PWRR

Figure 3.8 illustrates the impact of the arrival rate variation on all involved flows, i.e. MD, AV and nMD. Here also, the worst case where λ_{MD} increases has been considered. In fact, MD and AV flows have better gain over FIFO but the delay of nMD flow exceeds the one in FIFO at arrival time above 0.45. Anyway, the time-sensitive data flows for healthcare application have low delay.

3.4.2 WBAN-peer networks QoS mapping

To support the mobility of the WBAN user, the system shall guarantee permanent connectivity and in this way the BAN coordinator shall deliver its data via any available network according to the system QoS requirements. Thus, when the WBAN gets disconnected from a WIFI AP, it can then switch to UMTS for example and if many networks are available, it can choose one according to the link quality and QoS requirements. These networks define QoS traffic classes and priorities that help in mapping with WBAN. The QoS traffic classes in the WBAN are prioritized from 0 for the lowest to 7 for the highest and their management goes up to the BAN coordinator. In the LTE, there are many traffic priorities but we focus on the QCI (1-9) that the eNodeB uses to deliver different traffic from the clients. In UMTS however the traffic classes (Conversational, Streaming, Interactive and Background) have no numerical priorities even if they are classified from the lowest to the highest. It is the same for WIMAX (UGS, ertPS, rtPS, nrtPS, BE).

For all these networks the traffic classes from the clients access to the service at the master device according to the access priorities. These master devices are access point for WLAN, eNodeB for LTE and UMTS and Base station in WIMAX. In our model, the BAN coordinator is considered as the client for those previous master devices. Thus, as the traffic will be scheduled at the master device, the goal here is to range packets in desired order before they get to the scheduler at the master device; what gives two scheduling stages. Even if the user priorities (UPs) defined in WBAN are designed for intra WBAN communication, we will use them to map the traffic for the pre-scheduling.

Mapping the WBAN UPs with the peer networks QoS classes, the class numbers, the related typical services and the assigned priorities are considered. The main goal here is to force the system to offer the service needed by the WBAN traffic or anticipate in traffic scheduling at master device. Let B, W, X, U and L denote WBAN, WLAN, WIMAX, UMTS and LTE-A respectively with the following traffic priority orders:

$B = (B_7, B_5, B_3, B_1) = (EM, MD, AV, nMD)$

$W = (w_1, w_2, w_3, w_4) = (AC_{VO}, AC_{VI}, AC_{BE}, AC_{BK}),$

$X = (x_1, x_2, x_3, x_4, x_5) = (UGS, ertPS, rtPS, nrtPS, BE),$

$U = (u_1, u_2, u_3, u_4) = (CO, ST, IN, BK),$

$L = (l_1, l_2, l_3, l_4, l_5, l_6, l_7, l_8, l_9) = (QCI_5, QCI_1, QCI_3, QCI_2, QCI_4, QCI_6, QCI_7, QCI_8, QCI_9).$

The mapping function $Q_B(i)$ is defined based on different typical services following Equation 3.15 and Table 3.1 illustrates the mapping function values.

$$Q_B(i) = \begin{cases} (B_7, B_5, B_3, B_1) = (w_1, w_2, w_3, w_4), \text{when } i = W \\ (B_7, B_5, B_3, B_1) = (x_1, x_2, x_3, x_4), \text{when } i = X \\ (B_7, B_5, B_3, B_1) = (u_1, u_2, u_3, u_4), \text{when } i = U \\ (B_7, B_5, B_3, B_1) = (l_1, l_4, l_2, l_3), \text{when } i = L \end{cases} \tag{3.15}$$

TABLE 3.1: QoS mapping for WBAN and some wireless networks

	mapped WBAN	**WLAN**	**WIMAX**	**UMTS**	**LTE-A**	**Typical services**
High Priority	7-EM	AC_{VO}	UGS	CO	$2 - QCI_1$	Voice live, call
$\Uparrow$	5-MD	AC_{VI}	ertPS	ST	$3 - QCI_3$	Real time gaming
$\Uparrow$	3-AV	AC_{BK}	rtPS	IN	$4 - QCI_2$	Video live, video call
Low Priority	1-nMD	AC_{BE}	nrtPS	BK	$5 - QCI_4$	Non live video, streaming

In order to support the PWRR analytical results, some simulations have been performed in NS3 simulator to see the behavior of LTE, WIMAX and WIFI when the PWRR strategy and the Q_B function are implemented. Therefore the E2E delay is evaluated assuming that all traffic classes have the same arrival rate and the same service time.

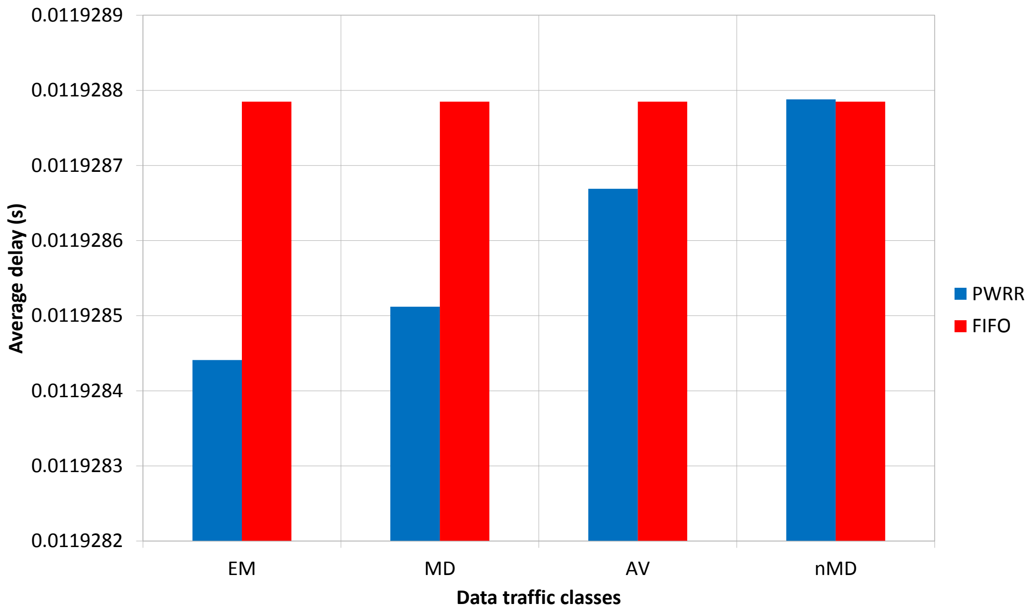

FIGURE 3.9: Average end to end Delay Delay in LTE

Figure 3.9, Figure 3.10 and Figure 3.11 show the average end-to-end delay of all data traffic classes in LTE, WIMAX and WIFI respectively. In fact, the proposed scheduling scheme has considerably mitigated the delay of EM and MD traffic classes in the three considered scenarios, and the EM traffic classes still have the better delay than all, especially than MD traffic classes. This is due to the PS scheme where EM traffic classes keep the high priority over MD traffic classes. Moreover, one can observe that the EM end-to-end delay decreases almost by half in PWRR than in FIFO scheme.

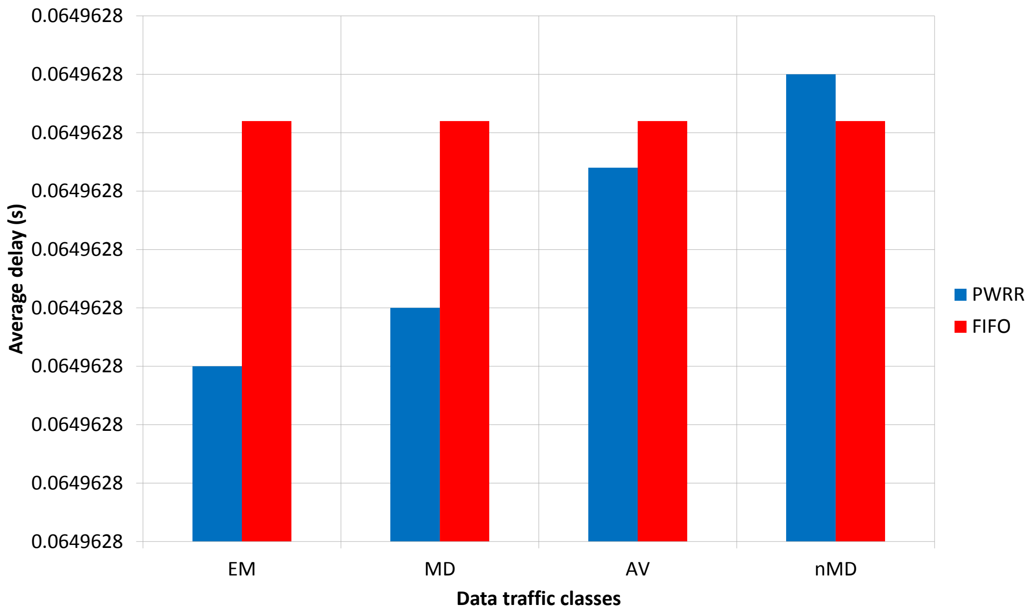

FIGURE 3.10: Average end to end Delay Delay in WIMAX

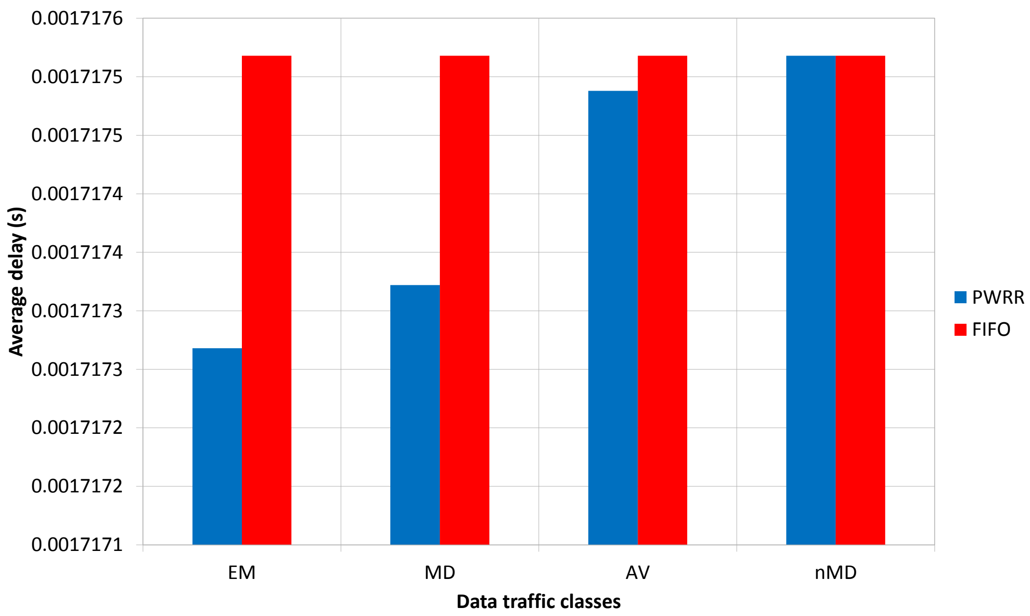

FIGURE 3.11: Average end to end Delay in WIFI

3.5 Conclusions

This chapter presents a survey of achieved and running projects in the field of WBAN based RMS and other related works. It also defines a general model of a WBAN-MS by proposing a 4-tiers architecture expected to offer much flexibility and allow much mobility to tiers likely to move. As the WBAN and its peer-networks present a wide heterogeneity, a bridge structure is designed focusing on the scheduling mechanism, QoS mapping function and delay especially for data traffic classes very sensitive to loss or delay. It is the case of data related to health or real-time applications. For this end, it was suggested to implement the Priority Weighted-Round Robin as a scheduling strategy to force off WBAN schedulers to consider application requirements. Analysis and simulations show that PWRR mitigates so much the waiting time of time-sensitive data traffic classes up to reduce more than half for EM traffic classes and more or less a third for MD traffic classes.

However, seeking for rising the quality of the system, there remain some features such as energy consumption, throughput, etc. to improve. Therefore the next chapter is focusing on cooperation.

Chapter 4

Cooperation Mechanisms for WBAN

4.1 Introduction

Within a WBAN, the sensor node's location can be far from the coordinator or node-coordinator link be blocked up due to different body postures, up to make the link quality worse and thus be out of reach. In that situation a helper node is required to relay data between the hub and the node. It is the case when a WBAN subject is making household chores. Although a simple one-hop topology is widely adopted for WBAN, it is insufficient to achieve WBAN reliability requirements since the shadow effect occurred due to body tissues and body motion is strong what can lead to signal attenuation. Besides, it is shown that a WBAN having set a single-hop star topology communication is likely to promote large path losses [68] and the interference in closest WBANs and nodes goes increasingly. Hence, the standard [2] defines an optional two-hop cooperative WBAN communication to overcome that issue. In addition, many efforts have been made to face up important WBAN challenges such as reliability, energy efficiency, interference mitigation and supporting multi rates throughput [69].

Considering the case of a group of WBANs such as elders in retirement home or athletes on work out, it is important to ensure data transmission even in the critical situation: connection lost, energy lack or poor network coverage. Taking advantages of the group interactions, relaying and cooperation would solve those issues and increase packet delivery ratio while optimizing energy consumption. When the communication link is between the nodes within the same WBAN, we call it intra WBAN cooperation whereas for others communication links are related to inter WBANs cooperation.

Throughout this chapter, cooperation motivations are first given, a network of WBANs is then defined with its related advantages and challenges. Different cases of cooperation are further investigated. Our cooperative proposals for intra WBAN communication as Decode and Merge technique to increase data exchange and for inter WBANs communication to optimize energy consumption and increase network lifetime are finally described.

4.2 Why, when and how to cooperate?

As WBAN subject can take may positions or make different motions with limbs such patient in household chores, sportsmen in workout, firefighters and soldiers in battle field, these weak communication links can be blocked or attenuated due to path loss resulting from the body tissue. For example, as illustrated by the Figure 4.1, moving from (a) to (b) some links are blocked or weakened leading to intra WBAN cooperation by creating new links with relays:

In (a): Link B – H blocked $\rightarrow$ B – D – H; link A – H weak $\rightarrow$ A – C – H
In (b): Link D – H blocked $\rightarrow$ D – C – H; link A – H weak $\rightarrow$ A – C – H, A – B – H

In fact, the propagation of wireless signals in body area communications experiences fading due to many factors such as diffraction, reflection, energy absorption by the body tissue, and shadowing by body and clothes [70]. Generally, the location of the transceiver on/in human body, the posture/movement of human body, and the working frequency are the

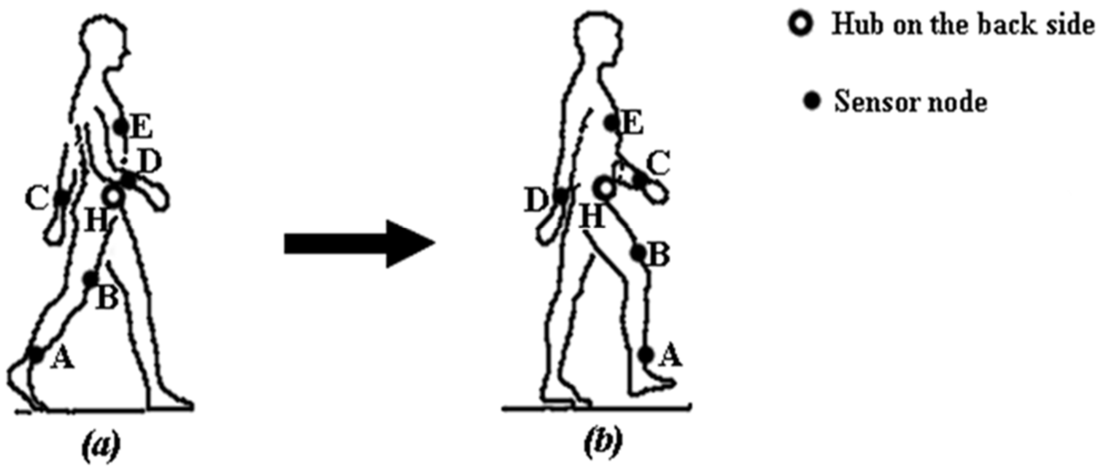

FIGURE 4.1: Effect of the blocking correlation between direct and indirect paths

main causes of the fading (i.e., the large-scale and small-scale fading) [71]. Therefore, when a link is blocked or very weak, a sensor node could find another sensor node as a helper to send his data to the gateway. Another reason to cooperate results in the situation occurs when the link is very weak, i.e, with a very low RSSI. The sensor node sends his data with many tries and timeouts; in this situation the sensor node wastes much energy and time.

However, in the environment with many WBANs, i.e. the place where WBAN subjects are gathered and work together, the inter WBAN cooperation need should come out in the cases of connection loss, distance to access point or energy lack. The cooperation may thus be carried out at three different communication levels (Figure 4.2) with some scenarios of solutions as explained in the following paragraphs.

1. **Coordinator-Coordinator:** A coordinator of a given WBAN should need help from other WBANs for data conveying in the following cases:

    - *Connection loss:* connection to remote station sometimes breaks down and when a coordinator has collected data to send, it can seek help from its neighbors.

- *Distance to access point:* the more the transmission distance increases, the more the energy consumption and path loss increases too what weakens the communication link . Thus, when a coordinator is far from the access point, it can use distance information and/or link quality from others and cooperate with them to convey its data.

2. **Coordinator-Node:** It can happen that a coordinator is unable to serve as a gateway for its sensor nodes because its battery depletion. In this case, it shall inform its sensor nodes before it goes off by supplying information relating to possible better routes and the nodes can ask cooperation service from the closest coordinator.

3. **Node-Node:** In the case of transmission incapability of neighbor coordinators, their respective nodes shall cooperate as follows: a node of $WBAN_1$ has its coordinator power down and a node of $WBAN_2$ is in the same situation except that it can ask for help from the coordinator of $WBAN_3$ which is near and whose residual energy is enough for that service. Therefore, the node of $WBAN1$ can contact the node of $WBAN_2$ to convey its data to the coordinator of $WBAN_3$. When sensor nodes of different WBANs have to cooperate, their group must be composed of at least three WBANs. We assume that all the WBANs of the group implement the same security policy and the same application. Also, only wearable sensors with a long sensing period can be involved in this cooperation.

4.2.1 The NetBAN

For many cases of application areas such as nursing home, military/firefighting, game in groups, etc. the WBAN subjects form a special ad-hoc network (Figure 4.2) and cooperate in exchanging or relaying data to achieve many goals: optimize energy consumption, prolong network lifetime, allow group navigation, improve data delivery, etc. This concept of cooperation is called here *"NetBAN"*.

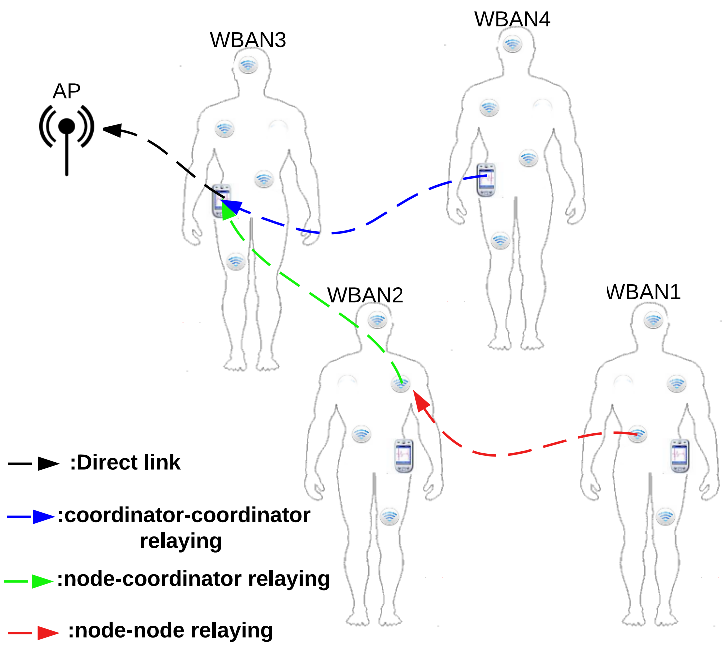

FIGURE 4.2: An example of netBAN communications

To achieve the NetBAN's goals however, protocol layers such as network and data link layers shall be involved in routing and scheduling data transmission. Thus, some routing protocols and algorithms have been proposed for a intra-WBAN transmission to convey data from sensor nodes to the coordinator either via a relay node [72] or by direct link. However, according to our knowledge, there is so far no technique proposed to route packets for a group of WBANs if needed. Furthermore, mobile devices such as smart phones of nowadays are getting more intelligent and consequently invading daily human life but they still have battery problem as their lifetime is only for a few hours. Power saving is a main challenge for wearable devices and more specifically for implants as the energy shortage would affect the main expected applications of these devices. It is therefore fashionable to develop low energy consumer technologies particularly in WBAN area. It is also mandatory to develop protocols and algorithms that minimize energy consumption to achieve the network long lifetime.

The NetBAN is a special ad-hoc network given the different communication paths expected to occur. Unlike the simple ad-hoc network where communication links are homogeneous, a NetBAN has heterogeneous communication links: coordinator to coordinator, Node to coordinator or Node to Node.

4.2.2 Advantages and implementation challenges

As stated before, the NetBAN intends to achieve certain goals such as minimize energy consumption, maximize network lifetime, share alert messages, ensure data delivery, permit group navigation and cooperative localization etc. The reader should note that the network lifetime means here the network operating duration until a sensor node gets unable to transmit its data either by its coordinator or via another coordinator by relaying; unlike the classic ad-hoc networks where the lifetime counter stops at the moment the first node steps down due to battery depletion. To achieve the aforementioned goals, there are many requirements challenging the implementation of this kind of network to make it work properly. In fact security when relaying packets is an important challenge if subjects involved in the group are crowded with others the packets could be intercepted. The routing mechanisms and cross-layer to accommodate routing mechanisms to MAC protocol are also other challenges. However, the NetBAN intends to offer many and interesting benefits that the challenges could not prevent its implementation given that they can be addressed. Cooperation in a NetBAN can be either permanent and/or triggered. Nevertheless, permanent cooperation and triggered cooperation are not mutually exclusive in the way that the first is expected to improve the quality of service (QoS) of a dedicated application and the second intends to improve the QoS in terms of parameters affecting the overall working mechanism.

4.2.3 Permanent cooperation

Many applications and services related to NetBAN require permanent cooperative communication. It is the case of group navigation where each subject in the group needs to share information with others to allow cooperative localization or alert messaging.
Let us assume for instance that a sensor node senses an electrocardiogram (ECG) value exceeding the normal threshold. It sends it directly to the coordinator which in return shares this with his neighbors and transmits it to the processing remote station. Depending on the application, the shared message shall alert all neighbor WBANs. Alert messaging is a key functionality for monitoring systems such in heart attack neighbors shall get alerted and intervene before emergency service, or in military battlefield when a soldier is injured his team mates should be alerted. A coordinator involved in this cooperative needs to have a strong scheduling mechanism based on time or event.

Furthermore, as a sensor node is composed of two main parts, one for sensing and an other a radio transmission, it is also necessary to optimize the use of the latter to reduce energy consumption. In some other situations, it is needed to set a two-hop topology to ensure the coverage of all nodes. Thus, the relayed node and the relaying node on one hand, and the relaying node and the coordinator on the other hand, are in permanent cooperative transmission.

4.2.4 Triggered cooperation

In some cases, cooperative communication is prompted by battery depletion or connection loss or weakness, what means that this cooperation case is not involved in if there is no energy or connection issue. Therefore it steps in from a certain threshold of residual energy or transmission link quality. In fact, taking the same case as previously, of elders gathered in a retirement home or athletes in workout or else military/firefighters on battlefield and all equipped with WBANs, the cooperation need can occur whether when the residual energy is not enough (under a given threshold) or when connection is lost (the link quality is under a certain threshold).

4.3 Intra WBAN cooperation

The coexistence of many WBANs is still a major challenge due to interference that occurs while exchanging information. In [73] was investigated the possible coexistence of multiple mobile WBANs where one WBAN sets cooperative communication with two relays and it was shown that this two-hop topology improves better co-channel interference mitigation than the single-hop topology. Moreover, the same authors extended their study and found that the opportunistic relaying reduces significantly interference [74]. Importance in setting this topology has been also explored by considering whether the WBAN PHY is narrow-band [75–78] or UWB [79] and in all these studies significant performance benefits have been achieved. However, no works on the two-hop topology for intra WBAN communication, have so far taken into consideration transmissions flow optimization.
Despite of talking about interference mitigation and performance improvement in WBAN, the energy optimization has to be taken into account to assure the reasonable network lifetime. In fact, many efforts have been made in developing protocols that minimize energy consumption and the MAC layer protocol is likely to provide the best tools to achieve this goal. Thus, many energy efficient MAC protocols for WBAN and requirements of a good WBAN MAC protocol have been identified and various approaches of WBAN MAC protocols are comparatively analyzed. Therefore the authors of [80] proposed a unified hybrid and cooperative MAC to satisfy WBANs requirements such as guaranteed QoS, multiple physical layer support and adaptability to traffic variations. Authors in [81] elaborated a survey on WBAN MAC protocols for energy efficiency and presented a cross layer architecture as a good way to achieve important energy gain. Furthermore, some authors propose to act on the data transmission to increase network lifetime. It is the case of Joint Aggregation MAC [26] that is designed to work for data collection tree.

Apart from interference occurred in the coexistence of WBANs or nodes and energy optimization, cooperation and relaying are also interesting aspects especially in WBAN communication. Cooperation can be relaying and vice versa according to the mechanisms set to exchange information within the network. Cooperative relaying was studied in [27] to evaluate energy efficiency performance and it was found that multi-hop cooperation is more energy efficient that single-hop communication. Contrary to Huang et al.[27], Braem et al. [82] evaluated the difference of performances between static relaying and dynamic cooperative relaying for short-range high path loss sensor networks and the conclusion remains that multi-hop is more efficient than one-hop. However, in our knowledge no work has so far studied the possibility to enhance data flow or evaluate transmission performance of WBAN cooperation while keeping energy optimization, what our proposal focuses on. In addition, due to different body postures and movements, the direct links between sensors are frequently blocked resulting in a higher packet error rate (PER). Miyu and Shinsuke [83] proposed a cooperative relaying scheme for lowering the PER in a WBAN. For each node on a human body, the proposed scheme smartly and autonomously assigns a node as a cooperator out of other nodes and the cooperator relays packets from the node for a BAN coordinator to overcome the problem of blocking of direct link between them. It is in the specific scope of intra WBAN communication that we suggest a cooperative relaying mechanism based on MAC protocol, that merges data at the relaying node to increase data exchange without overloading the whole network flow with control packets. In addition, we propose an algorithm for the initialization phase when a two hop topology is set. We define a Decode and Merge technique that maintains the relaying mode by merging frames from relayed and relaying nodes. By doing so, a MAC format resizing is required. Apart from maintaining cooperative communication, this technique increases the general throughput without increasing the energy consumption, management and control flows. Furthermore, it increases the ability to resist against interference. Our proposed solution falls in cooperation and relaying by resizing MAC frame format defined by the standard, merging packets to reduce transmission flow and therefore increase data transmission rate while optimizing energy consumption. Regarding the MAC Frame, its format consists of fixed-length MAC header and Frame Check Sequence (FCS) and a variable-length MAC frame body as it is illustrated by Figure 4.3.

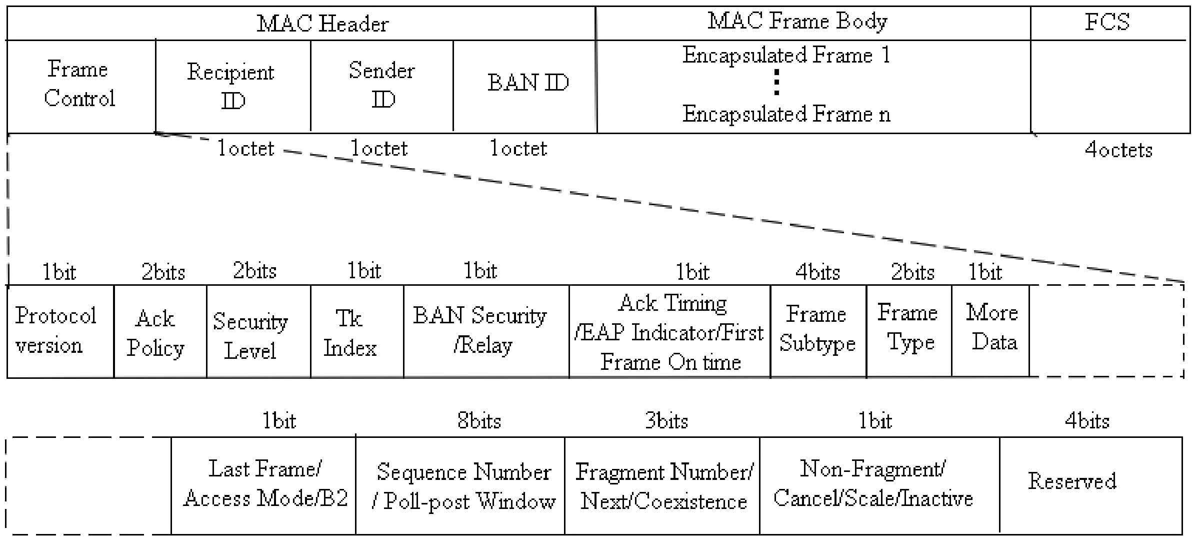

Figure 4.3: IEEE 802.15.6 MAC Frame format

In the two-hop extension topology, it is stipulated that a relayed MAC Frame has to be encapsulated in a relaying MAC Frame as formatted in Figure 4.4. This way of encapsulation reduces the space of payload given the redundancy of some header fields of the encapsulated frame in the resultant frame. In this chapter we propose a new mechanism of encapsulation at the relay node.

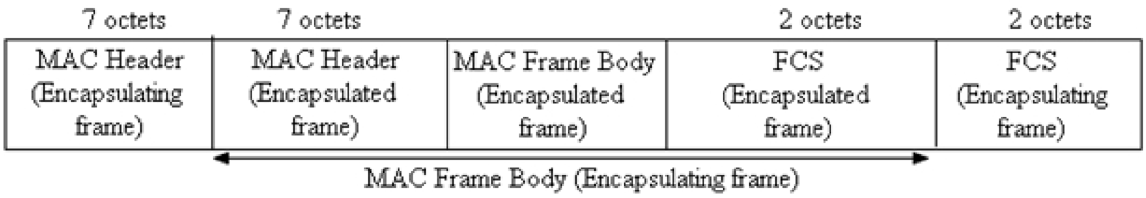

Figure 4.4: General IEEE 802.15.6 frame encapsulation format

4.3.1 Proposed approach

Our proposed approach is based on two main ideas: combining frames from relayed nodes into one at relay node and resizing MAC frame format to gain space to increase data flow.

4.3.1.1 MAC Frame reformatting

As observations from the MAC formatting described in the previous section, there is redundancy of information in some fields such as BAN ID, Receipt ID, Sender ID, Reserved, etc. Furthermore, a frame of 255 octets of frame body and 9 octets of frame header is too long for physiological data like temperature, glycemic level, heartbeat, etc. except the case of multimedia data. Therefore we propose to merge bit per bit frames from the relayed nodes into a single frame at a relaying node before getting to the hub. This merging operation is like interleaving operation with uniform inter-leaver and benefits for instance from burst error correcting advantages. Thus, when a node set as relay receives a packet to relay, it checks its integrity using the FCS field and removes some unnecessary fields. If it is not in the transmission schedule, it pushes it into the buffer stack. But, if it is possible to send, it checks whether the packet is urgent or the buffer is empty. If so, it encapsulates and sends it straightway. If not, it merges it with buffer packets and sets MFN (Merged Frames Number) field of the resultant frame with the number of merged frames before it sends it. Accordingly, the merging process is done as follows:
Given m MAC frames $R_1, \dots, R_i \dots, R_m$ of length n each, and whose bits are ordered as $R_i = b_{i1}, \dots, b_{in}$, the coded relayed MAC frame body after merging is set as follows:
$R = B_1, \dots, B_j, \dots, B_n$ where $B_j = b_{1j}, \dots, b_{ij}, \dots, b_{mj}$
Example: $m = 2, n = 8$
$R_1 : \underbrace{0}_{b_{11}}1001100 \quad and \quad R_2 : \underbrace{1}_{b_{21}}0101010$
$R : \underbrace{01}_{B_1=b_{11}b_{21}} \quad 10010011100100$

Figure 4.5 and Algorithm 1 illustrate the merging frame format and process respectively.

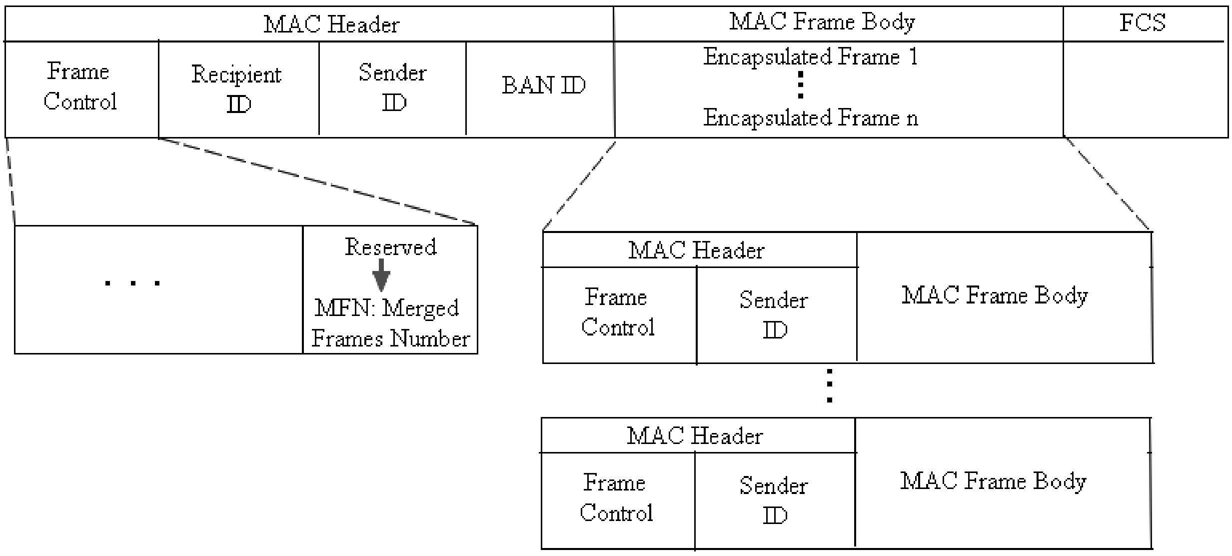

FIGURE 4.5: General merged frame encapsulation format

Algorithm 1 Decode and Merge

```
if a node receives a packet then
    Check packet integrity with FCS and Decode
    Drop useless fields: Recipient ID, BAN ID, FCS
    if Received Packet is not Emergency AND Buffer is not empty then
        Merge packets (received packet with buffer packets)
        Encapsulate
    else
        Encapsulate
    end if
    Send packet
end if
```

This process follows some principles and assumptions:

1. The Frames to be merged must be from the closest traffic type or have the same user priority (UP) if this latter is above 4. Furthermore, they must not exceed 255 octets long if merged. For our simulations we considered all frames as being from the same traffic type and same UP.

2. For data packets, the relaying is only ascending, i.e. from nodes to the hub and for INIT packet, the relaying is only descending, i.e. from the hub to nodes.

4.3.1.2 Frame transmission scheme

The algorithm 2 assumes that each node can reach a hub and vice versa, in at most two hops. A same idea of algorithm has been developed in [72] but that algorithm is for routing at network layer, therefore we chose a technique that works at MAC layer. In fact, by using the IEEE 802.15.6 MAC frame format, a Hub broadcasts an initialization beacon to discover the nodes by setting Relay field to 0. To define this initialization beacon we used a reserved field in MAC Frame Control as a management subtype with Frame Subtype value of **0111** and **INIT** as Frame subtype name.

Algorithm 2 Initialization phase

```
The Hub broadcasts an INIT beacon with Relay ← 0
if a node receives an INIT beacon then
    if Relay == 0 and is the first then
        Use it
        Relay it with Relay ← 1 and SenderAddress ← NodeID
    else
        if Is the first then
            Use it
        else
            if the previous has Relay == 0 then
                Discard it
            else
                Compare its LQI with the LQI of the previous
                Choose the best link, i.e. the Relay Node
                Use the chosen
            end if
        end if
    end if
end if
```

When a node receives an INIT beacon with Relay set to 0 it understands that it is at one hop from the hub therefore it uses it and forwards it after setting “SenderAddress” to its ID and Relay field to 1. When a node receives an INIT beacon with Relay set 1 as illustrated by Algorithm 1 and Figure 4.5 it understands that it is at two hops from the hub and discards it. If it has previously received an INIT beacon, it keeps the best link to the source for its subsequent transmissions using LQI (Link Quality Indicator).

If a node finds it is capable of relaying, it sets Relay field to 1 and broadcasts a beacon to notify others. Thus, the relaying capability is calculated taking into account the amount of frames in the buffer, the energy and the quality link according to the formula expressed by Equation 4.1.

Therefore a node is capable of relaying when:

$$FE > 0 \quad AND \quad LQI > TV \tag{4.1}$$

Where $FE = RE - 8 \times Pn \times Fs \times Eb - TE$

With:
FE: Functional Energy that allows a node to relay, RE: Residual Energy, energy left in the battery; TE: Threshold Energy, minimum energy that allows to send SOS message; Pn: Packet number, the number of packets in the buffer; Fs: Frame size (octets), length in octets of the MAC frame; Eb: Energy per bit, energy consumed by a bit sent what is on average 10pJ [84]; TV: Threshold Value, value between 0 and 255 [11]: it was shown in [85] that a LQI of 105 or beyond corresponds to maximum of link delivery ratio in IEEE 802.15.4.

Then, when a node receives a beacon with Relay field set to 1 from an other node with a better link than the one it is connected to, it sets it as its new relay by sending a connection request. Finally, when a node is a relay it uses algorithm 1 to send data to the hub. Algorithm 3 summarizes all this idea. However, due to the constraints of simulation, we chose relay nodes before the simulation start.

Algorithm 3 Cooperation and Relaying

if a node is capable of relaying **then**
  Relay $\leftarrow 1$
  Broadcast a beacon
end if
if a node receives a beacon with *Relay* $== 1$ from best link **then**
  Connection Request
  Transmit data to Relay
end if
if a node is Relay AND Receives Connection Request **then**
  Connection Assignment
  Algorithm 1
end if

4.3.2 Performance evaluation and results discussion

Considering the top part the WBAN depicted by Figure 4.6.a, if the two hop topology is set as defined in the standard, the relay node R will have to transmit 3 frames as illustrated by Figure 4.6.b if it has data to transmit too. However, as shown by Figure 4.6.c, if Decode and Merge Cooperation is applied, only one transmission will be required.

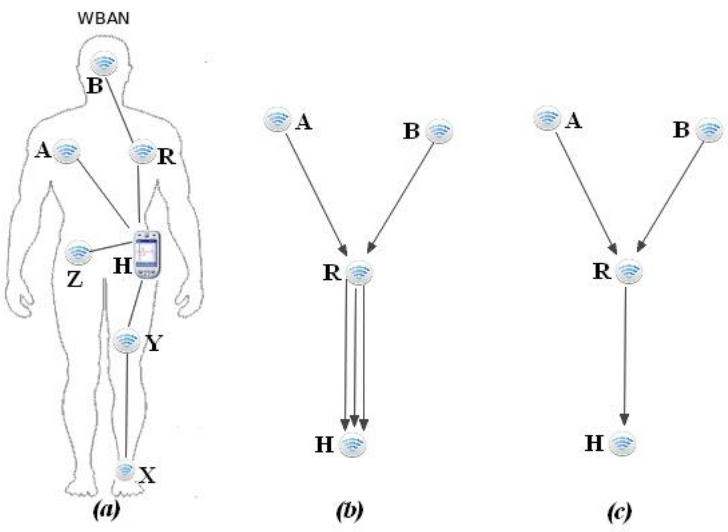

FIGURE 4.6: Example of WBAN with two-hop topology transmission models

In other words, let us take N the number of relayed nodes and r the number of relays with $N > r$. If all the nodes (relayed and relay nodes) have packets to transmit, $N + r$ packets will be delivered to the hub in $2N + r$ transmissions for normal WBAN defined in the standard while the same amount of packets will take only $N + r$ transmissions when using Decode and Merge. Therefore, if $N + r$ packets require $2N + r$ transmissions and T time for the WBAN model defined by the standard, $N + r + N - r = 2N$ packets will be delivered when using Decode and Merge in the same time T, that to say a gain of $N - r$. By generalizing previous results, we have:

-$Packets = PR * T * (N + r)$ without Decode and Merge;

-$Packets = PR * T * 2N$ with Decode and Merge;

-$Gain = \frac{N-r}{2N}$ what gives about 25.00% in our case.

Where PR is packet rate.

Assuming that the nodes have all the capacity to overcome saturation, this gain depends on the relation $\frac{N-r}{2N}$ that increases when N increases for a given value of r. Table 4.1 gives for example the gains for $N \leq 6$.

TABLE 4.1: Estimated gains (%) for $N \leq 6$

r	**N=2**	**N=3**	**N=4**	**N=5**	**N=6**
1	25.00	33.33	37.50	40.00	41.67
2	-	16.67	25.00	30.00	33.33
3	-	-	12.50	20.00	25.00
4	-	-	-	10.00	16.67
5	-	-	-	-	08.33

As simulation tool, we used Castalia [86], a network simulator based on omnet++ [87] and dedicated to low range sensor networks. Herein, some performance evaluation criteria are considered: general throughput (exchanged packets), energy consumption and transmission quality as interference variation. By exchanged packets we mean the amount of both transmitted and received packets including control, management and data packets. In addition, transmission quality refers to either success or failure of packets transmission due to collision, low sensitivity or interference. Simulation parameters set in table

4.2 include sensor data rate, sensor initial energy and simulation duration values which are simulator default parameters, as we found that their replacement has no influence on expected results and the results depend on the merging and the number of merged frames.

TABLE 4.2: Simulation parameters

Node	**Type**	**Energy**	**simulation time**	**PR**
Node 0	Coordinator	18720 J	50 s	5 kbps
Node 1	relay node			
Node 2	node			
Node 3	relay node			
Node 4	node			
Node 5	node			

Results depicted by Figure 4.7 show how our solution outperforms the standard model if we consider the amount of transmitted data packets. In fact, the node 0 which is set as a hub has indeed a big amount of data packets because it is a only one node set as a receiver. In this simulation case, the overall gain calculated from data packets is about 23 % . The node 1 and node 3 which are set as relays have increased their data flows as they relay data from nodes 2, 4 and 5 and their own data. The frames combination at those relayed nodes makes the increase less important in data flow than the general flow. However this does not have a bad impact on the general quality of transmission considering results in Figure 4.8 and Figure 4.9.

Ultimately, during a same simulation duration (50 s), the amount of data packets (Figure 4.7) is higher for our proposition than the standard model. Hereby, our proposal improves data transmission. Figure 4.8 illustrates failure and success transmissions. Failure is due to either below sensitivity, or interference or collision. Comparing our proposition with the standard model, success transmissions are higher and failure transmissions little in our proposal than in the standard model. In addition, relay nodes seem to promote the success of other nodes' transmissions. It is an observation from Figure 4.9 that depicts the transmission success despite of interference: the gain is important for other nodes as they are helped by the relay nodes but a slight regression is observed at the relay nodes. This can be explained by the fact that they have to manage packet flows from and to the

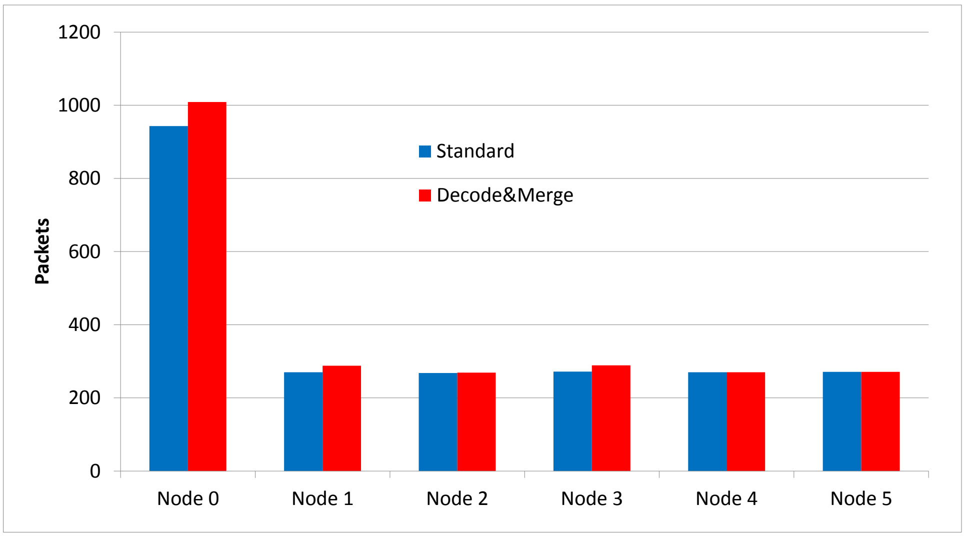

FIGURE 4.7: Exchanged data packets

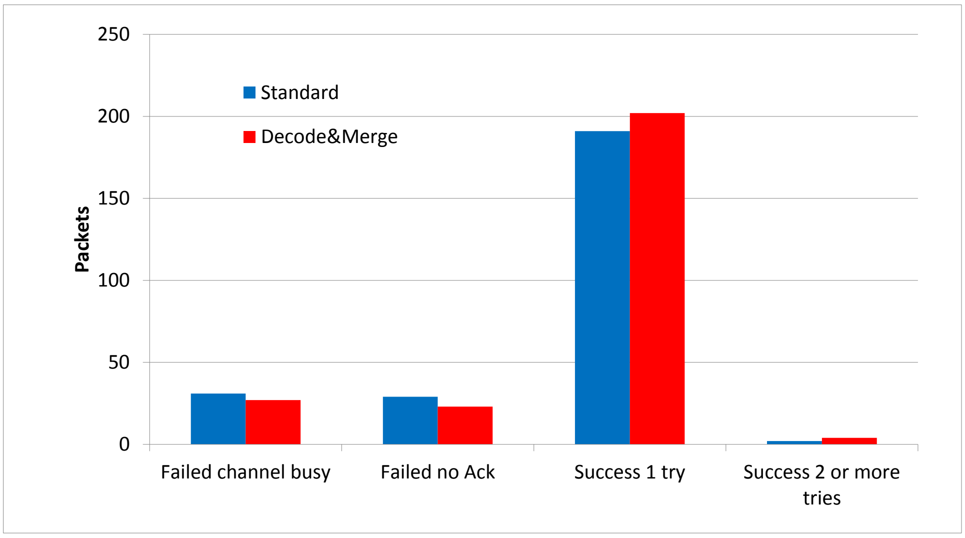

FIGURE 4.8: Failure and success transmissions

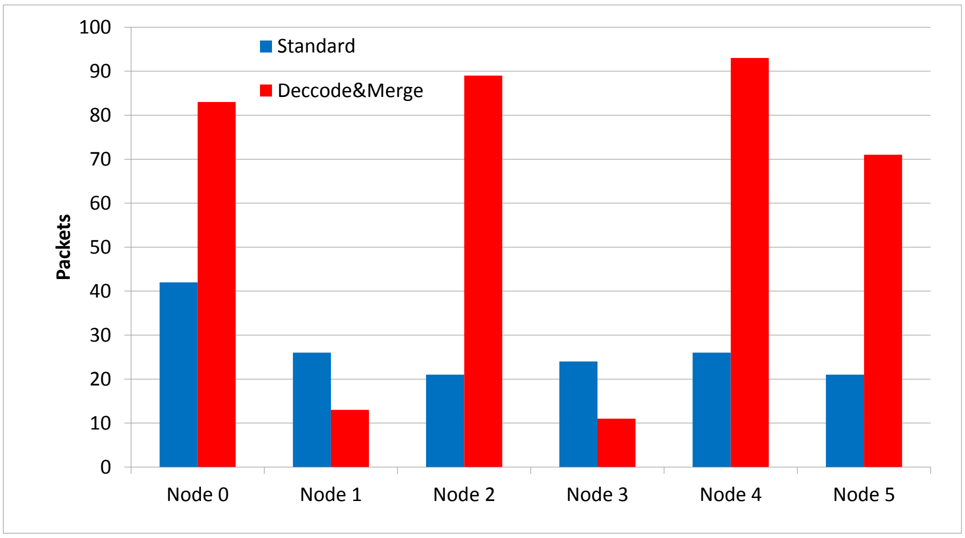

FIGURE 4.9: Packets delivered despite interference

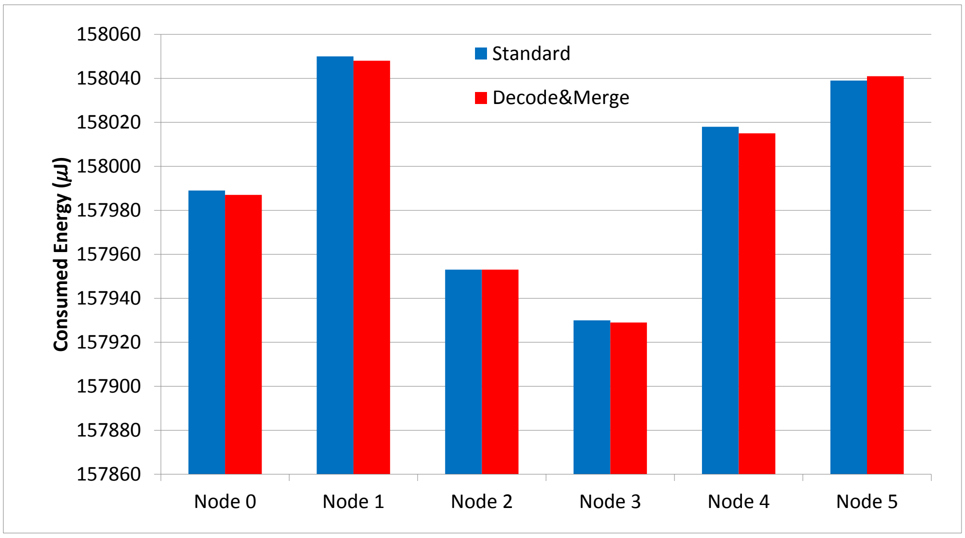

FIGURE 4.10: Consumed energy

hub as well as from and to the sensor nodes. Hence, we get to the same conclusion as previous work that two-hop topology in more efficient than one-hop in terms of interference mitigation.

Regarding energy consumption, results depicted by Figure 4.10 show that our proposition maintained the energy consumption level and some micro joules have decreased. This results in the fact that some nodes such as relays send few data packets than others but these packets are resultant from other packets combination.

4.4 Inter WBANs cooperation

Some authors such as in [72] proposed routing mechanisms for intra WBAN routing to increase throughput, energy-awareness [88, 89] and network lifetime [90] and treated inter WBAN security [91], but routing mechanism for a group of WBANs by considering energy efficiency is so far not proposed.

Many energy aware routing protocols for WBAN have been proposed and the routing is only for nodes within a WBAN. Related works differ from each other by considering a factor helping to save energy. Therefore the study in [92] focuses on energy efficient fuzzy routing protocol. The main purpose of the proposed fuzzy routing is to determine the cost value of a link between two sensor nodes such that the life of a sensor network is maximized. The proposed protocol assumes that the sensors know their location information and have access to their own battery level so as to adjust transmit power according to the distance between the source and the destination. Authors found that Protocol based on fuzzy inference system computation reduces power consumption when compared to classical routing protocol.
Authors in [28] considered the mobility factor in proposing a new routing protocol for heterogeneous Wireless Body Area Sensor Networks (WBASNs), the Mobility-supporting Adaptive Threshold-based Thermal-aware Energy-efficient Multi-hop ProTocol (M-ATTEMPT)

that supports mobility of human body with energy management. It is also the case in [93] where first shows that the minimum energy routing schemes in the literature could fail without considering the routing overhead involved and node mobility. They then proposed a more accurate analytical model to track the energy consumptions due to various factors and a simple energy-efficient routing scheme Progressive Energy Efficient Routing (PEER) to improve the performance during path discovery and in mobility scenarios. However, the link cost is the main factor in [90]: Global routing protocol in wireless body area networks is considered and augmented with a novel link cost function. This cost function was designed to avoid relaying through nodes which spent more accumulated energy than others. Thus, Global routing using Dijkstra's algorithm was augmented with that novel cost function and as result, each node's link costs are dynamically changed to balance energy use in the network what increases network lifetime.

The concept of NetBAN (inter BANs communication) comes down to Mobile Ad-hoc NETwork (MANET) or WSN by considering a BAN coordinator as a node of MANET or WSN in regard of all WBAN specificities. Therefore the proposed routing protocols and algorithms for these two last areas can be adapted to NetBAN. In [94] energy-aware routing strategy for WSNs was presented. The approach optimizes the use of various energy types within a network based a on maintenance schedule for each sub-network. By optimizing energy use for the nodes, the network is supposed to prolong its lifetime. Thus, [95] made performances comparison of three routing protocols in terms of network lifetime for the same network scenario: Dynamic Source Routing (DSR) and Minimum Maximum Battery cost Routing (MMBCR), Ad-hoc OnDemand Distance Vector Routing Protocol (AODV). It was found that MMBCR improves network lifetime by selecting route with maximum battery capacity.

In the same idea of prolonging network lifetime, [96] proposed an energy efficient optimized link state routing (EE-OLSR) by modifying the way the multipoint relays are selected and the route is built so as to offer network scalability and increase network lifetime. Also, LAEEBA (Link-Aware and Energy Efficient scheme for Body Area Networks) was proposed in [97] as a reliable, path loss efficient and high throughput routing protocol for WBANs. To reduce path-loss effects and increase network lifetime, single-hop and multi-hop communication schemes have been used taking advantages of their characteristics. The relay selection function takes maximum residual energy and minimum distance to sink as main criteria. LAEEBA protocol maximizes the network stability period and increases nodes lifetime.

Furthermore, in [98] was proposed an energy efficient cluster-based routing protocol for WBANs, named as semi-autonomous adaptive routing in wireless body area network (SEA-BAN) that distributes the energy dissipation evenly among the body nodes and enhances the network lifetime. It is both a cluster-based and one/multi-hop transmission based routing protocol using energy level and spatial information of the body nodes to formalize an adaptive routing. In comparison with multi-hop transmission model, SEA-BAN doubly improves the network lifetime.
These interesting works are unfortunately limited either to intra WBAN routing or to inter WBANs exclusively. None is so far focused on taking advantages of combination of both intra and inter WBAN routing to insure data delivery and network lifetime, what is the purpose of this work. Regarding the wireless sensor network (WSN) in general and particularly WBAN, it is mandatory to develop protocols and algorithms that minimize energy consumption to achieve a long life of node's battery especially for implants. IEEE 802.15.6 standard seems to offer opportunities to increase data flow while optimizing energy consumption. Moreover, as the radio part of the node is big energy consumer, it is likely to optimize its usage by limiting transmissions or sometimes turning it on/off when necessary. In the following, we will focus on the triggered cooperation by proposing a routing solution based on energy optimization.

4.4.1 NetBAN routing solution with energy awareness

This NetBAN routing mechanism focuses on two main points: The first is the network lifetime prolongation by energy consumption optimization. The OLSR protocol is modified to energy-aware OLSR (EA-OLSR) by defining a multipoint relays (MPRs) selection algorithm based on energy monitoring and the routing table computation is modified. The second is data delivery mechanism in even difficult network conditions: cooperative transmission shall occur in three communication levels, i.e. coordinator to coordinator, node to coordinator and node to node. In the general scenario, sensor nodes are connected to the coordinator in star topology way and the coordinator is connected to a gateway in the same way (star topology). The coordinator shall switch to ad-hoc configuration when he looses connection and when his energy level reaches the $StopThreshold$, he shall not accept any relay transmission from other coordinators but rarely from sensor nodes.

4.4.1.1 EA-OLSR

The Optimized Link State Routing (OLSR) protocol [99] is a robust routing protocol relying on optimization of the route between a source and destination in terms of number of hops. The OLSR strength is based on the concept of selection of MPRs [100]. The MPRs nodes are selected to forward messages during the flooding process instead of letting all nodes to do so, what substantially reduces the packets overhead compared to a classical flooding mechanism. Also, these MPR nodes are used to build data transmission routes between the source and the destination.
Studies already done to compare OLSR with other routing protocols, OLSR shows interesting results in terms of throughput or delay [101] or else mobility [102]. These results motivated our choice of optimizing OLSR in order to make it more energy efficient and adaptable to the NetBAN case. The energy aware OLSR proposed in this chapter intends to increase the overall network lifetime by balancing consumed energy by each node with

the length of the route. Thus, each node periodically calculates its lifetime using mainly residual energy and packet rate.

Let $RLT_i(t)$ then be a remaining lifetime and $RE_i(t)$ be residual energy of a node i at instant t. Then, the remaining lifetime of a node i at instant t is given by the formula in Equation 4.2.

$$RLTi(t) = \frac{RE_i(t)}{RE_i(t-1) - RE_i(t)} \tag{4.2}$$

There two major contributions with EA-OLSR: MPR selection algorithm and route building heuristic based on Topology Control (TC) packet transmission. In fact, the RLT value is transmitted in the hello packet and used as parameter in MPR nodes election and route building process.

- MPR election algorithm

Unlike Rango et al. [96] who use residual energy to modify its willingness (In OLSR, the Willingness field specifies the will of a node to carry and forward traffic for other nodes), this MPR election algorithm uses the remaining lifetime RLT of each coordinator to make choice of node forwarder by comparing with other coordinators' RLT values. The problem in [96] is that a coordinator can set his willingness to low value whereas other coordinators with high value of willingness could have low lifetime. The principle to select the MPRs is: *choose the smallest set of one-hop neighbors having great remaining lifetime to cover all the two-hop neighbors*. In fact, if two coordinators have the same number of two-hop neighbors, the one with long lifetime will be chosen as depicted in Algorithm 4.

For more clarity before algorithms details, some notations and conventions are set and refer to those used in [103]. Considering a node i, let $N_1(i)$ be the neighborhood of i, the group of nodes which are in i's transmission range and share a bidirectional link with i. Let $N_2(i)$ then be the 2-neighborhood of i, the group of nodes which are neighbors of at least one node of $N_1(i)$ but which do not belong to $N_1(i)$. i.e. $k \in N_2(i) \iff \exists j \in N_1(i) | k \in N_1(j) \land k \notin N_1(i)$

Now, for a node $j \in N_1(i)$, let $d_i^+(j)$ be the number of nodes of $N_2(i)$ which are in $N_1(j)$ but not in $N_1(i)$. i.e. $d_i^+(j) = |N_2(i) \cap N_1(j)|$ and $N_i^1(j) = N_2(i) \cap N_1(j)$

For a node $k \in N_2(i)$, let $d_i^-(k)$ be the number of nodes of $N_1(i)$ which are in $N_1(k)$: $d_i^-(k) = |N_1(i) \cap N_1(k)|$. It denotes the number of nodes in i's neighborhood that i can pass by to reach k Accordingly, $N_i^2(k) = N_1(i) \cap N_1(k)$ denotes the set of nodes in i's neighborhood that i can pass by to reach k

$RLT(i)$ and $w(i)$ are the remaining lifetime and the willingness of the node i respectively.

Algorithm 4 MPR selection algorithm with energy awareness

$\forall j \in N_1(i)$
if $w(j) = 0(WILL\_NEVER)$ **then**
    Remove j from $N_1(i)$
end if
$\forall j \in N_1(i)$
if $\exists k \in N_i^1(k) | d_i^-(k) = 1$ **then**
    Add j in $MPR(i)$
    Remove j from $N_1(i)$ and $N_i^2(k)$ from $N_2(i)$
end if
while $N_2(i) \neq \emptyset$ **do**
    $\forall j \in N_1(i) | d_i^+(j) = max(d_i^+(s), \forall s \in N_2(i))$
    Add j in D
    if $|D| > 1$ & $\exists s \in D | RLT(s) = max(RLT(j), \forall j \in D)$ **then**
        Add s in $MPR(i)$
        Remove s from $N_1(i)$ and $N_i^2(k)$ from $N_2(i)$
    else
        Add j in $MPR(i)$
        Remove j from $N_1(i)$ and $N_i^2(k)$ from $N_2(i)$
    end if
end while

- Route building algorithm

Regarding the route building, the way the TC packet is sent and processed in the classic OLSR is now modified. In fact, the TC packet in the classic OLSR is generated by every node having been chosen as MPR and contains all its neighbor nodes. However, the TC packet in our EA-OLSR is generated by every node and is empty. Additionally, it contains a field of remaining lifetime as in hello packet. It is then broadcast in the network and

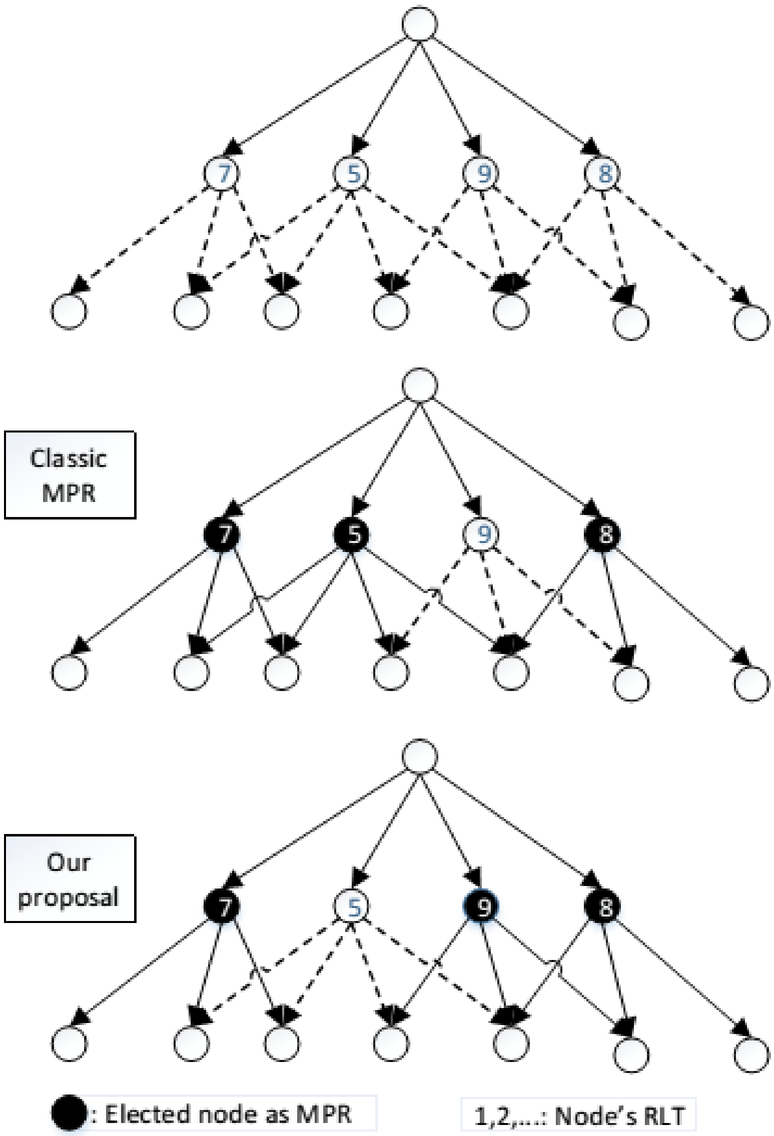

FIGURE 4.11: MPR election techniques comparison

forwarded following the principle of MPR. Each node receiving the packet checks whether it is its generator or it passes by once again and discards it. If not, it shall use it to build the route between the originator and the receiver. It then adds its address, increments the counter and forwards it if it is chosen as an MPR by the sender. Our MPR election policy in comparison with the classic MPR is illustrated by Figure 4.11.

At each coordinator receiving the TC packet, the route table is built following the principle is: *choose the shortest route with the most coordinator lifetime.* That to say, between two routes, the one having the great lifetime sum of all involved coordinators will be considered. Every time that the MPR table values change, the TC packet will be sent and the routing table shall be updated at the TC packet receiver what serves to maintain the routing table.

Unlike the classic OLSR where the route is built according to the optimization of the number of hops, in EA-OLSR the route with great lifetime is chosen.

Algorithm 5 TC packet sending and route building

```
Receive TC packet
if I am its originator then
    Discard
else
    if the packet have already passed (T_seq > ANSN) then
        Discard
    else
        if there exists a route to its originator then
            Compare the new route's lifetime with the old one
            Record the route with maximum lifetime
        end if
    end if
end if
if I am an MPR of its sender then
    Append my address
    Forward the packet
end if
```

Before using EA-OLSR as part of NetBAN routing solution, an energy consumption analysis is first performed by comparing it with classic OLSR and EE-OLSR.

4.4.1.2 NetBAN routing principles

This NetBAN routing proposal described in flow chart Figure 4.12 for node and flow chart Figure 4.13 for coordinator consists of two main parts:The first part concerns the intra-WBAN routing and the second is related to the inter WBANs and off WBAN routing.

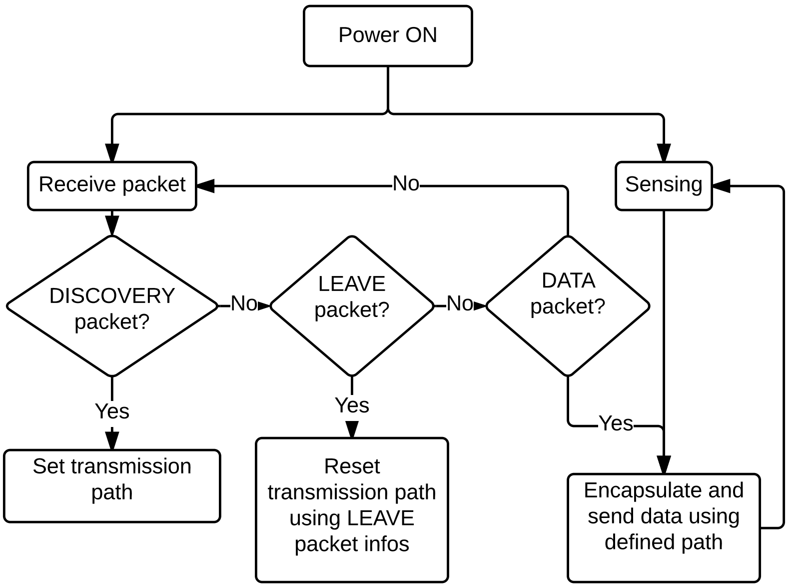

FIGURE 4.12: The node operating mode

The first part consists in a *WBAN initialization*. This part is actually an intra WBAN routing mechanism that was first proposed in [103] but here we add and give more details to make it working at routing layer. Thus, the coordinator broadcasts a *DISCOVERY* packet to discover its nodes. This DISCOVERY packet carries some information such as RE and TTL. Upon receiving a DICOVERY packet with $TTL = 2$, a node decrements TTL by 1 before it rebroadcasts the packet. If a node receives the packet with $TTL = 1$it does not forward it and sets the node it receives the DISCOVERY packet from as an intermediate (a relay) to the coordinator. $TTL = 2$ means that the node is in direct link with the coordinator and $TTL = 1$ means that the node is at two-hop from the coordinator. We assume that there is no need to update the whole WBAN as nodes are set to last as long as possible. This first phase is only valid for the NetBAN while the following should be used in any MANET for energy awareness.

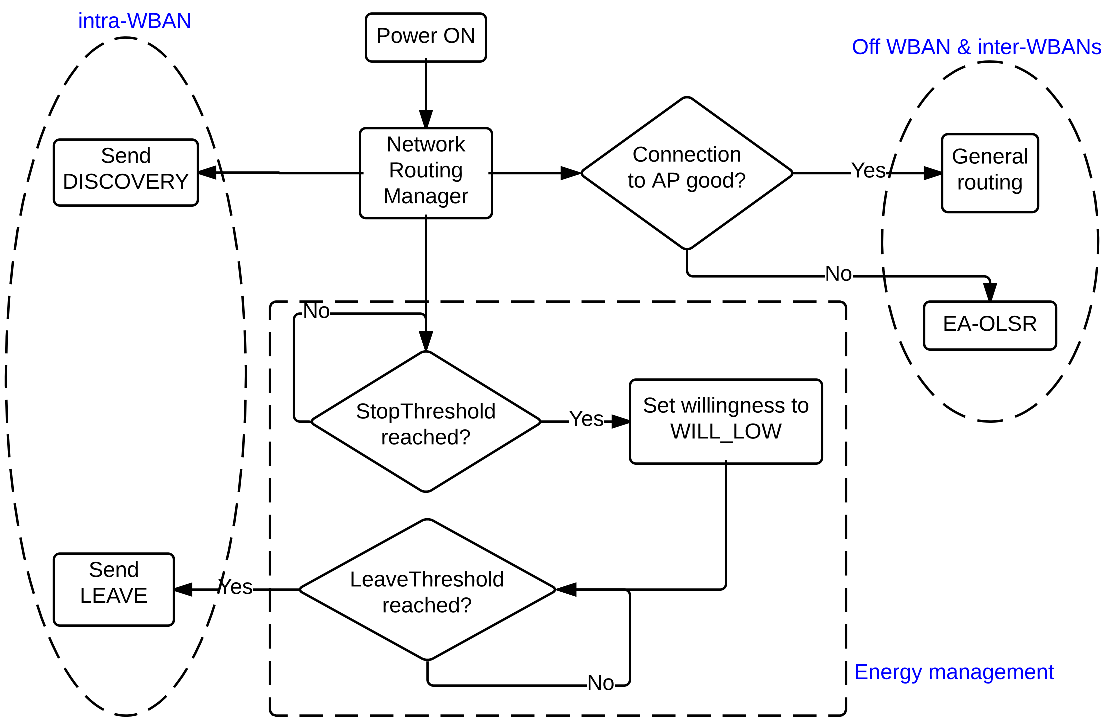

FIGURE 4.13: The coordinator operating mode

Algorithm 6 A node operating mode

Waiting for DISCOVERY packet while sensing
if Receive a DISCOVERY packet **then**
    if $DISCOVERY.TTL == 1$ **then**
        $NextHopAddress \leftarrow CoordinatorAddress$
        $NextHopRE \leftarrow DISCOVERY.RE$
        $SetDISCOVERY.TTL \leftarrow 1$
        $SetDISCOVERY.RE \leftarrow SelfRE$
        Broadcast DISCOVERY packet
    else
        if $NextHopAddress == NULL$ OR $NextHopRE < DISCOVERY.RE$ **then**
            $NextHopAddress \leftarrow SenderNodeAddress$
            Send response to the coordinator
        end if
    end if
    Define transmission path
end if
Send sensed or relayed data using defined path

The second part consists of three different states mutually exclusive. Each coordinator shall first communicate directly with an Access Point (AP) to deliver packets to a remote station using static routing or shall second switch to ad-hoc mode using EA-OLSR defined previously or finally leave its sensor nodes transmit their data themselves.

In fact, while there is no connection or energy issue, the coordinator transmits its packets while it is connected to the AP in star topology. It is for example, the case when a coordinator as a smartphone is connected to an WIFI AP. This state is likely to be optimal and the coordinator can easily serve for relaying. When the connection to the AP breaks down, it switches to the second state using EA-OLSR by starting to send hello packets to its neighbors. The EA-OLSR hello packet is reformatted to carry out additional necessary information such as Remaining Lifetime RLT. Thence, the *Reserved* field is divided into two fields: one byte as *Reserved* and other byte as RLT. As the inter-WBAN communication intends to occur in applications with a very low and high mobility such as elders at retirement home or athletes in sport training, the HELLO packet is periodically exchanged after a hello period *HelloInterval* and this period is determined according to some factors.

In fact, given *lowMobSpeed* for low mobility speed and *highMobSpeed* for high mobility speed, average mobility is *mobSpeed* given by Equation 4.3.

$$mobSpeed = (highMobSpeed + lowMobSpeed)/2 \tag{4.3}$$

Moreover, for a coordinator with *cov* as a transmission range, the Hello period is given by Equation 4.4.

$$HelloInterval = \frac{cov}{mobSpeed} \tag{4.4}$$

Every time that the MPR table values change, the TC packet will be sent and the routing table shall be updated at the receiver. During these states the coordinator shall set willingness filed to WILL_LOW if his residual energy level reaches the *StopThreshold*.

In this way he would save energy by not permitting others send him packets to relay. However he shall relay packets of sensor nodes whose coordinator is no longer operating. The final state occurs when the residual energy level reaches the *LeaveThreshold*. In this way, the coordinator has to inform his sensor nodes about his incapability for serving as a gateway. In fact, each coordinator normally collects data from its sensor nodes and conveys them to the remote station and periodically checks its *RE*. As the coordinator updates and keeps in its routing table the information relating to RE of its neighbors, when its *RE* has reached the threshold *LeaveThreshold*, it informs its nodes by locally broadcasting in the whole WBAN a LEAVE packet containing possible routes before it ceases its services. A LEAVE packet could contain the route to the nearest coordinator with enough energy to convey data.

4.4.1.3 Performances analysis

In this section the different phases where a node or a coordinator expends energy are investigated and efforts to optimize the energy consumption are made accordingly. In fact, the energy is expended during transmission, reception, listening and working routine phases and in this order, the energy consumption goes decreasingly. However, the energy consumption is not the same in all the WBANs due to the number of nodes different from one WBAN to another or the transmission rate is note the same. Considering the Figure 4.14, let us assume that packet rate in (a) is higher in H2 due to much sensed data by its related node N than in H1, what means that H2 expends more energy and will fall down earlier than H1. Moreover, if in (b) packet transmission rate is the same in N, N1 and N2, H2 will expend more energy than H1 though. Here, the network falls down means, that at least one WBAN is unable to find a way to deliver his data the the gateway.

In fact, considering that the most energy is expended during transmission and assuming constant other causes of energy consumption such as reception, overhearing and internal computations, a coordinator will expend per second:

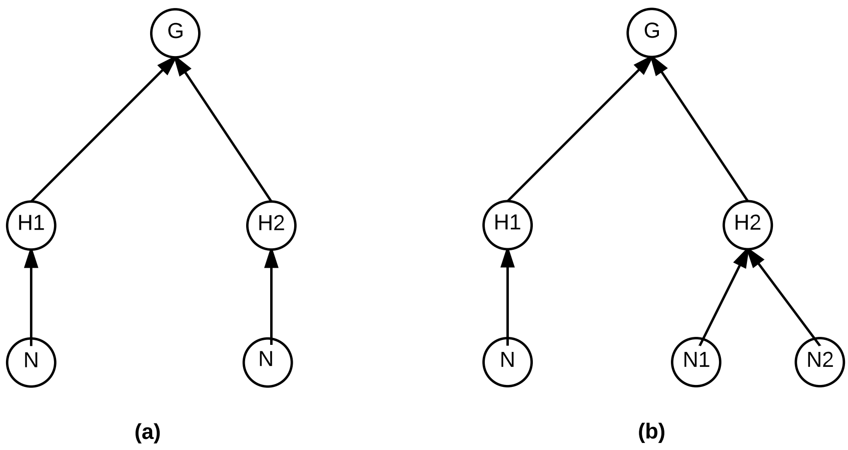

FIGURE 4.14: Example of a NetBAN configuration

$$E = \lambda r + \gamma \tag{4.5}$$

Where λ the battery drain per transmitted packet, r the packet rate (per sec) and γ the expended energy by other causes assumed constant. If this coordinator relays packets from m other coordinators and that these latter transmit with the same packet rate r_i, the energy consumption rate will be:

$$E_c = \lambda(r + r_i m) + \gamma \tag{4.6}$$

With B the energy of a full battery, the lifetime of the coordinator is $L_c = B/E_c$. If the coordinator decides to stop relaying others' packets at $StopThreshold$ of his energy, he will prolong his life of δ

$$\delta = \frac{B - stopThreshold}{E} - \frac{B - stopThreshold}{E_c} \tag{4.7}$$

Thus, his lifetime becomes $L = L_c + \delta$

4.4.2 Simulation results and discussion

In this section the performance results from simulations of our approach are reported and described by comparing obtained results with normal implementation without energy optimization. The network lifetime, average energy consumption per coordinator and data delivery are considered as simulation metrics.

4.4.2.1 Simulation testbed and parameters

NS3 simulator [104] which is a discrete-event network simulator with particularly a very well built energy module is used for simulation to deal with energy consumption optimizations. Thus the existing OLSR was modified to EA-OLSR and a bridging module to cope with intra WBAN communications was added. In the chosen scenario in NS3, 25 nodes have been used including one taken as the main AP and other remaining 24 forming 8 WBANs with 2 sensor nodes and a coordinator, each, as illustrated by the Figure 4.15.

```
19   20        21   22        23   24
 \   /          \   /          \   /
  \ /            \ /            \ /
   6-------------7-------------8
   |             |             |
   |             |             |
13 | 14       15 | 16       17 | 18
 \ | /          \ | /          \ | /
  \|/            \|/            \|/
   3-------------4-------------5
   |             |             |
   |             |             |
   |          9  | 10       11 | 12
   |           \ | /          \ | /
   |            \|/            \|/
   0-------------1-------------2
```

FIGURE 4.15: Experiment topology

To study the effects of battery depletion and connection failure, two testbed configuration are considered: In the first configuration all nodes and coordinators are static so as to study only the behavior of the network according to the energy consumption. The second configuration includes mobility factor: each WBAN (a coordinator with its nodes) moves following a direction taken randomly to allow the possibility of connection failure. In both configurations, only sensor nodes generate and transmit packets to the AP through their coordinators. The sensor nodes in a WBAN send their packets to the coordinator using static routing till the moment they receive the LEAVE packet. The coordinators however use EA-OLSR to route packets to the AP. Table 4.3 gives the parameters used for simulation.

TABLE 4.3: Simulation parameters

Parameters	**Values**	
Environment	100x100 m	
Number of WBANs	8: 2 sensors with a coordinator, each	
AP	1	
Transmission rate	10 packets/sec	
Initial energy	3000 J per node	
StopThreshold	1000 J	
LeaveThreshold	50 J	
Simulation time	3601s = 1h	
Network topology	intra WBAN: star inter WBAN: ad-hoc	
Mobility	1.None	2.Random direction

4.4.2.2 Results and discussion

However, before evaluating the all NetBAN routing solution (intra and inter WBAN), a brief test has been done to evaluate energy consumption between the the proposed EA-OLSR (inter WBAN) with EE-OLSR and the classic OLSR, using only 9 coordinator nodes including one taken as an access point deployed in dynamic grid environment. Figure 4.16 reports the energy consumption comparison between the classic OLSR, EE-OLSR and EA-OLSR. It is clear that EE-OLSR is really energy efficient but EA-OLSR outperforms all. It is also noticed that in both EA-OLSR and EE-OLSR the energy consumption tends to get uniformly distributed on all coordinator nodes in the network.

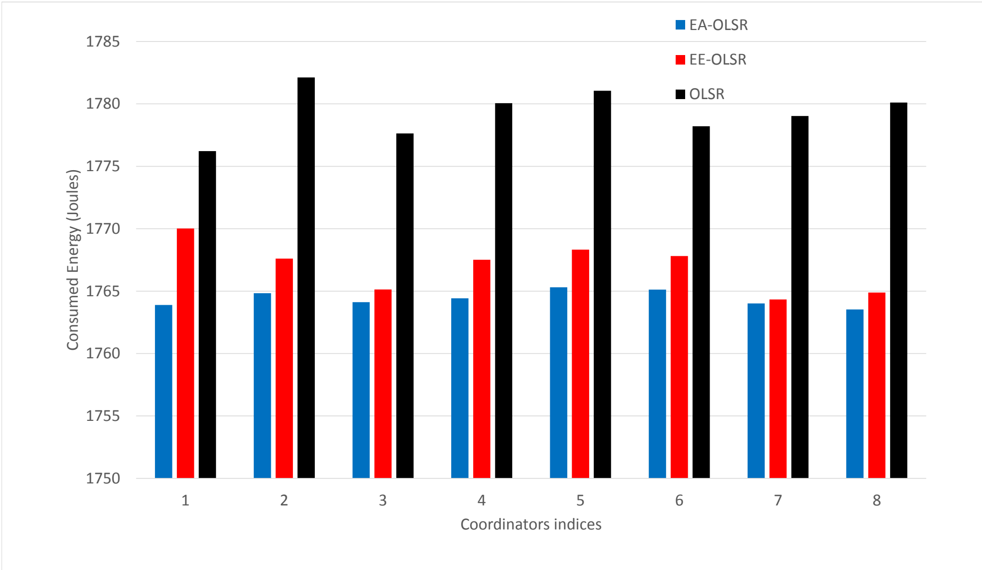

FIGURE 4.16: Energy consumption study of OLSR versions

Figure 4.17 brings out the energy gain of the proposed routing solution in the testbed without mobility. After an hour of simulation, a coordinator with inter WBAN routing configuration gains in average 498.97 J over the one without inter WBAN routing configuration what corresponds to about 12.224 min. This gain is probably due the uniform distribution of energy consumption in the network performed by the EA-OLSR.

TABLE 4.4: Network lifetime comparison with and without inter-WBAN routing with mobility configuration (velocity: 1 m/s)

Our inter-WBAN routing solution	**Without routing technique**
Test 1: 4978 s Test 2: 4870 s Test 3: 4902 s Test 4: 4910 s Test 5: 4880 s	
Average: **4910 s**	**3662 s**

In the testbed with mobility effect, five tests have been conducted because of the random mobility, likely to produce different results. As illustrated by table 4.4, the simulation ran until the first coordinator drops at 3662 sec, that to say 01:01:02. However, the

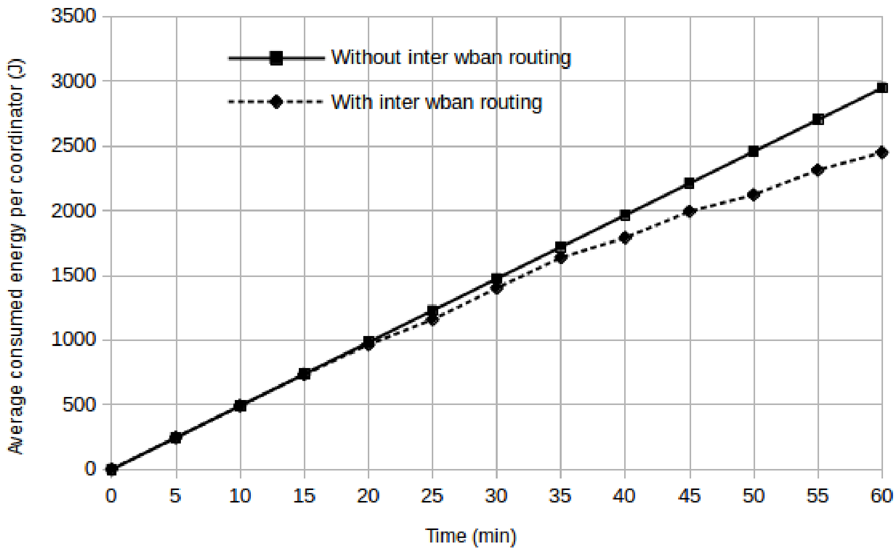

FIGURE 4.17: Average energy consumption per coordinator with and without inter-WBAN routing

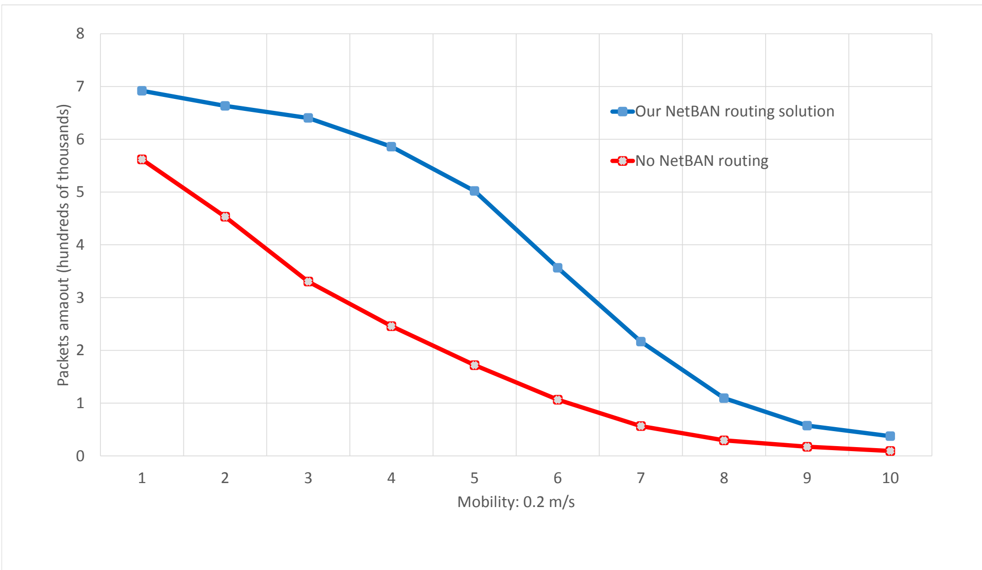

FIGURE 4.18: Delivered packets comparison with and without inter-WBAN routing: mobility effect

proposed routing protocol stopped after 4910 sec, i.e. 01:21:50. This average gain of 20 min representing 30% in network lifetime seems to result from two main contributions: the uniform distribution of energy consumption and the involvement of the sensors in sending themselves their packets via close coordinators from the time the energy level reaches *LeaveThreshold* as stated before. In addition, it is noticed that the coordinator node consumes more energy when it is mobile. An average of 4 J more per coordinator has been noted for an hour of simulation when mobility is applied.

Regarding the data delivery, the gain is about 24.148 % for low mobility and 16% for high mobility in proposed scenario (Figure 4.18). This gain is not however proportional to lifetime gain probably because of the network reconfiguration from one threshold to another or mobility effect.

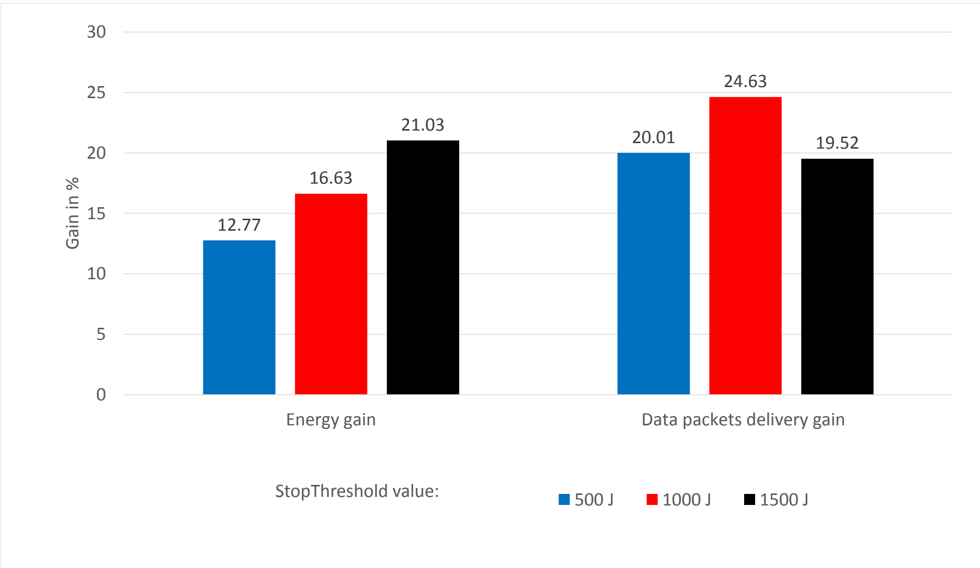

FIGURE 4.19: Thresholds definition by energy and packets amount gains comparison

It is very necessary to note that the definition of these thresholds remains a very interesting and important task as it influences the performances of the mechanism. In fact, a comparison between three *StopThreshold* values in order to choose the value used in the previous tests is made. Therefore, a value of 1000 J was chosen as illustrated by Figure 4.19.

4.5 Conclusions

Based on the idea that many WBAN applications are designed to be operational in the environment with groups of WBANs such as retirement home, hospital or sport field, the group interactions are likely to offer many benefits despite of challenges in implementation. The NetBAN, a new concept of network of BANs is proposed and presents its benefits and also its implementation challenges. In addition, an energy aware routing solution for NetBAN is proposed, aiming to make a node always find a way to convey data even in the case of problems related to energy lack or connection loss. The proposed routing solution involves three levels of communication: coordinator to coordinator, coordinator to node and node to node. Simulation results show better improvement in network lifetime and data delivery.

Regarding intra WBAN cooperation, Decode and Merged technique is proposed to enhance MAC protocol in to two-hop topology. This technique is based on resizing frame format, frames combination and multiple input frames for single output frame. Simulation results showed that our proposition increases general throughput and specially the amount of data packets delivered to the coordinator. Moreover, the ability of transmission in interference conditions has increased. It was also shown that the energy consumption has been optimized what gives to our technique more energy efficient.
However, a work focusing on interference mitigation at relay nodes and effect study on relaying capability from multiple requests of relaying are required despite of the global performance achieved in this work.

Due to the WBAN subject mobility, the localization service is needed and in the next chapter, the cooperation is also used to improve the localization performances.

Chapter 5

WBAN Localization Mechanisms

5.1 Introduction

Some decades ago, localization or tracking have been attracting attention of researchers and developers for private or public use: security and monitoring. Localization and tracking were originally the result of a high necessity for military applications what led to the creation of GPS. The necessity of public security has then arisen what led to the positioning on cellular network, wireless sensor network [105] and with camera surveillance system. Localization or tracking algorithms are different from one another according to the involved technology and the working environment. Therefore the WLAN technology is often used for indoor localization [106]. In [107] an applicable and scalable method using Wi-Fi fingerprints was proposed. In outdoor environment, the GPS is still a more accurate system with limitations for indoor environment. To overcome this GPS lack of working in indoor environment, the use of smartphone is studied in [108]. Some of them use fingerprinting method what consists of a long procedure. Thus, [109] set a mechanism that does not require any training phase to overcome that problem. For cellular network technologies like GSM or New Generation Mobile Networks, some algorithms are proposed: GSM Cell-ID based positioning mechanisms are studied in [110] showing challenges and improvements and a 3G based localization method is proposed in [111]. Another technology studied for indoor environment is UWB [112] whose localization algorithm is more accurate but requires additional equipment. The localization problem for mobile node [113] is becoming more and more an interesting topic because of a widespread increase in deployment of mobile systems and applications [7] that are getting part of our daily life.

The most used mechanisms for WSN are based either on distance or on angle (AOA) and algorithms developed still have less accuracy especially in indoor environment despite of the significant accuracy achieved in outdoor environment with GPS. However, those mechanisms are not all suitable for WBAN localization. This is due to the fact that the WBAN localization mechanisms can either involve all sensors or only the BAN coordinator or that a WBAN subject is mobile or else that the number of nodes involved are less numerous than in WSN. Therefore the major issues for the WBAN is to design an efficient localization mechanism with a good accuracy and suitable for indoor and/or outdoor environment while taking into account the mobility and cooperation where possible.
According to our knowledge, there are so far very few works explicitly done for WBAN localization and tracking. Hence, we tried in this chapter to investigate some localization and tracking mechanisms suitable for WBAN localization and tracking by considering the mobility factor and their behavior in various environments, and gave our proposals for indoor and outdoor environments.

5.2 Why, when and how to locate?

Many WBAN applications require localization service in many cases such as Medical or health applications [32, 33] where they include assistance to patients, disabled persons and elders [34]. It is obviously important that a patient as WBAN subject needs to be localized for secureness in the case of emergency state. In sports [10], apart from muscle activity monitoring, these applications require localization of sportsmen location such as in marathon or forest adventure. For soldiers and firefighters also, the location is important for security, guidance, replacement or wounded rescue.

Localization here is for the WBAN subject, however, posture (fall or motion) detection is also one of the most services necessary for WBAN. Recent works dealt with this issue in WBAN and present some improvement. The physical movements of the body can be detected by the sensors especially accelerometers and the WBAN monitoring system can then detect a fall and generate a warning signal. This is what was done in [114] by using a hitachi H34C accelerometer. Authors in [115] gave an example of a WBAN scenario utilizing the recent IEEE802.15.6 standard using a system with multi-accelerometers for monitoring Parkinson's disease and fall detection. Fall detection is a very necessary and challenging service in outdoor unlike indoor where a rich infrastructure can be found. In outdoor, this task relies only on wearable sensors. Therefore in [116] was proposed and implemented a system consisting of a smartphone and a wireless sensor node for detecting fall on the road with an alerting system. Like in [116], in [117] was designed a fall detection system using a combined use of a smartphone and smartwatch.

Locating a WBAN implies locating the person forming this WBAN by determining the position of the Personal Device. In this way, inter-WBAN and WSN localization mechanisms are alike. However the WBAN localization mechanisms present some specificities comparing with WSN localization mechanisms:

5.2.1 Specific requirements

Mobility: As a WBAN is related to a person and this latter is mobile, all the WBAN applications assume that the person can move, what is not always a matter for WSN. Therefore, it is crucial to consider mobility when designing a WBAN localization mechanism. Unlikely WSN where the mobility occurs in the knowledge of the device, the mobility in WBAN is governed by the WBAN subject without necessarily informing the devices. Thus, the mobility factor increases the complexity of localization algorithm design.

Scalability: The scalability of a localization system is its ability to adapt to the change of the network behavior and localization conditions. Particularly to WBAN, a person can move to different environments, for example from indoor to outdoor environment, be alone or be in group of people, etc. Therefore, it is so important to set the mechanisms that improve scalability when designing a localization system so that localization or tracking algorithm should be adaptive to these different changes.

5.2.2 General requirements

Accuracy is an important, most used and required criteria to evaluate a localization algorithm performance. However, it is obviously impossible to get exact location with a localization algorithm and thus its performance can be assessed in terms of the error value. There are some commonly used computational errors such as average localization error (ALE), root mean square error (RMSE) and geometric mean error (GME) [105] and are computed as Euclidian or Manhattan distance as follows [118]:

$$ALE = \begin{cases} \frac{1}{N_t}\sum_{i=1}^{N_t}\sqrt{(\hat{x}_i - x)^2 + (\hat{y}_i - y)^2} & , Euclidian \\ \frac{1}{N_t}\sum_{i=1}^{N_t}(|\hat{x}_i - x| + |\hat{y}_i - y|) & , Manhattan \end{cases} \tag{5.1}$$

$$RMSE = \sqrt{\frac{1}{N_t}\sum_{i=1}^{N_t}((\hat{x}_i - x)^2 + (\hat{y}_i - y)^2)} \quad , Euclidian \tag{5.2}$$

$$GME = \begin{cases} \sqrt[N_t]{N_t\prod_{i=1}^{N_t}((\hat{x}_i - x)^2 + (\hat{y}_i - y)^2)} & , Euclidian \\ \sqrt[N_t]{(\prod_{i=1}^{N_t}(|\hat{x}_i - x| + |\hat{y}_i - y|)} & , Manhattan \end{cases} \tag{5.3}$$

Where N_t denotes the number of trails, (x, y) is the true measured location and $(\hat{x}_i, \hat{y}_i)$ is the estimated location.

Other requirements for localization algorithm are *cost* that can be assessed as material or energy, *time* as response period, *robustness and fault tolerance* that requires the algorithm to work even with incomplete information, *complexity* and *coverage*.

5.2.3 Localization process

Most of localization algorithms operate in two main stages [119]: The first stage named ranging phase [120] consists in the collection of information needed to estimate the node location. The second phase, called the location estimation phase consists of computing data collected in the previous phase to estimate the location. In some localization mechanisms using data base such as fingerprinting, there is an offline phase preceding up-mentioned phases consisting of collecting and saving information relating to locations and measurements for subsequent use.

5.2.3.1 The ranging phase

In ranging phase, localization algorithm tries to collect information necessary for location estimation. This information collection relies either on distance with techniques such as Received Signal Strength Indicator (RSSI), Time Of Arrival (TOA), Time Difference Of Arrival (TDOA), or on angle with Angle of Arrival (AoA) as techniques [121]. Another technique resulting from ToA/TDoA is TW-ToF (two way time of flight, with its improvements) that is efficient as it overcomes the synchronization issue and is likely to be more accurate especially in indoor localization when used with UWB transmission [122]. A survey of hybrid of ranging or measurement techniques including ToA/RSSI, TDoA/RSSI, ToA/AOA, TDoA/AoA is given in [123]. An additional ranging technique is hop-count method that assumes that the distance between two nodes are equal finds the distance between two interested nodes by the number of hopes. The DV-Hop localization algorithm results from the hop-counting technique [124].

5.2.3.2 The location estimation phase

In this second stage the algorithm estimates the node position using appropriate mechanisms and these mechanisms are triangulation, trilateration, least square, centroid, maximum likelihood estimation [125]. The triangulation method is used when the angle of the direction from which the signal is received is estimated instead of distance and trigonometry laws of sines and cosines are applied [126]. Regarding trilateration/multilateration, the method gets the nodes locations by calculating the intersection of three circles after estimating the distance between the node and each anchor from the received signal strength, and this distance constitutes the radius of circle. If the intersection is not a single point, ranges contain some errors.

The principle of trilateration is as follows: As shown on the Figure 5.1, given the three anchors A, B and C with the coordinates (x_a, y_a), (x_b, y_b) and (x_c, y_c) respectly and S the node with unknown location (x, y); assumed that the distances between these anchors and S are respectely d_a,d_b and d_c we get a system of equations [127]:

$$\begin{cases} \sqrt{(x - x_a)^2 + (y - y_a)^2)} = d_a \\ \sqrt{(x - x_b)^2 + (y - y_b)^2)} = d_b \\ \sqrt{(x - x_c)^2 + (y - y_c)^2)} = d_c \end{cases} \tag{5.4}$$

The coordinates of S can be obtained from the following equation:

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} 2(x_a - x_c) & 2(y_a - y_c) \\ 2(x_b - x_c) & 2(y_b - y_c) \end{bmatrix}^{-1} \times \begin{bmatrix} x_a^2 - x_c^2 + y_a^2 - y_c^2 + d_c^2 - d_a^2 \\ x_b^2 - x_c^2 + y_b^2 - y_c^2 + d_c^2 - d_b^2 \end{bmatrix} \tag{5.5}$$

When the trilateration method uses more than three anchors required it becomes the multilateration method as illustrated in the Figure 5.1-c. The centroid mechanism is used for sensor nodes localization thanks to its simplicity in implementation and works as follows: the unknown node receives from anchors the information about their location coordinates and estimates its position by centroid formula :

$$(x_{est}, y_{est}) = (\frac{x_1 + \cdots + x_N}{N}, \frac{y_1 + \cdots + y_N}{N}) \tag{5.6}$$

Although this mechanism is simple it presents some deficiency on the location accuracy. For this reason many researches have been launched to improve its performance. It is the case of Particle Swarm Optimization (PSO) algorithm used with centroid method in [120] to enhance position accuracy.

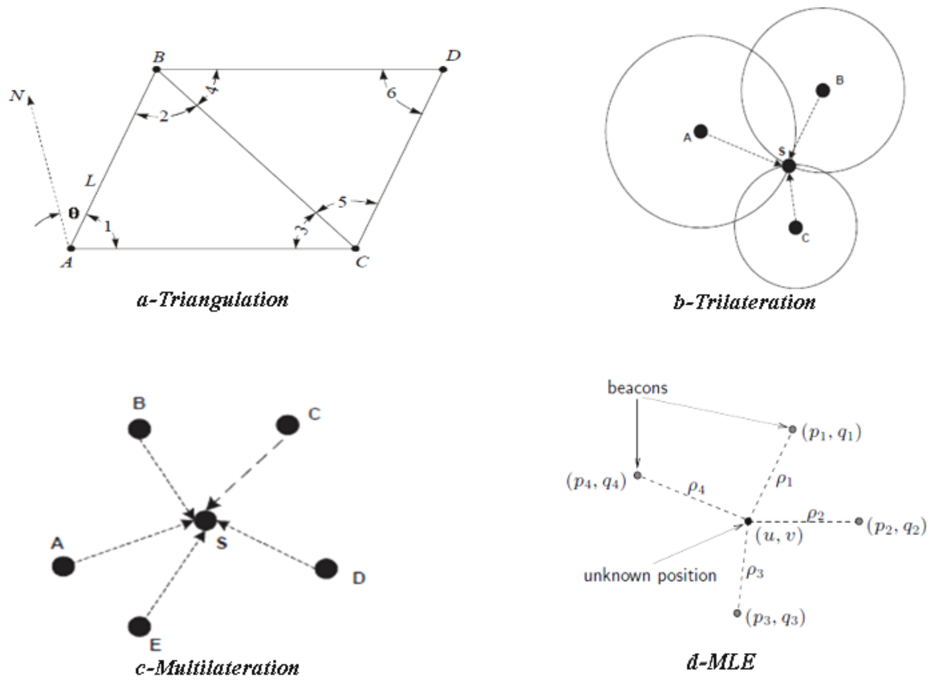

FIGURE 5.1: Localization mechanisms

As for Least Square (LS) method [128], it is a standard approach to approximate solution of over determined systems, i.e., sets of equations in which there are more equations than unknowns. "Least squares" means that the overall solution minimizes the sum of the squares of the errors made in the results of every single equation. Given Equation 5.6, the LSE consists in estimating a vector $\hat{x}$ that minimizes $||A\hat{x} - y||$

$$y = Ax - \omega \tag{5.7}$$

Where x is what we want to estimate, y our measurement, ω a measurement error and i^{th} row of A represents the i^{th} node of i^{th} measurement. Considering the Figure 5.1-d with four anchors and their distances to an unknown node location, four nonlinear equations in two variables u and v are set:

$$\rho_i = \sqrt{(u - p_i)^2 + (v - q_i)^2} \tag{5.8}$$

For i= 1,2,3,4 and ρ_i is the measured distance from an unknown position (u, v) to anchor i. By linearizing Equation 5.8, (u, v) is calculated afterwards [129].

About Maximum Likelihood Estimation (MLE) [130, 131] that is based on classical statistical inference theory, it should be used to estimate location using TOA, RSS, connectivity, or AOA measurement techniques, providing that a statistical model is available. MLE estimates the position of a node by minimizing the gap between the measured values and estimated values.

To improve the localization method in terms of accuracy, some strategies have been used together and bio-inspiration has been also applied. For bio-inspired method as meta heuristic which is a procedure designed to find a solution to a complex problem, Particle Filtering, PSO (Particle Swam Optimization) [132, 133], BFA (Bacterial Foraging Algorithm), DE (Differential Evolution), GA (Genetic Algorithm) are very representative and are likely to achieve good results. The Hybridism takes advantages in using two or more approaches from a same categories to build up an algorithm that would perform a task better than when it was taken alone.

5.3 A survey on localization mechanisms for WBANs

There are many algorithms proposed generally for WSN localization. As all those algorithms do not fit WBAN localization, we investigate in this section some of them that are likely to fill WBAN localization requirements. A categorization according to algorithm functional features is proposed.

5.3.1 Algorithms based on geometry

5.3.1.1 APIT

APIT (Approximate Point In Triangle) algorithm [134] uses as possible as a small number of anchors. It divides the neighborhood area of these anchors into many overlapped triangles. And if the number of anchors increases, the size of triangles decreases what improves the node location accuracy. This algorithm can adapt to many localization cases especially WBAN localization. Figure 5.2-a

5.3.1.2 ROCRSSI

Like APIT Algorithm described above, ROCRSSI (Ring Overlapping based on Comparison RSSI) [135] algorithm uses anchor nodes too and RSSI technique in measurement phase. Rings are generated when receiving signals from all sensors and anchors nodes: For each anchor node, if the signal strength received from a sensor node is between the signal strength received from two anchors nodes, this sensor node is located in a ring limited by these two anchors nodes. For example, given three anchors nodes A, B and C and a sensor node S. Assume that anchor node A sends out beacon messages and signal strength received are compared as follows $RSSI_{AB} > RSSI_{AS} > RSSI_{AC}$, then sensor node S is likely to fall within the ring limited by B and C. ROCRSSI seems to overcome the APIT incapability where the sensor node to locate is out of the triangle. In this case

ROCRSSI can solve this problem as it uses rings that include all the points under the outer radius. However, it is inadequate for single WBAN localization; it could be fit in inter WBANs cooperative localization and in distributed way.

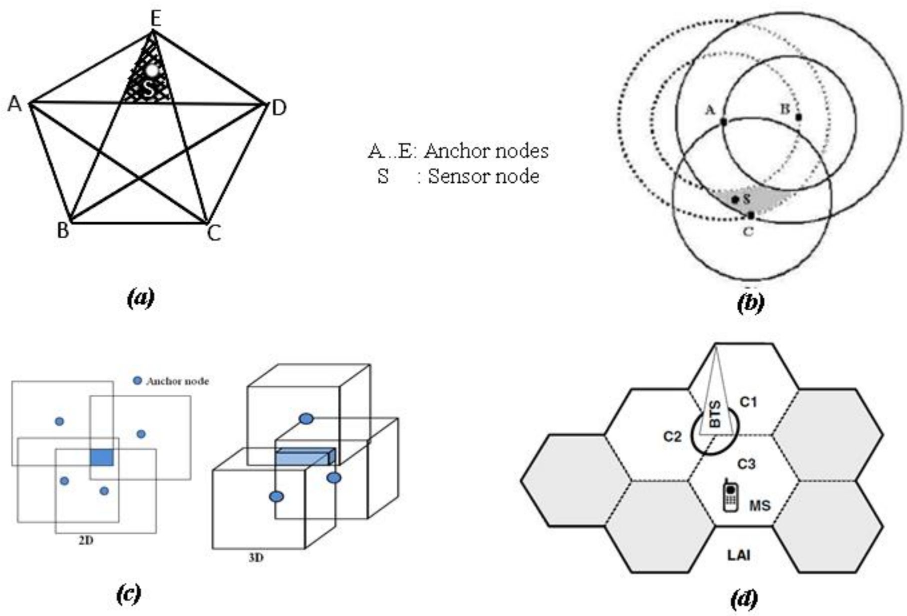

FIGURE 5.2: Localization algorithms: a) APIT, b) ROCRSSI, c) Bounding box, and d) GSM based Cell-ID

5.3.1.3 Bounding box

Like APIT or ROCRSSI, Bounding box algorithm uses squares instead of triangles or rings. Each anchor builds around itself a square box or a cube with edges equal to twice the maximum range between anchors and each unknown node considers its location to be in the intersection of all anchors boxes or cubes it receives signal from. In this way the intersection size is reduced more and more according to the number of anchors the sensor node is connected to. Thus, it can behave as anchor and help other unknown nodes to locate [120].

Algorithm 7 ROCRSSI [113]

RSSI propagation
$Numberofsamples \leftarrow N$
for all $t = 1 : T$ **do**
  Broadcast beacon message
  if $t = T$ **then**
    Take mean of sampled received from neighbors $\sum(RSSI/N)$
  end if
  Broadcast RSSI message
  RSSI message=mean of RSSI + ID
  RSSI estimation process
  Inputs:
  Assume that the sensor node S wants to conclude its location
  A, B, C denote anchor nodes; $RSSI_{AB}$, $RSSI_{AC}$, $RSSI_{AS}$ *are the received signal strength*
  Ring set R=()
  if $D_{AS} > D_{AB}$ and $D_{AS} < D_{AC}$ **then**
    $R_I(A) = D_{AB}$ *and outer radius will equal to* $R_0(A) = D_{AC}$
  end if
  if $RSSI_{AB} > RSSI_{AS}$ and $RSSI_{AS} > RSSI_{AC}$ with A, B,S and C in the same direction **then**
    S is in the shaded area (See Figure 5.2-b)
    Generate a ring R centered at A with inner radius d_1 *and outer radius* d_2
  end if
end for

5.3.1.4 MDS-MAP

MDS-MAP [125] is a centralized algorithm for determining relative locations of nodes in known bound given the distances between each pair of nodes. MDS-MAP uses a technique from mathematical psychology called multidimensional scaling (MDS). MDS-MAP is almost a direct application of the simplest kind of multidimensional scaling: classical metric MDS. The algorithm has four stages, which are as follows:

Step 1: Gather ranging data from the network and form a sparse matrix $R = (r_{ij})$, where r_{ij} is the range between nodes i and j, or zero if no range was collected (for instance if i and j are physically too far apart or $i = j$). This stage of information collection can be performed by using the well-known techniques such as RSSI, ToA, TDoA, and TW-ToF. The more this technique is precise, the more MDS-MAP will be accurate.

Step 2: Generate a complete matrix of inter-node distances D by running a standard all pairs shortest path algorithm (Dijkstra's, Floyd's) on R. D is such that $D = [d_{ij}]$ with $d_{ii} = 0$ and $d_{ij} + d_{ik} \geq d_{jk}$

Step 3: Estimate node positions X by running classical metric MDS on D. Mathematical equations for classical MDS is as follows:

$$d_{jk}^2 = d_{ij}^2 + d_{ik}^2 - 2d_{ij}d_{ik}cos(d_{jik}) \tag{5.9}$$

$$d_{ij}d_{ik}cos(d_{jik}) = (X_j - X_i).(X_k - X_i) \tag{5.10}$$

$$\rightarrow (X_j - X_i).(X_k - X_i) = 1/2(d_{ij}^2 + d_{ik}^2 - d_{jk}^2) \tag{5.11}$$

By choosing one position as origin, construct a matrix B as follows $B = (b_{ij})$ with

$$b_{ij} = 1/2(d_{0j}^2 + d_{0k}^2 - d_{ij}^2) \tag{5.12}$$

With the diagonal matrix V and Eigen-decomposition U, it results in $B = UVU^T$ X can be computed in the wanted dimension like $X = UV^{1/2}.V^{1/2}$

Step 4: Transform the solution X into global coordinates using some number of fixed anchor nodes. MDS-MAP performs well if all pair-wise measurements of the whole network are provided and its performance improves if ranging measurement improves too. This algorithm does not use anchor nodes very well, since it effectively ignores their data until stage 4 and this is its advantage. However, when anchor number increases, its performance decreases very much. Another issue as a centralized algorithm is that it should not be applied for non-cooperative model.

5.3.2 Bayes filter based algorithms

The Kalman and Particle filters are Bayesian algorithms that update an estimate of the system state recursively and find the innovations driving a stochastic process basing on a sequence of observations. The Kalman filter tries to reach this goal by linear and Gaussian projections, while the Particle filter uses a sequential Monte Carlo method, especially for nonlinear/non-Gaussian models. These methods are used for WBAN localization and tracking with inertial navigation system or RSSI [136].

5.3.2.1 Kalman Filter (KF)

The KF is used as optimal solution for Bayesian problem and a linear and Gaussian system by assuming that the posterior density is Gaussian at each time of the evolution. It operates in two phases: initialization and update phase in which prediction and correction steps go alternatively. The equations for different phases can be found in the work of [137]. For the nonlinear system as in WBAN tracking problem, some KF sub-optimal filters such as Extended Kalman Filter (EKF) and Unscented Kalman Filter (UKF) [138] or linearized KF could be used. The following are the KF common equations.

Prediction

$$\hat{x}_{t|t-1} = F_t \hat{x}_{t-1|t-1} + B_t u_t \tag{5.13}$$

$$P_{t|t-1} = F_t P_{t-1|t-1} F_t^T + Q_t \tag{5.14}$$

Update

$$K_t = P_{t|t-1} H_t^T (H_t P_{t|t-1} H_t^T + R_t)^{-1} \tag{5.15}$$

$$\hat{x}_{t|t} = \hat{x}_{t|t-1} + K_t(z_t - H_t \hat{x}_{t|t-1}) \tag{5.16}$$

$$P_{t|t} = (I - K_t H_t) P_{t|t-1} \tag{5.17}$$

Where Q is the process noise covariance and R is measurement noise covariance. $P_{t|t-1}$ is the priori estimate error covariance. $P_{t|t}$ is the posteriori estimate error covariance. $\hat{x}_{t|t-1}$ is the priori state estimate at step t. $\hat{x}_{t|t}$ is the posteriori state estimate at step t. K_t is the Kalman gain, z relates to the state measurement and H matrix relates to the observation model.

5.3.2.2 Particle filter (PF)

PF is used for nonlinear or non-Gaussian systems. As WBAN localization problem has these characteristics, PF seems to be a good choice. Particle filter is a recursive mechanism which uses Bayesian Posterior probabilistic distribution method to estimate sensor node location and random particles for probability density function sampling. It uses likelihood function for weighting these particles. In other words, PF is a sequential Monte Carlo mechanism used to approximate the optimal Bayesian recursion by means of point mass representation of the posterior densities [139]. A generic PF algorithm consists of some steps described by Algorithm 8:

Algorithm 8 PF working steps

1: **At the initial instant:**
2: *Particles generation*
3: *Weighting each particle*
4: *Particles selection (resampling)*
5: **for** each next instant: **do**
6:     *Generation of observation model*
7:     *Transition according to observations*
8:     *Weighting each particle*
9:     *Particles selection (resampling)*
10: **end for**

In the case of WBAN localization problem, the algorithm must be reformulated to be adapted to the problem regarding to the location and movement tracking. Authors in [139] have proposed a PF model for indoor environment using RSSI measurement. The adopted approach is to weight generated particles by RSSI measurements and sample them under different power settings. With a series of prediction weighting and resampling processes the algorithm achieves a posterior belief of node position.

PF is used in cooperation with DV-Distance algorithm to track wireless sensor node position in [140].

5.3.3 Schemes based on Data Base

Some mechanisms use data base to infer position when performing localization task and the data base is set up during the offline phase. It is the case of mechanism used in Global System Mobile (GSM) with Cell ID, Fingerprinting for often indoor localization, Hidden Markov Model (HMM), etc.

5.3.3.1 Cell ID:

In Cell ID based mechanism, a Base Transceiver Station (BTS) covers a set of cells grouped into a cluster identified by a Local Area Identifier (LAI) and each of these cells has a unique identifier Cell-ID as shown in the Figure 5.2-d (i.e. C1, C2 and C3). A Mobile Station (MS) continually chooses a cell to exchange data and traffic signaling with the corresponding BTS. The BTS broadcasts both the LAI and the Cell-ID to its cells of the cluster and a MS of a given cell receiving these messages can approximate its location using the geographical coordinates of the corresponding BTS from its Cell-ID knowledge. This mechanism has as benefits as drawbacks: It does not require any equipment upgrade what makes it simple and economic [141]. However, as the position accuracy in this mechanism depends on the cell size whereas this one is uncertain, it suffers from deficiency of accuracy. The map-snapping, movement prediction or combination of mechanisms to improve GSM Cell-ID based tracking accuracy were proposed in [141]. Cell-ID based mechanism is a good choice for WBAN positioning providing that the WBAN node has a GSM interface therefore it can be positioned like a GSM mobile station.

5.3.3.2 Fingerprinting:

The fingerprinting mechanism operates in two phases as detailed in [141]. In the first phase, called offline phase, the network area is divided into cells whose coordinates are known. Next, the RSSI of all anchors are registered in a database and a radio map is created. In the second phase called online phase, location estimation is done by comparison between received and registered RSSI using probabilistic or deterministic methods. Although this mechanism performs a good accuracy, it is complex, heavy and challenging especially in the first phase and requires a wide space for database.

5.3.3.3 Hidden Markov Model (HMM):

The interest of HMM in localization is that it can model sequential stochastic states where the current state depends only on the previous state. As the states are hidden and a sequence of observations generated from a sequence of states can only be observed, the observations represent the hidden nodes assuming that they are generated from states by a Gaussian probability density function [142]. Like fingerprint method, HMM based localization works into two phases: online and offline phases. During offline phase a HMM is constructed with its estimated parameters. From this construction, each state of the model denotes a location in the discrete physical space while observation from a state represents the ranging readings from anchors. During online phase, the user is moving in the area of interest receiving ranging information anchors and estimates his location. More details can be found in the work of Obaidur et al. [113].

5.3.4 Built-in technology based schemes

5.3.4.1 GPS system

The GPS (Global Positioning System) [143] is the most known and used positioning system in the world. It consists of a constellation of 24 satellites or more that continually broadcast their positions and direction. Thus, the GPS receiver can calculate its location by trilateration. The GPS performs a good accuracy, however it presents many drawbacks like the fact that the accuracy depends on the number of visible satellites, the set up time which can be quite long and the power consumption is relatively high. Moreover, it only operates in outdoor environment. To overcome some GPS drawbacks, the Assisted-GPS (A-GPS) is proposed. A-GPS requires Base Transceiver Stations and both the BTS and MS must be upgraded. All these GPS limits make the system difficult to be used for WBAN localization even if it attracts attention of users and researchers.

5.3.4.2 Smart phones

Nowadays, the new smart phones are equipped with many sensors likely to help in localization such as GPS receiver, accelerometer, magnetometer, gyroscope, sensor for proximity, for temperature, etc. Dead reckoning [144], the most technique used in autonomous robot control like Simultaneous Localization And Mapping (SLAM) becomes an interesting technique in WBAN localization. As these smart phones can serve or behave as BAN coordinator, some algorithms and systems have been developed combining many techniques. It is the case of Locate Me [145] that combines fingerprinting and the maps of WI-FI access points and mobile cells, WI-FI and mobile communication radio fingerprints with accelerometer [108], dead reckoning and fingerprinting with particle filter [146]. Pedestrian dead reckoning based systems, People-Centric Navigation [147] the concept of mobile node collaboration into Pedestrian Dead Reckoning, Escort [148] and CompAcc [149] have used smart phones. All those algorithms and systems need learning process to improve the localization accuracy. Dead reckoning is still suffering from error propagation over time. However, it was shown that if it is combined with other techniques it becomes more accurate.

5.3.4.3 UWB system

Localization based on UWB transmission has attracted attention of researchers as precision of distance measurement depends on wireless technologies. In fact, UWB is robust to NLoS (Non-Lines of Sight) as the UWB time resolution is precise enough to exclude signals delayed by reflection. Interesting works on localization show important results such as the system developed by Time Domain Corporation [150] that achieved high accuracy.

5.3.5 Comparative study: Performances evaluation

This study intends to compare cooperative and non-cooperative solutions in terms of accuracy and the capability to find a node's location; therefore three techniques are chosen: trilateration, cooperative trilateration and decentralized MDS. For trilateration as a non-cooperative and commonly used technique, a node covered by at least three anchors can estimate its location following the model described in section 5.2.3.2. For cooperative trilateration, two models are considered: in the first, when a node is estimates its location it then behaves as an anchor and help others estimate theirs; in the second, a node communicates with its neighbors to measure peer-to-peer distances and utilizes local MDS (see section 5.3.1.4) with anchors. In simulation test bed, a 2-dimensional space of 100x100 is considered with 4 anchors and 15 mobiles nodes moving following a random path.

Figure 5.3 shows the performances in terms of RMSE of node location and Figure 5.4 illustrates the mean error, mean time of execution and percentage of non-located nodes along the simulation and the results are highlighted in Table 5.1. It is clear that the distributed MDS outperforms all but takes much time of execution what should compromise

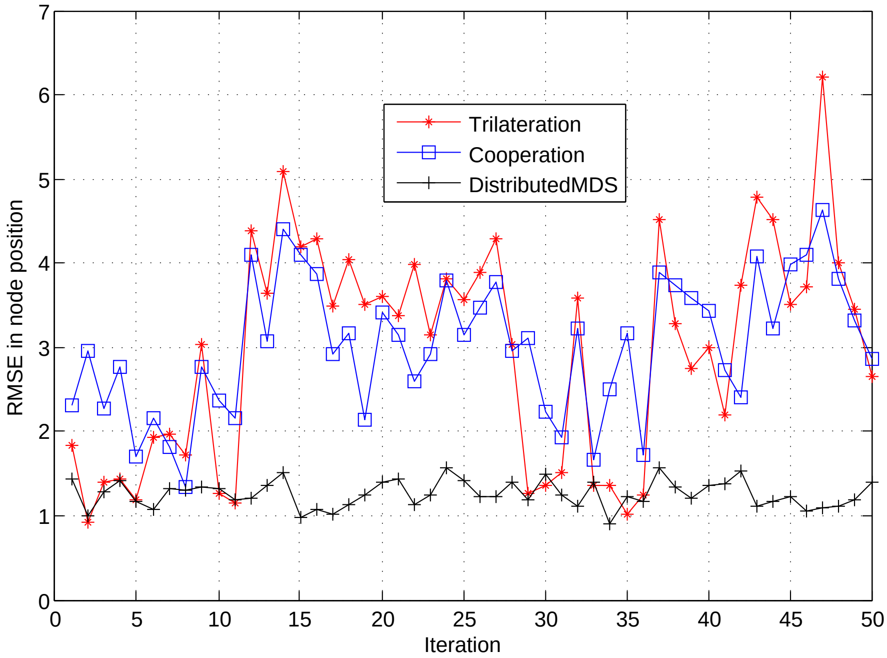

FIGURE 5.3: Comparison in terms of error

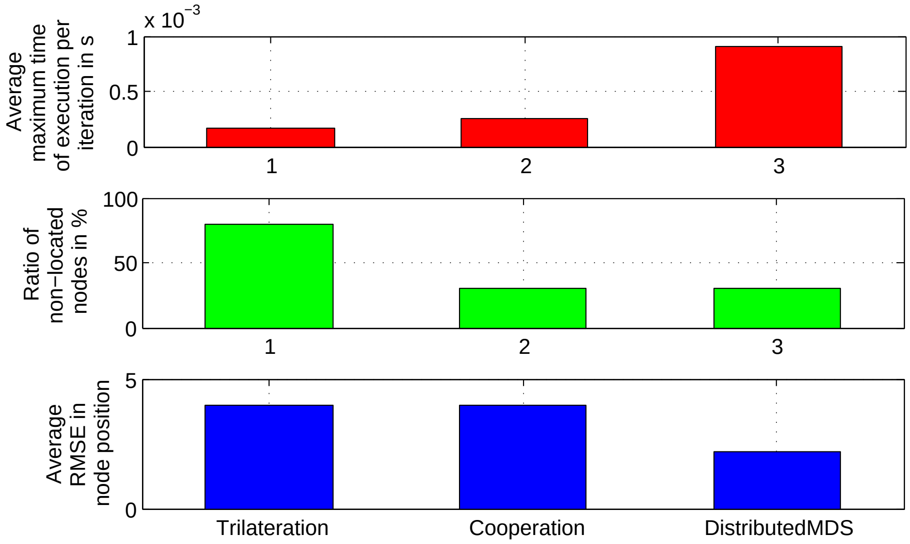

FIGURE 5.4: Comparison in terms of error, localizability and time of execution

it in WBAN. The trilateration technique seems to perform well except that the number of non-located nodes is higher. For cooperation technique, the three studied parameters are quite acceptable for WBAN localization, therefore we will consider this latter for further improvement.

TABLE 5.1: Performances comparison

	Trilateration	**Cooperation**	**DistributedMDS**
Mean error	3.8649	4.0205	2.2592
Mean time of execution (ms)	0.1913	0.2386	0.9219
Amount of non-located nodes	83.33	30.00	30.00

5.3.6 Discussion on WBAN localization and tracking tips

Even though some WSN localization mechanisms can fit some WBAN localization requirements, additional treatment and consideration of specificities are necessary. In this section, we discuss the main interesting points for WBAN localization and tracking that are not studied or stressed in up-mentioned works.

Mobility consideration: In many WBAN operating environments, WBANs as people move even with a slight speed or are likely to move. Furthermore, related applications often work in real time. Considering tracking as a recursive process of localization or positioning of an object in movement, designing tracking algorithms is more suitable than designing static localization algorithms. A tracking algorithm for real time application should consider the update time in terms of movement speed as an important factor. If we assume that v is the WBAN movement speed and ϵ is the acceptable error, he update rate r should be:

$$r < \frac{\epsilon}{v} \tag{5.18}$$

This is to avoid the update after the WBAN subject has changed his location. From the previous point of view, Bayes filters based algorithms should meet requirements of tracking more than geometrical based algorithms. Algorithms based on data base could also be applied but they need a well-designed measurement phase considering real time requirement [151].

Nodes number consideration: For some WBAN applications many WBAN subjects are in group: at home for elders, in sport such as marathon or group adventure, in military on battlefield for soldiers or firefighters. However, some people live alone with no fellow aside and in the case of monitoring with localization, fingerprinting mechanism with a great number of anchors is required.

Environmental consideration: Some WBAN indoor applications such as public building surveillance, surveillance in shopping malls, hospital patients surveillance, family monitoring, etc. require to take into consideration the building shape, i.e. if the building comprises many floors the subject position has to be known even in bottom, middle or top. Thus, localization algorithm should focus more on 3D localization. It should be more relevant if a localization algorithm can adapt to any change of environment dimension, for example from 2D to 3D or indoor to outdoor. It is also suitable and reasonable to design centralized algorithms for indoor use and distributed algorithms for outdoor use.

Technology consideration: WBAN localization and tracking mechanisms should focus on UWB transmission especially for indoor localization. This is at first motivated by the best accuracy achieved with measurement techniques based on UWB transmission, and then because WBAN transmission channels are mostly based on UWB. Smart phones are now flourishing worldwide and can help to experiment WBAN localization algorithms and even work as BAN coordinator. Dead Reckoning is also a good mechanism for localization given that many involved sensors can be easily found in smart phones despite the localization error propagation but it can be mitigated if it is associated with other techniques [146].

5.4 Cooperative localization: from posture detection to body localization

Posture detection is efficient when sensors work cooperatively. Then, the localization of each wearable node helps to detect any body posture. In this way, Jihad et al. [152]) proposed a cooperative solution to locate wearable nodes by feeding the Extended Kalman Filter (EKF) with inter-node range measurements through impulse Radio-Ultra Wideband (IR-UWB) and detect any body motion. Therefore, referring to what stated in section 5.2 about body posture detection and the previous comparative study results, we introduce in this section the idea of performance enhancement of cooperative localization technique using the body posture detection.

5.4.1 System Model

Assuming that each node can communicate with its neighbors and measure the peer distance using adequate technique (for example two way time of flight), let us consider a D-dimensional (D=2, 3) network consisting of n mobile nodes with unknown locations and velocities and m with known locations (anchors). We denote the location and the velocity of the node $i = 1 \ldots n, n+1 \ldots n+m$, x_i and v_i respectively. The distance between the node i and the node j is given by the Euclidean distance as follows:

$$d_{ij} = \sqrt{(x_i - x_j)^2} \tag{5.19}$$

However, the range measurement r_{ij} is actually erroneous and is given by $r_{ij} = d_{ij} + w$, where w is a measurement error.

Let us define the state of our system at instant t as $X(t) = [x(t)v(t)]^T$, where $x(t)$ and $v(t)$ are the coordinate and the velocity vectors of the target node at instant t.

Suppose that we have a mobile node like pedestrian, the system can detect whether he is running, walking or immobile. When a node stops moving it stays in the same location as its velocity cancels out and we model these three different states with $s(t)$ as follows:

$$s(t) = \begin{cases} \alpha_r, \text{if } running \\ \alpha_w, \text{if } walking \\ \alpha_s, \text{if } static \end{cases} \tag{5.20}$$

For simplicity of simulations, we model only two states: walking and static with α_w=1 and α_s=0.

Therefore, the state of the system at instant $t + 1$ is given by

$$X(t + 1) = F(t)X(t) + B(t)u(t) + w(t) \tag{5.21}$$

and the measurement model is as follows:

$$y(t) = H(t)X(t) + e(t) \tag{5.22}$$

where $F(t)$ and $B(t)$ are state transition and input matrices respectively, and $u(t)$, $w(t)$ and $e(t)$ are control input, driving and measurement noise vectors. with zero-mean and a covariance matrix $R(t)$. It is assumed that $p(w) \sim N(0, R)$ is gaussian noise with covariance $R(t)$ and $p(e) \sim N(0, Q)$ is gaussian noise with covariance $Q(t)$, and $u(t) = s(t)$ for our model.

For our system, at each instant t we can measure the position by cooperative trilateration and if unvailable there is possibility to measure the velocity using posture detection and calculation from current and previous location to infer it. Assume that the nodes move with a constant velocity, this mobility is ruled by the following law:

$$\begin{cases} x(t+dt) = x(t) + st * dt \times v(t) \\ v(t+dt) = v(t) \end{cases} \tag{5.23}$$

The general update and prediction KF equations are given in section 5.3.2.1 and the following are related matrices where variables are taken in D=2.

$$F = \begin{pmatrix} 1 & 0 & st*dt & 0 \\ 0 & 1 & 0 & st*dt \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \qquad B = \begin{pmatrix} st^2/2 & 0 & 0 & 0 \\ 0 & st^2/2 & 0 & 0 \\ 0 & 0 & st^2/2 & 0 \\ 0 & 0 & 0 & st^2/2 \end{pmatrix} \qquad H = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

5.4.2 Simulations

As evaluation metrics, maximum error for accuracy, ratio of non-located nodes and execution time are considered while varying the number of nodes. The same scenarios as in the previous section on comparative study is considered.

Figure 5.5 depicts the performances in terms of RMSE of node location and Figure 5.6 makes performances comparison supported by numerical results highlighted in Table 5.2. The node localizability represents the first improvement where, with cooperative posture detection (cooperativePD), the system is able to localize all nodes at each instant of simulation. For localization accuracy, the result shows about 50% of improvement. However, the time of execution increased slightly but is still acceptable. With deep research, we think that the use of body posture detection could be more efficient than many other techniques and could behave as dead reckoning for node tracking.

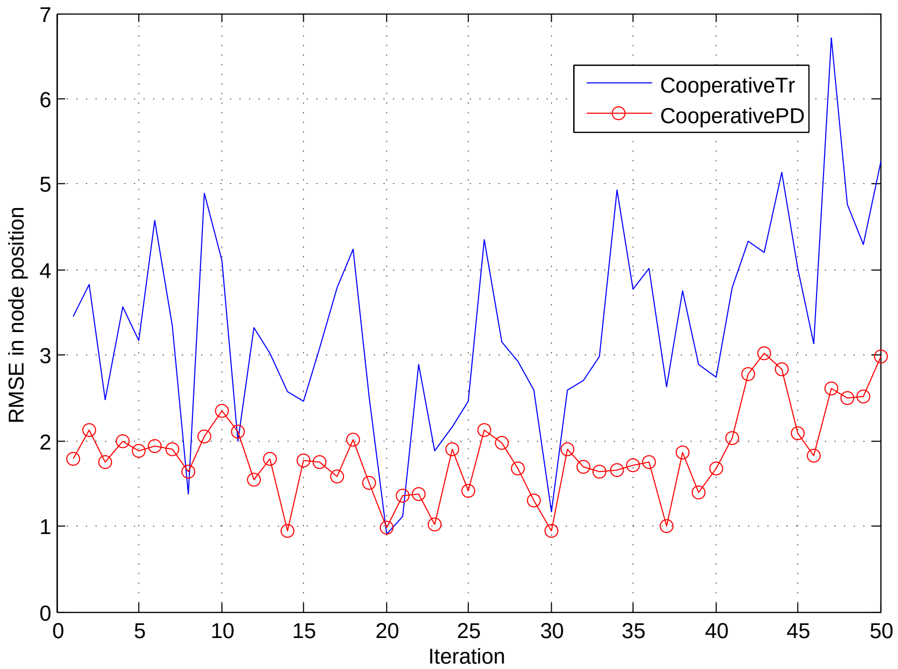

FIGURE 5.5: Comparison in terms of error

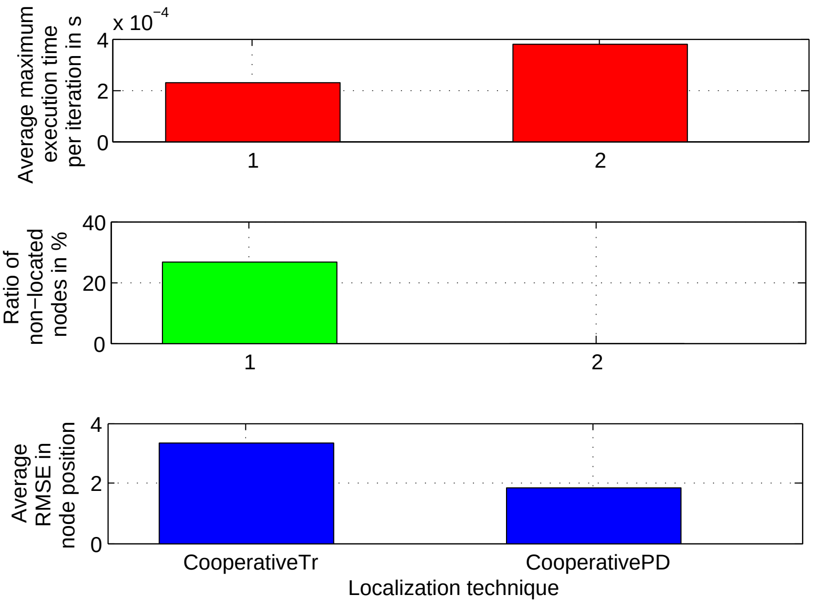

FIGURE 5.6: Comparison in terms of error, localizability and time of execution

TABLE 5.2: Performances comparison

	CooperativeTr	**CooperativePD**
Mean error	3.6219	1.8400
Mean time of execution (ms)	0.2269	0.3805
Amount of non-located nodes	28.6667	0.00

5.5 Indoor localization

Even if the localization problem of a mobile node in outdoor environment has been efficiently resolved by using Global Positioning System (GPS), localization in indoor environment is still challenging in terms of accuracy. Some related works using RSS fingerprints have been proposed with varied methodologies [153]; these include the work in [141] that presents an alternative mechanism based on fingerprinting and intends to use a minimum number of anchor nodes. In addition, the indoor area is thought as a matrix consisting of rows and columns and the location of the mobile node is presented as a cell in this matrix. The k-Nearest Neighbor (k-NN) in the matching algorithm most used [154]. Mechanisms based on fingerprinting are more accurate for indoor localization but the radio map requires a regular maintenance for recalibration. Authors in [155] proposed a new concept known as the asynchronous interval labeling that intends to solve the problem by generating user's place labels with the mobile accelerometer. However, [156] studied and proposed a mobile phone system based, the SurroundSense, which tries to get good accuracy by using ambient fingerprints built with acoustic, optical, motional and weather attributes. The localization accuracy can also depend on the site size: if this latter is wide and the anchor nodes do not cover the whole site, the accuracy is worst. Authors in [157] have proposed a distributed location estimation method to solve the problem: the location space and the input signal are divided into clusters according to the visible access points. Unfortunately, the accuracy for indoor localization based on range measurements from RSS is also affected by the Non-Line-Of-Sight (NLOS) conditions i.e. scattering and reflections at different objects and the fingerprinting mechanism can be the solution [153]. A localization method for a grid environment was proposed in [158]. Although positioning in indoor environment is still an important issue for existing systems, using UWB technology allows to achieve a better accuracy indoor as UWB signal has the ability to go through objects such as walls [159] what is demonstrated in [160] where achieved accuracy is at nearest centimeter. However, all devices do not use this technology yet especially if one wants to use access points this would lead to new infrastructure what means the increase of the cost. Therefore, our proposal focuses on the single WBAN indoor localization aiming to achieve a high accuracy and is based on centralized architecture to overcome the energy consumption limitations for the sensors. For experiments we chose to use existing access points in NLOS conditions to maximize the quality of the model.

5.5.1 Proposed approach

We propose a new approach for WBAN indoor localization using a combination of Fingerprinting, PSO [133] and Kriging [161]. PSO is chosen instead of other matching algorithms such as Nearest Neighbor because of its simplicity and efficiency especially in solving continuous problem. Kriging method finds its interest in helping to interpolate non-fingerprinted points' values where PSO particles can be located at any moment. Thus, with a minimum error, it generates other data without being big space consumer.

As for the second phase, PSO is used as a matching algorithm in which each particle compares the RSSs received from the mobile device with the RSSs stored in the database and corresponding to the current particle's position. If this position is not fingerprinted, corresponding RSS values are estimated using Kriging method. The distance between the particle's location and each recorded location in the database is computed using the five closest locations' values to interpolate the current particle's location. The position where a particle's fitness value is less than or equal to a threshold value, the fitness optimal value (FOV), or is the smallest of others at the end of algorithm, corresponds to the mobile device's location. Figure 5.7 is a flow diagram that illustrates all the localization process. Our approach provides three main contributions: it first intends to achieve good

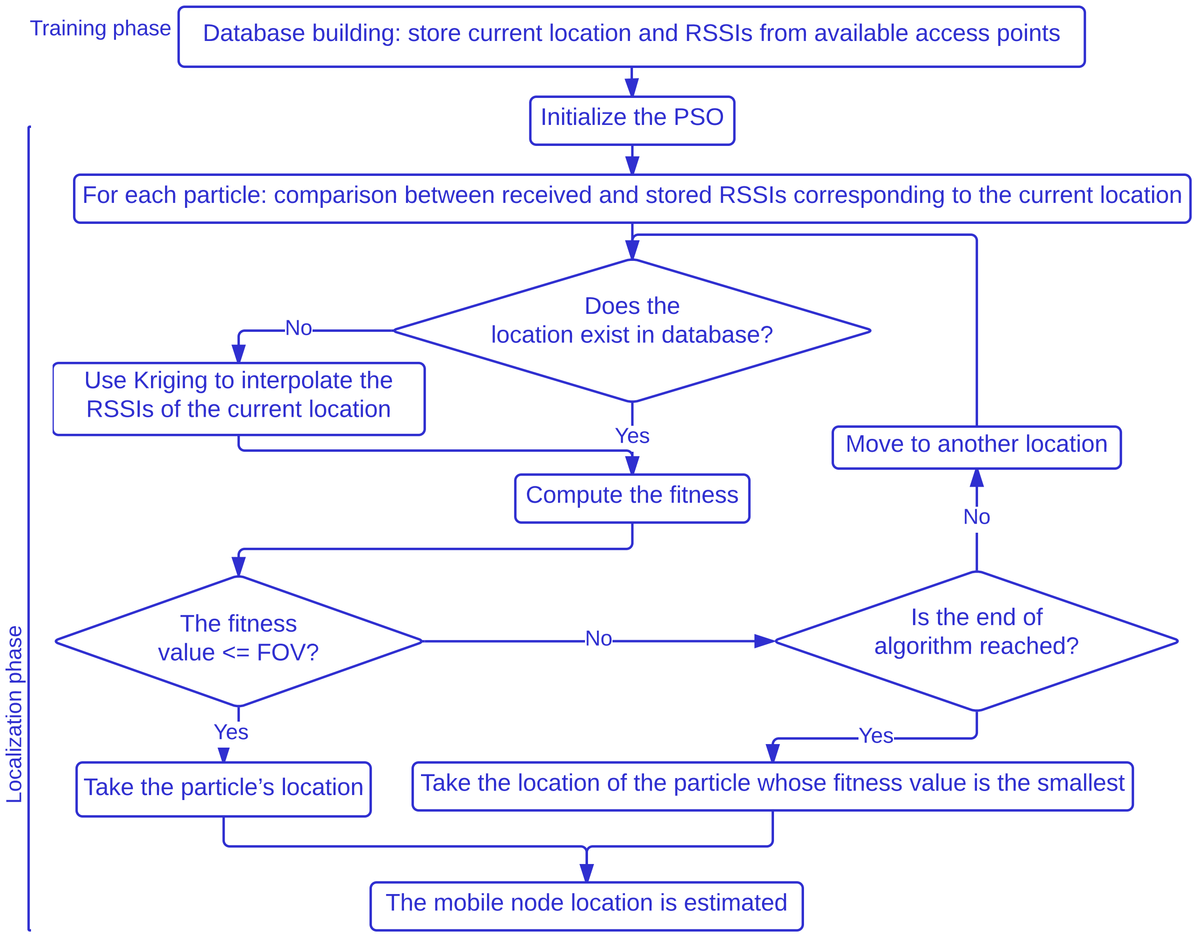

FIGURE 5.7: Kriged fingerprinting flow diagram

accuracy, then aims to overcome the problem related to the fact that a mobile node must stop moving while it is collecting RSSs (Received Signal Strength) from access points and finally, it is designed to be specific to indoor WBAN field.

5.5.1.1 Fingerprinting

As mentioned before, Fingerprinting consists of two phases: a training phase and a localization phase. In a training phase a mobile device moves through the environment recording the RSSs from a group of access points in their radio coverage range and its current location. For our approach, the device's current location is always one of the grid's points. Hence, the radio scan is considered as a measurement, the physical position where the measurement is performed as a location and the recording of the signal strength as a reading. To build a radio map of a room, a mobile device, a coordinator of the WBAN, takes a series of measurements in multiple locations of the room. Each measurement is composed of several readings, one for each radio source in range. Once the training phase is complete, the localization phase can be launched: a client can estimate its location by performing a measurement and feeding it to a localization algorithm (PSO+Kriging), which estimates the client's location based on the similarity of the signal strength signatures between the testing and the training points.

5.5.1.2 PSO

PSO is a population based iterative parallel search algorithm that originally models the way crowds of individuals like fish or birds moving towards an objective. It is a population-based stochastic approach to solve continuous and discrete optimization problems. PSO consists of a population (or a swarm) of s particles each of which represents a potential solution. The particles explore an n-dimensional solution space while minimizing or maximizing, according to the problem form, the objective function f commonly called $fitness$. The fitness of a particle close to the global solution is lower (in the case of minimization) or higher (maximization) than the one that is farther [133]. In our case, the objective function is to minimize the diversion between the RSSs fingerprinted or estimated and RSSs captured by the mobile device. At instant t, each particle i occupies a position X_{id} and moves with a velocity v_{id}, $1 \leq i \leq s$ and $1 \leq d \leq n$, where s stands for the particles number and n the space dimension. Each particle has a memory to store $pbest_{id}$, the position where it had the best fitness, and $gbest_d$, the best position found so far among all particles or in its neighborhood if it is defined. If neighborhood is defined like in our case, $pbest_{id}$ is the best position among the neighbors of each particle. At each iteration k, velocity v_{id} and position X_{id} of each particle are updated using Equation 5.24 and

Equation 5.25.

$$v_{id}(k+1) = \chi * (\underbrace{\omega * v_{id}(k)}_{A} + \underbrace{c_1 * rand_1 * (pbest_{id} - X_{id})}_{B} + \underbrace{c_2 * rand_2 * (gbest_{id} - X_{id})}_{C}) \tag{5.24}$$

$$X_{id}(k+1) = X_{id}(k) + v_{id}(k+1) \tag{5.25}$$

Where $rand_1$ and $rand_2$ are random numbers uniformly distributed between 0 and 1, ω an inertial weight and c_1 (cognitive parameter) and c_2 (social parameter) the acceleration coefficients. χ is the constriction factor. By using the constriction factor, the amplitude of the particle's oscillation decreases, resulting in its convergence over time. Apart from the value given by Equation 5.26

$$\chi = \frac{2}{|2 - \varphi - \sqrt{\varphi^2 - 4\varphi}|} \tag{5.26}$$

Where $\varphi = c_1 + c_2, \varphi \leq 4$,

we found suitable to use a dynamic value of χ given by Equation 5.27:

$$\chi = \frac{1}{1 - it} \tag{5.27}$$

Where it is current iteration. **A** corresponds to the physical component of the movement and the ω parameter controls the current movement influence on the future movement. This component influences the particle's trend to follow the current direction.

B corresponds to the cognitive component of the movement led by the c_1 parameter. Its influence is that the particle tends to move towards the best position it had occupied before.

C corresponds to the social component of the movement led by the c_2 parameter. This component makes the particle to move to the best position found in its neighborhood or in all the search space. Since its introduction in [162], PSO has been much modified to be adapted to many different environments. Many versions of PSO have been proposed and applied to solve optimization problems in diverse fields. The force of PSO resides in better parametrization of the inertial weight and acceleration coefficients and even the constriction factor. The Algorithm 9 illustrates the PSO version used in this work.

5.5.1.3 Kriging

The kriging method is a spatial prediction mechanism used to estimate a value at a given location using observed values at surrounding locations. The spatial interpolation is an estimation problem modeled by Equation 5.28:

$$F(X_0) = \sum_{i=1}^{m} \omega_i \times F(X_i) \tag{5.28}$$

Where X_0 is a location where the $F(X_0)$ value is unknown, X_i is one of m surrounding locations where $F(X_i)$ values are known and ω_i are weight coefficients.

Given Equation 5.28, the kriging method consists of calculating the unbiased weight coefficients ω_i using the semivariogram modeled by the Equation 5.30. These weights are unbiased by applying the condition set by Equation 5.29.

$$\sum_{i=1}^{n} \omega_i = 1 \tag{5.29}$$

$$\gamma(d) = \frac{1}{2n(d)} (\sum_{i=1}^{n(d)} (v(X_i) - v(Y_i))^2) \tag{5.30}$$

Where $n(d)$ is a number of location pairs (X_i, Y_i) of distance d and $v(X_i)$ is the value at the location X_i. In other words, possible combinations by two of all locations are done to

Algorithm 9 The full version of PSO

Initialization:

- ω, c_1 and c_2
- maximum allowable iterations: k_{max}
- $X_{max}, X_{min}, v_{max}, v_{min}$
- FOV: f_{Opt}

for each particle i **do**
  for each dimension d **do**
    Initialize X_{id} randomly: $X_{min} \leq X_{id} \leq X_{max}$
    Initialize v_{id} randomly: $v_{min} \leq v_{id} \leq v_{max}$
  end for
end for
Iteration $k = 0$
while $(k \leq k_{max})$ AND $(f(gbest) > f_{Opt})$ **do**
  for each particle i **do**
    Compute $f(X_i)$ (if neighborhood defined, use $pbest_i$ the best neighbor of particle i)
    if $f(X_i) < f(pbest_i)$ **then**
      for each dimension d **do**
        $pbest_{id} = X_{id}$
      end for
    end if
    if $f(X_i) < f(gbest)$ **then**
      for each dimension d **do**
        $gbest_d = X_{id}$
      end for
    end if
  end for
  for each particle i **do**
    for each dimension d **do**
      Compute velocity $v_{id}(k+1)$ using (5.24)
      Restrict v_{id} to $v_{min} \leq v_{id} \leq v_{max}$
      Compute position $X_{id}(k+1)$ using (5.25)
      Restrict X_{id} to $X_{min} \leq X_{id} \leq X_{max}$
    end for
  end for
  $k = k + 1$
end while

measure the distance between them and a matrix of distances is set. For each distance d, all location pairs of that distance are counted and their number gives $n(d)$ Practically, the exponential model is used to compute the variogram following Equation 5.31.

$$\lambda(d; a, s, r) = \begin{cases} 0 & , d = 0 \\ a + (s - a) \times (1 - e^{(\frac{-1.5 \times d}{r})}) & , d > 0 \end{cases} \tag{5.31}$$

Where a is a nugget, s is a sill, r is a range of the exponential model and d the distance.

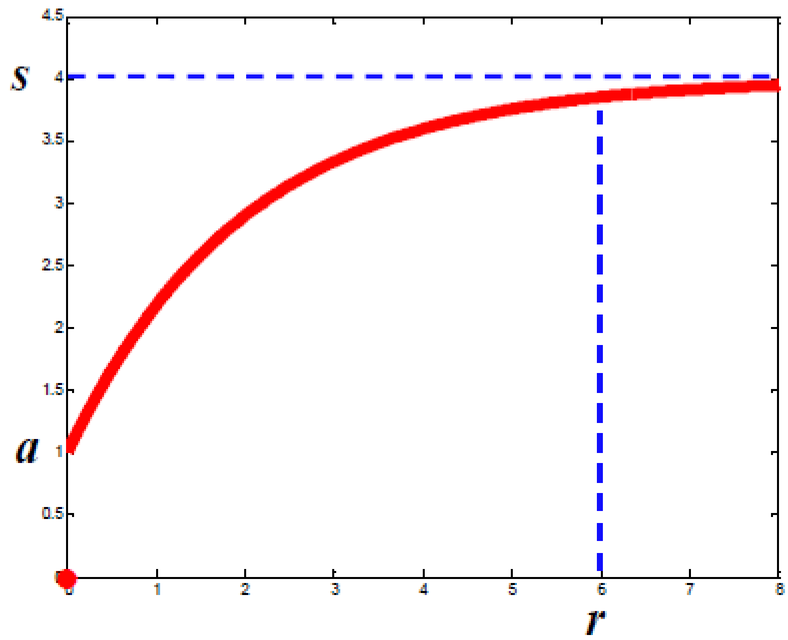

FIGURE 5.8: Exponential variogram fit

Figure 5.8 illustrates the exponential variogram fit with visible values of nugget, sill and range. Using Equation 5.31, we build a square matrix of distances from all pairs of involved points, calculate its semivariogram and then turn it into a data covariance matrix as follows:

$$K = [s - 0.5 \times \lambda(d(X_i, X_j))]_{ij} \tag{5.32}$$

$, i = 1 \ldots n; j = 1 \ldots n$

Thus, we obtain the kriging system with unbiased condition as follows:

$$\begin{bmatrix} K & 1 \\ 1 & 0 \end{bmatrix} \times \begin{bmatrix} \omega \\ \mu \end{bmatrix} = \begin{bmatrix} \lambda^* \\ 1 \end{bmatrix} \tag{5.33}$$

With μ the Lagrange parameter, λ^* is solution to the semivariogram expression given by Equation 5.34 and ω is a vector of kringing coefficients.

$$\gamma^* = [s - \lambda(d(X_1, X_0)), \ldots, s - \lambda(d(X_n, X_0))] \tag{5.34}$$

Where $d(X_i, X_j)$ stands for the distance between two point locations with $i, j < n$ and n the number of all point locations. Hence, we solve the system given by Equation 5.35 to find the coefficients $\omega = (\omega_1, \ldots, \omega_n)^T$.

$$\begin{bmatrix} \omega \\ \mu \end{bmatrix} = \begin{bmatrix} K & 1 \\ 1 & 0 \end{bmatrix}^{-1} \times \begin{bmatrix} \lambda^* \\ 1 \end{bmatrix} \tag{5.35}$$

Where 1 beside K is a vector of the same length as the matrix K.

5.5.2 Experimental setup, results and discussion

In a real scenario case, we assumed that a patient equipped with a WBAN for blood pressure, heartbeat or other physiological indicator is at home dealing with his daily life activities but needs to be monitored by a remote station over network connection for any critical situation. It is then necessary to send patient's location with physiological data to know whether the emergency warning indicator is due to an accident or an environmental effect of the place where he is located so as to initiate a prompt action whenever necessary [158]. Thereby, we developed a centralized algorithm that processes data from mobile device of the patient to determine its location. We led experimental analysis in a room of the Laboratory of Electronics and Information Technologies (LETI) that we divided into square cells of 1.5 m of side and covered by five access points as shown in Figure 5.9.

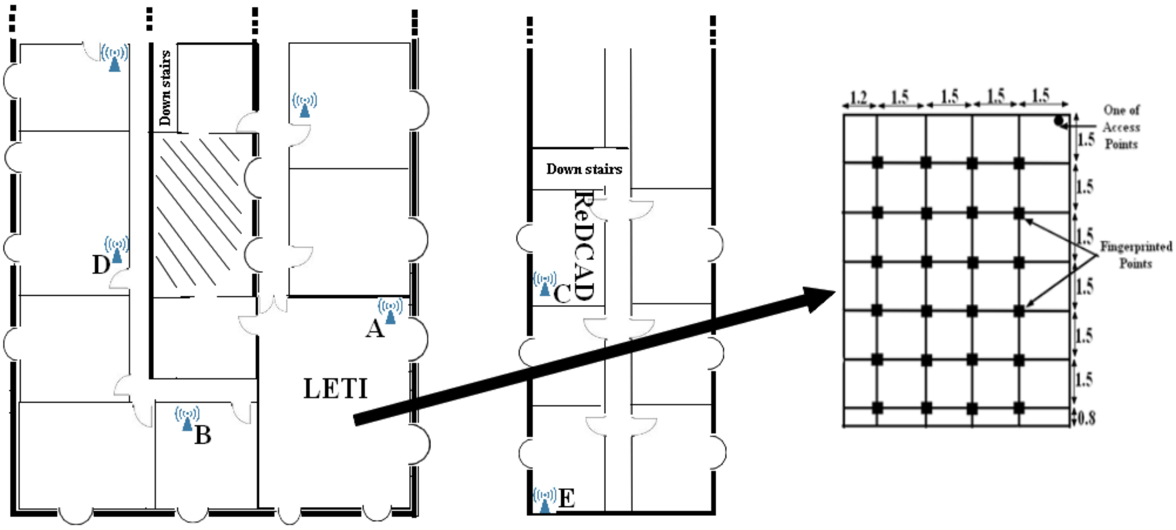

FIGURE 5.9: Experiment test bed view

The tests have been performed on a laptop Dell core2 duo, CPU T6670 @ 2.2 GH with Windows7 32 bits and installed memory of 4 GB. The inSSIDer [163] which is a Wi-Fi network scanner application for Microsoft Windows and Apple OS X developed by MetaGeek was used to collect data while the processing has been carried out with Matlab. During the fingerprinting training phase, each grid point is recorded with RSSs from five access points collected during 10 seconds and saved in database as a matrix: $P_k = (a_{i,j}), 1 \leq i \leq 6, 1 \leq j \leq 7, 1 \leq k \leq 24$. It was noted at most 6 RSS different values during those 10 seconds. Each row of the matrix represents different RSS values from one access point with their average at the end except the 6^{th} which represents the grid point coordinates and collector device's location as illustrated below:

$$P_4 = \begin{pmatrix} 57 & 59 & 54 & 53 & 52 & 52 & 55.50 \\ 77 & 77 & 74 & 74 & 74 & 73 & 74.83 \\ 88 & 88 & 88 & 82 & 82 & 80 & 84.66 \\ 83 & 83 & 79 & 79 & 79 & 81 & 80.66 \\ 85 & 85 & 85 & 85 & 85 & 90 & 85.83 \\ 6 & 1.5 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

Therefore, our database is modeled like: $FP = P_1, P_2, \ldots P_n$ with n the number of points recorded. In localization phase using PSO, particles are initialized with fingerprinted points' locations and each particle evaluates the fitness function modeled as the Root Mean Square Error (RMSE) following Equation 5.36:

$$f = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (\hat{x}_i - x_i)^2} \tag{5.36}$$

Where $N = 5$, is the number of access points, $\hat{x}_i$ is the RSS value of access point i for current particle's location and x_i is a corresponding RSS received from a mobile device. All parameters used for PSO are set in table 5.3.

TABLE 5.3: PSO parameters

Parameters	**values**	**Parameters**	**values**
X_{max}	(9,7)	ω	0.5
X_{min}	(0,0)	χ	1/(1-it)
v_{max}	5	FOV	0.7
v_{min}	-5	$NbrPrt$	50
c_1	1.1	k_{max}	200
c_2	3	$NbrPrtNeigh$	$NbrPrt/10$

Where $NbrPrt$ is the number of particles and $NbrPrtNeigh$ is the number of the particles in each neighborhood. If the particle's location is not recorded, the Kriging mechanism is used to interpolate it using the five closest recorded points' values. As the kriging method requires a semivariogram model, we studied our database distribution using Equation 5.30 and found that it can fit with the exponential model with $a = 0, s = 27.24$ and $r = 6.48$, on one hand.

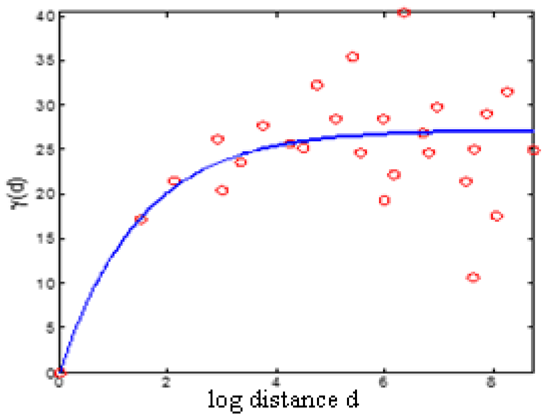

FIGURE 5.10: Empirical vs. Exponential variogram fit

On the other hand, the signal strength can be modeled theoretically as follows [164]:

$$RSS(dBm) = A - 10 \times n \times \log_{10}(d) \tag{5.37}$$

We empirically found that $A = -40dB$ and $n = 1.2$ model well our database distribution. In fact, as shown in table 5.4, RSS measurements from an access point at different distances have been made and for each distance the RSS variation during 10 s was recorded with their average.

From Equation 5.37, values in table 5.5 were generated by varying the value of n.

Figure 5.11 encompasses data from table 5.4 and table 5.5 and illustrates the variation and the suitable value of n.

TABLE 5.4: RSS variation in terms of range

Range	RSS	Average
1 m	-40 -41	-40.5
2 m	-44 -43 -45	-44
3 m	-47 -48 -50	-48
4 m	-47 -46 -48	-47
5 m	-47 -48	-47.5
6 m	-49 -50	-49.5
7 m	-49 -50	-49.5
8 m	-49 -50 -51	-50
9 m	-50 -51 -52	-51

TABLE 5.5: Theoretical RSSI in terms of range and n values

Range	RSS, n=1	RSS, n=1.2	RSS, n=1.5
1 m	-40.000000	-40.000000	-40.000000
2 m	-43.010300	-43.612359	-44.515440
3 m	-44.771212	-45.725455	-47.156810
4 m	-46.020599	-47.224719	-49.030890
5 m	-46.989700	-48.387640	-50.484550
6 m	-47.781512	-49.337815	-51.672260
7 m	-48.450980	-50.141176	-52.676470
8 m	-49.030899	-50.837079	-53.546340
9 m	-49.542425	-51.450910	-54.313630

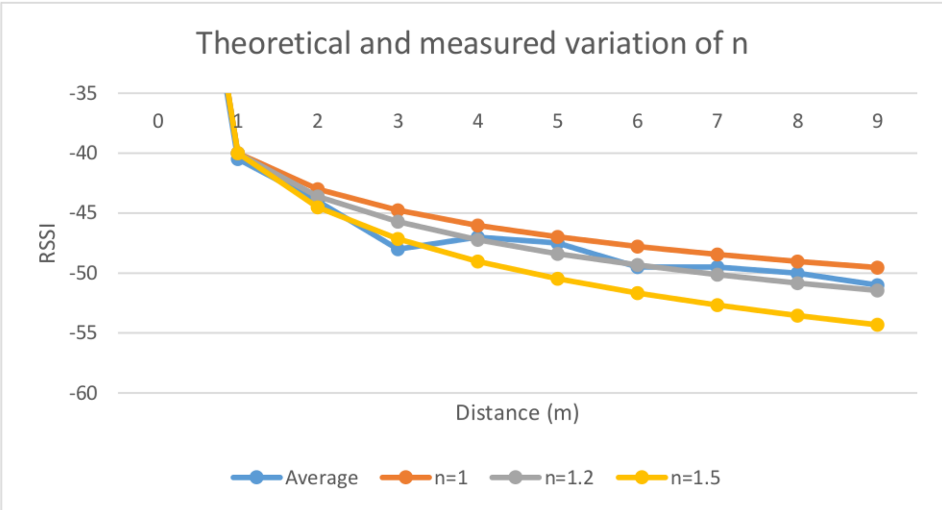

FIGURE 5.11: Theoretical and empirical variation of n

Thence, Equation 5.37 becomes as follows:

$$RSS(dBm) = -40 - 12 \times n \times \log_{10}(d) \tag{5.38}$$

Therefore we used the dynamic part of Equation 5.38 to fit the semivariogram and Equation 5.32 becomes:

$$K' = [s - 6 \times \log_{10}(d(X_i, X_j)) \times \lambda(d(X_i, X_j))]_{ij}, \quad i = 1 \ldots n; j = 1 \ldots n \tag{5.39}$$

Note that the values of A and n are specific to our experiments; in other words, these values depend on the environment and have to be calculated.

As our approach includes PSO that works with random values, tests have been performed three times and the results are reported in Table 5.6.

TABLE 5.6: Test error collection

Coordinates (m)	**Test1: Error (m)**	**Test2: Error (m)**	**Test3: Error (m)**	**Mean Error (m)**	**FrPr* Error (m)**
(1.5,1.5)	1.0214	0.9566	0.9002	*0.9594*	*0.8989*
(1.5,4.5)	0.3562	0.3421	0.3911	*0.3631*	*1.1222*
(3,3)	0.1254	0.1978	0.1120	*1.1450*	*1.5000*
(3,6)	0.2641	0.2441	0.2190	*0.2424*	*1.1180*
(4.5,1.5)	0.8791	0.9082	1.0324	*0.9399*	*1.0000*
(4.5,4.5)	0.2451	0.2982	0.3159	*0.2864*	*1.2431*
(6,3)	1.2222	1.4585	0.4810	*1.0539*	*1.5000*
(6,6)	0.7334	0.8159	0.9475	*0.8323*	*2.6920*
(7.5,1.5)	1.0914	1.2167	1.1614	*1.1565*	*0.9242*
(7.5,4.5)	0.8153	0.8129	0.7925	*0.8194*	*1.1200*
(9,3)	0.8256	0.7254	0.9251	*0.8253*	*1.0000*
(9,6)	1.0010	0.8253	0.9120	*0.9127*	*1.2010*
(4,5)	0.9345	1.1022	1.0054	*1.0140*	*1.3231*
(5,2)	1.2055	1.5011	0.9157	*1.2074*	*0.9982*
(5.5,3.5)	1.4012	1.1108	1.2109	*1.2409*	*1.2562*
(3,4.5)	1.5655	1.0736	0.6633	*1.1008*	*0.7071*
(6,1.5)	1.2607	1.6864	1.0642	*1.3371*	*1.1180*
(2,2)	0.9907	1.1669	1.5922	*1.2499*	*1.0000*
(8,6)	0.2121	1.0000	0.2588	*0.4903*	*3.6056*
(8,3)	1.5091	1.0245	1.1781	*1.2372*	*1.5000*
(8,1)	0.7412	1.0209	0.9586	*0.9069*	*3.3541*
(9,4)	0.9883	0.9911	0.7677	*0.9157*	*1.4142*
(7,4)	0.8043	0.1819	0.1827	*0.3896*	*1.0000*
(6.5,3)	1.5039	1.0502	0.8704	*1.1415*	*1.5811*
Mean Error (m)				**0.9069**	**1.4240**

*FrPr: fingerprinting

Table 5.6 shows the mean error values of our proposal in comparison with the fingerprinting mechanism using k-Nearest Neighbor as matching technique. The fingerprinting utilizes for each point of the grid the average of RSS values received during the 10 s of training phase. The test has been done on 12 point locations of the grid with other 12 non-recorded points so as to balance the efficiency of our proposal and all those locations cover the whole experimental room. The overall mean error for our approach is about 0.9069 against 1.4240 for fingerprinting. Moreover, the accuracy evaluation of our approach has been extended to comparison of its mean error values with those obtained in other related works as illustrated in Table 5.7. We notice that our approach outperforms all fingerprinting based mechanisms for indoor localization.

TABLE 5.7: Mean error values of localization mechanisms

Mechanism	**Error (m)**
Smartphone based indoor localization [146]	3
Closest neighbor [136]	3.32
Statistical method [136]	2.88
Kalman filter [136]	2.56
Particle filter [136]	1.86
Particle filter+INS [136]	1.53
Closest neighbor RADAR [136]	3.88
Propagation model [136]	4.91
Propagation model+RADAR [136]	3.88
Simple triangulation model [136]	5.73
Alternative fingerprinting [141]	1.5
Fingerprinting -knn	1.4042
Kriged Fingerprinting	**0.9069**

Our approach aims firstly to increase the indoor localization accuracy so that a mobile node in a fingerprinted room can be localized with a minimum error value. Secondly, in some proposed fingerprinting localization methods, the mobile node has to stop moving for a given time, the time used in offline phase to collect signal strength from all access points in range. However, our proposal is instantaneous and the mobile node can still moving while receiving and sending RSS what is suitable to an unaware subject during the localization phase: the localization algorithm is running in background. In a real case, a patient equipped with a sensor does not need to know when it is sensing, receiving or sending data. Finally, the interpolation method (kriging) avoid to build a huge fingerprinting database and helps estimate the RSSs in a non-fingerprinted point. But, the more the fingerprinted points are close each other, the higher the localization accuracy will be.

5.6 Outdoor localization

As stated in previous sections, a very known system for outdoor localization is still the GPS. However, the WBAN localization for outdoor environment requires specific techniques due to the WBAN specificity and constraints such as energy. As the outdoor environment is unpredictable area where it is impossible or difficult to use additional infrastructure, anchorless or mobile anchor based techniques and techniques based on natural data are the best candidate. Some WBAN applications often require rapid system deployment in unknown environment leading to complicated definition of a localization service. These applications such as search and rescue (by firefighters for instance), force tracking by soldiers, and adventure make impossible the use of any pre-existing and fixed infrastructure. In such infrastructure-limited scenarios, cooperation between network nodes sounds to be a good candidate for self-location information. Considering the case of firefighters combating the flames, there is a risk of being imprisoned of the fire and not able to escape. In this case they need to be secured. Therefore, knowing a firefighter's location he can be guided towards an escape issue or the fire focuses or else be sent a secure team if he remains in the same position for long time. However it is impossible to know in advance the place of fire accident to fix localization infrastructure support. In the following a Kriged Kalman Filter based on gravity (KKFG) is proposed. Our KKFG is a cooperative solution based on environmental data using kalman filter and kriging techniques.

5.6.1 Proposed approach: kriged KF based on gravity

Geoffrey et al. [165] used the measurements of the atmospheric air pressure (AAP) on the nodes to precisely locate these latter. Accordingly, one can think of the use of natural data such as atmospheric air pressure, Earth gravity or gravity on the surface of the Earth (GV), Earth magnetization, magnetic susceptibility (MS, MS is the degree of magnetization of certain materials in response to a magnetic field application), pollution degree (CO_2

content or emission fCO_2), etc. to locate the whole WBAN. Based on that idea from [165], the KKFG is hence proposed. The key point of this proposal is the use of environmental data to deduce relevant information such as location, therefore it relies on the anchors mobility that decreases their number and the use of a kalman filter and kriging. In fact, all WBAN nodes cooperate to measure the GV and neighbor WBAN subjects in turn cooperate to infer their locations if they are not covered by 3 anchors.

5.6.1.1 Ranging technique

As described before in section 5.2.3.1, there exists many ranging techniques that can be classified into two main categories: synchronous ranging schemes and asynchronous ranging schemes. For example, TDoA is a synchronous ranging scheme and requires all the nodes to be globally synchronized whereas TW-ToF is asynchronous and does not require any time synchronization between the nodes. In synchronized mode a mobile node periodically broadcasts a beacon packet containing its departure time. Once the anchors receive the beacon they measure the arrival time deduce the delay by calculating the subtracting the two instants of time. The distance between the nodes is calculated by multiplying the speed of signal propagation with this difference.

The RSSI ranging technique is often used as it does not require additional infrastructure but the results are still more inaccurate. An other technique based on angle requires additional infrastructure as existing devices are not equipped with related sensor. However it is more accurate than the previous. The time of flight (ToF) is an other technique that encompasses the time of arrival (ToA) and TDoA. These techniques are more accurate than the previous but are synchronized.

Taking advantages of UWB transmission capability to overcome the issue of signal obstacle penetration [150], ToA can use this transmission for ranging so as to enhance the location accuracy. Given the problem of synchronization in ToA, the two-way ToF is suggested. However, this is done with error that can be mitigated using some filtering techniques.

In the work of Pedro and Kamin [166, pg. 179], the comparison between ToF and RSS performances show that ToF increases as the distance grows whereas the RSS is unstable in terms of correlation with the distance and a symmetric double-sided ToF was proposed in [122]. Our proposal is assumed to use the UWB TW-ToF technique in ranging phase given the high accuracy achieved by Time Domain Corporation [150].

5.6.1.2 Localization

Our proposal intends to use a small number of anchor nodes. By this end, the anchor WBAN subjects with GPS receiver all the working field and the WBAN subjects with unknown locations infer their locations with trilateration using information from the anchor WBAN subjects. When an WBAN subject gets its location it behaves as an anchor WBAN subject and helps others to estimate their locations. Broadcasting locations in the network by all WBAN subjects, the network becomes full connected and self-cooperative positioning.

5.6.2 Problem formulation

It is assumed that the WBAN subjects are equipped with sensors able to measure GV and to use TW-ToF ranging technique. When a WBAN subject i receives a ranging request broadcast by WBAN subject j, it responds by appending its local GV g_i and its location x_i if it knows it. In this way, the WBAN subject j has information on its neighbors' local GVs and eventually the locations and the distance to them. If three WBAN subjects or more in its neighborhood know their locations, it then uses trilateration to infer its location and kriging is used when less than 3 neighbor WBAN subjects know their locations as illustrated by Figure 5.12. The kriging operation is the same as described in section 5.5.1.3 except that here GV values are used instead of RRSI values and all neighbors values are considered instead of five only . All the WBAN subjects predict their location using KF. Let consider a network of n mobile WBAN subjects distributed randomly in a

2-dimensional space (with extension to 3-dimensional space) among which r ($r \geq 3$) are anchor WBAN subjects and m remainder are subjects with unknown locations.

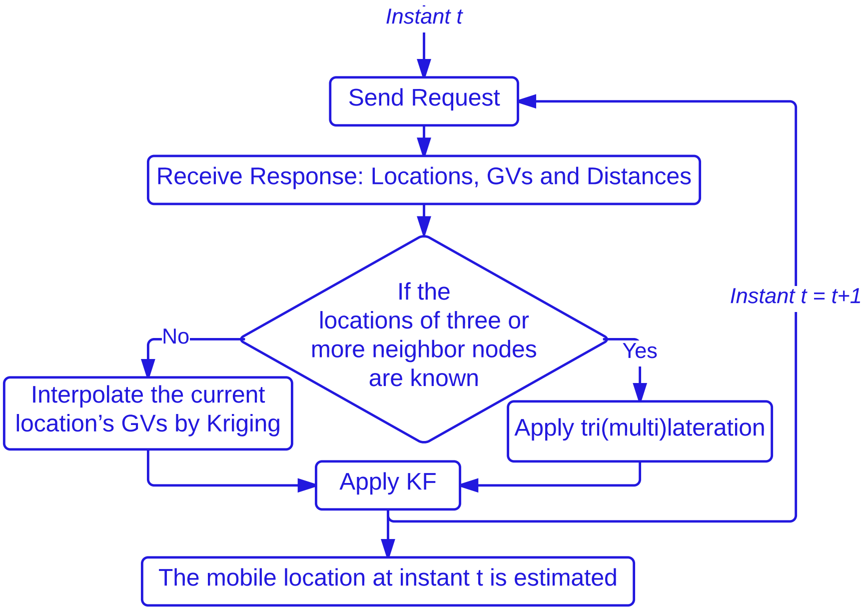

FIGURE 5.12: The KKF algorithm flow chart

The general update and prediction KF equations are given in section 5.3.2.1 with F, B, H, Q, and R the matrices and x and z the vectors as parameters. The measurement vector $z = (z_x, z_y, v_x, v_y)$ contains the position and velocity readings. Assuming that the GPS receiver is more accurate, the noise is added by randomly offsetting the actual position values provided by the GPS. x and P start out as the 0.

For unknown subjects, considering that the value obtained by ranging technique contains some error, H is set with e_p and R with e_m as errors. The estimated location with the location value obtained with multilateration and kriging should improve the accuracy.

In this work the GV which can be easily calculated by many equipments with sensors such as smartphone is used, providing that they have high resolution of detection and calculation. Unlike the very popular belief that the gravity is a constant, the GV varies due to a certain number of natural effects: rotation of the Earth and latitude (r), elevation above the sea level or altitude (h), variation mass of the Earth (m), tidal variation that is due to the gravitational pull of the sun and moon (t) and other factors such as the AAP. According to Glen [167], the variation of g (Δg in m/s^2) due to these effects is such that: $\Delta g(r) = \pm 0.03$; $\Delta g(h) = \pm 0.0001$ for 1 km; $\Delta g(m) = \pm 0.0006$; $\Delta g(t) = \pm 0.000003$.

The Gravity variation due to latitude variation h is given by the expression 5.40 according to International Gravity Formula [1].

$$g_0 = 9.7803267714(\frac{1 + 0.00193185138639 sin^2 h}{\sqrt{1 - 0.00669437999013 sin^2 h}}) \quad m/s^2 \tag{5.40}$$

g_0 is called normal gravity.

Taking into account all possible effects, the general expression of local GV is given by [167] as follows:

$$g_i = 9.7\underbrace{8}_{r}0\underbrace{3}_{h+m}2\underbrace{6}_{t} \quad m/s^2 \tag{5.41}$$

It was shown in [168] that the GV distribution has a power semi-variogram model (Eq.5.42) combined with Gaussian model (Eq.5.43) and the combined structure is given by the expression 5.44.

$$\gamma_1(d) = \gamma(d; a, b) = \begin{cases} 0 & , d = 0 \\ a + bd^{\lambda} & , d \neq 0 \end{cases} \tag{5.42}$$

where $0 \leq \lambda \leq 2, a \geq 0, b \geq 0$ with $\omega_1 = 1$

$$\gamma_2(d) = \gamma(d; r, s, a) = \begin{cases} 0 & , d = 0 \\ a + (s - a)(1 - e^{-3(\frac{d}{r})^2}) & , d \neq 0 \end{cases} \tag{5.43}$$

where $a \geq 0, s \geq a, r \geq 0$ with $\omega_2 = 1, r = 10$

[1]Established by the World Geodetic System 1984. There are earlier versions of this formula

The combined expression $\gamma(d) = \omega_0 + \omega_1\gamma_1(d) + \omega_2\gamma_2(d)$ is as follows:

$$\gamma(d) = \gamma(d; r, s, a) = \begin{cases} 0 & , d = 0 \\ \omega_0 + \omega_1(a + bd^{\lambda}) + \omega_2(a + (s - a)(1 - e^{-3(\frac{d}{10})^2})) & , d \neq 0 \end{cases} \tag{5.44}$$

In our case $\omega_0 = 0$, $a = 1$, $b = 3$, $s = 3$, $\lambda = 0.6$

5.6.3 Performances analysis

In the simulation, two different scenarios in 100x100 m 2-dimension space are set up to evaluate our model using matlab tool. For all simulation scenarios, the worst case with a minimum of anchors, 3 anchors are considered . In the first scenario 3 WBAN subjects are considered while varying the WBAN subjects' velocity. In the second, the velocity is set to 10 m/s, referring to the first scenario result and the number of WBAN subjects is varied. It is assumed that only the distance between locations influences the GV variation. For anchors there are no control actuators, so the control vector and matrix (B) are ignored. However this is taken into account for WBAN subjects.

$$F = \begin{pmatrix} 1 & 0 & 0.2 & 0 \\ 0 & 1 & 0 & 0.2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad H = \begin{pmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \quad Q = \begin{pmatrix} 0.1 & 0 & 0 & 0 \\ 0 & 0.1 & 0 & 0 \\ 0 & 0 & 0.1 & 0 \\ 0 & 0 & 0 & 0.1 \end{pmatrix}$$

$B = I$ and $R = e_m I$ where I is identity matrix.

The error evaluation is done following the Euclidian RMSE expression 5.2.

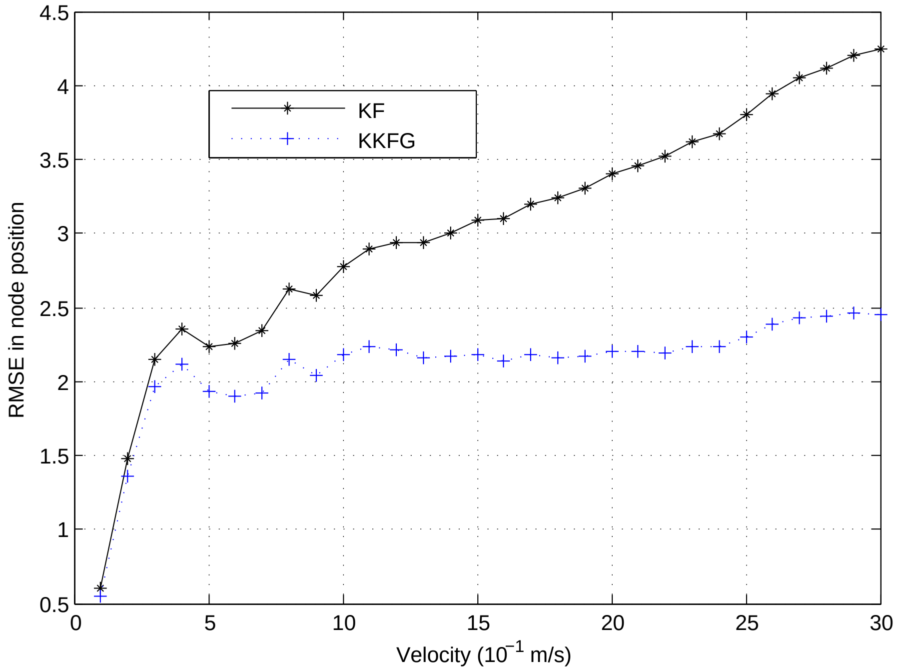

FIGURE 5.13: Average RMSE of WBAN subject location vs. velocity

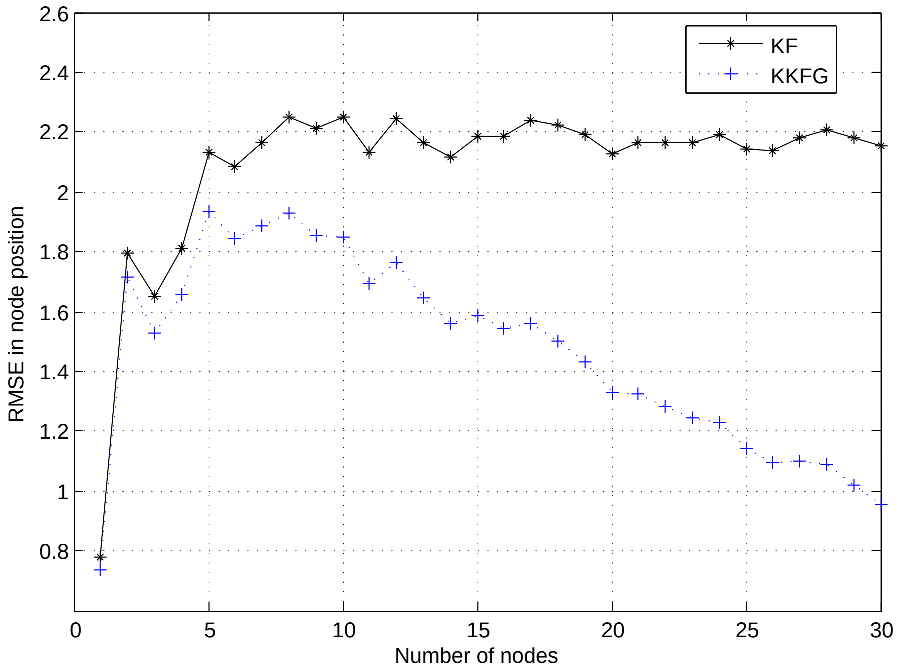

FIGURE 5.14: Average RMSE of WBAN subject location vs. number of WBAN subjects

Simulation results present much performance in terms of location error if we compare with the Kalman Filter (KF). Results of the first scenario illustrated in Figure 5.13 show that our proposal behaves as a spherical semi-variogram with a sill of 2.5 m and a range of 10 m/s while the KF loses its performance with the velocity increase. For the second scenario however (Figure 5.14), the KF stabilizes at about 5 WBAN subjects with error value of 2.5 while this value decreases. It is noted that our proposal performance increases with the number of the WBAN subjects. With these results, it is interesting to explore deeper the opportunity of using data found in the nature to improve WBAN services and locate devices in particular.

5.7 Conclusions

Many works are still confusing about WBAN localization and WSN localization as there is so far no specific works for WBAN localization. In this chapter a detailed and commented investigation of localization algorithms and mechanisms likely to be used for WBAN localization and tracking is presented by grouping them into many categories that can depend on the interest of applications. In addition, a comparative study made accordingly showed better performances of cooperative techniques over non-cooperative techniques. Many strategies involved in are also presented while giving specificities of WBAN localization. Thus, a cooperative technique based on body posture detection (cooperative PD) has been introduced, leading to cooperative technique improvement. Some tips for WBAN localization and tracking are also discussed so as to enhance performance of WBAN localization systems that will subsequently be designed.

Furthermore, a new approach for indoor WBAN localization regarding to the case of a single person was proposed . A related centralized algorithm has been proposed intending to overcome the energy consumption issue. Our proposed approach shows good performances in terms of localization accuracy and the use of kriging method reduces the memory space consumption.

Finally, a kriged kalman filter based on gravity is proposed for outdoor localization using mobile anchors to infer locations of a mobile WBAN subject and cover the navigation space. We believe that the performances of this proposal open the doors to the use of data found in the nature to perform many useful operations such as localization.

Chapter 6

Conclusions, Open issues and Perspectives

At the end of this thesis project, we summarize in this section all achieved points, review some points appeared as contribution or issues for monitoring systems and WBANs. We also draw different perspectives from this thesis.

6.1 Summary and Conclusions

Throughout this thesis we focused on the communication between sensors within a WBAN and between the WBANs themselves to enhance the transmission quality and optimize energy consumption by defining cooperative mechanisms. We also defined the architecture of a monitoring system based on WBAN by taking mobility into account.

We first presented the WBAN technology in chapter 2. In that presentation we gave the two main standards, IEEE 802.15.6 and IEEE 802.15.4, especially their PHY and MAC layers' features. We also gave different types of sensors and physiological monitored signals. With WBAN applications and services investigated in that chapter, we showed how is important to design a monitoring system by considering the mobility of the WBAN subject.

We then designed in chapter 3 a model of a WBAN monitoring system likely to take away any constraint of a user's mobility, i.e. the movement of the monitor and the WBAN subject himself. We thus defined a 4-tiers architecture and proposed some mechanisms for tiers interactions. The link allowing permanent connectivity was studied and a proposal of a scheduling mechanism for preventing time-sensitive data from starvation has been defined. Some essential and challenging features led us to set cooperation mechanisms to solve some issues such as energy consumption, data throughput, delay, latency, etc. Also, the survey of applications and related projects led to the interest of localization service for the system for example in the case of emergency, rescue, subject surveillance and tracking, etc.

The cooperation mechanisms have been then studied in chapter 4. Given that within a WBAN it was demonstrated that a two-hop topology is more efficient than one hop for interferences mitigation and that nodes can be located far from the coordinator what needs a relay node, we found interesting to define cooperation mechanisms. We thus defined a MAC cooperative mechanism that decodes and merges data at a relay node what increased the data delivery and the ability to transmit even in interference conditions without increasing energy consumption. From the observation that for many other application areas WBAN subjects are in group, the inter WBAN cooperation is necessary. We thus defined a concept of network of BANs, named NetBAN, where subjects can share information and help each other in relaying data and optimizing energy consumption. A routing protocol intending to enhance energy and prolong network lifetime has been defined, implemented and evaluated.

In chapter 5, we dealt with localization and tracking mechanisms for WBANs. We found that this problem is not yet studied enough for WBAN and needs much attention. We then tried to survey mechanisms likely to be applied in WBAN field and made a comparative study. Then, some proposals have been made to efficiently improve the localization service.

Thus, a cooperative technique based on posture detection to improve the cooperative trilateration has been proposed. For indoor environment we proposed a kriged fingerprinting that revealed to much accurate in comparison with other existing techniques. For outdoor environment, a cooperative mechanism using kalman filter and kriging techniques on gravity and named kriged kalman filter based on gravity (KKFG) is proposed. It is based on environmental data, herein the g value: the gavity on the surface of the Earth.

As conclusions,
• The WBANs are attracting and promising technologies if we consider their application fields especially healthcare and current and achieved projects. Therefore, the monitoring systems based on these technologies need a robust and consistent design.
• Cooperation and relaying mechanisms are very helpful in optimizing energy consumption, increasing data delivery, if they are used when necessary.
• Localization is an important service for the monitoring system in some application areas; in outdoor environment the GPS system is still much used and accurate, however related issue of energy consumption is still posed and in indoor environment there is still a need of accurate mechanism. A mechanism using UWB is a promising solution due to the signal characteristics.
• This thesis presents the features of WBAN monitoring systems, contributes in addressing some problems related to the system services and gives the paths to eventual future researches.

6.2 Open issues

Apart from existing issues in WBAN not yet addressed, given the recentness of this technology, this thesis project opened the door to other issues that need attention of researchers and should make user's life easier once addressed.

• **Privacy:** A the WBAN concerns vital data, people could be reluctant and complaint for their privacy. The works to improve privacy are necessary by setting for example techniques of authentication, encryption, session management, etc.

With the new network configuration led to NetBAN, here are some other issues:

• **Routing:** In NetBAN routing protocols are necessary for data conveying given that existing protocols are for only intra-WBAN routing. By defining these protocols, energy consumption, network coverage, connectivity and interference features should be taken into account.

• **Security:** Sharing data between two or more persons requires some other security mechanisms to be set and in the case of NetBAN, it imperative to define these mechanisms so as to prevent foreign people to intercept or corrupt data.

• **Interferences:** A WBAN-MS is a heterogeneous network and represent cohabitation of many wireless technologies and in the case of NetBAN the network density increases. A work focusing on the interference mitigation would be with great importance even if standards have set some related mechanisms.

• **Energy:** Energy is still a big issue for nowadays applications and communication tools. For WBAN, devices and related protocols need to reduce at maximum the energy consumption. Regarding the protocol stack of the device, either in the layers defined in the standards (PHY and MAC) or in routing mechanisms and applications, energy optimization should be among the first issues to address.

• **Localization:** In this thesis, a brief view on localization in WBAN has been given, however a full work is needed to help these monitoring systems be more serviceable while keeping privacy of the users. Particularly, the technique based on body posture detection is a promising solution in similar with dead reckoning if optimizations are made, and the use of data from nature for outdoor localization. Therefore deep work is necessary.

6.3 Perspectives

As perspectives,

• With the notion of NetBAN, we plan to design a cooperative MAC solution for intra-WBAN and inter WBANs communications

• We also plan to develop a working system with real devices and integrate the solutions proposed in this thesis.

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République Tunisienne
Ministère de l'Enseignement Supérieur, de la Recherche Scientifique et de la Technologie

Université de Sfax
École Nationale d'Ingénieurs de Sfax

Ecole Doctorale
Sciences et Technologies

Thèse de DOCTORAT

Ingénierie des Systèmes Informatiques
N° d'ordre: 690/15

DESIGN AND PERFORMANCES EVALUATION OF A WBAN MONITORING SYSTEM FOR MOBILE PEOPLE IN A COOPERATIVE ENVIRONMENT

Audace MANIRABONA

الخلاصة: الهدف من هذه الأطروحة هو تقديم نظام مراقبة WBAN ذو جودة عالية للمستعمل. تنقسم هذه الأطروحة إلى 3 أقسام رئيسية: في الجزء الأول اقترحنا بنية ذات 3 مستويات خاصة ب WBAN-MSs لتمكينهم من التنقل بسهولة, الجزء الثاني يتناول مشكلة تبادل المعلومات بين WBAN-MSs داخل أو خارج WBANs. أما الجزء الثالث و الأخير فإنه تناول مشكلة التموقع داخل WBAN.

Résumé : L'objectif des travaux de cette thèse est d'offrir à l'utilisateur un système de surveillance WBAN de qualité résistant aux effets de la mobilité. Cette thèse se compose de 3 parties principales : La première propose une architecture à 4 niveaux pour les WBAN-MS afin de leur permettre de mieux supporter la mobilité, la seconde traite la coopération intra et inter-WBANs, la troisième et la dernière traite le problème de localisation dans les WBANs avant de conclure et donner les défis de recherche.

Abstract: The main goal of this thesis is to offer to a user a system with a high quality of service by considering the mobility effects. Three main parts are setup: the first proposes 4-tier architecture for WBAN-MS to sustain mobility, the second deals with the intra-WBAN and inter-WBANs cooperation and the third and last part undergoes the localization problem in WBAN. Finally, new horizons are described as open issues.

المفاتيح: التموقع ,تعاون,نظام مراقبة ,تنقلية,WBAN, NetBAN

Mots clés: BAN, NetBAN, système de surveillance, coopération, localisation, localisation coopérative, mobilité

Key-words: WBAN, NetBAN, monitoring system, cooperation, localization, cooperative localization, mobility.