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Energy Saving and Link Efficiency in Wireless Communication of Body Area Networks Literature survey

Mohammed Abdulrahman Dawood Al-obaidi

Master of Science

Supervisor

Asst. Prof. Dr. Abdullahi Abdu Ibrahim

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Energy Saving and Link Efficiency in Wireless Communication of Body Area Networks Literature survey

By

MOHAMMED ABDULRAHMAN DAWOOD AL-OBAIDI

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____
Asst. Prof. Dr. Abdullahi Abdu Ibrahim

Supervisor

Thesis Defense Jury Members:

Asst. Prof. Sefer KURNAZ	School of Engineering and Natural Sciences, Altinbas University	____________________
Asst. Prof. Dr. Abdullahi Abdu Ibrahim	School of Engineering and Natural Sciences, Altinbas University	____________________
Asst. Prof. Dr. Zeynep ALTAN	Engineering and Architecture Faculty, Beykent University	____________________

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

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Mohammed Abdulrahman Dawood Al-obaidi

DEDICATION

This thesis is dedicated to family especially my father and mother who encouraged me from first stages of my life to study and work hard. They gave me self-confidence to achieve more and more in my life, and to do my best in educational field, therefore even these simple words will not reward them for their great efforts.

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ABSTRACT

Energy Saving and Link Efficiency in Wireless Communication of Body Area Networks Literature survey

Al-obaidi, Mohammed Abdulrahman Dawood,

M.Sc., Electrical and Computer Engineering, Altınbaş University

Supervisor: Assist. Prof. Dr. Abdullahi Abdu Ibrahim

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The Wireless Body Area Network (WBAN) was highlighted and got great attention by scientific and technical researchers during the last years because of the huge and different applications that depend on it especially the medical field, and due to the limited power of these sensors, the extending of the wireless network sensors life became an important target for researchers. In our research we introduced a novel design to extend the network life and to reduce the power consumption through adding a smart sleep state to SIMPLE protocol. We classified the sensors types into critical sensors (CS) that related to the patient critical life that any delay or error in information transmission may cause bad consequences on patient's life, and non critical sensors (NCS) that relates to patient normal and non-urgent information therefore they can go to sleep mode according to a specified time table. We also suggested a Scheduled Time Report (STR) that can be prepared and submitted by the patient's supervisor doctor according to the patient case in order to send the patient's information depending on the STR and then go to smart sleep mode when there is no need for data transmission. In our research we also suggested after sending the information by the NCS according to the STR, it should send a Receipt Acknowledgment Request (RAR) in order to ensure the reception of data to the sink node (SN) in the right way. This RAR is so important since any missing in information for any reason will be a real problem because the information is transmitted one time every sleep cycle and the next info will be sent after NCS waking up. Moreover, in order to enhance the Quality of Service (QoS) and network lifetime, we introduced a solution to improve the cost function (CF) of SIMPLE protocol by adding a factor of performance to the CF in order to determine the best route for data transmitting. The route will be determined according to the lower CF and the data will be transmitted through that route.

Keywords: WBAN, network lifetime, energy consumption, sleep mode, cost function

ÖZET

Vücut Alanı Ağlarının Kablosuz İletişiminde Enerji Tasarrufu ve Bağlantı Verimliliği (Literatür taraması)

Mohammed Abdulrahman Dawood Al-obaidi,

Yüksek Lisans, Elektrik ve Bilgisayar Mühendisliği, Altınbaş Üniversitesi

Danışman: Assist. Prof. Dr. Abdullahi Abdu Ibrahim

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Kablosuz Vücut Alanı Ağı (WBAN), özellikle tıbbi uygulamalara bağlı olan çeşitli uygulamalar nedeniyle son birkaç yılda büyük ilgi gördü ve sensörlerin sınırlı enerjisi nedeniyle, ağ ömrünün uzatılması WBAN'lar için önemli bir hedef haline geldi. Bu yazıda, SIMPLE protokolüne akıllı uyku modu eklenerek enerji tüketimini azaltmak ve ağ ömrünü uzatmak için yeni bir tasarım sunulmuştur. Sensör tiplerini, hastanın yaşamıyla ilgili kritik sensörlere (CS) ayırdık ve veri göndermedeki herhangi bir gecikme, hastanın yaşamında felaket sonuçlara neden olabilir ve belirli bir zaman tablosuna göre uykuya dalabilen kritik olmayan sensörler (NCS) . Bu STR'ye bağlı olarak veri göndermek ve daha sonra hiçbir bilgi iletilmesine gerek olmadığında uykuya dalmak için hasta amiri doktor tarafından hasta durumuna göre verilen planlanmış bir zaman raporu (STR) önerdik. Tasarımımızda, verilerin NCS ile kontrol edilmesini de önerdik, bu nedenle ölçülen veriler gözetmen doktor tarafından belirlenen kritik değerlerin üstünde veya altında ise, sensör uyanma moduna geçecek ve veriler normal duruma dönene kadar veri aktarmaya devam edecektir. daha sonra sensörü tekrar programlanmış uyku moduna (SSM) döndürecektir. Ayrıca NCS'nin, verilerin havuz düğümüne (SN) başarıyla ulaştığından emin olmak için STR'ye göre verileri gönderdikten sonra bir alındı onay isteği (RAR) göndermesini önerdik; çünkü veriler her uyku döngüsünde yalnızca bir kez iletildiğinden ve sonraki veriler uyandıktan sonra, STR'ye bağlı olarak belki uzun bir süre sonra iletileceğinden, herhangi bir nedenle eksik veriler gerçek bir sorun olacaktır. Ayrıca, ağ ömrünü ve hizmet kalitesini daha da iyileştirme

çabalarının bir parçası olarak, verileri iletmek için en uygun yolu seçmek için SIMPLE maliyet denklemine performans faktörü ekleyerek SIMPLE protokolünün maliyet işlevini (CF) geliştirdik. En düşük CF'ye sahip rota seçilecek ve veriler bu rota üzerinden iletilecektir.

Anahtar kelimeler: wban, ağ ömrü, enerji tüketimi, uyku modu, maliyet işlevi

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LIST OF ABBREVIATIONS

ABP	:	Ambulatory Blood Pressure
AMS	:	Analog-Mixed Signal
BLE	:	Bluetooth Low Energy
CF	:	Cost Function
CGM	:	Continuous Glucose Monitoring
COST	:	Component Oriented Simulation Toolkit
CS	:	Critical Sensors
ECG	:	Electrocardiography
EEG	:	Electroencephalography
EERDT	:	Energy Efficient and Reliable Data Transfer
EFC	:	Electric Field Communication
ELN	:	Electrical Linear Networks
EMG	:	Electromyography
FDA	:	Food and Drug Administration
FMI	:	Functional Mockup Interface
FMU	:	Functional Mockup Unit
GLP	:	Glucose Profile
HBC	:	Human Body Communication
HRP	:	Heart Rate Profile

HTP	:	Health Thermometer Profile
IEEE	:	Institute of Electrical and Electronics Engineers
ISM	:	Industrial, Scientific Medical
LSF	:	Linear Signal Flow
MAC	:	Medium Access Control
MB-OFDM	:	Multi-Band Orthogonal Frequency Division Multiplexing
MBU	:	Mobile Base Unit
MEMS	:	Micro Electro Mechanical Systems
MICS	:	Medical Implant Communication Service
NB	:	Narrowband
NCS	:	Non-Critical Sensors
PAWis	:	Power Aware Wireless Sensors
PDA	:	Personal Digital Assistant
PuOx	:	Pulse Oximetry
QoS	:	Quality of Service
RAR	:	Receipt Acknowledgment Request
RFID	:	Radiofrequency Identification
RIP	:	Respiratory Inductive Plethysmography
R-SIMPLE	:	Reliable Stable Increased-throughput Multi-hop Protocol for Link Efficiency
RSSI	:	Received Signal Strength Indication

SIMPLE	:	Stable Increased-throughput Multi-hop Protocol for Link Efficiency
SN	:	Sink Node
SNSE	:	Sensor Network Simulator and Emulator
SPI	:	Serial Peripheral Interface
SPL	:	Sound Pressure Level
SSM	:	Scheduled Sleep Mode
STR	:	Scheduled Time Report
TAEO	:	Temperate Aware and Energy Optimized
TDF	:	Timed Data Flow
TDMA	:	Time Division Multiple Access
TOSSF	:	TinyOS Scalable Simulation Framework
UART	:	Universal Asynchronous Receiver Transmitter
UWB	:	Ultra Wideband
WBAN	:	Wireless Body Area Network
WBSN	:	Wireless Body Sensor Network
WLAN	:	Wireless Local Area Network
WMAN	:	Wireless Metropolitan Area Network
WMTS	:	Wireless Medical Telemetry Service
WPAN	:	Wireless Personal Area Network
WWAN	:	Wireless Wide Area Network

1. GENERAL INTRODUCTION

1.1 INTRODUCTION

The aging of the population is a global phenomenon. It is mainly due to the overall improvement in the quality of life and health of everyone in developed countries. In addition to this aging, an increase in the need for long-term care has been recorded. This is a direct consequence of the growing number of sick elderly people.

In this context, the implementation of systems to reduce hospital costs and minimize the presence of medical staff remains an approach under serious consideration. It is therefore a matter of providing health and home assistance services for frail people or people with loss of autonomy (measurements of physiological parameters, administration of medication, detection of falls, etc.). This remote maintenance has become possible with technological advances, particularly in the field of telecommunications, networks and information processing.

This is also known under the name of medical tele monitoring, it aims at the remote monitoring of people suffering from chronic diseases, individuals with physical abilities degraded by aging, and post-operative subjects. It thus responds to patients' wishes to reduce hospitalization times, while promising economies of scale through out-of-hospital care.

This vision of medical tele monitoring consists of “watching over” the people in care. This involves measuring and controlling certain physiological parameters of the person remotely and reporting them to the practitioner to carry out the diagnosis and define the treatments. It is thus possible to improve personalized medical follow-up and ensure the well-being of the patient through the dissemination of alerts in the event of an emergency.

In a hospital, this monitoring of physiological parameters is based on medical sensors linked by cables to a control unit which interprets and displays the data received. The rise of new technologies as well as the progress made in the field of telecommunications offer the opportunity to carry out this remote monitoring and to allow the patient to continue a normal life. This approach promotes the use of wireless technologies to acquire data in a less cumbersome way. In this sense, it is possible to use a network of wireless sensors on board a patient to remotely and in real time measure his temperature, heart rate or blood pressure. These networks belong to the WBAN or wireless body network family. This classification is made according to the wireless technologies adopted. In fact, each family has its own IEEE communication standards which define the transmission frequencies used, the transmission rates and the communication ranges. The WBAN family of networks concerns networks with short ranges (of the order of a few tens of meters) often based on the IEEE 802.15.x communication standards. It is intended for communications around the human body. It can include wireless links to a central unit (mobile phone or to a smartphone or to a tablet or even to a computer).

In addition, such networks consist of electronic devices communicating through wireless links, whose primary functions are to collect and transmit data. These smart, miniature, and low-cost devices are called "sensor nodes". According to the physiological parameter to follow, a node may be on the surface of the body, as in the case of temperature or implanted in the body, as for the measurement of glucose levels in the blood. In both cases, it is characterized by the ability to acquire, process and communicate information. It is also connected, directly or through another node, to a central unit or base station. This collects the data from each node in order to transmit them to establishments and healthcare professionals.

In order to take good care of the person and guarantee their well-being, international standards regulate the implementation of wireless medical sensor networks. In its catalog "ISO / TC 215: Health Informatics" [1], the International Organization for Standardization ISO addresses several aspects of remote patient monitoring: communication between personal health devices (ISO / IEEE 11073), " interoperability of telehealth systems and networks (ISO / TR 16056), etc. In the United States, the FDA (Food and Drug Administration) has proposed, in addition to regulations, a guide for the implementation of radiofrequency communication in medical devices (quality of service, coexistence, electromagnetic compatibility, etc.) [2]. Thus, wireless medical sensor networks will have to face strict constraints of security, fault tolerance, measurement quality and transmission in addition to the needs of low energy consumption [3].

1.2 BACKGROUND INFORMATION

The rise of new technologies as well as the progress made in the fields of microelectronics, telecommunications, networks and information processing have led to the appearance of new tools and communicating objects that improve our quality of life. Among these communicating objects we are interested in sensors.

Over the past decades and due to the advancement of embedded systems and wireless technologies, Wireless Sensor Networks (WSN) or Wireless Body Sensor Network (WBSN), have been increasingly used in many fields. Among these areas, we are interested in WBSN for medical applications.

Imagine a set of small, autonomous electronic devices, equipped with sensors and capable of communicating with each other via a wireless medium, each of these small devices constitutes a medical sensor node. These nodes deployed on the patient's body or in his environment together form a network of medical wireless sensors that is capable of monitoring the patient's state of health by collecting physiological information and then communicating this information to a remote medical team.

One of the major challenges of the world in recent decades has been the continuous increase in the elderly population in developed countries. Hence the need to provide quality care to a rapidly growing population, while reducing health care costs. So the implementation of systems to reduce the hospital costs of patients and minimize the presence of medical staff is a real challenge.

In this context, much research work focuses on the use of wireless medical sensor networks in WBAN (Wireless Body Area Network) systems, to facilitate and improve the quality of care and remote medical monitoring. These networks are characterized by the mobility of their sensor nodes, by their ease of deployment and their self-organization, which is an advantageous point for the monitoring of the elderly, people with reduced mobility, people at risk and people with chronic diseases as well as for monitoring their living environment.

Medical wireless sensor networks are used today in medicine to monitor certain vital signs such as temperature, blood pressure or heart rate, etc. So WBAN systems not only improve the quality of life of patients, but also monitor patients in real time and intervene as quickly as possible in emergency cases.

Wireless Sensors Networks (WSN) are a real revolution in wireless computer networks and micro electromechanical MEMS (Micro Electro Mechanical Systems) systems.

The advances made in the fields of microelectronics and wireless communication technologies in recent decades have made it possible to produce, at a reasonable cost, micro sensors, which are true on-board systems. These sensors have three functions: capture the values of physical quantities, process information using these collected values and communicate them through a network of sensors.

The deployment of several sensors on the human body, in order to collect physiological data (temperature, blood pressure, heart rate, etc.) and transmit them autonomously to one or more collection points, forms what is calls a body network of wireless sensors - Wireless Body Area Network (WBAN).

A medical wireless sensor network is a set of nodes (each node representing a sensor) which are deposited on moving objects or individuals. Each node can communicate with the other nodes which are located in its coverage area. The data collected by these nodes are communicated directly or via the other nodes step by step to a collection point called "base station" or "sink". This base station has more storage capacity and processing power than the sensors. It can also have a role of network controller and it sometimes acts as the link between the user and the network.

The use of these sensors in the medical field offers enormous benefits and brings new comforts to patients such as patient mobility, remote monitoring of the elderly and disabled, as well as long-term care.

Wireless sensor networks are used in medicine today to monitor certain vital signs. The use of wireless networks could improve the quality of care: the absence of restrictive electrical installations, the reduction in the size of the wires connecting the sensors to the treatment unit, the ease of installation as well as the freedom of movement for the patient.

They make it possible not only to improve the quality of life of patients, who can stay at home, but also the monitoring of patients in real time as well as the intervention as quickly as possible in the event of an emergency (for example if the measurements returned by the sensors are abnormal). Multiple medical sensors are deployed on the patient's body to measure multiple physiological parameters. The measured data will then be sent to the medical team over a broadband network so that they can monitor the patient's condition and take action in an emergency [4].

1.3 PROBLEM STATEMENT

The framework in which this thesis is placed is medical tele monitoring to watch over the health and well-being of people. Wireless medical sensor networks are therefore essential for the deployment of such applications. However, their adoption for medical monitoring still faces several challenges and technological obstacles. These locks are linked on the one hand to the particularities of the nodes in terms of resources (energy, processing power, memory, etc.) and on the other hand to the needs of the medical application (maintaining the integrity of the information after transmission, data encryption, etc.). Consequently, particular difficulties were noted in the design of these networks.

A first technological challenge lies in the reliability of the node [5]. It is expressed first by fault tolerance: signaling the problem and reorganizing of the network. It also includes the accuracy of the measurements taken from the person as well as their integrity after automated processing / transfer.

A second lock to consider concerns the wireless transmission of medical data. The quality of service, noted QoS, is one of the most important concepts [6]. It is necessary because of the integration of several nodes with different transmission needs in the same network. This diversity in the network requires, on the one hand, a differentiated treatment according to the specific needs of each one and on the other hand, the satisfaction of the needs of the medical application, particularly in terms of time.

In addition, the security of the medical data transmitted is an aspect of great importance [6]. This is to provide the confidentiality, integrity and availability of information while preventing unauthorized parties from gaining access to it. The security mechanisms applicable for other communication networks are not suitable for medical sensor networks due to the limitation of energy, memory and processing power resources. Lighter security techniques must therefore be developed.

More particularly, the energy constraint constitutes a major concern of wireless medical sensor networks [5]. Indeed, these networks are often limited in energy and therefore sensitive to its consumption. The small size of the components in the sensor nodes requires low capacity batteries. These batteries can be combined with energy recovery systems from the environment or from the human body [7]. However, their exhaustion leads to dysfunction and the risk of interruption of patient follow-up. In addition, their replacement / recharging by the elderly patients / can be inconvenient, difficult and sometimes impossible, especially for implanted sensors. It is therefore essential that these batteries last as long as possible, or even throughout the monitoring period [3].

1.4 OBJECTIVES

The main objectives of this thesis are to enhance the power saving of WBAN network and to increase network reliability in addition to improve the network stability and to extend the life time of the network. The sub objectives of this thesis are introducing a novel design of WBSN that achieve the main objectives of the thesis, and also providing modified protocol with new model in order to achieve the data integrity and meet the basic goals of this thesis.

1.5 RELATED WORKS

The wireless sensors networks WSN consist of sensor nodes that deployed and distributed physically for different uses, like monitoring, battle fields supporting technology, hazardous or environmental areas, health care, and more. The sensor node has data storage, communication, sensing, and data processing components. The sensor nodes sometimes called in the literatures as computer with sensing capability [8,9,10]. The WBAN is considered as a new sub field of WSN for specified objectives. WBAN was developed to achieve communication between sensors in health field and to manage them remotely. They generally placed around, on, or in the patient body [11]. The main purpose of WBAN is to monitor the health of human body using remotely managed sensors. So the sensors are fixed in, on, or around organs of the patient and precisely used to check patient's information, like glucose level, body temperature, blood pressure, heart rate, and more. The WBANs are simply wireless sensor networks fixed in some places of human body to get data related to the vital patient information [12,13,14,15,16]. WBAN has many important roles, like monitoring the situation of the patient in real time, especially for those patients who need immediate medical interaction or some urgent or necessary medications. On other hand the WBAN in general have some constraints concerning limitation of power sources [12,17]. Therefore, WBAN require a mechanism to reduce power consumption during data transmission from the sensors to SN. As WBAN sensors operates with limited power sources, these constraints require using the least amount of the power during data transmitting from normal sensors to SN. In [18,19] the authors suggested using single hop topology and multi hop topology during routing step. In this suggestion each node will choose a route that achieves the min. number of hops to reach the SN. The 1st possible choice is transmitting data from sensors nodes to SN in through one hop. This choice is preferable when the sensors nodes located near from the SN. The other choice is using multi hop method using some nodes that gathers information from other sensors and forward it to the SN. These nodes called forwarder node. This suggestion aims to decrease the power consumption and increase the data packets sent successfully to the SN. These challenges declare the importance of delivering effective protocols to overcome the problems of limited energy sources. Some of the important issues related to WBAN problems are how to deal with limited energy sources and low bandwidth. Any how some current methods don't use the model of real WBAN radios [11,18,19] and they did not develop this approach using event driven simulations to reach results and scenarios more realistic [20].

One of the problems in WBAN that researchers paid attention and delivered different solutions is routing, because of the limited power resources and limited bandwidth, therefore many researches have been delivered. In [21] the authors discussed many practical subjects for the implementation of WBAN in healthcare services. they proposed a multi-hop WBAN structure pattern that consist of four processes, the transmission efficiency enhancement, the mobility support, and the clustered topology setup. As a supplementary advantage, the suggested pattern accomplishes an energy-efficient features by reducing the overall control messages number. In order to get the benefit of multi hop in WBAN, the authors took in their consideration many factors when designing the WBAN. One of these factors is that the WBAN design should support and overcome problems of human movement and network distances changing. Also the design of WBAN should have solutions for node failure. And also one of the important things that the network designers should take in consideration is the distribution of the loads on the nodes. The authors suggested TDMA with multi-channel to transmit information between the child node and the parent node in each group, therefore a different channel band should be assigned for each group. The network that the authors suggested has many advantages, like it can solve the problem of energy concentration by avoiding considering the distance from the source to the destination. And secondly using virtual group and reduce the transmitting range in order to reduce the possible interference between inner WBAN node and the outer WBAN node, and this may be helpful in enhancing the efficiency of data transmission. To solve mobility problem, the authors took in their consideration normal human activities and recovery of network after its fail. They suggested the following approach for the network: When control messages received by a child node, it will check the RSSI values for the messages coming from the parent nodes. If the RSSI values received for several times were lower than predefined values, then the child node will try to find other control messages stronger than those coming from the parent nodes. When these child nodes find control messages more powerful within their communication boundaries so that they can receive messages easily, they send a request to transfer to another groups, and that means that the child node submit a request of transfer from its group to a new group when the parent node be far from it and it cannot communicate with it easily. This mechanism provides the ability of child nodes transferring between groups and then overcome network failure. the authors also suggested a low power consumption and a low delay using CICADA. To schedule data transmission between the nodes TDMA was used. It offered a tree structure to ensure the data are received successfully by the sink. A multi-hop method in WBAN that focused on reducing the total number of control messages was suggested. In [22], the author suggested a procedure to give reliable energy-efficient communication. The author used time slot allocation, which used fuzzy logic. The proposed scheme reduced the wasted time slots and allowed reliability to the network. In order to enhance network performance, the authors suggested an algorithm to check the parent nodes that save energy and then be the least cost nodes in order to transmit the data. In [24], a different procedure was suggested to minimize the power loss in WBAN route communication that introduced two ways for communication: if the sensor node located near the SN, then it can transmit the data through only one hop and send data directly to the SN, but if the sensor node was located far from the SN and more than defined threshold, then it should send the data through multi hops. in [25] a same procedure but with different idea was used. The authors suggested a protocol of routing such that if the data was important or critical, then single hop will be used. But if the data are normal and not so important, multi hop method and forwarder nodes will be used [20]. In [26], a protocol of routing that increases the network life and stability was introduced. In this approach the authors select the sensor nodes with minimum distance to other nodes and sink node with maximum residual power as a forwarder node. Furthermore, a schedule depending on TDMA was added to reduce power consumption. On other hand we can notice the important data will follow the TDMA schedule and then may increase the delay. In [27], the authors suggested a protocol to solve the problem of routing. The authors in this protocol take in their consideration the heat problem, hot spot issue, stability and energy management. The weak point in this approach is the power saving as it achieves the minimum amount of power saving because the sensor nodes still transmit the date regardless of its importance. In [28], dual sink node WBAN architecture was suggested to improve the network life time and quality of service. The authors suggested using three algorithms, which are GSS algorithm for scheduled transmission and SMNN to classify the data into normal SN and emergency SN, the other algorithm is PWR in which optimal route will be selected, and finally IA-MAC algorithm which is a modification of MAC protocol.

1.6 MOTIVATION

The WBAN usually used to monitor patients' health. But main problem with WBAN is the limitation of energy sources. Therefore, many researches – including this research – tries to introduce some solutions for this problem. Many power-efficient routing methods were studied to transfer the data from the body sensor to the server. This importance comes from the fact that it is very necessary to receive critical data of the patients without errors in order to enable doctors to know the actual case of the patient. And then take wright decision. In [29], the authors suggested a novel protocol in which the mobility became easier with low throughput but with more hardware cost. The authors suggestion is to put a SN at the patient's wrist. when the wrist (SN) became far from the nodes, it will use a relay node to collect data from the SN. The problem of this suggestion is that when a man moves his hand away, the connection between the sensor node sand the SN will be lost. This disconnection will lead to more power consumption in SN and relay nodes. And also data packets may be dropped and then important and critical data will be lost too. To reduce the power consumption and increase the throughput, the authors of [18] suggested SIMPLE protocol, which is a new method that achieved stability with longer time. According to this approach the nodes consume less power and therefore still alive for a longer period of time. Furthermore, the low power consumption and the long stability period of the nodes will lead to high level of throughput.

1.7 CONTRIBUTION OF THESIS AND SIGNIFICANCE OF THIS STUDY

The contribution of this thesis to the knowledge is increasing the network lifetime, enhancing the stability, improving the reliability, and increasing the power saving of the WBANs by introducing the following additions:

- A novel design of WBSN with multi hop nodes and single SN. In this design we improved the residual energy, throughput, stability, and network life time of the WBSN. The data and sensors were classified into critical sensors, non critical sensors, critical data, and non critical data.
- We introduced R-SIMPLE protocol (Reliable Stable Increased-throughput Multi-hop Protocol for Link Efficiency) in which we enhanced SIMPLE protocol and added performance factor to the cost function of SIMPLE.
- Adding smart sleep mode to SIMPLE protocol.
- Enhancing the data integrity and reliability through sending Receipt Acknowledgment Report (RAR) immediately after data transmission depending on the scheduled time report (STR) in order to ensure that data had reached to the SN successfully. After receiving the RAR the SN can go to scheduled sleep mode (SSM) according to the STR.

1.8 THESIS ORGANIZATION

The remaining parts of this thesis were organized as follows:

In chapter two we provided literature review and discussed the architecture of WBANs and WBAN networks, we also compared between WBANs and WSNs and showed the differences between them, then we clarify the subsystems of a WBAN medical monitoring system and explained the BAN subsystem, the PAN subsystem, the Gateway Subsystem, wide area networks, and the end user. We then explained the WBAN network topologies and their classification into point-to-point topology, star topology, mesh topology, and tree topology. In the same chapter we discussed the sensor nodes and medical sensors, we explained each type of them which are accelerometer and gyroscope, blood glucose sensor, blood pressure sensor, CO2 gas detector, ECG sensor, EEG sensor, EMG sensor, pulse oximetry (PuOx) sensor, and temperature and humidity sensors.

We also discussed the WBAN systems in the medical field and the advantages of WBAN systems in this important field in addition to the applications of WBANs in the medical monitoring field, then we explained them in details, which are monitoring of activities of daily living, fall and motion detection, medication monitoring, the location of patients or the medical team, health monitoring, Bio-monitoring, and disease prediction. And finally we talked about the latest scientific findings in WBAN Systems Research Projects.

In this chapter we also discussed a very important and sensitive issue which is the challenges and constraints of WBAN networks. In the challenges subject we explained the energy challenge, Fault tolerance and security. After that we discussed the network availability, data confidentiality, authentication, data integrity, and data freshness. In the constraints of the WBAN networks subject we explained the material constraints and network constraints with scientific details.

we also discussed the biomedical sensor networks and the medical telemonitoring. We explained the objective of Medical telemonitoring, constraints in the medical monitoring field, and construction of a medical telemonitoring system. Also we explained the biomedical sensor networks, WBAN network family, and data transmission topology. In the same chapter we talked about the basic elements of the sensor node which are acquisition block, processing unit, and storage unit. Then we explained each of the communication module: IEEE 802.15.6, ZigBee, Bluetooth Low Energy (BLE), and radiofrequency identification (RFID), and then we discussed the main concepts. At the end of this chapter we summarized the main ideas discussed in the chapter.

In chapter three we discussed the main problems of WBAN which are energy sources and energy recovery. We talked about the batteries and super capacity, and then we explained the energy recovery of photovoltaic system, thermoelectric system, and electromechanical system kinds, piezoelectric system, electrostatic system, and electromagnetic system. At the end of this chapter we focused at the important design factors.

We also discussed the estimation of energy consumption and the existing technical solutions by network simulators which are general network simulators and specific Ad Hoc network simulators. We talked also about the virtual prototyping tools and operating system emulators, tinyOS and Contiki with hardware emulators. Then we declared the multi-domain simulation tools and coupling of simulators, and explained the Functional Mockup Interface (FMI) and Co-simulation and co-emulation platform. In this chapter we also explained the Simulink and System C-AMS. At the end of this chapter we gave a brief conclusion of the chapter.

Chapter four is the most important chapter as we introduced our solution for the problem and our methodology of our work. We discussed the previous solutions and then we declared the details of solution. Firstly, we presented R-SIMPLE: The developed protocol with performance enhancement, then we talked about the single-hop and multi-hop strategies with selection of next hop, SIMPLE and R-SIMPLE protocols. Then we explained how we classify sensor types and data types. In addition, we introduced smart sleep mode with SSM and RAR.

In chapter five we concluded the thesis and suggested some points for the future work.

2. LITERATURE REVIEW

2.1 WBAN NETWORKS

2.1.1 Comparison Between WBANs and WSNs

2.1.1.1 Definition

Wireless Sensors Networks (WSN): A wireless sensor network is an ad-hoc network with a large number of nodes. These nodes are sensors capable of collecting and transmitting environmental data autonomously. The position of these nodes is not necessarily predetermined. They can be randomly dispersed in a geographical area, called a “well field” corresponding to the terrain of interest for the phenomenon captured.

Wireless Body Area Networks (WBAN): a wireless body sensor network is a network made up of mini-sensors that are portable or implanted in the human body. Each sensor node is generally capable of detecting one or more physiological characteristics from the human body or its environment. The sensor node stores and then transmits the measured data - via a wireless network - to a central processing device known as a personal server. WBANs have more requirements in terms of security and sensor miniaturization compared to WSNs.

2.1.1.2 Difference Between WBAN and WSN

Here we present the differences between WBAN and WSN which are classified according to several factors. Table 2.1 summarizes these differences [4].

Table 2.1 Differences between WBAN and WSN

	WBAN	**WSN**
Deployment	On the human body	In places that are not easily accessible
Density	Not dense	Dense

Type of actions	Periodic actions	Actions at irregular intervals
Latency	Easily accessible, low latency	Difficult to access, high latency
Mobility of nodes	Mobile nodes	Stationary nodes

Deployment and density: The number of sensor nodes deployed by the user depends on various factors. Typically, knots in WBANs are strategically placed on the human body, or are hidden under clothing. WBANs do not employ redundant nodes to deal with various types of failures. As a result, the number of nodes in WBAN networks is not dense.

In contrast, in WSN networks, nodes are often deployed in places that are not easily accessible, which requires placing a higher number of nodes to establish a redundancy architecture in order to bypass node failure problems.

Data Rate: Most WSN networks are used for event monitoring, where these events can occur at irregular intervals. On the other hand, WBANs are used to measure physiological activities and actions which can occur in a more periodic way and can give rise to data flows with relatively stable rates.

Latency: In the case of WBANs, replacing the batteries for the sensors is much easier compared to the case in WSN networks whose nodes may be physically inaccessible after deployment. As a result, it may be necessary to maximize battery life in a WSN network. The latency time in WBANs is smaller compared to the latency time in WSNs because of the reduced number of hops.

Mobility: In the case of WBAN networks, people carrying sensors can move around and therefore the sensor nodes are mobile nodes unlike WSN nodes which are usually considered as stationary nodes

2.1.2 The Subsystems of a WBAN Medical Monitoring System

A complete health monitoring WBAN system is divided into five subsystems [32]:

- The BAN (Body Area Network) subsystem.
- The PAN (Personal Area Network) subsystem.
- The gateway to wide area networks (WAN: Wide Area Network).
- Wide area networks.
- The end user of the medical monitoring application.

2.1.2.1 The BAN Subsystem

It consists of a network of sensors and RFID (Radio Frequency Identification) tags that are deployed on the patient's body. There are several types of these sensors. For example, sensors that measure the patient's ECG, EEG, temperature, blood pressure, etc.

2.1.2.2 The PAN Subsystem

This subsystem is made up of environmental sensors and devices deployed around the patient. Environmental sensors, such as sensors that measure air pressure, temperature, light and humidity, can help provide rich information about the environment in which the patient is. Devices like video cameras are still used to monitor and locate the patient in real time.

2.1.2.3 The Gateway Subsystem

It is responsible for establishing the connection between the BAN and PAN subsystems on the one hand and wide area networks on the other. The gateway can be a portable device worn by the user such as a PDA (Personal Digital Assistant), a smart phone, a sensor node deployed in the environment as well as a laptop computer.

2.1.2.4 Wide Area Networks

For a remote monitoring and tracking scenario, a network infrastructure is inevitable. The gateway can transmit information to one or more network systems depending on the application. The network systems used can be cellular networks, ordinary telephone networks, satellite networks or the Internet network.

2.1.2.5 The End User

The last subsystem is made up of the end user of the medical monitoring system who is represented by the medical team (doctors, nurses). In this subsystem, the collected medical data is interpreted and the necessary actions are triggered.

2.1.3 WBAN Network Topologies

In this section, we describe the topologies most used for the deployment of WBAN networks. We distinguish the following topologies: point-to-point, star, mesh and tree. Figure 2.1 shows these four topologies [4].

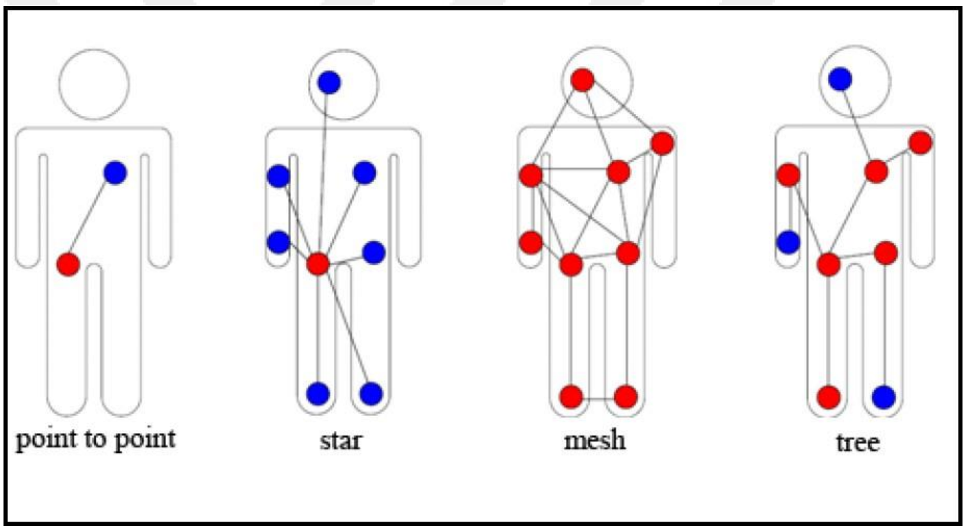


Figure 2.1 WBAN network topologies

2.1.3.1 Point-to-point topology

This is the simplest topology in networks. This topology is intended for a single link, for example between a data collector and a sensor node.

The main advantage of this topology is the simplicity which often allows the use of a simple protocol, low latency and high throughput. The downsides include its limited functionality as well as poor coverage.

2.1.3.2 Star Topology

A topology in which all nodes are connected through a central node is a star topology. These nodes can only send or receive a message to or from the single central node. They are not allowed to exchange messages directly with each other. The central node acts as a relay between the different nodes to date, this topology is the most proposed and used for WBAN networks.

This topology has advantages which can be summed up by the simplicity, the low power consumption of the nodes and the lower communication latency between the nodes and the central node. On the other hand, its major drawback is the vulnerability of the central node because the entire network is managed by a single node.

2.1.3.3 Mesh Topology

A topology with full connectivity between nodes is a mesh topology. In this case (called "multi-hop communication"), any node can communicate with any other node of the network if it is within transmission range. A node wishing to transmit a message to another node outside its transmission range, can use an intermediate node to send its message to the recipient node.

The advantage of using the mesh topology is the ability to scale up the network, with redundancy and fault tolerance, and good coverage. On the other hand, the drawbacks of such a topology are the high energy consumption induced by the multi-hop communication as well as the latency created by the passage of messages through several nodes before reaching the destination node.

Using a mesh topology is a primary consideration in any situation where reliability and flexible communication take precedence over energy efficiency and network life.

2.1.3.4 Tree Topology

A tree topology contains a vertex with a branch structure below. The connections between the nodes are structured hierarchically, which means that each node can be a child to a higher level node and a father to a lower level node.

This topology divides the network into sub-parts so that it becomes easier to manage. It has good fault tolerance, good coverage, high bandwidth and low latency. But however, father nodes can consume a lot of energy [4]. Table 2.2 summarizes the advantages and disadvantages of each of the topologies described above.

Table 2.2 The advantages and disadvantages of topologies in WBANs

Topology	Advantages	Disadvantages
Point-to-point	-Simplicity -Low latency -High flow	-Limited functionality -Low coverage
Star	-Simplicity -Low energy consumption -Low latency -High bandwidth	-Vulnerability of the central node
Mesh	-Redundancy -Faults tolerance -Good coverage	-High energy consumption -High latency
Tree	-Good fault tolerance -Good coverage -Low latency -High bandwidth	- Energy consumption of the parent nodes

2.2 SENSOR NODES

2.2.1 Definition of a medical sensor

A sensor is a device whose task is to transform an observed physical measurement into a generally electrical measurement which will in turn be translated into binary data that can be used and understood for an information system.

A medical sensor consists of a sensor equipped with a specific electronic circuit capable of measuring one or more physiological parameters.

So: sensor + specific electronic circuit = medical sensor.

2.2.2 Medical Sensors

In this section, we describe several types of medical sensors used in medicine and which are commercially available [31], [43], [44]. Examples of these medical sensors are shown in Figure 2.2 and 2.3 below.

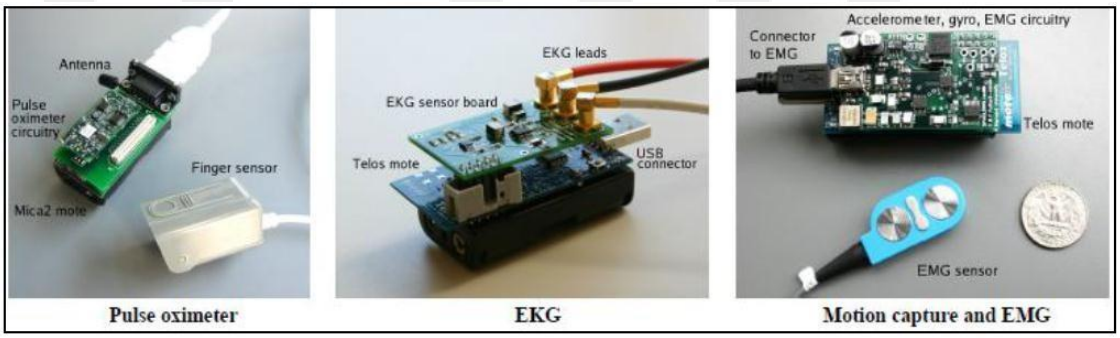


Figure 2.2 Examples of medical sensors

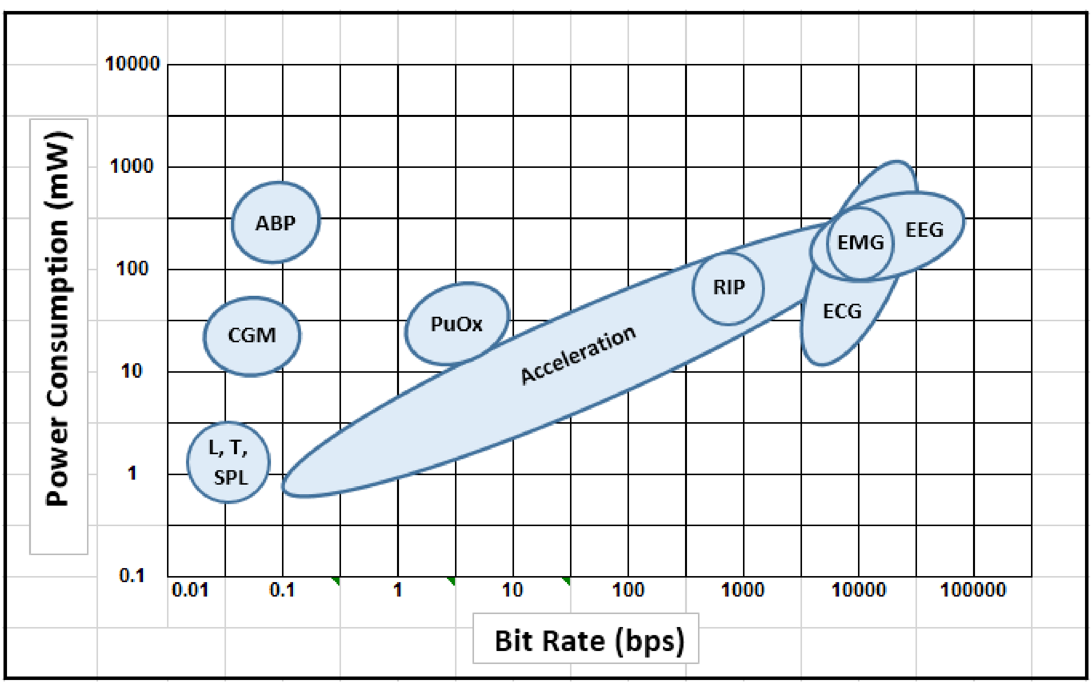


Figure 2.3 “Average power consumption vs bit rate” for body sensors

Where ABP: Ambulatory Blood Pressure; CGM: Continuous Glucose Monitoring; L, T, SPL: Light, Temperature, Sound Pressure Level; PuOx: Pulse oximetry; RIP: Respiratory Inductive Plethysmography; ECG: electrocardiography; EMG: electromyography; EEG: electroencephalography

2.2.2.1 Accelerometer and Gyroscope

The accelerometer is used to recognize and monitor body posture (sitting, standing, walking and running). This monitoring is essential for many applications, including healthcare. The posture monitoring system is based on 3 triaxial accelerometers which are placed on strategic places of the human body.

The Gyroscope is used for measuring or maintaining orientation and can be used in conjunction with accelerometers for monitoring physical movement.

2.2.2.2 Blood Glucose Sensor

It is used to measure the concentration of glucose in the blood. Traditionally, glucose measurements are done by pricking a finger and extracting a drop of blood. A glucometer is used to analyze the blood sample and give a digital readout of the glucose level.

2.2.2.3 Blood Pressure Sensor

The Blood Pressure Sensor is a sensor designed to measure systolic and diastolic pressures in human blood, using the oscillometric technique.

2.2.2.4 CO2 Gas Detector

It measures the level of carbon dioxide gas to monitor changes in the level of CO_2, as well as to monitor the concentration of oxygen during human respiration.

2.2.2.5 ECG Sensor

Electrocardiography is a method that measures the electrical signals produced by the heart. It allows you to assess cardiac activity (heart rate, interval between two beats) by intercepting the electrical activity that comes from the heart muscle.

Electrocardiography (ECG) is a graphical representation of the electrical potential that controls muscle activity in the heart. This potential is collected by electrodes on the surface of the skin. It makes it possible to highlight various cardiac anomalies and has an important place in diagnostic examinations in cardiology.

2.2.2.6 EEG Sensor

Electroencephalography (EEG) is a method of brain exploration that measures the electrical activity of the brain through electrodes placed on the scalp. It is often represented as a tracing called an electroencephalogram. The EEG is an examination that provides information on the neurophysiological activity of the brain over time and in particular of the cerebral cortex, either for diagnostic purposes in neurology or in research in cognitive neuroscience.

2.2.2.7 EMG Sensor

An electromyogram is an examination that records the electrical activity of a muscle or a nerve. The EMG sensor measures the electrical signals produced by the muscles during contraction or during rest. It can detect peripheral nerve damage and muscle damage.

2.2.2.8 Pulse Oximetry (SpO2 or PuOx) Sensor

Pulse oximetry or oxygen saturation is a method of measuring the oxygen saturation of hemoglobin in the blood capillaries. We speak of pulsed oxygen saturation: PuOx. A small clip with a sensor is attached to the person's finger. The sensor emits a light signal that passes through the skin. According to the absorption of light by oxygenated hemoglobin and total hemoglobin in arterial blood, the measurement is expressed as the ratio of oxygenated hemoglobin to the total amount of hemoglobin.

2.2.2.9 Temperature and Humidity Sensors

The temperature sensor is used to measure the temperature of the human body and / or the environment surrounding the patient. The humidity sensor is used to measure the humidity of the environment surrounding the patient. An alarm signal can be emitted if a number of changes are measured.

2.2.2.10 Summary

Table 2.3 below summarizes the sensors mentioned in the previous paragraphs along with their functions and data rates [4].

Table 2.3 Sensors used in WBAN systems and their function, topology and throughput

Name of Medical Sensor	Function	Topology/Data Bit Rate
Accelerometer and Gyroscope	monitor body posture and physical movements	star/high
Blood Glucose Sensor	measures the concentration of glucose in the blood.	star/high
Blood pressure sensor	measures systolic and diastolic pressure in human blood.	star/low
CO2 gas detector	measures the level of carbon dioxide to monitor the oxygen concentration during human respiration.	star/very low
ECG sensor	measures electrical signals produced by the heart and helps assess cardiac activity.	star/high
EEG sensor	measures the electrical activity of the brain.	star/high
EMG sensor	measures the electrical signals produced by muscles.	star/very high
Pulse oximetry (PuOx) sensor	measures the oxygen saturation of hemoglobin.	star/low
Temperature sensor	measures the temperature of the human body and / or the environment surrounding the patient.	star/very weak
Humidity sensor	measures the humidity of the environment surrounding the patient.	star/very weak

As we noticed in this chapter, there are different types of sensors that could be used in medical sector [4].

2.3 WBAN SYSTEMS IN THE MEDICAL FIELD

2.3.1 The Advantages of WBAN Systems in the Medical Field

One of the major challenges of the world in recent decades is the continuous increase in the population of the elderly in developed countries. Population studies predict that in the next 20 years, people over 65 will represent 20% of the total population [32]. Hence the need to provide quality care to a rapidly growing population, while reducing health care costs.

Medical applications of wireless sensor networks are improving the quality of care and medical monitoring, especially for the elderly and patients with chronic illnesses. This by offering several advantages in the medical field.

Figure 2.4 shows a remote medical monitoring system for the elderly [4].

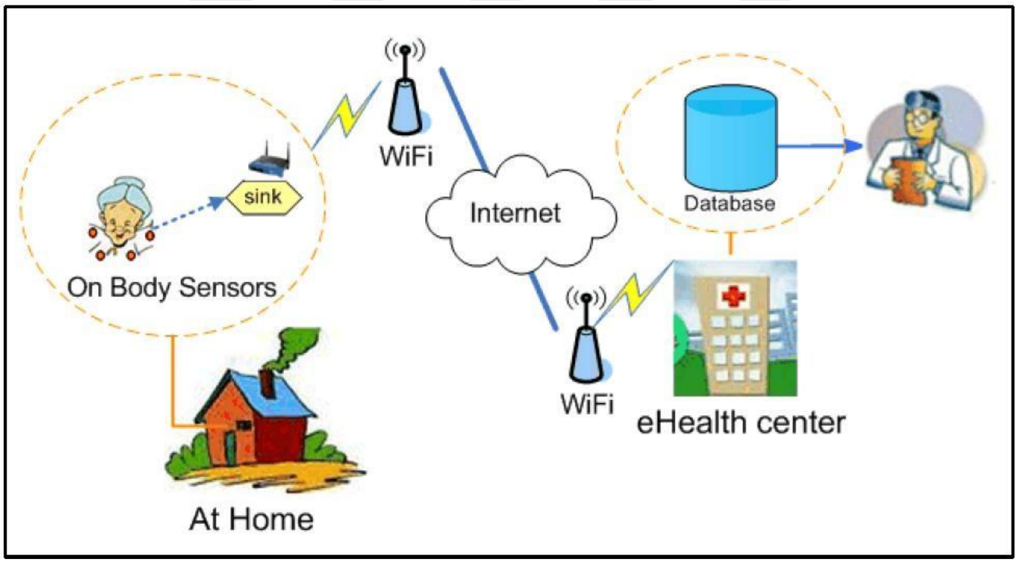


Figure 2.4 Remote medical monitoring of the monitoring

The main advantage of such a system is the capability of remote monitoring. With remote monitoring, identifying emergency situations for patients at risk will become easier and people with cognitive and physical impairments can lead more independent and easier lives.

Quick identification of emergency situations like heart attacks or sudden falls is enough to save a patient's life. Without these real-time medical monitoring systems, these situations will not be identified, hence an important benefit provided by WBAN systems is real-time monitoring.

Much of modern medicine would not be possible or profitable without bodily sensors such as thermometers, blood pressure monitors, blood glucose meters, electrocardiography (ECG), electroencephalography (EEG), and various forms of imaging sensors. The ability to continuously monitor the physiological state of the patient is also essential for interventional devices such as pacemakers and insulin pumps.

The sensor networks can also be used to ensure permanent monitoring of vital human organs using micro-sensors that can be swallowed or implanted under the skin (blood sugar monitoring, cancer detection, etc.). They can also aid in the diagnosis of some diseases by taking physiological measurements such as blood pressure, heartbeat, etc. On the other hand, these networks can detect abnormal behaviors (falling from a bed, shock, screaming, etc.) in dependent people (disabled or elderly).

Among the advantages of WBAN systems we again cite: freedom of movement for the patient and long-term care for patients with chronic diseases. Figure 2.5 summarizes the benefits of WBANs in the medical field [4].

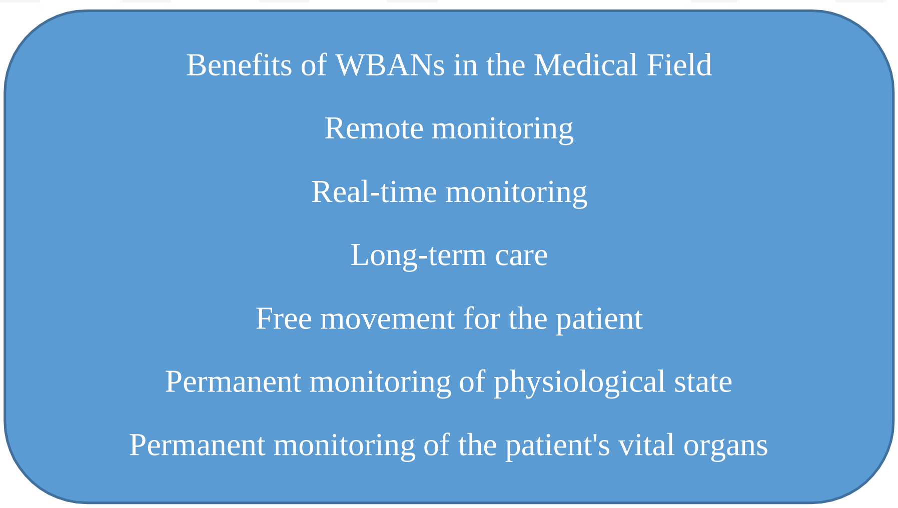


Figure 2.5 The benefits of WBANs in the medical field

2.3.2 Applications of WBANs in the Field of Medical Monitoring

There are several medical applications for monitoring the health of patients in general and the elderly in particular. When these applications are explored, we observe that the main target categories are [32]:

- The monitoring of activities of daily living
- Fall and movement detection
- The localization
- The monitoring of medication
- Health monitoring
- Bio-monitoring
- The prediction of diseases

2.3.2.1 Monitoring of Activities of Daily Living

In this category, applications attempt to help the elderly in their homes to improve their quality of life. The sensors observe the daily activities of these people and share the observed data with the medical teams, where the data will be processed and analyzed [33]. This data can give clues to the person's state of health, and allow the medical team to intervene in necessary cases.

2.3.2.2 Fall and Motion Detection

Fall detection and motion detection applications focus on physiological conditions such as posture and fall detection for people who require special care. For example, the elderly who are susceptible to sudden fall which can lead to their death or patients recovering from an operation [32].

2.3.2.3 Medication Monitoring

Not taking drugs is common in the elderly and patients with chronic diseases [32], especially when cognitive impairments are presented. Therefore, monitoring and medication reminder for these kinds of patients is very important because it can help them survive independently.

2.3.2.4 The Location of Patients or the Medical Team

In health monitoring systems, the tracking application can be used to help people with cognitive disabilities. They can also be used to identify patient locations when an alarm situation has arisen such as an epileptic seizure.

In addition, in a hospital, tracking systems can be used to monitor places visited by patients to identify nosocomial infections or to locate doctors and paramedics in emergencies.

Another medical scenario is an emergency or disaster. People are equipped with small wireless badges, which could guide rescue teams and medics to deal more effectively with higher numbers of casualties [33]. For example, the first rescuer to arrive in a disaster area or in an area where there is an accident with a large number of victims, would place a wireless sensor on each patient. This sensor can send the vital signs and location of each patient to the nearby medical team.

2.3.2.5 Health Monitoring

Patient health monitoring is the most studied type of application in ubiquitous healthcare systems. Commonly used vital signs in order to obtain complete information on the state of health of patients are: ECG, EEG, respiration rate, pulse oximetry, body temperature, heart rate, blood pressure, etc... [32], [33], [34], [36].

In a hospital or home care scenario, patients are equipped with tiny, portable wireless sensors that measure vital signs. This would allow doctors and nurses to continuously monitor the health of their patients and react to changes such as respiratory failure, cardiac arrest, etc.

Monitoring the glucose level using a wireless sensor implanted under the patient's skin can help the healthcare team monitor the glucose level in patients with diabetes and anticipate their insulin needs. In addition, insulin can be injected automatically when a certain threshold of the glucose level is reached [34].

For millions of asthma patients around the world [34], a sudden allergic attack can cause a serious threat to their life. A wireless sensor network system can help them by presenting them with sensor nodes that can detect allergens in the air and report the condition to physicians and / or patients on a permanent basis.

Cardiovascular disease causes a large number of deaths in developed countries. Most of these deaths could be avoided if the doctors had been made aware of the patient's current condition. Sensor nodes installed on the patient's body in a discreet manner will be able to send vital information regarding irregular heartbeats to medical personnel, allowing them to prepare for the necessary treatment in advance, while monitoring the health status of the patient. patient.

For patients who have undergone operations or treatments in hospital that require a long recovery period at home, a wearable sensor system can monitor these patients and provide accurate assessments to guide the rehabilitation process.

2.3.2.6 Bio-Monitoring

Another medical application for wireless sensor systems is bio-monitoring, where a series of sensors can collect and examine samples from air, soil, or water to predict the epidemiological spread of a disease. This allows state officials and health facilities to respond quickly by taking a series of emergency actions [33].

2.3.2.7 Disease Prediction

Studies have shown that cancer cells give off nitric oxide, which affects the blood in the area around a tumor. Sensors with the ability to detect these changes in the blood have the ability to identify cancer cells, allowing doctors to diagnose tumors [34].

2.3.3 The Latest Scientific Findings in WBAN Systems Research Projects

The medical community finds great interest in the use of wireless sensor networks. Indeed, several projects and research work have been carried out to develop systems using wireless sensor networks. They are mainly used to monitor the health status of patients within the hospital. All these applications aim to create an active and permanent monitoring of patient health. We cite among these projects:

- The STAR project for distributed tele-assistant system [37], consisted in designing a platform dedicated to the monitoring of people suffering from heart rhythm disorders. Indeed, cardiac arrhythmias are phenomena that are difficult to diagnose due to their intermittent and very random nature.

As part of the STAR project, the patient is equipped with an intelligent wireless sensor capable of acquiring and analyzing their ECG signals in real time. Indeed, the sensor uses a “Bluetooth” wireless transmission module which enables it to communicate with a gateway present in the patient's home and connected to the Internet. Then the data collected by the sensor is sent via the Internet to a treatment and intervention center located in a hospital.

- The CodeBlue project was one of the first projects developed by Harvard University using wireless sensor networks. It consists in equipping patients with sensors recording physiological information such as heartbeats, oxygenation level, etc. [38], [46]. In the event of an abnormal reading on the patient, the sensors transmit the information to a PDA (Personal Digital Assistant) type device worn by a member of the nursing staff to warn him so that he can intervene on the patient as quickly as possible. This project led to another project at Harvard University, the Mercury project [39] which aims to monitor patients with Parkinson's disease or suffering from epileptic seizures.

- The MobiHealth project is one of the first European projects on the development of a network of wireless sensors for health, based on GPRS and UMTS mobile telephony technologies [40]. The WBAN network consists of sensors and actuators and a mobile base unit MBU acting as a hub (star topology). GPRS communication is used for communication between WBAN and phone / PDA. Then, the data collected by the latter is transmitted via UMTS to the monitoring center [47].

- The RESIDE-HIS project is a smart housing for health project. This is the work of a collaboration between the TIMC and CLIPS laboratories in Grenoble (by the two teams AFIRM and GEOD [41]). A nomadic remote assistance vest called "VTAMN" is developed. It embeds different types of sensors with different types of data collected: weight, oxygen level in the blood, heart and respiratory rate and blood sugar. The data is sent to a remote monitoring center.

- The BANET project aims to provide models and technologies to design a wireless communication system optimized for a wide range of applications (in the field of electronics, medical and sport), using a network BAN [35]. The long term goal for BANET is the maximum reduction in the energy consumption of the BAN network.

- The SMART project was developed to monitor the physiological signals of patients in emergency department waiting rooms [31]. There have been cases in which the medical team has found that the patient's health deteriorates rapidly while waiting in an emergency room. As time is of great importance in this kind of situation, patient's life cannot be risked due to lack of attention given in emergency rooms. To help solve this problem, the SMART system can be used to collect data from different patients waiting in an emergency room, and send this data to a central computer which collects and analyzes the data to issue an alert signal if the health condition of a particular patient deteriorates. This way, patients can receive treatment before their condition worsens.

- The CareNet project is developing a wireless remote medical monitoring system that enables the healthcare team to efficiently access data from the sensor network through a unified medical record system [31], [42].

- The ALARM-NET project offers a system of medical care by the continuous monitoring of the patient using body sensors [31]. ALARM-NET implements a network of wireless sensors that allows medical personnel to continuously monitor the state of health of patients.

The variety of applications of medical sensors discussed in this chapter shows the big advantage of using the wireless body sensors in the medical field [4] and how can they facilitate the work of doctors in the hospitals, on the other hand they give the patients additional free areas to go outside the hospital and act their normal life but with doctor monitoring all the time.

2.4 THE CHALLENGES AND CONSTRAINTS OF WBAN NETWORKS

2.4.1 The Challenges of WBANs

Medical applications of a wireless sensor network system place stringent demands on system reliability, quality of service, power consumption, privacy and data security. So, WBAN medical sensor networks present several challenges. Among these challenges we cite:

2.4.1.1 The Energy Challenge

The main factor limiting the life of a sensor network is energy. So energy optimization is a challenge that is encountered in almost all application areas of wireless sensor networks, including medical applications. Current sensors have periods of sleep during their inactivity to preserve their battery. The sources of energy consumption in a sensor node come mainly from the sensing unit, the data processing unit and the communications unit (wireless transmission and reception) [35].

Communications are the most expensive actions in terms of energy and calculations are less important. It is therefore strongly necessary to limit the number of communications between sensors and if possible the quantity of calculations [45].

2.4.1.2 Fault Tolerance

In wireless sensor networks, one or more sensors may not function properly, because the sensors are entities sensitive to state alterations such as climatic phenomena (humidity, heat, etc.) or due to a low battery. In these cases, the network must be able to detect this type of error and remedy it, in order to transmit the information and allow the network to always be operational [45].

2.4.1.3 Security

Medical applications place stringent demands on end-to-end system reliability and data delivery [36]. The communication of medical data between sensors in a WBAN system is subject to security requirements such as network availability, confidentiality, authenticity, integrity and data freshness.

2.4.1.3.1 Network Availability

The network must be able to be available at all times, i.e. that the sending of information must not be interrupted, just as the flow of information must not be stopped. In the case of a reactive sensor network, a sensor that detects an event must be able to transmit this information at any time to the base of the sensor network to inform it [46].

2.4.1.3.2 Data Confidentiality

The network must ensure that the data transmitted is confidential and cannot be read by devices or people other than the medical team (doctors, nurses, etc.). A person outside the network must not be able to read the information exchanged. The data should be hidden or encrypted in such a way that no one can access it.

2.4.1.3.3 Authentication

The authentication of the sensors is necessary to ensure that the identity declared by a sensor is that of the declaring sensor. In the absence of a mechanism allowing to clearly authenticate a node of the network, many attacks can be set up.

2.4.1.3.4 Data Integrity

The data circulating on the WBAN network must not be able to be altered during the communication. It is therefore necessary to ensure that no one can capture and modify network data. Also, it is necessary to verify that the data have not undergone alterations due to a malfunction of the equipment, which is a significant risk on sensors sensitive to alterations of states.

2.4.1.3.5 Data Freshness

By data freshness we mean whether the data is recent or not. This means that it is necessary to ensure that the data transmitted corresponds to a present state. The freshness of the data thus guarantees that these data do not reflect a past state [46].

2.4.2 The Constraints of WBAN Networks

A medical wireless sensor network is a special network which has a number of constraints compared to a conventional computer network. These constraints are the result of limitations concerning the memory of the sensor, its energy reserve, its processing capacity as well as the use of wireless communication. The constraints in a medical wireless sensor network are classified into two categories: hardware constraints and network constraints [48], [49]. Table 2.4 summarizes these constraints.

Table 2.4 constraints in WBSN

Material Constraints	Network Constraints
Limited memory and storage space	Uncertain communication

Limited Energy Limited computing capacity Low flow	Uncertain communication

2.4.2.1 Material Constraints

These constraints are linked to the material and physical capacities of the sensors, which represents a handicap for the security needs which generally require additional resources. All security approaches require a certain amount of resources to implement, including data memory, space for code, and energy to power the sensor. However, these resources are currently very limited in a tiny wireless sensor.

Limited memory and storage space: A sensor is a small device with very little memory and limited storage space. So to build an efficient security mechanism, it is necessary to limit the size of the code of the security algorithm.

Limited Energy: Energy is the main barrier to wireless sensor capabilities. When adding a security code to a sensor node, we are interested in the impact that security has on battery life. The additional energy consumed by the sensor nodes due to security is related to the processing required for the security functions.

Limited Computing Capacity: Despite advancements in the manufacture of increasingly powerful sensors, current sensors have significantly reduced computing capacity. This low computing capacity does not allow the use of complex algorithms, and particularly cryptographic algorithms which are greedy in CPU resources [34], [45].

Low throughput: The current throughput in sensor networks does not exceed a few hundred kilobytes per second.

2.4.2.2 Network Constraints

Another security threat to the sensor is unreliable communication. Much of the security of sensor networks relies on a well-defined protocol, which in turn depends on communication.

Uncertain Communications: Wireless communications are generally uncertain because packets can be lost or damaged due to radio transmission. This lack of reliability in the communication constitutes an additional problem for the sensor nodes.

The challenges and constraints of WBAN network discussed in this chapter had motivated the researchers to study and give different type of solutions from different sides [4], and our study in this thesis is a contribution to give some solutions.

2.5 BIOMEDICAL SENSOR NETWORKS

2.5.1 Medical Telemonitoring

Medical telemonitoring is a branch of telemedicine. It allows doctors to remotely monitor, analyze and interpret a person's physiological parameters. It involves the installation of a network of biomedical sensors on the person being monitored [50].

2.5.1.1 Objective of Medical Telemonitoring

Medical telemonitoring aims to protect so-called “at risk” people. This term includes the elderly, the chronically ill, and postoperative patients.

This technology is beneficial to the medical profession as well as to patients. It improves the remote medical monitoring (post-therapy, preventive and curative) of the elderly and those suffering from chronic pathologies. It also promotes home support and helps protect the person without affecting their daily life. In addition, it makes it possible to avoid the prolongation of certain hospitalizations and leads to a reduction in the costs of medical care. A final objective would be to provide personalized support to the patient.

2.5.1.2 Constraints in the Field of Medical Monitoring

Several conditions must be met in order to monitor the physiological parameters of the individual. These requirements can be summarized as follows:

- Personal safety: The sensors worn must be biocompatible; They must not pose any risk to the health and well-being of the person [51].

- Portability: Remote monitoring involves the installation of smart sensors, worn by the person or implanted in their body. A first implementation constraint is therefore that of portability. The devices mounted should therefore be of suitable size and few in number [52].

- Mobility management: A network of biomedical sensors must ensure mobility adapted to the needs of patients. It is therefore necessary to maintain connectivity for travel, especially in the home. In the event that the person leaves the network coverage area, appropriate storage algorithms must prevent the loss of information.

- Feedback of information to the person followed: The patient must have access to the medical data collected by the sensors.

- Ergonomics or ease of use: the graphical interface must be simple and suitable for the person [51].

- Respect for private life: the medical data of supervised persons must be protected and secured [53].

- Data security: Data security is an essential aspect. Protecting patients means realizing the importance of the medical data transmitted. At this level, security threats include modification of data, impersonation, tracking of person's activity, etc... Encryption algorithms and techniques must be adopted [54].

- Low cost of deployment: This technology should be accessible to anyone regardless of their economic status. The installation costs of biomedical sensors must therefore be reasonable.

Other constraints can be summarized by ease of installation, robustness of the network, interoperability, as well as maintaining data integrity during transfer and / or processing [55].

2.5.1.3 Construction of a Medical Telemonitoring System

The diagram in Figure 2.6 shows the architecture of a medical telemonitoring system. It is made up of three levels [56]:

- Sensor nodes: These are smart sensors worn by the patient. These nodes constitute a network. They are responsible for the monitoring process. Each makes it possible to monitor one or more physiological parameters. A node must be able to measure, store and transmit its data to a processing base.

- Personal server: It is also called a base station or a processing base. Located close to the person, its role is to collect, using a short-range communication protocol (Bluetooth, ZigBee, etc.), the data from each node. This information can be processed and used either directly by the patient, or via another long-range network (Internet, GSM, etc.), by a healthcare professional. In other words, the base station is a means of communication with the sensors, a user interface, as well as a link to the medical server. Typically, it can be a Personal Digital Assistant (PDA), a smartphone, or a computer.

- Medical server: It receives data from the base station and integrates them into the patient's file. This information will therefore be accessible to doctors and healthcare professionals. The medical server can also generate recommendations or alerts.

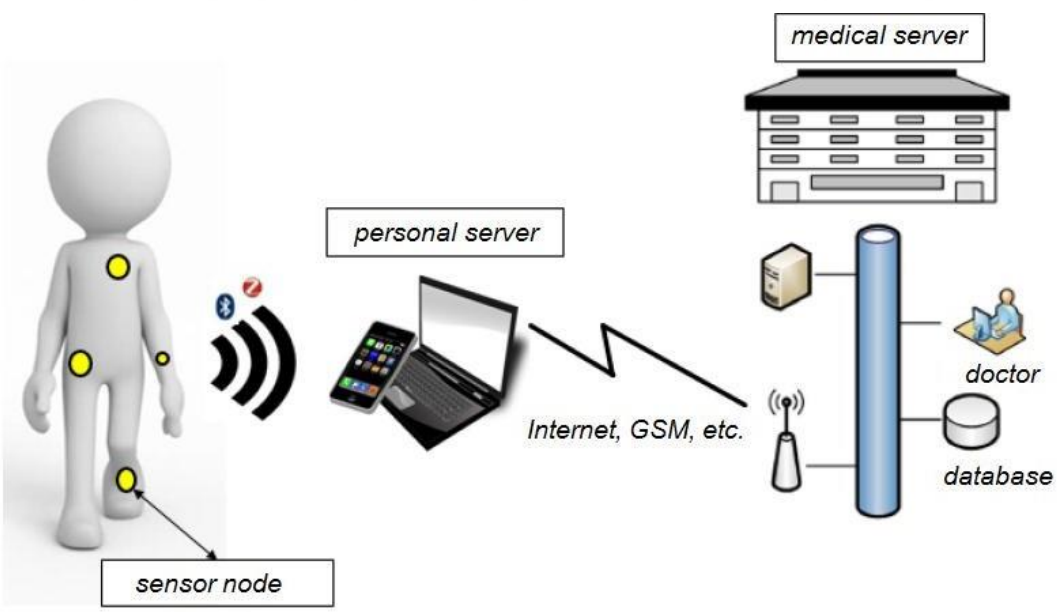


Figure 2.6 Architecture of a medical telemonitoring system

2.5.2 Biomedical Sensor Networks

Remote monitoring of physiological parameters is via embedded wireless medical sensor networks on the person. These networks belong to the WBAN or wireless body area network family.

In this paragraph, we introduce the term WBAN before explaining the topologies applicable to this family of networks.

2.5.2.1 WBAN Network Family

By definition, a wireless network is a network based on communication by electromagnetic waves between terminals located in a more or less extensive geographical borders. This concept of geographic borders has made it possible to classify wireless networks according to their dimensions.

Figure 2.7 shows the dimensions of the main families of wireless networks [3]. We distinguish the Body Area Networks (WBAN -Wireless body area network), personal (WPAN - Wireless Personal Area Network), local (WLAN - Wireless Local Area Network), metropolitan (WMAN - Wireless Metropolitan Area Network) and wide area (WWAN - Wireless Wide Area Network).

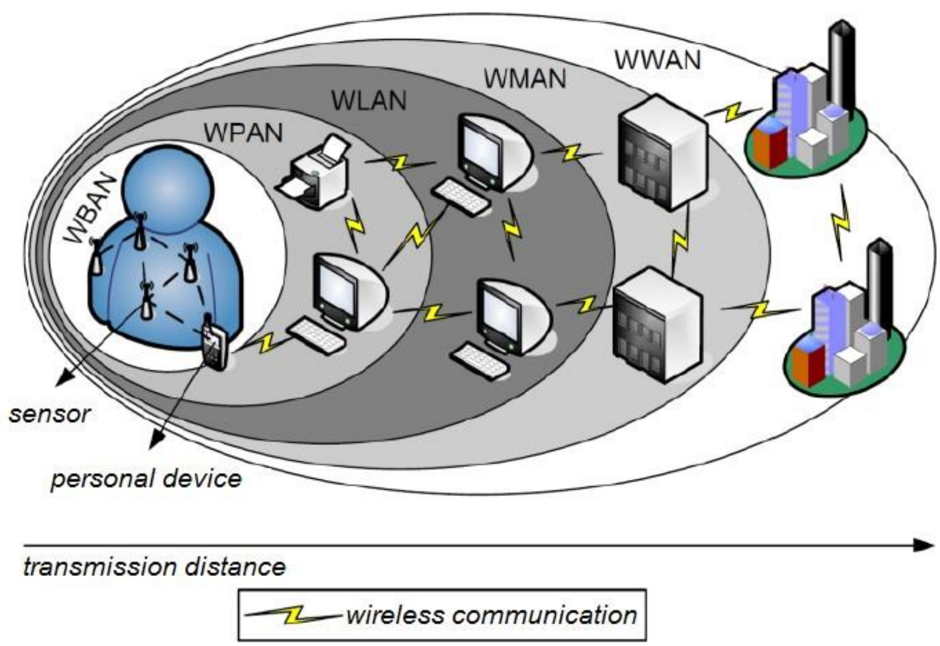


Figure 2.7 Dimensions of wireless networks

2.5.2.2 Data Transmission Topology

Data transmission from one node to the base station can be done directly or through other nodes. This organization constitutes the topology of the network. There are two solutions applicable to WBAN type networks.

- Single-hop star topology: In WBAN networks, the distance between sensor nodes and the processing base is on the order of a few meters. This is why many proposals in the literature adopt a single-hop star topology [16]. This topology involves direct communication between the base station and each node. Its major drawback is linked to the reliability of the central node; if it goes down the whole network stops functioning. Another drawback is related to scalability: increasing the number of sensors can overload the central node.

- Multi-hop star topology: This solution was proposed in [57]. In this case, the peripheral nodes transmit their data to the processing base via intermediate nodes. Information thus travels along various paths through several jumps. The implementation of an effective routing protocol is essential.

Table 2.5 presents a comparison between them [3]. Due to the limited number of nodes, the single hop star topology is the most widely used in biomedical sensor networks.

Table 2.5 Comparison between single-hop and multi-hop topologies

Item	Single-hop star topology	Multi-hop star topology
Energy consumption	Increases with the distance between the node and the base	The closest nodes will consume more energy
Transmission delay	Minimal	Depends on configuration
Interference	The most distant nodes of the base transmit with greater power thereby increasing interference	Each node transmits to the neighboring node thus maintaining a low transmission power and minimizing interference

Reliability	A node that goes down does not affect the rest of the network	The part of the network that includes the failed node must be reconfigured.

2.5.3 Basic Element: The Sensor Node

A network of wireless sensors therefore consists of several nodes. Each node is made up of an acquisition block, a data processing part, a memory unit, a communication module and a power supply [52]. Figure 2.8 is a block diagram showing the structure of a wireless sensor node.

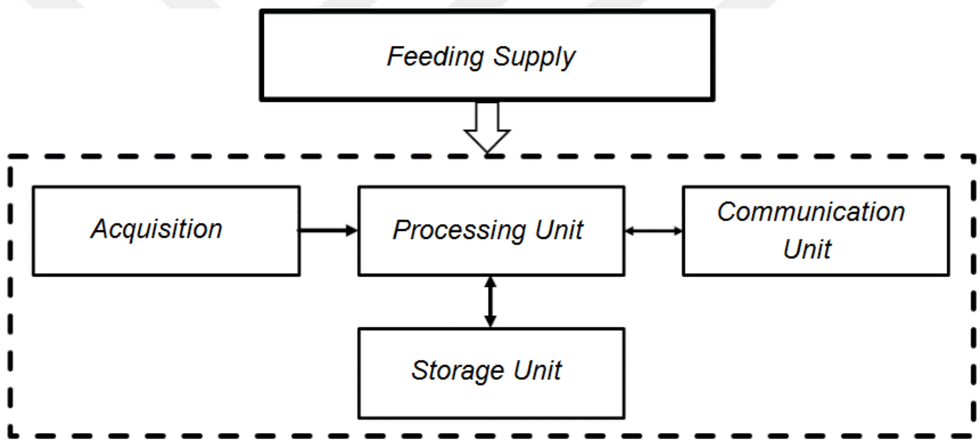


Figure 2.8 Components of a sensor node

2.5.3.1 Acquisition Block

The function of the acquisition unit is to collect and transform the physiological parameter into an exploitable electrical quantity. It generally includes a sensor and signal conditioning (filtering, amplification, etc.). In the situation of medical applications, the signals monitored may be of an electrical (ECG, EMG, EEG, EOG), mechanical (blood pressure, movements), thermal (body temperature), optical (pulse oximetry), acoustics (heart and respiratory sounds).

These parameters are monitored using “non-intrusive” techniques - without lifestyle changes - and essentially “non-invasive” - without access to internal organs or piercing the skin. Thus, the methods of measurements through the skin are preferred. This indeed represents a surface area of

1.5 to 2.3m2. It is next to all the vital organs of the human body and offers sites for measuring vital signals.

Sensors mounted on the surface of the skin will therefore make it possible to measure the main physiological parameters. Table 2.6 presents the description of some physiological signals as well as the corresponding sensor [3].

Table 2.6 Brief description of each physiological parameter and the corresponding sensor

Physiological signal	Sensor Signal	description
Cardiac frequency	Ag / AgCl electrodes or Pulse oximeter	Number of heart beats per minute
Pulse oximetry	Pulse oximeter	Blood oxygen concentration
Blood pressure	Inflatable cuff monitor	the force exerted by blood on the inner walls of the arteries
Temperature	Temperature sensor	Ability of the body to maintain a normal temperature
Electrocardiogram	Ag / AgCl electrodes	Electrical activity of the heart

2.5.3.2 Processing Unit

The processing unit combines an analog-to-digital converter and a microprocessor. It makes it possible to recover the data coming from the acquisition block and to process them. It is also responsible for controlling the elements of the node, therefore for activating and resting.

This unit often consists of a microcontroller. It is an integrated circuit that brings together the following elements:

- A processor for data processing and device control.
- A programmable memory (ROM) containing the instructions of the program driving the application
- A data memory (RAM) dedicated to the temporary data necessary for the calculation.
- Peripherals such as analog-to-digital converters, meters, communication bus controllers (Universal Asynchronous Receiver Transmitter UART, Serial Peripheral Interface SPI, etc.) and I / O ports.

The consumption of a microcontroller is proportional to its speed of execution. In addition, it depends on the complexity of the processing and management of the elements of the node. Adding features will, for the same processing speed, lead to an increase in the duration of task execution and therefore in the consumption of the microcontroller. It will then be necessary to make a compromise between speed of execution, addition of functionalities and consumption.

It is also important to consider the consumption in standby mode: this mode generally occupies the preponderant part of the operation of a sensor node. During this mode, the non-active elements of the microcontroller (clocks, processor, peripherals, etc.) go into a dormant state, thus saving energy.

Finally, the choice of a microcontroller is made according to the functionalities required while taking into account its cost, its current consumption as well as its supply voltage.

2.5.3.3 Storage Unit

The data from the sensors must be transmitted to the base station. However, the success of this step is not guaranteed. Adding a memory chip therefore makes it possible to store data and prevent the loss of information. The consequence is of course more reliable operation but at the cost of higher consumption. The choice of a memory chip is made taking into account its capacity, its communication interface, the write / read / erase options (by byte, page, etc.), its supply voltage, its current consumption, and its cost.

Non-volatile memories are preferred for storage since they retain data in the event of a power failure. In particular, memories of the EEPROM (Electrically Erasable Programmable Read-Only

Memory) or Flash type, erasable and programmable by electric current, can be used. Another type of non-volatile memory is FRAM (Ferroelectric RAM). This is a recent technology that combines high performance and low power operation. Its disadvantage is more limited storage capacities and a high manufacturing cost.

2.5.3.4 Communication Module

The communication module aims to transmit the information collected by the node to the base station. Although it is possible to adopt wireless optical communication, a radio frequency link offers several advantages in terms of patient mobility. This unit consumes the most energy. It is made up of two parts: a transmitter and a receiver. The transmitter is responsible for transmitting the measured data as well as the status of the node to the base station. The receiver is useful for receiving data, or requests, or acknowledgments.

The choice of wireless technology depends on the requirements of the application, in particular:

- the communication range (the distance between node and base station;
- energy consumption;
- the type of modulation;
- the bit rate, the speed of transmission.

In the context of medical telemonitoring, we are interested in small-scale networks making it possible to cover all the sensors worn by the person. These networks are based on short range, low power radio frequency communication. We describe the corresponding wireless technologies below. Some of them are standardized and are subject to IEEE (Institute of Electrical and Electronics Engineers) communication standards.

2.5.3.4.1IEEE 802.15.6

The IEEE 802.15.6 standard was published in 2012 as a communication standard dedicated to WBAN networks [58]. The IEEE defines it as: "A communication standard optimized for low-power devices that operate on, in or around the human body (but not limited to humans) to serve a variety of applications (including medical), consumer electronics, entertainment and more”.

It defines three physical layers: Narrowband (NB), Ultra Wideband (UWB) and Human Body Communication (HBC). Each layer operates in a different frequency band and offers different data rates.

- Narrowband: This layer has 7 frequency bands: MICS - Medical Implant Communication Service (402-405 MHz), WMTS - Wireless Medical Telemetry Service (420-450 MHz and 863-870 MHz) and ISM - Industrial, Scientific and Medical (902-928 MHz, 950-956 MHz, 2.36-2.4 GHz & 2.4-2.45 GHz) [59].
- Ultra Wideband: UWB operates between 3.1 and 10.6 GHz. It offers two technologies: IR UWB - Impulse Radio UWB and MB-OFDM UWB - Multi-Band Orthogonal Frequency Division Multiplexing UWB. IR-UWB transceivers are simpler to design and less power consuming than MB-OFDM UWBs; they are therefore more suitable for networks of biomedical sensors [60].
- Human Body Communication: The HBC layer uses Electric Field Communication (EFC) technology and operates in the two frequency bands of 16 MHz and 27 MHz with a bandwidth of 4 MHz.

In the context of medical telemonitoring, the choice of the physical layer will depend on the parameter monitored and the location of the nodes (implants, on the body, or in the environment). Thus, the HBC layer is suitable when the human body is used as the transmission medium for the communication between the nodes. In turn, the UWB layer, offering throughput between 0.4875 and 15.6 Mbps, is suitable for applications requiring high throughput. Finally, the NB layer is more suitable for low power, low throughput medical monitoring applications compared to UWB.

Based on the literature review conducted throughout this thesis, transceivers based on the IEEE 802.15.6 standard are limited to research work and are not available as commercial modules.

Finally, this standard is a promising approach for facilitating effective health monitoring and revolutionizing health care systems.

2.5.3.4.2 ZigBee

Based on the 802.15.4 standard, this technology aims to offer a simple, inexpensive solution, the radio part of which has reduced consumption and self-organization capabilities. It is therefore used in communications at very low power and over short distances [61].

The ZigBee is capable of operating in the 2400, 915 and 868 MHz frequency bands. These bands offer different data rates. The ZigBee can also connect up to 255 nodes. These devices can be organized according to mesh, hybrid, hierarchical or star topologies.

ZigBee is well suited for medical applications [62]. Indeed, it offers low energy consumption, good security, and low cost. In addition, The ZigBee Alliance has developed a specific medical profile: The ZigBee Health Care [63].

2.5.3.4.3 Bluetooth Low Energy (BLE)

Bluetooth Low Energy was first introduced by Nokia as Wibree in 2006. It was associated with Bluetooth in 2010 with the introduction of Bluetooth 4.0 [64]. It offers a low-consumption solution for integration into connected objects: watches, medical monitoring devices or sensors for athletes.

Bluetooth Low Energy technology operates in the ISM (Industrial Scientific Medical) 2.4 GHz band. It adopts a star topology of a master and its slaves.

Bluetooth Low Energy is a promising solution for medical remote monitoring applications. Indeed, it is distinguished by a lower energy consumption than that of the ZigBee [65]. It is also compatible with all electronic devices with a Bluetooth 4.0 communication interface such as smartphones, tablets, etc. [66]. In addition, BLE uses adaptive frequency hopping to prevent interference with devices operating in the same frequency band. It is subsequently a compatible, reliable and secure means of communication. In addition, a number of health-related BLE profiles have been specified in order to standardize the format for transferring medical data. These include: Health Thermometer Profile (HTP) for body temperature, Heart Rate Profile (HRP) for heart rate, and Glucose Profile (GLP) for glucose level [67].

2.5.3.4.4 Radiofrequency Identification (RFID)

Radio identification (RFID) is a method of retrieving data from a distance using markers or radio tags (RFID tags).

An RFID system includes a reader and an RFID tag. The RFID tag stores information in order to transmit it to the reader connected to the processing system (computer, smartphone, etc.). The good progress of this phenomenon depends on the position of the marker in relation to the reader. In addition, the frequency used in RFID systems varies according to the desired performance. A higher frequency has the advantage of allowing an exchange of information (between reader and marker) at higher flow rates while a lower frequency will benefit from better penetration into the material.

The adoption of RFID technology in medical sensor networks poses several challenges such as interference, data security, cost, as well as efficiency. This technology is rather involved in identification tags for:

- The location of patients, drugs, etc.
- Identification and verification: each patient is provided with an RFID tag giving access to his medical file.

2.5.3.4.5 Discussion

In a medical telemonitoring system, the data acquired by the sensors are not directly transmitted to the decision-making centers. Rather, they are collected by a base station linked to the medical server. This transmission takes place using low-power radio frequency communication protocols. Choosing the right protocol is critical to the design of the wireless sensor network. As part of this work, we are particularly interested in commercialized technologies allowing experimental validation of the proposed simulation tool. The IEEE 802.15.6 standard will therefore not be considered for this discussion.

The choice of the right technology for the application is based on the location of the base station relative to the nodes so as to provide a certain level of mobility suited to the patient's needs. It is possible to adopt a base station with a fixed position or one that moves with the patient.

As RFID transmission depends on the position of the reader relative to the tag, this technology does not appear to be suitable for on-board medical sensor networks. Rather, it is integrated into identification tags, often in the form of bracelets, giving access to the patient's medical file in the event of an emergency or medical treatment.

Thus, Bluetooth Low Energy and ZigBee technologies seem best suited to the application. Table 2.7 presents a comparative description of their characteristics [3]. Preferring one over the other depends on the intended architecture of the system.

- Base station attached to a fixed room: In this case, the base station is fixed. It is located in a room of the house. Its role is to collect information from the nodes and transmit it to health professionals. The ZigBee is considered the best solution for this architecture. Indeed, its communication range allows it to cover the entire home while the Bluetooth Low Energy coverage area is limited to the room itself. The ZigBee therefore maintains the connectivity of the nodes during the movements of the patient in his home, thus ensuring a better level of mobility.

- Mobile base station: The base station is a mobile device constituting an access point to the medical server. Due to the short distance between the base station and the sensor nodes, it is preferable to adopt more energy efficient transmission technologies than ZigBee. According to Bluetooth SIG, BLE technology will be incorporated into the majority of smartphones in 2018. A smartphone (or tablet) equipped with BLE can thus easily be used as a processing base. This approach ensures patient mobility and maintains node connectivity during these movements inside and outside the home.

In conclusion, the integration of BLE in smartphones, its communication ranges as well as its level of consumption make it the best candidate for data transmission within a network of biomedical sensors.

Table 2.7 Characteristics of some radio technologies for medical sensor networks

	ZigBee	**Bluetooth Low Energy**
Type	LAN (Local Area Network)	PAN (Personal Area Network)
Topology	Star, mesh, hierarchical	Star

Number of jumps	Multi-jump	Single jump
Transmission speed (Bit Rate)	250 Kbits / s at 2.4 GHz 40 Kbits / s at 915 MHz 20 Kbits / s 868 MHz	1 Mbps
Scope	10-75 m	5-10 m

The medical telemonitoring had really protected the elderly, the chronically ill, and postoperative patients and gave big contribution in the medical field [3].

3. ENERGY SOURCES AND ENERGY RECOVERY

3.1 INTRODUCTION

A sensor node must have a power supply to provide the energy necessary for its operation. There are different types of energy resources. Choosing one depends on the size (sensor size, location of the node, etc.), the battery life and the features required by the application. It is also possible to combine several sources.

3.2 BATTERY

This form of power is the most widely used in wireless sensor networks. It stores electrical energy through a chemical reaction. The main interest of batteries is their available energy density. They are characterized by low leakage currents for long term storage. They also have the advantage of providing a stable supply voltage allowing them to be connected directly to electronics [68].

The batteries may or may not be rechargeable. Non-rechargeable, or batteries, are single-use. They are characterized by higher energy densities. However, the design of the node should provide for a simple replacement once this source is exhausted. On the other hand, a rechargeable battery, or accumulator, can be recharged from another source of energy. Control electronics must therefore be put in place. Note that the energy density of accumulators decreases over time (discharge, aging).

Li-Ion batteries and thin-film batteries are the most widely used in wireless sensor networks. They differ from each other in shape, energy density, charging circuit, leakage currents and prices.

3.3 SUPER-CAPACITY

Super capacitors store energy in the form of an electrostatic field. They are a compromise between rechargeable batteries and standard capacities. They have the advantage of having a longer lifespan and a shorter charging time. Their major drawback lies in the very large leakage currents. They are then used for short-term storage. Their use also requires a source of energy and control electronics to recharge them. Table 3.1 shows a comparison between Li-Ion batteries, thin film batteries and super capacitors [3].

Table 3.1 Comparison of Li-Ion, Thin Film and Super capacitors

Item	Li-Ion	thin-film battery	Super-capacity
Voltage (V)	3.6	4.2	2.3
Number of cycles	500-1000	5000-40000	1 million
Self-discharge	Moderate	Negligible	High
Loading time	Hours	Minutes	Second-minutes
Capacity	0.3-2500mAh	12-700 µAh	10-100 µAh
Harmful effect on the environment	High	Low	Low

3.4 ENERGY RECOVERY

Another solution of powering the sensor nodes is to recover energy from the human body (Figure 3.1) or the environment [69]. It reduces dependence on batteries as well as maintenance costs (replacing batteries, etc.). It also protects the environment (chemical waste).

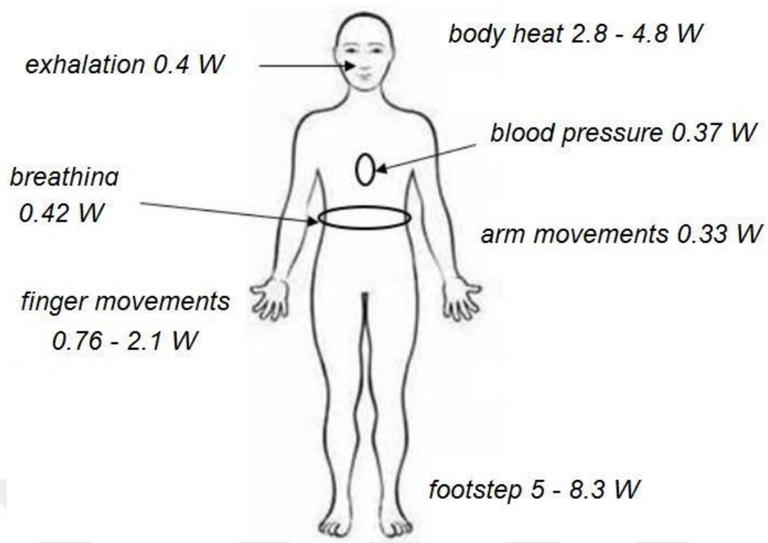


Figure 3.1 Energy recoverable from the human body

There are four main approaches for energy recovery: photovoltaic recovery, thermoelectric recovery, electromechanical recovery and radio frequency energy recovery. A comparison is shown in Table 3.2

Table 3.2 Comparison between energy recovery approaches [3]

Property	Electromechanical	Thermoelectric	Photovoltaic	Radio frequency
Performs in the dark	Yes	Yes	No	Yes
Efficient in an indoor environment	Yes	Yes	Limited	Yes
Independent of surrounding conditions	Yes	No	No	No
Requirements	Movable organ	Thermal contact	Exposure to light	RF waves
Mass / Volume	Low / medium	Low	Low	Low
Form	Variable	Steady	Steady	Steady

3.4.1 Photovoltaic System

A photovoltaic cell converts light into electrical energy. This operation depends on three factors: aging, lighting (spectral composition, angle of incidence and intensity) and temperature. Thus, the voltage supplied by a photovoltaic cell drops over time and its efficiency is inversely proportional to the temperature. In addition, the current generated depends on the number of photons received and therefore on the illumination: solar, incandescent or fluorescent lamp.

In the context of medical telemonitoring, it is possible to exploit this type of systems to recover the energy of the lighting in the patient's environment. Thus, the energy available for photovoltaic recovery varies between 100 and 1000 $\mu W.cm^{-2}$ for artificial lighting and can reach 100 $mW.cm^{-2}$ for solar lighting. This energy is converted into electrical energy with an efficiency of between 5 and 30% [70].

This energy harvesting technology is applicable to portable nodes exposed to light such as the EEG (Electroencephalography) sensor proposed by Matiko et al. [71]. However, the sizing of the system must be done according to the available light source especially as the spectral composition of the light varies with the illumination (sunlight, incandescent lamp, fluorescent lamp, and LED-based lighting). In addition, we must take into account the variation in power recovered depending on the daily activity of the person, in particular sleep and movement.

3.4.2 Thermoelectric System

Thermoelectric generators convert a spatial temperature gradient into electrical energy according to the principle discovered by T. J. Seebeck in 1821. Their operation depends on this gradient as well as on the materials used to assemble the modules. Semiconductors are good thermoelectric materials whose performance has been maximized by doping control. In particular, Bismuth Tellurium (Bi2Te3) and Antimony Tellurium (Sb2Te3) perform the best at room temperature.

The use of thermoelectric generators in medical sensor networks aims to recover the thermal energy dissipated by humans. This involves converting the temperature gradient between the human body and its environment (figure 3.2). According to [72], the average power density recovered with a 15 mm thick thermoelectric generator is 25 μW / cm^{-2} at an ambient temperature of 22 ^oC.

This type of generator is the most used for medical sensor networks. The authors offer a set of self-powered biomedical sensors thanks to thermoelectric recovery. The generators involved can be worn directly as in the case of the pulse oximeter [73] or an EEG sensor. They can also be integrated into clothing such as an ECG sensor.

A disadvantage of this type of recovery is that the clothes limit the power dissipated by reducing the temperature difference between the skin and the inside of the clothes. Another is the toxicity of the materials used, especially tellurium and antimony.

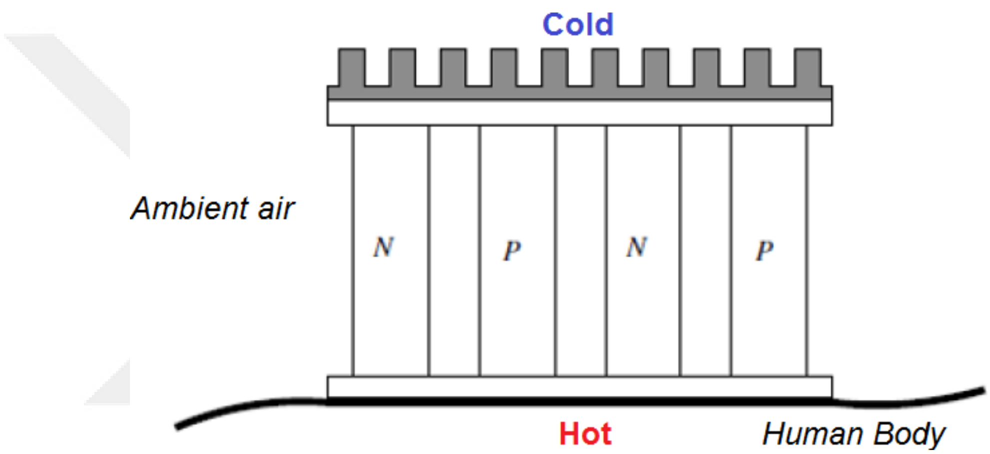


Figure 3.2 Recovery of thermal energy dissipated by the human body

3.4.3 Electromechanical System

An electromechanical system converts the energy recovered from mechanical phenomena (vibrations, stresses, shocks, deformations) into electrical energy. In the context of medical telemonitoring, this involves in particular generating electricity from the movements of the human body.

The recovery of electromechanical energy from humans differs from that in industrial settings. Thus, devices mounted on a machine are subjected to sinusoidal vibrations of high frequencies (greater than 50 Hz) and low amplitudes (less than 1 mm). In contrast, the source of mechanical energy associated with the human body is characterized by lower frequencies (≈1Hz) and consisting of pressures and forces.

There are three types of converters of mechanical energy to electrical energy: piezoelectric, electromagnetic and electrostatic micro-generators. Table 3.3 summarizes the advantages and disadvantages of each one [3].

Table 3.3 Advantages and disadvantages of the different approaches for electromechanical energy recovery

	Advantages	Disadvantages
Piezoelectric	High energy density	Difficult integration into microsystems
Electrostatic	Integration into microsystems	Requires a source of energy
Electromagnetic	Does not require an external energy source	Difficult miniaturization, performance Loss

3.4.3.1 Piezoelectric system

These energy recovery systems use the piezoelectric property of certain materials, that is, their ability to polarize electrically when subjected to mechanical stress (and vice versa). There are many piezoelectric materials such as ceramics (PZT), ferric oxides ($PbTiO_3$, $BaTiO_3$, $KNbO_3$…), etc.

The piezoelectric recovery of mechanical energy from the human body takes place primarily through plates attached to the heels. This approach has been exploited to recover the energy dissipated during walking. The power generated in was 8.3mW at the heel and 1.3mW at the toes. The problem associated with these systems lies in the transmission of energy to the nodes of sensors on board the upper part of the human body.

Another approach for piezoelectric recovery is to harness a piezoelectric band around a muscle that varies significantly in diameter during activity or a transducer anchored between two organs that move relative to each other [74]. However, these devices are wide and difficult to wear.

3.4.3.2 Electrostatic System

The electrostatic type generators are composed of two electric plates isolated from each other and pre-charged which will have a relative displacement with respect to each other under the effect of external vibrations. There are two operating modes: constant load and fixed voltage.

An electrostatic system has the advantage of being perfectly compatible with standard microsystems manufacturing technologies. It is therefore easily integrated into portable devices. On the other hand, its efficiency is lower than in the case of electromagnetic and piezoelectric recovery.

In addition, this type of energy recuperation requires a voltage source to generate the initial power. Its use for a medical sensor node requires association with a battery or, ideally, another energy harvesting module. The authors of [75] propose a system attached to the heels for the recovery of energy from a person's walking. It includes, in addition to a piezoelectric generator, an electrostatic system to increase the power supplied.

3.4.3.3 Electromagnetic system

An electromagnetic energy recovery device is composed of one or more magnets creating a constant magnetic field, and a coil immersed in this field. Mechanical excitation (vibration) makes it possible to generate a relative displacement between coil and magnet. This results in a change over time in the magnetic flux and the appearance of an electrical voltage.

Electromagnetic energy harvesting from the human body involves using the movements of the limbs, including the wrist, to generate electrical energy. Unlike electrostatic recovery, this type of generator does not need an auxiliary voltage source. It is also capable of converting up to 30% of the power supplied [76].

Electromechanical generators are already used in portable devices. Indeed, they are integrated in a multitude of systems marketed in particular watches (Seiko for example). an electromechanical generator has been proposed by Miah et al. This device, similar in size to an AA battery, generates electrical energy from the movement of a person's limbs. It is able to mechanically increase the frequency of the excitation and therefore the recovered electrical power. A maximum of 2.15 mW was obtained under forced vibration [77].

3.4.4 Radio frequency system

Radiofrequency energy harvesting involves transforming ambient electromagnetic waves into a DC voltage.

In the context of medical telemonitoring, it is possible to use these systems to recover radio frequency energy from wireless communication networks ubiquitous in the human environment, in particular GSM and WiFi. The available radio powers are detailed in [78]. They are converted into electrical energy with a high efficiency, which can exceed 30% in some cases.

The disadvantage of these systems lies in the low power densities available requiring a large area collecting antenna. This is mainly due to a strong attenuation moving away from the source. For a GSM station, the available power density is between 1 mW / m2 and 0.1 mW / m2 for a distance which varies from 25 to 100 m. This value is even lower for WLAN networks. In addition, the power densities emitted by such systems are limited by standards imposed for reasons relating to health, electromagnetic interference, etc.

One solution to this problem is to recover energy from a dedicated source. This is the case for the system proposed by Dementyev et al. in [79]. It is an RFID communicating EEG sensor that is powered by energy harvesting from the RFID reader itself. As the movement of the person is likely to interrupt this recovery, this system is more useful in the case of a stationary subject.

3.4.5 Discussion

Energy recovery to power biomedical sensors is a solution to increase the autonomy of the system. However, the energy harvested from the environment or from the human body depends on a person's mobility, physical activity, exposure to light, etc. It is therefore difficult to provide only energy recovery power. In order to ensure the reliability of the node, an ancillary source must be integrated into the circuit.

Take the example of a patient who is continuously monitored for pulse oximetry and heart rate. Both of these parameters are measured on the finger using a device called a pulse oximeter. In order to power the node, it is possible to consider an energy recovery circuit installed on the wrist. In this case, one can recover energy by a photovoltaic, thermoelectric, electromechanical, or hybrid system. Suppose a system which is self-powered by a combination of the three approaches and whose storage unit is a super capacitor. During the night, the powers recovered on the two photovoltaic and electromagnetic modules are zero. The node is powered only through the thermoelectric module. Knowing that the energy consumption of the node is of the order of Milliwatts and that the thermoelectric power generated is 25 $\mu W / cm^{-2}$ on average [72], it is impossible to keep this node operational until awakening of the patient.

In addition, powering other sensor nodes by energy recovery faces the same problem of irregularity in recovered power. This is in fact influenced by the lighting of the room in the case of a photovoltaic system, movement in the case of an electromechanical system, etc.

Thus, the battery remains the main source of energy for biomedical sensor networks. Its combination with energy harvesting modules is a promising approach to increase autonomy, provided that the constraints of portability and well-being of the person are respected.

3.5 IMPORTANT DESIGN FACTORS

The design of a WBAN wireless sensor body network should consider the following aspects:

- Robustness and precision
- Mobility management
- Miniaturization
- Fault tolerance
- Information security
- Biocompatibility
- Sensitivity to data loss

- Strategic deployment

  The evaluation of a network of biomedical sensors is therefore based on several criteria.

- Reliability: It can be summarized by two ideas. First, the failure of one node should not affect the functioning of others. Second, the accuracy of the measurements and the integrity of the data must be maintained during their automated transfer / processing.

- Quality of Service (QoS): QoS must be considered not only during the design of a WBAN type network but during the design of any other network. It is associated with four parameters: transfer rate, delay, disconnect and loss rate. The QoS required for monitoring a physiological parameter depends on the parameter itself and the frequency of measurements.

- Energy consumption: The sensor nodes worn by the person are often powered by accumulators or batteries. The replacement / recharging of these energy sources by the elderly / patients can be inconvenient, difficult and sometimes impossible especially for implanted sensors. The idea is therefore to maximize the autonomy of the node or even extend it over the entire monitoring period. However, increasing the energy capacity of the source requires larger power supplies and therefore opposes the portability constraint. Thus, energy consumption is the main limitation to the deployment of biomedical sensor nodes.

In general, the sensor node must have a power supply and energy resources to provide the energy necessary for its operation [3]. There are different types of energy resources and – as we noticed - it is possible to combine several sources.

3.6 ESTIMATION OF ENERGY CONSUMPTION: EXISTING TECHNICAL SOLUTIONS

As independence is the main issue for this type of application, estimating the energy consumption of a wireless sensor network will allow its architecture to be adapted (components, power sources, power supply, topology, etc.) according to the constraints of the application.

The need for a wireless sensor networks (WSN) simulation solution has contributed to the development of software combining models of the network and the hardware / software part. These models are all a description of behavior, but considered at different levels of concept, from the highest (functional) to the lowest (circuit). They therefore offer different compromises between the speed of analysis and the accuracy of the results obtained.

Thus, a multitude of approaches have been adopted for the simulation of wireless sensor networks. The authors of [80] provide overviews on different wireless sensor network simulators. They are divided into three main categories:

- Network simulators
- Virtual prototyping solutions
- Multi-domain simulation

3.6.1 Network Simulators

The network is an essential part of the simulation of distributed embedded systems. The first simulators designed are therefore based on network simulators. This first category includes generic network simulators and those of specific networks developed later.

3.6.1.1 General Network Simulators

A prime example of general network simulators is that of NS-2 [81], NS-3 [82], and OPNET [83]. These simulators were designed to simulate communications between different elements of the network. They are distinguished by the number of communications protocol implementations. However, the network is only part of the whole simulation. Another important issue is the implementation of the behavior of the hardware part. The downside of this type of software is the lack of an infrastructure to accurately model hardware components. This difficulty in modeling the material part prevents an accurate simulation of consumption. These simulators are subsequently only suitable for applications which require high-level functional models of the hardware platform.

3.6.1.2 Specific Ad Hoc Network Simulators

The specific ad hoc network simulators have been designed to overcome the shortcomings in generic network simulators. The majority follow a component-based approach. In addition to an interface for hardware-in-the-loop simulation, this software includes models for radio propagation and the hardware platform.

A first example is that of SNSE (Sensor Network Simulator and Emulator) [84]. It is based on COST (Component Oriented Simulation Toolkit) [85], a discrete event-based simulator following a component-based approach. It is distinguished by the inclusion of battery models, routing algorithms, and MAC protocols. A user interface, G-SNSE, has also been associated with it [86]. SNSE suffers from a lack of noise models and radio standard implementation (except IEEE 802.11).

Another example is PAWis (Power Aware Wireless Sensors). It is a network simulator geared towards wireless sensor networks [87]. It is based on OMNet ++, a discrete event-based simulation library following a component-based approach [88]. PAWis includes a radio propagation model capable of simulating attenuation as a function of distance and noise. It also has a graphical interface, that of OMNet ++. This can be deactivated to speed up the simulation.

PAWis also includes a tool to visualize the consumption of the different components. In order to estimate the execution processing time of the microcontroller, the designer provides some parameters of the algorithm thus making it possible to obtain an estimate of the number of cycles required.

The disadvantage of PAWis is related to OMNet ++. In fact, OMNet ++ is designed for the simulation of networks and poses problems of precision during the modeling of the material.

Finally, network simulators make it possible to simulate and evaluate the network part of distributed embedded systems. However, accurate simulation of hardware components is difficult without hardware modeling languages. This infrastructure is provided by the virtual prototyping tools evaluated in the following paragraph.

3.6.2 Virtual Prototyping Tools

In distributed embedded systems, the software part is developed according to the corresponding hardware platform. However, productivity constraints prevent the sequential development of hardware and software. They are generally worked on in parallel by two different teams in order to be integrated during the last design stage. The use of virtual prototypes brings the two processes closer together and limits integration uncertainties [89].

There are two approaches for virtual prototyping: operating system simulation platforms and hardware emulators.

3.6.2.1 Operating System Emulators

Due to the multitude of hardware platforms and operating systems available, it is necessary to simulate the application before implementing it in a node. The emergence of specific simulators made it possible to emulate the operation of the operating system on an ordinary PC. The application is thus tested without the need for hardware platforms. Some of these emulators include features related to network and power consumption.

3.6.2.1.1 TinyOS

TinyOS [90] is one of the most widely used operating systems for wireless sensor networks. The corresponding simulator is TOSSIM [91]. TOSSIM allows you to develop and test TinyOS applications in a virtual environment. These applications are developed in nesC, an extension to the C language specific to sensor networks [92]. It was designed for the simulation of nodes running the same application. It is therefore not able to simulate a heterogeneous network in terms of node architecture or application.

The energy consumption is estimated using extensions: PowerTOSSIM for TinyOS v1.x [93], PowerTOSSIM 2 or PowerTOSSIMz for TinyOS v2.x [94]. Other extensions with additional functionality have also been implemented. Thus, MOB-TOSSIM makes it possible to estimate energy consumption as a function of mobility [95]. Swarm-eTOSSIM models, in addition to operation and consumption, the variation of the capacity of the energy source as a function of time [96]. mTOSSIM, in turn, is useful for estimating system autonomy; It also makes it possible to determine the loss of radio transmission power as a function of distance and the discharge of the battery [97].

Another TinyOS simulator is the TinyOS Scalable Simulation Framework (TOSSF) [98]. Unlike TOSSIM, it allows to simulate several nodes which differ in architecture and in application. It also has more developed models for radio propagation. The downside to TOSSF is the lack of power consumption extensions.

3.6.2.1.2 Contiki

Another example of an operating system is Contiki [99]. Its simulator, COOJA, is implemented in Java [100]. Unlike TOSSIM, COOJA stands out for its flexibility. It allows simultaneous simulation of multiple nodes at the network, operating system and hardware levels.

Generally, operating system simulators cannot capture the low level events needed to estimate energy consumption. However, COOJA includes MSPsim, an instructional game simulator, to simulate cycle-accurate models [101]. MSPsim supports the Texas Instruments MSP430 processor and includes some hardware peripherals. The COOJAMSPsim platform has been extended to make it compatible with TinyOS applications [102].

Concerning the propagation models, extensions make it possible to model obstacles as well as radio interference [103].

Despite their advantages, COOJA and Contiki are not available for all architectures and hardware platforms [89]. They therefore limit the user's choice.

In conclusion, the use of operating system simulators for wireless sensor networks has two major drawbacks:

- Operating systems differ in performance; this difference should be evaluated during design
- These simulators are not able to capture low level events for estimating energy consumption.

3.6.2.2 Hardware Emulators

Hardware emulators make it easy to design software and hardware simultaneously to reduce time to market. They are able to execute machine code in a virtual environment. The simulated software can thus be applied directly to the target hardware platform.

Hardware emulators feature improvements over operating system simulators. Indeed, they allow the simulation of all compatible operating systems. In addition, they have better granularity for estimating the energy consumption of the microcontroller. This type of simulator offers a variety of approaches with different precisions. The choice depends on the needs of the application.

ATEMU was the first emulator to provide cycle-accurate microprocessor models [104]. It is designed for wireless sensor networks and allows to simulate a network of several nodes. In addition, ATEMU is not limited to a specific operating system. On the contrary, He can help develop one. ATEMU is dedicated to the architecture of the AVR microcontroller family offered by ATMEL. It is therefore suitable for nodes comprising these microcontrollers such as the MICA2. It is also distinguished by radio propagation models taking into account the distance and interference from other nodes.

ATEMU is a precise model. However, it is 30 times slower than TOSSIM [87] and does not consider energy consumption.

AVRORA is another simulator based on AVR emulator appeared. It aims to increase the simulation quality compared to ATEMU while keeping a precise cycle granularity [105]. It includes the precise cycle models of nodes (MICA and MICA2) and microcontrollers (ATmega128, ATmega64 and ATmega32). Although the initial goal of creating an accurate and scalable cycle simulator has been accomplished, AVRORA is still 50% slower than TOSSIM [105].

AEON is an extension to AVRORA for estimating energy consumption [106]. It includes a radio propagation model taking into account attenuation with distance. Its downside is again the lack of noise modeling.

ATEMU and AVRORA are still available. However, the latest versions date respectively from 2004 and 2007. Despite their precision, these simulators have a major drawback. Indeed, such a degree of precision prevents them from being generic. They must therefore be created for a specific hardware architecture and therefore lack flexibility. Therefore, they are not practical enough for simulating heterogeneous networks.

A more recent contribution is available in Symphony. This open source software, coded in C ++, allows you to test applications on various operating systems including TinyOS, Contiki and FreeRTOS. The core of the framework is formed by a virtual operating system and an emulation of the hardware platform. The whole thing is integrated into the ns-3 network simulator. The methodology adopted by Symphony is different from previous software. Thus, the modeling of the time and energy parameters of the components is done through measurements on real devices during the execution of a specific task [107].

Another approach to hardware emulation relies on SystemC [108]. SystemC is a library in C ++. It allows to model, at several levels of abstraction, hardware, software or mixed systems. It therefore provides the functionalities required to create simulators of distributed embedded systems. The hardware part is thus modeled in System C while the development of the network is done in C / C ++. A class of SystemC specific to networks, called SCNSL (SystemC Network Simulation Library), allows the hardware and network parts to be modeled in a single tool [109]. SCNSL has been used in IDEAO (hIerarchical DEsign plAtform for sensOr Networks Exploration) [110]. Hardware and communication protocol implementations have also been added. In order to determine the energy consumption, an instructional game simulator was implemented. It supports several microcontrollers (AVR and MSP430) [111]. IDEA1 is then able to simulate a heterogeneous network with precision at the hardware level. Nevertheless, the development of precise models of microcontrollers requires details sometimes not provided by the manufacturers [89].

Another consumption model based on System C has been proposed in. It is based on a modeling by functions where each one corresponds to an operation of the node in the network. This approach helps to study the impact of each activity on the energy consumption of the node, thus making it possible to distinguish the most consuming. Unfortunately, this tool is not available to the public.

3.6.3 Multi-Domain Simulation Tools

The simulators discussed in the previous sections have as their main function the modeling of one of the aspects among: network, hardware or software. On the contrary, multi-domain simulation platforms aim to completely model several domains.

There are a multitude of multi-domain modeling approaches. The first is to couple simulators for different areas. It is a complex task that requires creating efficient interfaces. The others are multi-domain modeling languages and tools.

3.6.3.1 Coupling of Simulators

The simplest approach for multi-domain simulation is to combine two specific simulators (each for a particular domain). However, the complexity of coupling simulators can be very significant. This is because simulators differ in terms of visualization, programming language, etc. Thus, the interfacing problem must be studied beforehand.

3.6.3.1.1 Functional Mockup Interface (FMI)

The FMI (Functional Mockup Interface) standard was launched in 2010 with the aim of unifying the interfaces of the various simulation tools and simplifying cooperation. Its most recent version dates from 2014 [112]. A model implementing the FMI standard is called a Functional Mockup Unit (FMU). Among the variables of its model, an FMU will define those whose values are accessible (the output variables), and those whose values can be fixed (the input variables). Thus, simulation tools compatible with the FMI standard are able to export their models in the form of FMUs and / or import existing FMUs to use them. The FMI standard provides that these exports / imports can take place at two levels [113]:

- FMI for Model Exchange: Models can be run from an external simulation tool capable of importing FMUs. This main simulation can then set the input variables and collect the corresponding output variables.

- FMI for co-simulation: In order to use a model in a co-simulation, it is necessary to encapsulate it in a shared library. The FMUs are then considered as slaves whose executions will be coordinated by a co-simulation master. In this way, the simulations are run in parallel.

FMI is a standard for managing the interoperability of different simulation tools. Its use allows you to import or export models in other simulations. HybridSim, for example, is a wireless sensor network simulator implementing the FMI standard. It allows to co-simulate TinyOS and Modelica models [114].

3.6.3.1.2 Co-simulation and co-emulation platform

The coupling of two simulators, each specific to its field, has been the subject of a multitude of works. The authors of [115] provide an overview of all co-simulation and co-emulation platforms. Table 3.4 summarizes some of them.

Table 3.4 Co-simulation platforms for wireless sensor networks

	Platform	Physics simulator	Network simulator
Co-simulation	PiccSIM	Matlab / Simulink	NS-2
	MAPNET	Matlab / Simulink	OPNET / Riverbed
	COSMO	Matlab / Simulink	OMNet ++
Co-emulation	GISOO	Matlab / Simulink	Cooja

3.6.3.2 Simulink

Simulink, developed by Math works, is a proprietary tool. It offers integration with the MATLAB environment. Truetime is a Simulink-based library focused on the simulation of networked controlled systems [116]. It was launched in 1999 and its most recent version dates from April 2016. Truetime includes radio frequency (WLAN, ZigBee and Ethernet) communication models, power consumption and a battery pack. It therefore allows the representation of on-board systems supplied by accumulators and the simulation of charging and discharging phenomena. However, Truetime is designed for real-time simulation. It is therefore not suitable for simulating wireless medical sensor networks that operate for months or even years, especially for implanted sensors.

3.6.3.3 System C-AMS

System C-AMS (Analog-mixed Signal) is a set of extensions to SystemC. It allows analog systems to be simulated [117]. SystemC-AMS includes three calculation models [117]:

- Timed Data Flow (TDF): It is a discrete time computational model. It is based on the sampling of continuous signals with a predefined time step. Since version 2.0, this time step can be dynamically modified: we speak of Dynamic-Timed Data Flow (DTDF). This modification is necessary to obtain satisfactory accuracy and performance.

- Linear Signal Flow (LSF): This is a continuous time computational model. It offers a set of modules such as addition, multiplication, integration and delay.

- Electrical Linear Networks (ELN): It is a continuous time calculation model specific to electrical circuits. It includes models (resistance, inductance, etc.) capable of describing the relationship between current, voltage and time.

Vasilevski et al. presented an energy model of a wireless sensor node. In this model, the node consumption was modeled in SystemC and the battery discharge in SystemC-AMS [119].

3.6.4 DISCUSSION

The design of wireless sensor networks is often too complex to be done in a single step. It is divided into several stages, from the initial specification to the final product. According to this approach, it is a question of designing a functional architecture before moving gradually into the details of the system, until the design of the circuits.

Thus, the modeling of a network, and more particularly of its energy consumption, must first be done at a high level of abstraction. We therefore need models that we can build quickly and that provide a reliable and accurate estimate of the energy consumption of the network. These models provide the opportunity to study the feasibility and evaluate multiple solutions early in the design cycle. They therefore make it possible to better control the energy consumption of the network in order to increase service life.

As shown in Table 3.5, the study carried out on sensor network simulators noted a lack of tools suitable for this purpose [3]. Indeed, some, in particular network simulators, do not allow reliable modeling of part of the system. They therefore do not meet the modeling needs for a precise simulation of the energy consumption of the network.

Other simulators, notably virtual prototyping tools, are based on very specific networks and nodes. They use predefined templates, often at a low level of abstraction, for the description of hardware and software. They therefore provide a detailed and precise simulation of energy consumption. However, the rapid construction of new systems is hampered by this degree of precision. These tools are therefore not suitable for exploring solutions, both hardware and software, at the start of design.

Finally, the set of tools studied does not allow the optimization of the design (choice of components, power supply, etc.) and energy management to be automated. On the contrary, they suppose a "manual" exploration of all the solutions by modifying each time the inputs of the simulation.

Table 3.5 Gaps in each tool compared to the consumption simulation objective at the start of the design

Simulator group	Simulator	Latest version date	Gap
Network simulator	NS-2	2011	Lack of precision when modeling the consumption of the hardware part
	NS-3	2016	
	OPNET	2016	
	OMNet++	2015	
	SENSE	2006	
	PAWis	2008	
Virtual prototyping	TOSSIM	2102	Real code-based simulation - not suitable for early design exploration
	COOJA	2015	
	Symphony	2014	
	Atemu	2004	Not suitable for rapid model building
	Avrora	2007	
	IDEA1	2015	Need for details not provided by the manufacturers for the modeling of microcontrollers.

Multi-domain simulation	TrueTime	2016	Real-time simulator not suitable for simulation over the operating time of medical networks

3.6.5 CONCLUSION

In 3.4, 3.5, and 3.6, we introduced the use of wireless medical sensor networks for monitoring people in the context of medial telemonitoring. We first exposed the constraints of the application domain before explaining the operation and the three-level architecture (sensor nodes, personal server and medical server) of a medical telemonitoring system.

We then focused on the networks of medical sensors. These networks belong to the family of WBAN networks. They consist of a limited number of nodes and therefore follow a single-hop star topology.

In addition, we have seen the general operation of a wireless sensor node. The latter is composed of an acquisition unit, a data processing part, a memory unit, a communication module and a power supply. We were particularly interested in wireless technologies and power.

Thus, we first conducted a study on the different radio frequency communication technologies suitable for the application: Bluetooth Low Energy, ZigBee, RFID and IEEE 802.15.6.

We then explored energy recovery systems to power medical sensors: photovoltaic, thermoelectric, electromechanical and radiofrequency. The observation made is then that the power supplied by energy recovery is likely to vary greatly depending on the movements of the person, their physical activity, their exposure to light, etc. In order to ensure reliability, a node's power supply must incorporate a battery that can be combined with one or more energy harvesting modules to increase runtime.

We then identified the design constraints for medical sensor networks: reliability, quality of service and energy consumption. We noticed at this level that the energy constraint is the main limitation to the deployment of these systems. It is therefore necessary to estimate the energy consumption of the system from the early stages of design [3].

4. WORK DONE AND PRESENTATION OF THE SOLUTION

4.1 INTRODUCTION

Advances in telecommunications and the advent of connected objects make it possible to use networks of medical sensors on board the person to monitor their health. This approach, known as medical telemonitoring, allows the physiological parameters of patients to be monitored remotely and abnormalities to be detected. The objective of the work is to help energy saving and link efficiency in designing wireless communications of body area networks.

In this regard, we introduce, at first, medical remote monitoring systems while focusing on the reliable communication and the constraints of the field of application. We then detail the formation and operation of a medical sensor network as well as its basic unit: the knot. We study more different energy saving methods available.

We then identify the main constraints linked to the design of these networks: reliability, quality of service, and energy consumption. Due to the energy constraint, it seems necessary to evaluate the tools and techniques available to estimate the consumption of a network of sensors. A comparative study and a summary are presented below. A new approach is also proposed here.

4.2 METHODOLOGY

Our methodology in this thesis is achieving the basic goals of the thesis - which are enhancing the power saving of WBAN network and increasing network reliability in addition to improving the network stability and extending the life time of the network - by introducing a novel design of WBSN that have a single sink node and multi-hop nodes in order to improve the lifetime of the WBSN network, throughput, stability, and residual energy of WBSN. In our methodology we classified the sensors in critical and non-critical sensors. And also we classified the data into critical and non-critical data. Also in our methodology we had provided a modified protocol with a new model in order to achieve the data integrity and meet the basic goals of this thesis. We added a smart sleep mode to our modified protocol and provided reliability and data integrity to the network in which the node sends a receipt acknowledge requests after data sending to ensure the arriving of data to the sink node without any gap or information lack.

4.3 PREVIOUS SOLUTIONS

Due to their small size, medical wireless body sensor networks are often limited in energy. Therefore, the energy constraints must be taken into account from the first stages of the design. A reliable estimate of the energy consumption of the system is therefore required. It allows the designer to study its feasibility and modify its architecture before physical implementation. Ideally, this estimation could be done by means of a simulation.

The main possible simulation solutions are described in the previous chapters. These tools are divided into three groups, each of which has certain shortcomings when simulating energy consumption at the start of design. In particular, the models implemented in these tools are not suited to this objective. Indeed, network simulators are not capable of reliable modeling of the hardware part. Additionally, virtual prototyping tools rely on low-level abstraction models that cannot be built quickly. In addition, all of these tools do not allow optimization of the design (choice of components, power supply, etc.) and energy management [3].

4.4 SOLUTION DECLARATION

4.4.1 R-SIMPLE: The Developed Protocol with Performance Enhancement

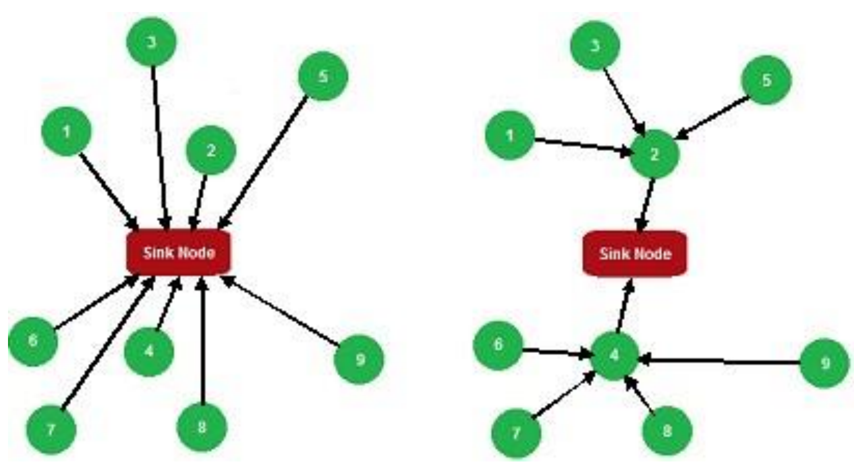
As we explained previously, the WBAN is wireless sensing nodes deployed in, on, or near some places of human body. Fig. 4.1 illustrates the WBAN topology fixed on the patient body with nine sensor nodes and one sink node located at the waist. The sensing node may be glucose, heart rate, body temperature, blood pressure, electrocardiogram (ECG), electroencephalogram (EEG), ... etc.

Figure 4.1 nine sensors nodes WBAN with a sink node placed in a patient body

The resources of the WBAN should be effectively used during information transferring between the sensor nodes and the SN, because these nodes have limited energy due to the limited power of their batteries. For this reason, many suggestions about routing methods were introduced. These suggestions give solutions for data transferring between the sensor nodes and the SN to overcome the sensor nodes limited power problem. On other hand, these protocols should also take in consideration the effective information transferring, as our main goal is to monitor the patients' health conditions for a long period of time.

4.4.1.1 Multi-hop and single-hop schemes

We have two methods of data transferring in WBAN, they are multi hop method and single hop method We have in single hop method, the data moved from the sensor nodes to the SN in one hop, but in multi hops method the sensor nodes select the best way to transfer the data, that means it maybe a single hop or multi hops depending on some conditions. In multi hop method, the sensor nodes will choose a neighboring node - according to some conditions - to be the forwarder or parent node. This node will aggregate the data from other neighboring nodes and send them to the SN. This idea is declared in Figure 4.2. This method of sensor nodes choosing to the forwarder node will reduce the energy consumption average through data transferring, and then increase the network stability and efficiency. Therefore, this method is considered a good way to overcome the limited resources of the WBAN. [18,19].



Single hop communication Multi-hop communication

Figure 4.2 Multi hop and single hop in WBAN

4.4.1.2 Next hop selection: R-SIMPLE and SIMPLE protocols

SIMPLE proposed a multi-hop WBAN scheme to increase network output and save energy. SIMPLE introduces the criteria of selection for a node to become a parent node or forwarder in this scheme. SIMPLE selects a new parent or forwarder in each round, in order to manage the energy consumption of the sensor nodes and to reduce the network's energy consumption. SN knows the node's identification, distance and residual energy status. The SN calculates all sensor nodes' cost function (CF) and transmits the CF to all nodes. Every node determines on the basic principle of the CF whether or not to be a forwarder node. If *i* is the node number, the cost function of the node *i* will be determined as follows:

$$C.F(i) = \frac{d(i)}{R.E(i)} \qquad (4.1)$$

Where *d(i)* is the distance from the node *i* to the SN, *R.E(i)* is sensor node *i* residual energy and can be calculated by subtracting the current node energy from the initial energies. A node is chosen to be as a forwarder when it will have the minimum CF. All adjacent nodes observe the forwarder node and forward their data to the it. The forwarder node aggregates data and then sends the aggregated data to the SN. Forwarder nodes must have maximum residual energy and minimum distance from the sink, which ensures that transporters can consume limited energy to move the data to the SN. Major Nodes such as ECG directly transmit the data to the sink and do not participate to the data transmission [18].

We note that SIMPLE requires to be further enhanced as the CF takes into account only two factors: the distance between the sensor and SN nodes and the residual energy of the sensor nodes; thus, the CF did not consider successful transmission to the SN, which is a main and major issue when selecting the forwarder node to be used for aggregating data. We have therefore developed SIMPLE to R-SIMPLE Protocol by adding a performance factor in the cost equation of SIMPLE to increase SIMPLE Protocol performance and reliability. The following is the developed CF.

$$C.F(i) = \frac{d(i)}{R.E(i).P(i)} \qquad (4.2)$$

In the previous equation, *d(i)* represents the distance from node I to SN, *R.E(i)* is the sensor node *i* residual energy and *P(i)* is the number of packets successfully reached SN per unit time.

4.4.1.3 Data type and sensor type classification

We have classified the sensors into critical sensors CS and non-critical sensors NCS in our work. CS senses and transmits urgent data such as ECG, that if a delay happened in the submission of the data may cause catastrophic consequences to the patient's life [23]. The NCS handles non-critical data, it acts sometimes but not all times like CS, it can sense and transmit critical data but in most of times it deals with non-critical data. We recommend the CS located near the SN, and not going to sleep mode or to be a forwarder, so as to minimize its energy consumption and extend the lifetime of the CS when dealing with urgent data. The NCS, however, will sense and check the information. If the NCS is critical, it will remain in the wake-up mode, continuously transmitting information according to the STR. in other case, If the sensed data is normal, the NCS can go to the SSM, as explained previously with more details. Sensor types and data types can be shown in binary form, as shown in table 4.1

Table 4.1 DATA TYPES AND SENSOR TYPES IN BINARY FORM

Binary form of sensor types and data types		***Sensor Types***	
		Non-critical	***Critical***
Data Types	***Non-critical***	00	10
	Critical	01	11

The following figure illustrates the logical approach for the sequential process according to the type of sensor and the type of data.

$$Sensor\ Type = \begin{cases} CS, & Transmit\ to\ SN \\ NCS, & Data\ type = \begin{cases} Critical\ data, & Transmit\ to\ least\ CF\ node \\ Non-critical\ data, & Turn\ to\ SSM \end{cases} \end{cases}$$

Figure 4.3: The sequential procedure logical approach

The general procedure discussed in this section is explained in Figure 4.4

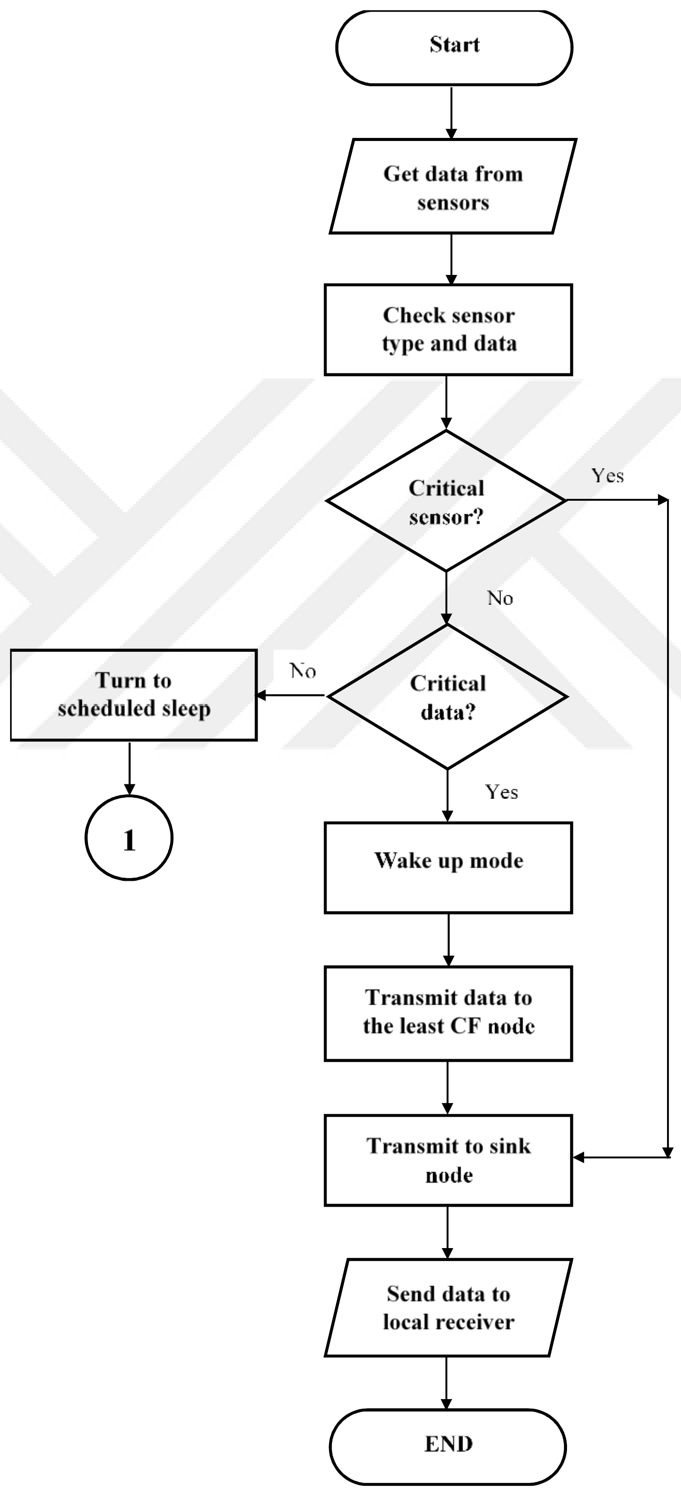


Figure 4.4: The proposed work flow chart

4.4.2 Smart Sleep Mode using RAR and SSM

In Figure 4.5 below, we suggested an intelligent sleep mechanism for the NCS that improves network life time, stability, performance, and residual energies of the WBSN.

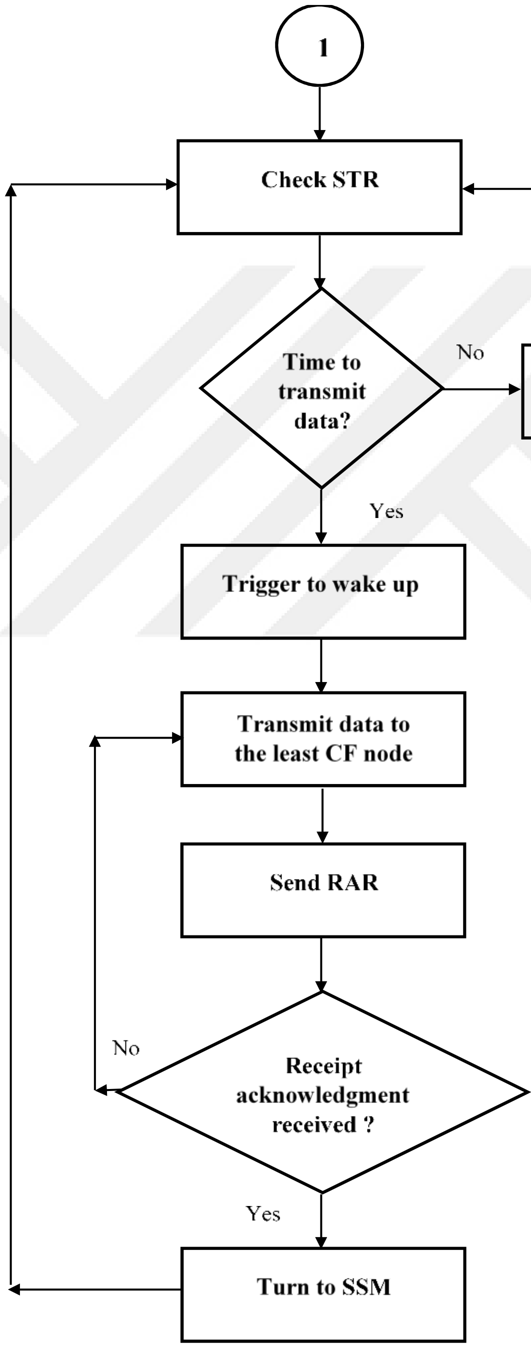


Figure 4.5: Sensor nodes scheduled sleeping flow chart

The concept of smart sleep mode using SMS and RAR can be summarized in the following points:

- The NCS may go into the scheduled sleep mode (SSM) according to the patient supervision doctor's schedule of sleep report (STR), so that the sensor can wake up and send data and go to sleep again.
- If the sensed data of the NCS goes above or below the control doctor specifies critical values, the sensor will switch to the wake-up mode and will still transfer data until the data is returned to normal condition.
- If NCS triggers to wake up under STR, it sends data and a request for receipt recognition (RAR). The node will return to SSM again when it receives a receipt confirmation. The receipt acknowledgment is used for turning the sensor node into SSM.
- If no receipt has been received by the sensor, it will continue to send RAR and data until it receives the receipt. When that happens it turns into SSM after receipt has been received.
- The advantage of RAR is to ensure the data reached the SN successfully; as the missing data is, for whatever reason, a real problem, since the data will be transmitted once each waking cycle and the following information will be transmitted, perhaps after a long time, depending on the STR after the waking time [120,121].

5. THESIS CONCLUSIONS

5.1 CONCLUSION AND DISCUSSION

In this research we presented the R-SIMPLE model, developed by adding to SIMPLE cost function a performance factor that enhance the performance of the function and ensures the data packets reaches to sink node successfully without losing od data.

In addition, we presented the new WBSN Design with a single sink node and multi hop nodes, which improves the network life time, stability, throughputs and residual energy for WBSN through the classification of sensors into critical sensors and non-critical sensors.

We have also added an intelligent sleep modus to the SIMPLE model where, in a scheduled time report, normal sensors may go to sleep mode according to the patient supervisor, so that the sensor can wake, transmit data, and go again to sleep. However, the sensor will turn to Wakeup Mode and continue to transmit data till the data return in the normal state, this happens when the data sensed is above or below the critical values specified by the doctor's supervisor.

We have also provided WBAN with reliability and data integrity, by sending a request for acknowledgement receipt following data submission, according to the planned time report, to ensure that the data successfully reaches the sensor node before moving into the scheduled sleep mode.

5.2 FUTURE WORK

For this thesis, we focused on the energy aspect of the design of WBSN networks form the theoretical point of view. We proposed to develop a protocol to enhance this design. This protocol is oriented towards energy consumption. It ensures a simplified modification of new model. In addition, it guides the researcher towards obtaining a model that respects the energy and medical constraints of the application, nevertheless a simulation can be done to this work in the future.

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