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Wireless Body Area Network Based-System For Pregnancy Monitoring: OMNeT ++ Simulation

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Dedication

This thesis is dedicated To my beloved parents, my cherished mother, whose love and invaluable advice have shaped me in ways that words cannot fully express. Her unwavering support and guidance have made me who I am today, and I am forever grateful for her amazing presence in my life.

To my father, for believing in me and supporting me and for always making me feel like his little princess no matter how old I get. His love and encouragement have been a constant source of strength and confidence.

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Abstract

Technology for women's health and pregnancy monitoring has lagged behind advancements in other medical fields. Existing monitoring technologies are expensive, complex, and not easily implemented in low-resource settings. This technological disparity further exacerbates health inequalities among women. Moreover, the lack of equipment and qualified medical staff, particularly in remote areas, compounds the challenges faced by pregnant women, limiting their access to essential healthcare services. This scarcity of healthcare professionals directly impacts monitoring practices and significantly contributes to the persistently high rates of maternal morbidity and mortality. Addressing these disparities requires advancements in affordable and user-friendly monitoring technologies tailored to women's health. One promising solution is the use of Wireless Body Area Networks (WBANs). In a WBAN, tiny devices are deployed on or around a human body, capable of detecting and collecting various vital signs and physiological parameters. In this work, the development and implementation of a WBAN monitoring system for pregnant women using the OMNeT++ simulator is proposed. The objective is to evaluate the effectiveness of the system under various scenarios. The proposed WBAN system would consist of wearable sensors capable of measuring parameters such as fetal heart rate, uterine contractions, blood pressure, and maternal vital signs based on the stage of pregnancy. These sensors would wirelessly transmit the collected data to a central monitoring unit, where healthcare professionals can remotely monitor the health status of pregnant women. Through this system, real-time data analysis and early detection of complications could be achieved, enabling timely interventions and reducing the risks associated with pregnancy and childbirth.

Keywords: *WBANs, Sensors, Monitoring system, Pregnancy, OMNeT++.*

Résumé

La technologie pour la santé des femmes et le suivi de la grossesse a pris du retard par rapport aux progrès réalisés dans d'autres domaines médicaux. Les technologies de surveillance existantes sont coûteuses, complexes et difficiles à mettre en œuvre dans des environnements à faibles ressources. Cette disparité technologique exacerbe les inégalités de santé entre les femmes. En outre, le manque d'équipement et de personnel médical qualifié, en particulier dans les zones reculées, aggrave les difficultés rencontrées par les femmes enceintes, en limitant leur accès aux services de santé essentiels. Cette pénurie de professionnels de la santé a un impact direct sur les pratiques de suivi et contribue de manière significative à la persistance de taux élevés de morbidité et de mortalité maternelles. Pour remédier à ces disparités, il faut faire progresser les technologies de surveillance abordables et conviviales, adaptées à la santé des femmes. Une solution prometteuse est l'utilisation de réseaux corporels sans fil (WBAN). Dans un WBAN, de minuscules dispositifs sont déployés sur ou autour du corps humain, capables de détecter et de collecter divers signes vitaux et paramètres physiologiques. Ce travail propose le développement et la mise en œuvre d'un système de surveillance WBAN pour les femmes enceintes à l'aide du simulateur OMNeT++. L'objectif est d'évaluer l'efficacité du système dans différents scénarios. Le système WBAN proposé se compose de capteurs portables capables de mesurer des paramètres tels que le rythme cardiaque du fœtus, les contractions utérines, la pression artérielle et les signes vitaux de la mère en fonction du stade de la grossesse. Ces capteurs transmettraient sans fil les données collectées à une unité centrale de surveillance, où les professionnels de la santé pourraient contrôler à distance l'état de santé des femmes enceintes. Grâce à ce système, l'analyse des données en temps réel et la détection précoce des complications pourraient être réalisées, ce qui permettrait d'intervenir à temps et de réduire les risques associés à la grossesse et à l'accouchement.

Mots-clés: *WBANs, capteurs, Système de surveillance, Grossesse, OMNeT++.*

الملخص

تقنية الرعاية الصحية ومراقبة الحمل للنساء تأخذ وقتًا أطول في التطور مقارنة بالتقدم في المجالات الطبية الأخرى. تكنولوجيات المراقبة المتاحة حاليًا مكلفة ومعقدة ولا يمكن تنفيذها بسهولة في البيئات ذات الموارد المحدودة. يؤدي هذا الاختلاف التكنولوجي إلى تفاقم العدالة الصحية بين النساء. علاوة على ذلك، نقص المعدات والكوادر الطبية المؤهلة، خاصة في المناطق النائية، يعزز التحديات التي يواجهها النساء الحوامل ويحد من وصولهن إلى الخدمات الصحية الضرورية. هذا النقص في الكوادر الصحية يؤثر مباشرة على ممارسات المراقبة ويسهم بشكل كبير في ارتفاع معدلات مرض ووفاة الأمهات بشكل مستمر. للتغلب على هذه الاختلافات، يتطلب التطور في تكنولوجيات المراقبة التي تكون بأسعار معقولة وسهلة الاستخدام ومصممة خصيصًا لصحة المرأة. واحدة من الحلول الواعدة هي استخدام شبكات المناطق الشخصية اللاسلكية (WBANs) . في WBAN ، يتم نشر أجهزة صغيرة على جسم الإنسان أو حوله، قادرة على اكتشاف وجمع مختلف العلامات الحيوية والمعلمات الفسيولوجية. في هذا العمل، يتم اقتراح تطوير وتنفيذ نظام مراقبة WBAN للنساء الحوامل باستخدام محاكي ++OMNeT. الهدف هو تقييم فعالية النظام تحت سيناريوهات مختلفة. سيتكون نظام WBAN المقترح من أجهزة ارتداء قادرة على قياس معلمات مثل معدل ضربات قلب الجنين وتقلصات الرحم وضغط الدم وعلامات الأم الحيوية بناءً على مرحلة الحمل. ستنقل هذه الحساسات البيانات المجمعة بشكل لاسلكي إلى وحدة مراقبة مركزية، حيث يمكن للمهنيين الصحيين مراقبة حالة صحة النساء الحوامل عن بُعد. من خلال هذا النظام، يمكن تحقيق تحليل البيانات في الوقت الفعلي والكشف المبكر عن المضاعفات، مما يمكّن التدخل في الوقت المناسب وتقليل المخاطر المرتبطة بالحمل والولادة.

الكلمات الرئيسية: WBANs، الاستشعارات، نظام المراقبة، الحمل، ++OMNeT.

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List of Abbreviations

BER	Bit Error Rate
BLE	Bluetooth Low Energy
CBM	Condition-Based Maintenance
CEMG	Capacitive electromyography
ECG	Electrocardiography
EHG	Electrohysterography
EMG	Electromyography
FFSNs	Full-Function Sensor Nodes
GPRS	General Packet Radio Service
GSM	Global Systems for Mobile
GSR	Galvanic Skin Response
IoT	Internet of Things
MAC	Medium Access Control
MEMS	Micro-Electro-Mechanical Systems
OMNeT++	Objective Modular Network Testbed in C++
PHY	Physical
PPG	Photoplethysmogram
QOS	Quality of Service
RFSNs	Reduced-Function Sensor Nodes

RHM Remote Healthcare Monitoring

SAR Specific Absorption Rate

SpO2 Oxygen Saturation

WBANs Wireless Body Area Networks

WSNs Wireless Sensor Networks

WPAN Wireless Personal Area Network

General Introduction

1. Context and motivation

Over the next three decades, the world's population is projected to increase by approximately 2 billion individuals, reaching 9.7 billion by 2050 a growth of around 25% United Nations Department of Economic and Social Affairs, Population Division (2022). Maternal mortality remains a critical issue, with 94% of approximately 287,000 deaths occurring in low-resource settings World Health Organization (2023), emphasizing the need for preventive measures. Developing countries face challenges in providing adequate healthcare, falling below the WHO's recommended thresholds for healthcare professionals per population. In remote areas, there are higher rates of pre-existing diabetes (2.5%) and pre-existing hypertension (1.0%) among mothers compared to regional areas (1.3% and 0.8%) and major cities (0.7% and 0.6%) Australian Institute of Health and Welfare (2023).

Addressing these challenges requires a significant financial investment in healthcare infrastructure as well as the recruitment and training of healthcare professionals, both of which incur substantial costs. This means that the sustainable development of societies relies on finding measures that optimize the existing health infrastructures and seek technological innovations that facilitate preventive healthcare measures and remote healthcare delivery. According to recent research, Wireless Body Area Networks (WBANs) have emerged as a promising technology for developing a health monitoring system Zhong et al. (2022).

WBANs are a particular type of sensor network using wireless sensor nodes that can be worn on or placed in the human body to measure physiological parameters such as blood pressure, temperature, heart rate. . . etc, enabling a patient's health to be monitored remotely Yaghoubi et al. (2022). They communicate with a special coordinator node, which is generally less energy constrained and has more processing capacities Negra et al. (2016).It is responsible for sending biological signals of the patient to the medical centre, enabling real-time medical diagnostics and informed decision-making. WBANs support a number of innovative and interesting applications. These applications include several areas such as military, ubiquitous health care, sport, entertainment and many other areas.

2. Problematic and Objectives

Pregnant women facing high-risk pregnancies require specialized monitoring, intensive care, and close medical supervision, often resulting in extended hospitalization. This allows healthcare professionals to closely monitor both the mother and fetus, administer appropriate treatments, and promptly respond to emergencies. However, within developing countries, pregnant women often face difficulties when seeking care at hospitals. Limited resources, including medical equipment and essential supplies, coupled with insufficient staffing levels and a lack of skilled healthcare professionals, contribute to prolonged waiting times, rushed consultations, and compromised quality of care. Furthermore, in remote areas, pregnant women encounter additional challenges, such as limited access to healthcare facilities, requiring long journeys and incurring extra costs to receive necessary care.

To address the aforementioned problems and ensure continuous real-time monitoring of pregnant women during pregnancy and childbirth, both in hospitals and at home, a hybrid wireless body area network (WBAN) system for pregnancy monitoring is proposed. The system aims to enable early detection and intervention of potential complications, thereby reducing the risk of maternal and neonatal mortality. By simulating the system using the OMNeT++ simulator, the effectiveness and feasibility of the proposed solution can be evaluated, providing valuable insights for improving the quality of prenatal care and enhancing maternal and neonatal health outcomes.

3. Thesis Structure

This thesis consists of four chapters, which are outlined as follows:

- **Chapter 1:** presents an overview of sensors and covers the essential aspects of Wireless Sensor Networks (WSNs) by defining the main concepts related to WSNs. It then specifically focuses on wireless body area networks (WBANs) as the particular type of WSNs that is the main focus of this thesis.
- **Chapter 2:** presents a comprehensive overview of WBANs monitoring systems by

categorizing various papers and research studies that have investigated the applications of WBANs in healthcare. It then specifically focuses on pregnancy monitoring systems, providing a global view through a detailed overview and discussion of the applications, advancements, and challenges of WBAN-based pregnancy monitoring systems.

- **Chapter 3:** provides a medical background on pregnancy and its complications, highlighting the significance of continuous monitoring in prenatal care. The chapter then introduces our proposed hybrid WBAN system for pregnancy monitoring, presenting a detailed conception and description of its key components, functionality, and technology integration. The chapter concludes by proposing various scenarios that will be simulated to showcase the practical application of our WBAN system in different monitoring situations.
- **Chapter 4:** presents a detailed simulation of the proposed system for monitoring pregnant women using the OMNeT++ simulator. The simulation is developed from scratch and includes communication aspects and sensor behaviour. Additionally, the chapter will discuss the results obtained from the simulation.

Chapter 1

Fundamentals about Wireless Body Area Network

1.1 Introduction

In recent years, wireless networking has become increasingly popular and more mobile due to the fundamental changes that it brings. This has allowed the appearance of a new type of wireless networks called Wireless Sensor Networks (WSNs) which have emerged as an important paradigm for data acquisition in a wide variety of domains, especially medical applications such as healthcare monitoring. A new generation of WSNs known as Wireless Body Area Networks (WBANs) have recently emerged as another new technology that consists of a small set of nodes equipped with biomedical sensors for monitoring the human body.

The remainder of this chapter presents a comprehensive overview of sensors and covers the essential aspects of Wireless Sensor Networks (WSNs) by defining the main concepts related to WSNs. Furthermore, a particular focus is devoted to profoundly introducing Wireless Body Area Networks (WBANs), and examining their architecture, requirements, technologies, and applications.

1.2 Overview of Sensors

Sensors have improved the everyday life of human beings through their applications in almost all fields by detecting physical stimuli and converting them into a machine or human-readable form. A sensor is a device that detects events or changes in its environment and converts physical phenomena into a measurable digital signal, which can be displayed, read, or processed further. A. Sharma et al. (2021)

1.2.1 Sensors Classification

Sensors can be classified into several categories based on various criteria such as the physical property being sensed, the type of output signal produced, the mode of operation, and the energy used Eren (2004). The following are some common classifications:

- **Physical property**: This classification is based on the physical sensed property as given in Table 1.1, such as temperature, pressure, light, sound, etc.

Table 1.1: Types and Properties of Sensors Eren (2004)

Types	Properties
Thermal sensor	Temperature, heat, flow of heat, etc
Electrical sensor	Resistance, current, voltage, inductance, etc
Magnetic sensor	Magnetic flux density, magnetic moment, etc
Optical sensor	Intensity of light, wavelength, polarization, etc
Chemical sensor	Composition, pH, concentration, etc
Pressure sensor	Pressure, force, etc
Vibration sensor	Displacement, acceleration, velocity, etc
Rain/moisture sensor	Water, moisture, etc
Tilt sensors	Angle of inclination, etc
Speed sensor	Velocity, distance, etc

- **Power source**: This classification is based on the type of power source, which can be categorized into:— passive sensors: do not require an external power source and rely on the energy of the signal they are measuring to generate an output signal), —active sensors: require an external power source to operate.

- **Output Signal**: In this case, the classification refers to the type of output signal produced by the sensor, such as voltage, current, resistance, etc.

- **Mode of Operation**: This classification is based on the way the sensor operates, such as the null type (using the opposing or balancing force principle), the deflection type (using a mechanical deflection mechanism)

- **Energy Used**: This classification is based on the type of energy used by the sensor, such as electrical, optical, mechanical, etc.

- **Technology**: This classification is determined by the technology used in the sensor, such as MEMS (Micro-Electro-Mechanical Systems), infrared, ultrasonic, etc.

There exist so many other ways to classify a sensor according to different criteria. The choice of classification depends on the user's specific needs and requirements, all of which are impossible to list.

1.2.2 Sensor Node Anatomy

A sensor node typically has three fundamental capabilities: sensory, computational, and wireless communication, as shown in Figure 1.1. The sensory capability enables the node to sense and acquire data from the surrounding environment. On the other hand, the computational capability allows the node to process and analyse the acquired data, manage communication activities, and execute control algorithms. Finally, the wireless communication capability enables the node to send and receive data and control information to and from other sensor nodes or a central sink node. Bar-Noy et al. (2005)

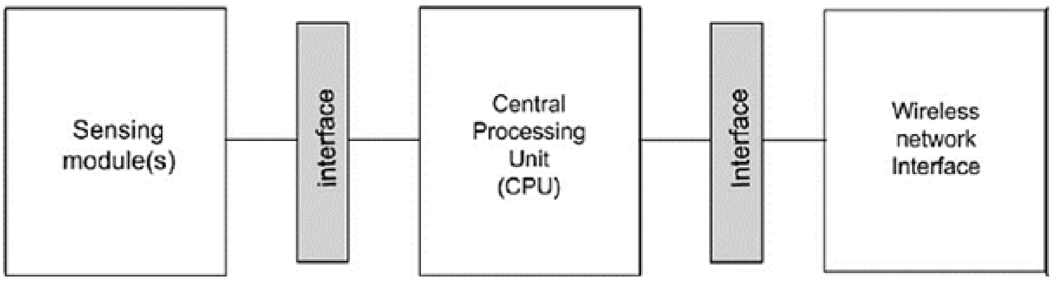


Figure 1.1: The Anatomy of a Sensor Node Bar-Noy et al. (2005)

1.2.3 Wireless Sensor Architecture

Several sensor models are offered according to the underlying application. In general, a sensor node consists of four basic components, namely a sensing unit, a processing unit, a communication unit and a power supply. Besides, depending on the target application, some modules may be included: GPS, solar cell, etc Ari et al. (2015). Figure 1.2 presents the general node architecture.

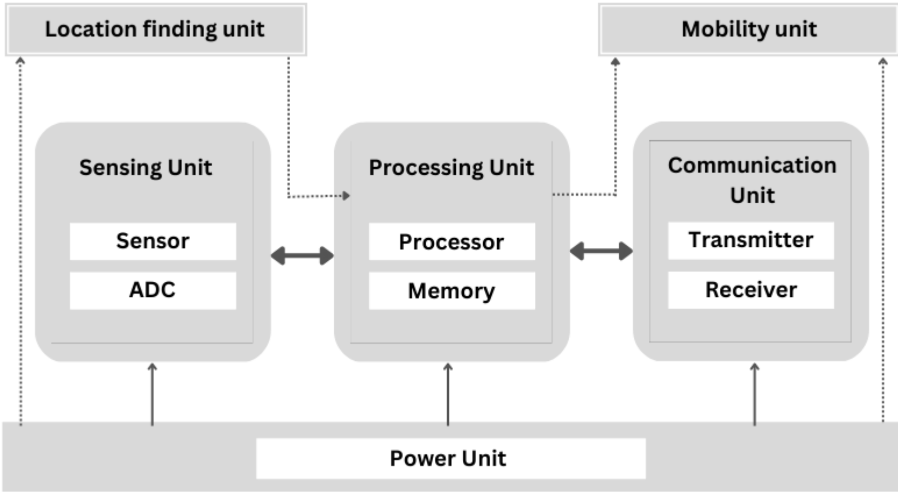


Figure 1.2: General Sensor Architecture

- **Sensing Unit:** This unit consists of two submodules: the sensor itself and an analogue-to-digital converter (ADC). The sensor produces analogue signals based on the measured physical parameters of the environment such as temperature, humidity, pressure, etc then the ADC converts them into usable digital signals and sends them to the processing unit Xia (2009).
- **Processing Unit:** This unit consists of memory to store the data generated by the sensing unit and a microprocessor or a microcontroller that is used to perform the sensor node tasks and processes the collected data and manage the functionality of the other sensor node components Xia (2009).
- **Communication Unit:** This unit typically includes a transceiver module that facilitates communication between the sensor node and other devices Xia (2009).
- **Power Unit:** This component is responsible for providing energy to other components in the node, and it can be stored in a battery, solar cells, or other energy sources. Its primary function is to ensure that the sensor node has a stable and continuous source of energy Xia (2009).

1.2.4 Sensor Deployment

Different deployment modes can be used based on the monitoring objectives and the characteristics of the area to be monitored. The two main approaches for sensor deployment include deterministic and randomized modes. Chen (2020); Tripathi et al. (2018)

1.2.4.1 Deterministic Deployment

Involves placing sensor nodes at predetermined positions to meet specific requirements such as coverage, connectivity, and expected lifetime. This approach is suitable for controlled environments such as office buildings, hospitals, and factories, where the positions of the sensor nodes can be planned in advance. However, deterministic schemes may not be suitable for harsh or hostile environments such as forests, deserts, or battlefields, where the sensor nodes may need to be air-dropped or distributed randomly.

1.2.4.2 Random Deployment

On the other hand, involves deploying sensor nodes randomly, often using an air-drop or other distribution method. This approach is typically used in harsh or hostile environments, where it may not be feasible to use a deterministic deployment method. Random schemes usually require more nodes and more complicated scheduling mechanisms to ensure coverage and connectivity.

Sensor nodes can also be classified as static or mobile, depending on their mobility. Static deployment is the most common approach and involves deploying fixed sensor nodes in a specific area. Mobile deployment, on the other hand, involves using mobile sensor nodes that can move around and track moving targets. Mobile sensor nodes can be useful in applications such as wildlife monitoring, search and rescue operations, and vehicle tracking.

1.3 Wireless Sensor Networks (WSNs)

Wireless Sensor Networks (WSNs) have been widely considered one of the most important technologies for the twenty-first century. A wireless sensor network (WSN) typically consists of a large number of low-cost, low-power, and multi-functional sensor nodes that are deployed in a region of interest. These sensor nodes are small in size but are equipped with sensors, embedded microprocessors, and radio transceivers. Therefore, they have not only sensing but also data processing and communicating capabilities. They communicate over short distances through a wireless medium and collaborate to accomplish a common task Zheng and Jamalipour (2009). Typically, a WSN consists of the following 3 components: sensor nodes, gateway and observer (user). Sensor nodes and gateways constitute the sensor field. Gateways and observers are interconnected via special networks or more commonly through the internet (see Figure 1.3).

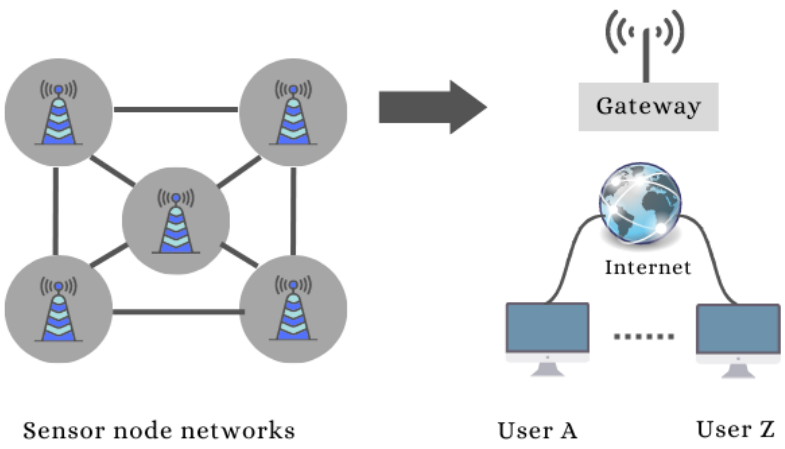


Figure 1.3: Wireless Sensor Network (WSN)

1.3.1 Data Collection Methods in WSN

The primary objective of data collection in wireless sensor networks is to gather a significant amount of data while minimizing the risk of data loss, which can be caused by the limited memory capacity of sensor nodes.

There are three types of data collection methods: data collection through mobile sensor nodes, data collection using a static sink approach, and data collection through mobility-based approaches. Nair and Jose (2013)

1. **Static sink approach:** In this approach, a stationary sink is utilized to gather data from sensor nodes and transmit it to the base station. However, this approach presents a challenge to energy efficiency since the sink node is responsible for collecting all the data from the sensors, which can lead to the formation of energy holes and a reduction in the network's lifetime.

2. **Mobile sensor node approach:** This approach involves the use of sensor nodes with mobility. This approach has the advantage of increasing the amount of collected data packets compared to the static sink approach. However, the resource limitation of the sensors, such as their reduced memory capacity and battery power, still poses a challenge for energy efficiency. The mobility of the sensors can help to overcome this challenge, but it may also lead to network lifetime reduction.

3. **Mobility-based approach:** This approach is categorized into a single mobile sink and multiple mobile agents that move along either a constrained or uncontrollable

path. This approach can increase the amount of collected data compared to the static sink and mobile sensor approaches, but energy efficiency and data loss can be challenging. Multiple mobile agents can help overcome these challenges, and mobile mules can be used for data collection in disconnected networks.

1.3.2 WSN Network Topologies

There are several different topologies commonly used in wireless sensor networks (WSNs). Here are some of the most widely used ones: Soparia and Bhatt (2014); Ekanayake and Hedley (2018)

1. **Peer-to-Peer (P2P):** In this topology, all the devices have an equal role in the network. This type of network structure is typically used for a single communication link, often between a data collector and a sensor sending readings.

2. **Star Topology:** Star topology is one in which all the devices are directly connected through the central node. It has the potential to realize low latency and high bandwidth. However, the hub is a single point of failure and the nodes can only communicate indirectly through the hub. Thus, a star topology has reduced reliability and limited scalability.

3. **Mesh Topology:** In a mesh topology, every device is connected to multiple other devices, providing multiple pathways for data to travel. This increases fault tolerance and self-healing capability, as well as facilitates scalability. However, the use of advanced communication protocols and routing capabilities leads to increased computation load and higher energy consumption. As a result, a mesh topology is best suited for scenarios where reliability and flexible communication are prioritized over energy efficiency and network longevity.

4. **Tree Topology:** A tree topology contains a top with a branch structure below. The connections between the nodes are structured hierarchically, which means that each node in the network is connected to the root node, as well as to other nodes on the same or a lower level It has a good fault tolerance, good coverage, high bandwidth and low latency. But still, the processing power and energy consumption is highest at the root node and keeps on decreasing as we go down the hierarchical order.

1.3.3 WSN Architecture

The most common architecture for WSN follows the OSI Model. Basically, WSN consists of five fundamental layers: application layer, transport layer, network layer, data link layer and physical layer. Added to the five layers are the three cross layers planes A. Alkhatib (2011) as shown in Figure 1.4.

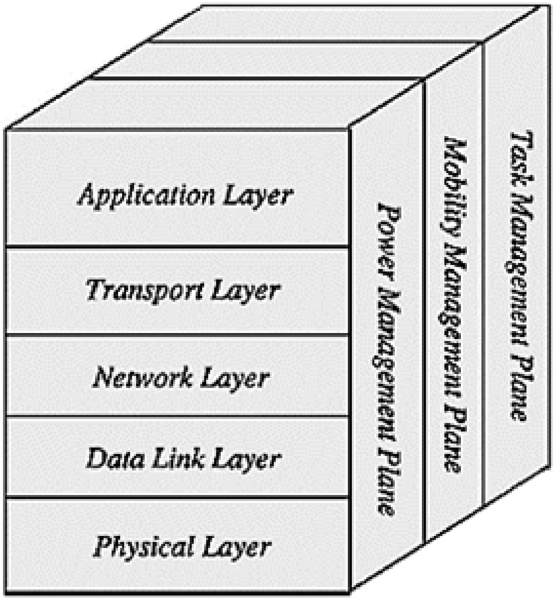


Figure 1.4: WSN Architecture A. A. A. Alkhatib and Baicher (2012)

The cross-plane layers are used to manage the network and make the sensors work together in order to increase the overall efficiency of the network.

1.3.3.1 Cross Layers Planes

1. **Power Management Plane:** It is responsible for managing the power level of a sensor node for sensing, processing and communication.

2. **Connection management plane:** It is responsible for configuring and re-configuring sensor nodes to establish or maintain network connectivity.

3. **Task Management Plane:** It is responsible for task distribution among sensor nodes to improve energy and prolong the network lifetime.

1.3.3.2 WSN OSI Layers

1. **Application Layer:** It manages traffic and provides software for various applications which send queries to obtain informationA. A. A. Alkhatib and Baicher

(2012).

2. **Transport Layer:** This layer is required in case of inter-network communication. Many protocols have been designed to provide reliability and congestion avoidance. Because of multi-hop communication, TCP is not suitable for WSNs A. A. A. Alkhatib and Baicher (2012).

3. **Network Layer:** This layer serves the function of routing which is a challenging task in WSN. Due to low power and limited memory, routing protocol has to provide reliable and redundant paths, for which many protocols are available according to the desired metric A. A. A. Alkhatib and Baicher (2012).

4. **Data link Layer:** It ensures reliability from point-to-point or point-to-multi point. Error control and multiplexing of data streams are also done by this layer. In WSN, Medium Access Control (MAC) has an important role to play. It provides higher efficiency, reliability, low delay and higher rates of communication A. A. A. Alkhatib and Baicher (2012).

5. **Physical Layer:** Can provide an interface to transmit a stream of bits over a physical medium. Responsible for frequency selection, carrier frequency generation, signal detection, Modulation and data encryption A. A. A. Alkhatib and Baicher (2012).

1.3.4 Applications of WSN

WSN are used in various applications to gather and transmit data from the physical world to a central location for analysis. Some of the most common applications of WSN include: Matin and Islam (2012); Kandris et al. (2020)

- **Military Applications:** Wireless sensor networks are likely to be an integral part of military command, control, communications, computing, intelligence, battlefield surveillance, reconnaissance, and targeting systems.

- **Area Monitoring:** In area monitoring, the sensor nodes are deployed over a region where some phenomenon is to be monitored. When the sensors detect the event being monitored (heat, pressure etc), the event is reported to one of the base stations, which then takes appropriate action.

- **Transportation:** Real-time traffic information is being collected by WSN to later feed transportation models and alert drivers of congestion and traffic problems.
- **Industrial Monitoring:** Wireless sensor networks have been developed for machinery condition-based maintenance (CBM) as they offer significant cost savings and enable new functionalities. In wired systems, the installation of enough sensors is often limited by the cost of wiring.
- **Agricultural Sector:** Using a wireless network frees the farmer from the maintenance of wiring in a difficult environment. Irrigation automation enables more efficient water use and reduces waste.
- **Health Applications:** Some of the health applications for sensor networks are supporting interfaces for the disabled, integrated patient monitoring, diagnostics, and drug administration in hospitals, telemonitoring of human physiological data, and tracking and monitoring doctors or patients inside a hospital.

Unlike other types of applications discussed so far, healthcare applications do not function as stand-alone systems. Rather, they are integral parts of a comprehensive and complex health and rescue system. This has led to the emergence of a new type of wireless sensor network known as a wireless body area network.

1.4 Wireless Body Area Networks (WBANs)

A Wireless Body Area Network (WBAN) is a special-purpose network considered the sub-field of wireless sensor networks (WSNs). The development of WBAN technology started around 1996 when it was presented by Zimmerman (1996) but he gave these body networks the name Wireless Personal Area Network (WPAN) from the beginning. Later on, PAN was redefined to be, e.g., cable replacement for up to 10 meters (e.g., Bluetooth) and the name WBAN evolved instead Bilstrup (2008).

A WBAN is a network built with different intelligent elements such as sensors, nodes, and actuators. This network is designed to work on the human body and its surroundings. The elements that conform to the network must be highly reliable, exhibit low consumption, be operational at a high range (maximum 5m), must be resistant to interference, and must be able to operate within a wide range of transmission speeds Hemanth et al. (2021). Figure 1.5 below provides a comparison between a WBAN network and other networks.

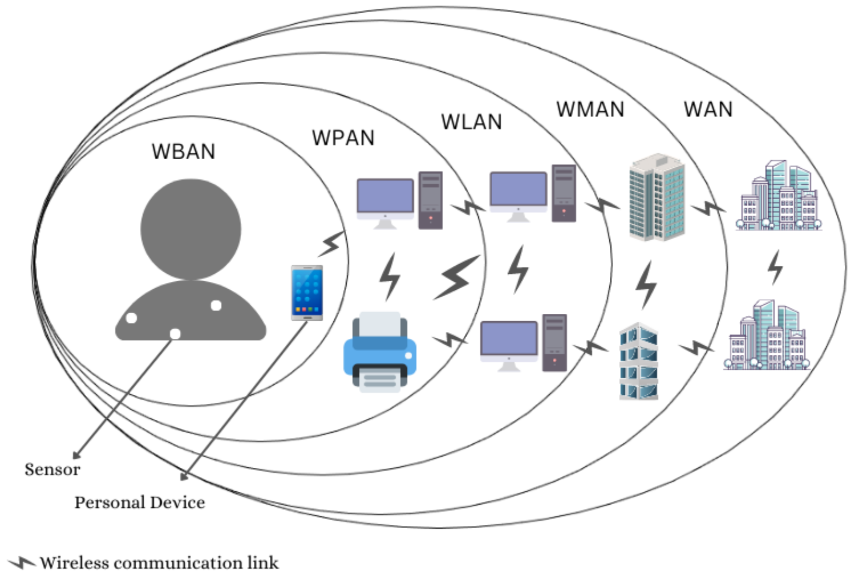


Figure 1.5: Positioning of a Wireless Body Area Network in the Realm of Wireless Networks

1.4.1 WBAN Vs WSN

Although the main purpose of both general WSN and WBAN is to gather and transmit data. However, the technical differences are in the implementation scenarios and use cases. It is crucial to understand the distinct characteristics of WSN and WBAN. Table 1.2 represents a schematic overview of differences between Wireless Sensor Networks and Wireless Body Area Networks, based on Kwak et al. (2010); Yaghoubi et al. (2022); Ullah et al. (2012).

Table 1.2: Comparison of WBAN and WSN Characteristics

Characteristics	WBAN	WSN
Scale	Body range (cm/m)	Environmental monitoring (m/km)
Node number	Fewer, limited in space	Many redundant nodes for wide area coverage
Node size	Small	Small as well as large
Node replacement	Difficult	Easy
Node task	Perform multiple tasks	Perform dedicated tasks

Table 1.2: Comparison of WBAN and WSN Characteristics

Characteristics	WBAN	WSN
Node lifetime	Several years/months	Several years/months, smaller battery capacity
Network topology	More variable due to body movement	Very likely to be fixed or static
Power supply	Hard to access and replace that of in-body nodes	Accessible, can be changed and replaced
Power demand	High	Low
Data rates	Heterogeneous	Homogeneous
Data Loss	More significant, may require additional measures to ensure QoS and real-time data delivery	Likely to be compensated by redundant nodes
Biocompatibility	A must for implants and some external sensors	Not a consideration in most applications
Security Level	Higher, to protect patient information	Lower
Wireless Technology	Low power technology	Technology Bluetooth, ZigBee, GPRS, WLAN
Standard	IEEE 802.15.6	IEEE 802.11.4
Mobility	Nodes share the same mobility pattern	Nodes are stationary

1.4.2 WBAN Architecture

Sensors collect physiological data from an individual's body, such as vital signs and other health-related information. The sensors transmit this data to concerned entities, for analysis and diagnosis. Based on the information received, decisions are made and appropriate actions are taken. This enables real-time monitoring and intervention, leading to more efficient and effective healthcare Yaghoubi et al. (2022).

A three-tier architecture for a WBAN communication system can be proposed (Figure 1.6):

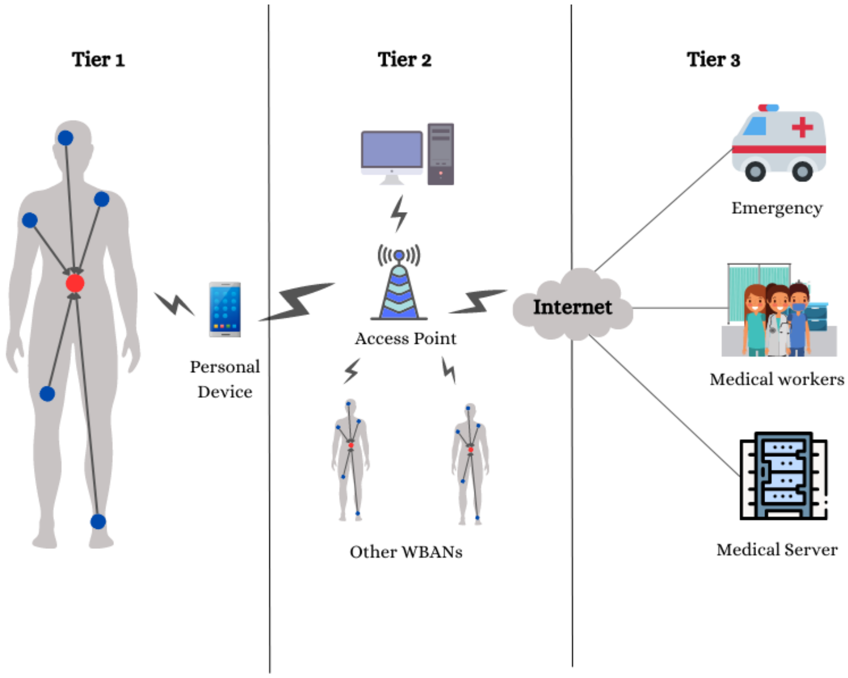


Figure 1.6: WBAN Architecture

1.4.2.1 Tier 1: Intra-WBAN Communication

In a single WBAN, there are more than one node, when we want to communicate between these nodes and not with any other BAN or outside the BAN we will be using Intra-WBAN communication Panhwar et al. (2019). It is a communication refers to two types of communications: Those between body sensors and those between sensors and a Personal Server or Device (PS/PD) Antonescu and Basagni (2013).

1.4.2.2 Tier 2: Inter-WBAN Communication

The personal device (PD) is the one that gathers all the information acquired by sensors and actuators. Once this information is collected by the PD, it has to be communicated through one or more access points (AP) to other networks that are easily reachable (e.g., Internet or cellular networks): This is the inter-WBAN communication Antonescu and Basagni (2013).

1.4.2.3 Tier 3: Beyond-WBAN Communication

There are plenty of network types such as local area network (LAN) and wide area network (WAN) when single WBAN is communicating outside its network with some other type of network is called Beyond-BAN communication, this is the third and last tier of this architecture Panhwar et al. (2019).

1.4.3 Network Topology

In Wireless Body Area Networks (WBAN), different network topologies as shown in Figure 1.7 are used to describe the communication structure among nodes. Some of the commonly used topologies in WBAN include peer-to-peer (P2P), mesh, cluster tree, hybrid and star. The choice of topology is based on the requirements of the application, such as scalability, robustness, energy efficiency, reliability, latency, and mobility. According to the IEEE 802.15.4 standard, sensor nodes can be divided into two types: full-function sensor nodes (FFSNs) and reduced-function sensor nodes (RFSNs). FFSNs have routing functions, while RFSNs can only perform peer-to-peer communication. RFSNs are usually deployed in cases where energy conservation is critical. Akbar et al. (2022)

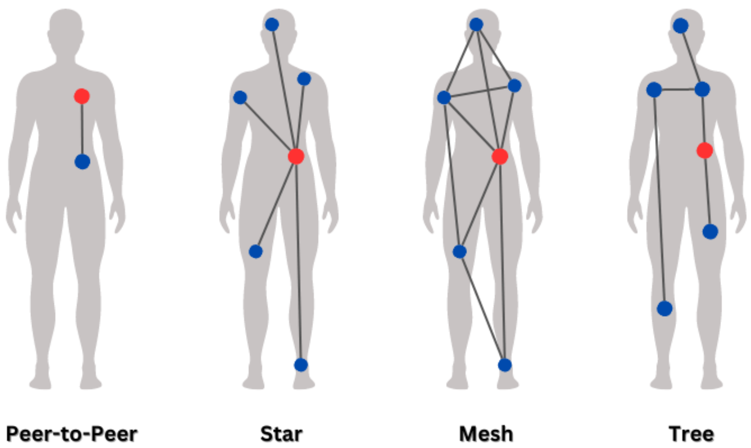


Figure 1.7: WBAN Network Topology

1.4.4 WBAN Communication Stack Layers

Generally, the 802.15 standards under the IEEE (Institute of Electrical and Electronics Engineers) define specifications for the Physical (PHY) and Media Access Control (MAC) layers. They do not specify protocols or services for higher-layer networking, transport, or application functions. As a result, other organizations or groups are typically responsible for developing these higher-layer protocols and services.

New Physical (PHY) and Medium Access Control (MAC) layers have been defined by the IEEE 802.15.6 (WBAN) working group for WBANs that offer low complexity, low cost, high reliability, ultra-low power, and short range wireless communication for in/on body nodes to forward physiological data to the access point Kwak et al. (2010). A description of Physical and MAC layer are given below.

1.4.4.1 Physical Layer (PHY)

The current IEEE 802.15.6 standard defines three PHY layers: Narrowband (NB), Ultra wideband (UWB), and Human Body Communications (HBC) layers. Hasan et al. (2019)

1. **Narrowband PHY (NB):** The NB PHY is responsible for activation/deactivation of the radio transceiver, Clear Channel Assessment (CCA) within the current channel and data transmission/reception.

2. **The Ultra-Wideband PHY (UWB):** The UWB PHY operates in two frequency bands: the low band and the high band. Each band is divided into multiple channels, with a bandwidth of 499.2 MHz for each channel. The low band consists of only three channels (1-3), with channel 2 being the mandatory channel with a central frequency of 3993.6 MHz. The high band consists of eight channels (4-11), with channel 7 being the mandatory channel with a central frequency of 7987.2 MHz. All other channels in the high band are optional. A typical UWB device in IEEE 802.15.6 must support at least one of the mandatory channels. The advantage of the UWB PHY is its low implementation complexity and the ability to generate signal power levels similar to those used in the Medical Implant Communication Services (MICS) band.

3. **The Human Body Communications PHY (HBC):** The HBC PHY operates in two frequency bands: one centred at 16 MHz and the other at 27 MHz, both with a bandwidth of 4 MHz.These two operating bands are valid in the United States, Japan, and Korea, while only the band at 27 MHz is valid in Europe. The HBC PHY is based on Electrostatic Field Communication (EFC) and provides a complete specification for WBAN communication, including the packet structure, modulation, preamble/start frame delimiter, and other key components.

1.4.4.2 Medium access control (MAC) Layer

The IEEE 802.15.6 working group has established a MAC layer to manage channel access, which is built on top of the PHY layer. The hub (or coordinator) is responsible for dividing the channel into a series of superframes for resource allocation, and selecting equal length beacon periods to define the boundaries of the superframes. The beacon periods can also be shifted by the hub. Beacons are usually transmitted in each beacon period, unless prohibited by regulations or inactive superframes. Hasan et al. (2019) The coordinator is responsible for channel access coordination through one of the following three access modes:

1. **Beacon mode with beacon period superframe boundaries:** In this mode, the beacons are transmitted by the hub in each beacon period except in inactive superframes or unless prohibited by regulations.

2. **Non-beacon mode with superframe boundaries:** In this mode, the beacons are transmitted by the hub in each beacon period except in inactive superframes or unless prohibited by regulations.

3. **Non-beacon mode without superframe boundaries:** In this access mode, every node itself defines its own time schedule.

There are three types of access mechanisms in each period of the superframe, which are:
a) Random access mechanism: This mechanism uses either CSMA/CA or a slotted Aloha procedure for resource allocation.
b) Scheduled access and variants (connection-oriented contention-free access): In this kind of access mechanisms, slot allocation is scheduled in one or multiple forthcoming superframes.
c) Unscheduled and improvised access (connectionless contention-free access): In this kind of access mechanisms, slot allocation is scheduled in one or multiple forthcoming superframes.

1.4.5 WBAN Requirements

Wireless Body Area Networks require specific devices and considerations to meet their unique requirements. This section delves into various device types employed in WBANs, the data rates involved, energy consumption considerations, and the importance of quality of service and reliability. Ullah et al. (2012)

1.4.5.1 Type of Devices

WBANs consist of sensors that are employed for monitoring, analysing, and transmitting information about the human body and its vital signs. These sensors provide feedback both to the users and to medical entities.
The devices used in WBAN can be classified into three categories based on their functions:

- **Sensors:** responsible for gathering information about the human body's physical parameters and then transmitting it. Sensor nodes can be placed in, on, or around a human body to monitor body functions and the surrounding environment.
- **Actuators:** a device that converts the electrical signals into the physical actions or events For example, a system consists of a sensor to detect a person's heart rate, and an actuator that delivers a shock to the heart in case of a heart attack. Actuators play an important role in WBANs, as they allow for real-time, autonomous control and intervention based on the data collected from the sensors.
- **Personal Device (PD):** is a type of device in WBAN that collects data from sensors and actuators and provides feedback to the user through an external gateway, actuator, or display. It typically consists of a power unit, processor, memory, and transceiver. PDs are also referred to as Body Control Units (BCUs), body gateways, or sinks, and may be implemented using a Personal Digital Assistant (PDA) or smartphone.

1.4.5.2 Data Rates

The data rate for different wireless body area network (WBAN) applications can vary greatly, with some applications requiring a few kbit/s and others requiring video streams of several Mbit/s. The data rates are determined by the sampling rate, range, and desired accuracy of the measurements. The aggregate data rate from multiple WBAN devices, such as multiple motion sensors, ECG, EMG, and glucose monitoring, can easily reach a few Mbit/s. The reliability of data transmission is measured by the bit error rate (BER), which is the number of lost packets. The required BER for a medical device depends on the data rate, with low data rate devices are able to tolerate a high BER, but devices with a higher data rate require a lower BER. The required BER also depends on the criticality of the data.

1.4.5.3 Energy

Energy consumption is a crucial factor as the size and weight of the batteries used in the nodes must be kept small, and the devices must operate for a long period of time without intervention. The energy consumption can be divided into three domains: sensing, communication, and data processing, with communication being the most power-consuming domain. To increase the battery life, devices should spend most of the time in sleep mode and minimize interference, which can increase energy consumption. Energy scavenging from on-body sources such as body heat and body vibration can help in extending the battery life. During communication, the devices may generate heat, which is absorbed by the surrounding tissue, and increase the body temperature, thus the energy consumption should be kept to a minimum and comply with international SAR (specific absorption rate) regulations.

1.4.5.4 Quality of Service and Reliability

In WBAN systems, ensuring proper quality of service (QoS) is essential for managing the risk of medical applications. The reliability of data transmission is a major concern, as it directly affects the quality of patient monitoring. The reliability can be evaluated in terms of end-to-end or per-link delivery of data, including the guaranteed delivery of data, in-order delivery, and delivery within a reasonable time frame. If the network reliability is low, it can result in fatal consequences if a life-threatening event goes undetected. Hence, maintaining high levels of reliability is critical for ensuring the safety of patients in WBAN systems.

1.4.5.5 Usability

A WBAN should have the ability to self-configure and maintain itself without the need for external intervention. The network should have quick reconfigurability and be able to set up backup routes when necessary. The sensor nodes should be small and located in appropriate positions depending on the application, while also being able to handle motion-induced channel fading and shadowing effects. The goal is to make the WBANs invisible and unobtrusive to the wearer.

1.4.5.6 Security and Privacy

The communication of health-related information between sensors in a WBAN and over the Internet to servers is considered private and confidential, and it should be encrypted to protect the patient's privacy. The medical staff collecting the data should be confident that the data is not tampered with and indeed originates from the patient. The network should be accessible even if the user is not capable of providing a password, for example in emergency situations. Security and privacy protection mechanisms consume a significant amount of energy, so they should be energy efficient and lightweight.

1.4.6 WBAN Standards and Technologies

In WBAN, various short-range technologies like Bluetooth, ZigBee, and IEEE 802.15.6 are used to communicate with the gateway. These short-range communication technologies have unique characteristics and support different operating frequencies and network topologies. A summary of the characteristics of the wireless technologies used in WBAN are provided in Table 1.3.

Table 1.3: Characteristics of Wireless Technologies Used in WBAN Hasan et al. (2019)

Technology	Operating Frequency	Data Rate	Coverage	Network Topology
Bluetooth V.1 802.15.1	2.4 GHz ISM	780 Kbps	10-150 m (on-body only)	Star
Bluetooth V.2 + EDR	2.4 GHz ISM	3 Mbps	10-100 m (on-body only)	Star
Bluetooth V.3 + HS	2.4 GHz ISM & 5 GHz	3-24 Mbps	10 m (on-body only)	Star
Bluetooth V.3 + LEE	2.4 GHz ISM	1 Mbps	10 m (on-body only)	Star
RFID (ISO/IEC 18000-6)	860-960 MHz	10-100 Kbps	1-100 m	Peer-to-Peer
Ultra Wideband (UWB)	3.1-10.6 GHz	110-480 Mbps	5-10 m (on-body only)	Star, mesh, cluster tree
ZigBee (IEEE 802.15.4)	868 MHz, 915 MHz, 2.4 GHz ISM	20, 40, 250 Kbps	30 m (on-body only)	Star, mesh, peer-to-peer, tree
Near Field Communication (NFC)	13.56 MHz	106, 212, 424 Kbps	Up to 20 cm	Star
ANT	2.4 GHz ISM	1 Mbps	30 m (on-body only)	Peer-to-Peer

1.4.6.1 ZigBee IEEE 802.15.4

ZigBee is a wireless technology that is used in WBAN for medical applications that require low-power consumption and text-based data transmission. It offers a long battery life and is easy to install and configure, and it supports various network topologies and many nodes. ZigBee operates at 2.4 GHz, 915 MHz, and 868 MHz frequency bands with data rates of 250 Kbps, 40 Kbps, and 20 Kbps, respectively. It offers three levels of security to prevent data from being changed or accessed by attackers. However, its low data rate makes it unsuitable for some medical applications that require high data rates and its use in hospitals for multiple patients is also limited. Additionally, its operation in the 2.4 GHz band may result in interference with other wireless systems. Arefin et al. (2017)

1.4.6.2 Blutooth

Bluetooth is an IEEE 802.15.1 standard commonly known as WPAN (Wireless Personal Area Network). Bluetooth is designed for short-range wireless communication and it forms a network called a piconet, where one device acts as a master and controls up to seven slave devices. It operates in the 2.4 GHz ISM band with a coverage range of 1 to 100 meters and a maximum data rate of 3 Mbps. Connection setup and data transfer take about 100 ms. In WBAN systems, Bluetooth can be used for communication between sensors and the personal device in the first tier, as it is widely supported and free. However, it is not ideal in terms of power consumption and is suitable for sensors with relatively high data rate requirements. Taleb et al. (2021)

1.4.6.3 WiFi IEEE 802.11

Wi-Fi is a wireless communication technology that provides fast, reliable, and secure communication. It comes in four standards (802.11 a/b/g/n) and operates in the 2.4 and 5 GHz frequency bands and can deliver data rates of up to 600 Mbps. It is integrated into most smartphones, laptops, and tablets, making it ideal for high-speed data transfer and multimedia applications. In WBAN systems, Wi-Fi is not commonly used in the first tier due to its high power consumption. Instead, it is used in the second tier for communication between the personal device (PD) and access points (APs). However, the use of Wi-Fi in WBAN systems is limited due to the high interference that can occur in the ISM bands it operates in. Arefin et al. (2017)

1.4.6.4 IEEE 802.15.6

IEEE 802.15.6 is a standard developed by a task group in 2007 for the standardization of WBANs, approved in 2012. It is used for implantable as well as wearable sensors and works at lower frequencies within a short range. The standard presents a MAC and physical layer design to support various medical and non-medical applications, defining a MAC layer that works with three PHY layers: human body communication (HBC), ultra-wideband (UWB), and narrowband (NB). It also provides a specification for the MAC layer to access the channel, using superframe time structures bounded by equal-length beacons through the coordinator. Taleb et al. (2021)

1.4.7 Applications of WBAN

Similar to other wireless networks, WBANs is able to transmit various types of data, such as voice, video, images, etc. via radio communication Arefin et al. (2017). For this reason, WBANs support a number of innovative and interesting applications. These applications include several areas such as smart health care, sport, entertainment and many others. WBAN applications are categorised medical or non-medical according to their target domain of application. Each application is further classified according to the position of the medical sensors in to implanted or wearable. As can be seen in Figure 1.8.

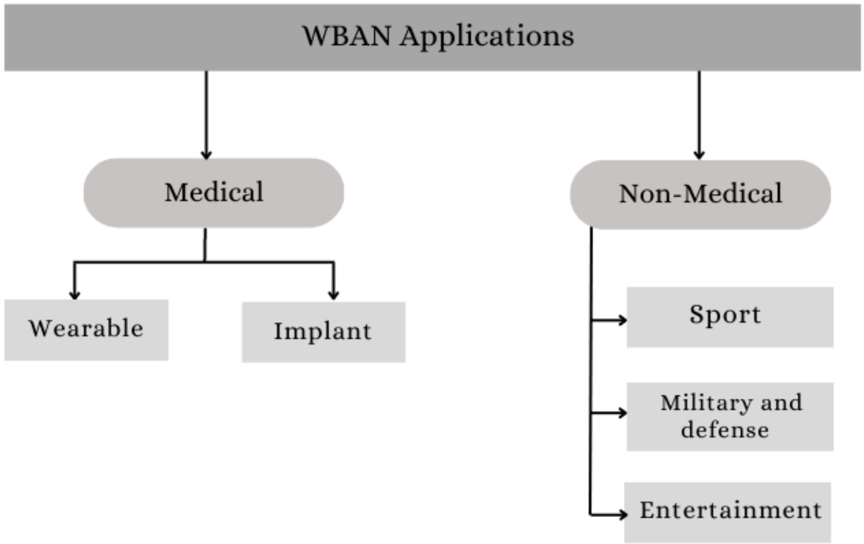


Figure 1.8: Applications of WBAN

1.4.7.1 Medical application

WBANs have a wide range of medical applications, including disease diagnosis, real-time patient monitoring, and telemedicine. These applications can help improve patient care and quality of life by providing continuous monitoring and early warning for life-threatening conditions Pervez Khan et al. (2009). The use of WBANs in medical applications can also lead to better health outcomes and reduced healthcare costs. Some specific medical applications of WBANs include monitoring of vital signs, sleep disorders, and rehabilitation. In this section, we present an overview of the main categories of medical applications.

1. **Telemedicine and Remote Patient Monitoring** Telemedicine and remote patient monitoring involves the use of integrated health information systems and telecommunication technologies to provide remote healthcare services. The system allows doctors to remotely diagnose and prescribe treatments based on real-time physiological data collected by body sensors. This type of smart healthcare system can be applied in various medical scenarios such as diagnostic procedures, chronic condition management, and post-surgery recovery. WBANs play a key role in remote patient monitoring by continuously measuring physiological parameters and providing real-time feedback to physicians. This can lead to better detection of organ failures, emergency situations, and more efficient treatment plans. Research in the field of telemedicine and remote patient monitoring has focused on various spe-

cific diseases such as cardiovascular diseases, diabetes, cancer, Parkinson's, asthma, Alzheimer's, and artificial retinal implant. Matin and Islam (2012)

2. **Rehabilitation** The purpose of rehabilitation is to help patients regain their normal functional abilities after they have been discharged from the hospital. This is done through a series of treatments that aim to correct any undesired movements and restore the patient to their desired state. In order to help patients recover as much independence as possible after a stroke, their movements need to be monitored and corrected to ensure proper motion patterns. This requires continuous monitoring of patients during rehabilitation, making movement detection and tracking an essential aspect of a home-based rehabilitation program. There are specific features of rehabilitation that make it a unique area of research, such as sensor diversity, multi-sensor data fusion, real-time feedback for patients, and virtual reality integration. Matin and Islam (2012)

3. **Assisted Living** Assisted living technology used to monitor the daily activities of people with disabilities or elderly and provide them with assistance as needed. It is wearable medical sensors can be used at home to detect changes in their movements, heart rate, and other physiological parameters of the living environment and then delivers the body data to a central station. In case of an emergency, the system can alert the health care centre for immediate assistance. This technology improves the quality of life for these individuals, allowing them to live more independently and maintain a healthy and safe lifestyle. Additionally, the monitoring data collected by these sensors can help healthcare professionals make informed decisions about the care of these individuals and provide them with more personalized treatment plans.Acampora et al. (2013)

4. **Biofeedback** Self-remote monitoring through the use of wearable wireless body area networks has become a reality. Sensors are placed or implanted on the human body to monitor various behaviours and conditions, including temperature, blood pressure, ECG, EMG, and more. The collected data is then accessed through the WBAN and used to provide biofeedback to the patient. Biofeedback refers to the measurement of physiological activity, along with other parameters, and relaying the information back to the user to help them learn how to control and modify their physiological activity in order to improve their health and performance. R. Li et al. (2017)

1.4.7.2 Non-Medical Application

1. **Sport**

   WBAN can be used in sport applications by providing continuous monitoring of the athlete's physiological activities during training or competitions. This data can be used to optimize the training process, prevent injuries, and enhance performance. The wearable WBAN devices can be equipped with sensors to measure various parameters such as heart rate, temperature, respiration rate, blood pressure, activity, posture, navigation, timer, and distance. By having real-time access to this data, coaches and trainers can make informed decisions about training and ensure the well-being of the athlete.Salayma et al. (2017)

2. **Military and Defence**

   WBAN technology is used in military and public safety to improve the soldiers' performance in dangerous situations by monitoring soldiers' vital signs and stress levels Taleb et al. (2021). We can also eliminate the threat at the individual level by simple getting data and performing certain necessary action. However, security is a critical concern in this case because of the sensitive data. Panhwar et al. (2019) Accomplished experiments are using auditory sensing elements to detect and limit short signals from mortars, weapon systems has been successfully carried out by ARL, the Army Research laboratory which will have a powerful consequence on deadliness and survivability in battlefields. R. Sharma and Kang (2019)

3. **Entertainment**

   The entertainment industry can benefit from the use of WBAN in multiple ways, such as using multiple wearable accelerometer and gyroscope to track body movements through motion capturing. WBAN is mainly utilized in three main domains: Salayma et al. (2017); Panhwar et al. (2019)

- Real-Time streaming: This includes video streaming, as well as audio streaming such as voice communication for headsets that are used for listening to explanations, illustrations, and multicasting (for example, conference calls).

- Consumer electronics: These applications include appliances/devices such as microphones, MP3 players, cameras and other advanced interfaces such as neural interfaces.

- Gaming, virtual reality, ambient intelligence areas, personal item tracking and social networking

1.5 Conclusion

This chapter provides an overview of sensors and explored the relationship between wireless body area networks (WBANs) and wireless sensor networks (WSNs). The discussion on WSNs underscores the unique characteristics and requirements that differentiate WBANs from WSNs.

In the next chapter, there will be an extensive examination of the existing medical monitoring systems, with a specific focus on the advancements and implications of Wireless Body Area Network technology.

Chapter 2

State of the Art: Medical Applications of WBAN

2.1 Introduction

With the rapid growth of the population and an increase in the average lifespan of individuals, healthcare systems face numerous challenges in providing efficient and effective medical treatment. The Wireless Body Area Network (WBAN) has emerged as a promising technology in response to the challenges faced by healthcare systems, by enabling continuous monitoring of physiological parameters to enhance health care delivery and monitoring. WBAN have the potential to improve the management of illnesses, reduce medical accidents, and increase public safety.

The objective of this chapter is to present a comprehensive overview of the existing literature and research studies that have investigated the various applications of WBAN technology in the healthcare field. The findings from these studies will be categorized and synthesized, allowing for a systematic analysis of their contributions. Additionally, a detailed examination of WBAN pregnancy monitoring systems will be conducted, with a specific focus on the primary research conducted in this area. The chapter will thoroughly discuss the challenges associated with the implementation of these systems.

2.2 A comprehensive Overview of WBAN Medical Monitoring Systems

The utilization of Wireless Body Area Network (WBAN) technology in the field of healthcare has emerged as a highly promising area of research and development. The rapid adoption of WBAN technology within the healthcare industry has facilitated continuous monitoring of physiological parameters, thereby augmenting healthcare delivery and surveillance. This comprehensive review aims to elucidate the healthcare applications of WBAN by categorizing relevant articles into four distinct domains: chronic condition monitoring, early detection prevention and monitoring, physical activity monitoring, and elderly care and safety monitoring. Through the organization of these articles into meaningful categories, this overview endeavours to provide a comprehensive understanding of the latest advancements and research in WBAN technology and its potential to improve patient health and well-being.

2.2.1 Chronic Condition Monitoring

This category includes researches that focus on monitoring and managing chronic medical conditions such as diabetes, heart disease, and epilepsy. These articles discuss various monitoring techniques and technologies that can be used to continuously monitor patients' health status and provide timely intervention when necessary. The goal of chronic condition monitoring is to improve patient outcomes, reduce hospital readmissions, and lower healthcare costs.

Huzooree et al. (2017) present a wireless body area network (WBAN) architecture for remote healthcare monitoring of diabetic patients. The proposed platform includes both invasive and non-invasive sensors to monitor the patient's health condition in real-time. The sensed data is then sent to the patient's smartphone, which forwards it to the medical server for easy accessibility by the physicians. The proposed WBAN aims to bridge the gap of information between patients and physicians, providing real-time and historical views of the patient's condition.

A new handheld bioimpedance system for monitoring body fluid status in home-based chronic kidney disease treatments was discribed by Ferreira et al. (2017). The system was evaluated against a commercial bioimpedance spectrometer and found to be equivalent in terms of measurement performance. The system comprises a custom-made handheld tetra-polar bioimpedance spectrometer and a textile-based electrode garment for total body fluid assessment.

C. Li et al. (2017) propose a pervasive monitoring system for remote medical applications that can send patients' physical signs in real-time. The monitoring scheme is designed based on interviews with medical experts and includes multiple physical signs and an environmental indicator. The system uses commercial wireless sensors, an Android smartphone as the connector, and a web-based application for doctors to query monitored data. The paper proposes an IoT-based heart disease monitoring system for pervasive healthcare service, and a prototype implementation is provided to demonstrate the system's functionality.

Gogate and Bakal (2018) propose a healthcare monitoring system for cardiac patients that continuously monitors body parameters such as heart rate, temperature, and SPO2. The system alerts caregivers in case of abnormalities and allows for remote access to data by authorized users such as doctors. The system achieves high accuracy and can be useful in ICU settings and for monitoring elderly people and babies. The system successfully addresses parameters such as availability, security, correctness, and efficiency.

In the study conducted by Borzì et al. (2019), wearable sensors such as inertial measurement units are being used to estimate motor fluctuations in domestic environments among patients with Parkinson's disease. The study demonstrates that these sensors have the capability to achieve sound performance, with high AUC (Area Under the Curve) values for freezing of gait and bradykinesia. The researchers are currently utilizing the SensorTile IoT module for further data processing and creating an electronic diary to monitor motor fluctuations, posture, and dyskinesia during daily activities.

Ng et al. (2019) describe the use of IoT technology for Remote Healthcare Monitoring (RHM) through the application of Electromyography (EMG) measurement. The proposed system is designed to improve medical treatment and physical therapy for chronic inflammatory myopathies. The capacitive electromyography (CEMG) monitoring system utilizes capacitive sensing methodology to address the limitations of conventional EMG measurement, achieving a noise floor of less than 2 mV and a high correlation with conventional wet contact electrodes. This makes it a highly efficient and effective solution for remote healthcare monitoring applications. The article provides in-depth information on the system's architecture, circuit design, and experimental results.

A real-time health monitoring system for palliative patients using an MSE-WBAN (Mobile Service Enterprise-Wireless Body Area Network) architecture was proposed by VK (2020). The system aims to provide continuous monitoring of patients' vital signs, including heart rate, blood pressure, oxygen saturation, and temperature, using wearable sensors. The system's accuracy and effectiveness are demonstrated through experimental results that show the successful real-time monitoring of vital signs of palliative patients using the proposed architecture.

The paper of Amine et al. (2020) presents an intelligent IoT system for remote monitoring of diabetic patients with a data classification model for automated detection and classification of glucose level data. The system not only monitors health data but also offers advanced services such as interoperability, local storage, and data processing. The proposed prediction system was evaluated by several machine-learning algorithms.

In their study, Hernandez and Cretu (2020) suggested an embedded system that utilizes a single IMU to monitor respiratory effort and body position in real-time during sleep. They employed an extended Kalman filter to combine the data obtained from the IMU. Although the method was tested on a small sample size, it demonstrated a strong correlation of 96% when compared to a piezoelectric belt used as a reference. The piezoelectric belt reflects the activity of respiratory muscles during the breathing cycle by measuring variations in length or tension.

Mucchi et al. (2021) introduced a tele-monitoring system for managing chronic diseases, addressing the need for remote monitoring and telemedicine. They propose an ICT architecture model targeting Family and Community Nurses (FCNs) and emphasize the importance of efficient patient follow-up. The system monitors clinical parameters, physical activity, and therapy compliance. The article presents the system requirements, network architecture, and service platform components for monitoring. Security and privacy considerations are also discussed. User interface design is highlighted, and preliminary evaluation results show the system's effectiveness in supporting nursing staff.

2.2.2 Early Detection, Prevention and Monitoring

This category includes articles that discuss real-time monitoring and detection techniques for various medical conditions such as falls, cardiac anomalies, and Parkinson's disease. These articles focus on developing monitoring systems that can detect and alert caregivers or medical professionals when a patient's health status changes, allowing for early intervention and improved outcomes. Real-time monitoring and detection systems can also help reduce the burden on healthcare professionals by automating some of the monitoring tasks.

The proposed WBAN system for patient monitoring in healthcare was introduced by H. Hassan et al. (2018). The system incorporates a range of sensors to measure patient parameters. The results demonstrate the system's high performance and its ability to operate effectively in various environmental conditions. By utilizing wireless communication, the system enables enhanced device mobility and cost reduction through the transmission of multiple parameters via a single node. This system grants physicians convenient access to patient information, offering potential improvements in patient monitoring and healthcare services.

The paper of Darwaish et al. (2019) presents a system for detecting and predicting cardiac anomalies using ECG data. It utilizes machine learning techniques, such as the Discrete Wavelet Transform and Bayesian Network Classifier, to analyse and classify recorded heartbeats into four categories: Normal Beat, Premature Ventricular Contraction, Premature Atrial Contraction, and Myocardial Infarction. The system achieves high accuracy rates for each category. The research emphasizes the importance of early detection and remote monitoring of cardiac anomalies using wearable devices and ECG sensors. The proposed system offers an automated solution for interpreting ECG data and improving healthcare services. Yundra et al. (2019) proposed a real-time heartbeats detection system called HEBEDES using a pulse sensor connected to a wireless body area network (WBAN) and a hybrid monitoring system. The system design allows access to heartbeats data via smartphones, SMS, and the internet. The accuracy of HEBEDES was confirmed by comparing its measurements to manual measurements using stethoscope and oximeter. The system was tested on six subjects with different physical conditions, and the results showed that the HEBEDES measurements had an error rate smaller than 2% and a value difference of only 0.02%.

The study was conducted by Grym et al. (2019) aimed to evaluate the feasibility and acceptability of using a smart wristband to collect continuous activity, sleep, and heart rate data from the beginning of the second trimester until one month post-partum in nulliparous women. The daily use of the devices was similar during the second and third trimesters, but decreased during the post-partum period. Problems with charging and synchronizing, discomfort, unreliable data, and fear of scratching babies were the main reasons for not using the smart wristbands.

Srinivasa and Pandian (2019) developed a wearable physiological monitoring system that utilizes a Wireless Body Area Network (WBAN) to measure various physiological parameters. The WBAN is composed of three sensor nodes and a sink node worn on the chest/wrist that sends data to a remote monitoring station for processing. The system was tested on 34 subjects and was found to be reliable and repeatable in measuring heart rate, body temperature, GSR, and blood pressure. Further research and clinical evaluations are needed to ensure its accuracy in everyday use.

An ECG patch monitor, developed by Charrad et al. (2020), is a device designed to collect and analyse cardiac data for patients with heart disease in real-world environments. Its primary objective is to prevent heart attacks and heart failure through the implementation of a real-time anomaly detection algorithm. Remotely controlled by the healthcare centre, the device enables doctors to call patients in emergencies, remotely perform electroshocks or drug injections, and locate the patient to dispatch an ambulance. However, the maintenance of the patch poses certain challenges that must be considered, including daily checkups, battery recharging, and medication expiration.

Cesareo et al. (2020) proposed a wearable device based on IMU to monitor breathing frequency continuously outside the clinical setting. It consists of two IMU units placed on the thorax and abdomen and a third unit as a reference for body/trunk motion. The device communicates via Bluetooth with a smartphone and uploads data on a web server for remote monitoring. The system has shown good reliability and accuracy in measuring breathing frequency during static conditions and slight indoor activities.

Mahmoud et al. (2020) developed a system that can detect and predict cardiac anomalies, with a specific focus on myocardial infarction (MI), premature atrial contraction (PAC), and premature ventricular contraction (PVC). The system can collect real-time ECG data using wireless body sensors in a wireless body area network (WBAN) environment. The research has four main components: ECG signal preprocessing, feature extraction, cardiac anomaly prediction, and false alarm removal for anomaly verification.

The research work of Jafer et al. (2020) describes the design process of a wireless body area network (WBAN) for remotely observing physiological signals from a patient. The WBAN includes various sensors, and Zigbee mesh topology was used to connect the RF units wirelessly. The WBAN architecture can be useful for remote patient care, and pilot trials were performed to evaluate its performance. The observed heart rate information was compared with other heart rate monitors, and the relationship between false alarms and missed detection was discussed.

El-Rashidy et al. (2020) proposed framework for remote monitoring and management of COVID-19 using IoT technology. The framework includes a patient layer, cloud layer, and hospital layer. The patient layer includes wearable sensors and a mobile app to track patients in real-time. In the cloud layer, a fog network architecture is proposed to solve issues of storage and data transmission, and in the hospital layer, a deep learning model is proposed for COVID-19 detection based on patient X-ray scan images. The proposed framework shows promising results compared to the state-of-the-art, with an accuracy of 97.95% and specificity of 98.85%. However, limitations include the accuracy of initial score-based identification, power consumption of wireless sensors, and the complexity of using fog nodes.

In the field of epilepsy detection, M. M. Khan et al. (2020) developed a wireless sensor network-based system that detects seizures and determines the patient's location, sending an alert to hospital staff or family members. Meanwhile, S. Hassan et al. (2022) focused on monitoring and preventing symptoms of Grand mal epilepsy Tonic-Clonic (GTC) seizure using various sensors such as Electrocardiogram (ECG), Electromyography (EMG), accelerometer 3-axes, and Dallas sensor for body temperature signals.

Kumar et al. (2021) developed a system which detects abnormal skin and dynamically adapts to the changing conditions of the skin by creating an energy-efficient data aggregation tree that covers the affected area while putting unnecessary sensors to sleep mode. The proposed system promotes telemedicine long-term data collection and has the potential to promote data-driven healthcare research and development. Further research is needed to explore the system's performance over a diverse set of skin conditions, the impact of a lossy environment on the performance, and the integration of a drug delivery system.

Preventing child mortality from pneumonia and other respiratory illnesses is crucial to achieving the UN's Sustainable Development Goals (SDGs). Non-ventilator hospital-acquired pneumonia (NV-HAP) is a severe but preventable cause of morbidity and mortality in hospitalized patients, but is not commonly tracked or avoided. A wireless sensor network (WSN) has been developed by Abubeker and Baskar (2022) to track VOCs and other atmospheric characteristics in real time to prevent the spread of NV-HAP.

Soundararajan et al. (2022) proposed an Optimal Health Support and Parkinson's Disease Analysis System (OHPAS) system that uses a deeply trained biosensors network environment to analyse PD symptoms. It offers a real-time patient monitoring environment, effective sensor data reduction, distributed sensor data analysis, day-wise PD symptom prediction, reactive PD alerts, and accurate early detection solutions. However, the proposed work has platform-level difficulties and product-level limitations that should be improved in the future.

2.2.3 Physical Activity Monitoring

This category includes articles that discuss various methods and technologies for monitoring physical activity levels in patients. This can be useful for tracking the progress of physical therapy, managing chronic conditions, or promoting healthy lifestyle choices. Physical activity monitoring can also help prevent falls and other accidents by identifying patients who may be at risk due to physical inactivity or other factors.

The paper of Msayib et al. (2017) describes an automatic system that monitors knee flexion in a domestic environment for patients recovering from total knee arthroplasty. The system consists of two small units that record knee flexion data during prescribed exercises and transmit the data to a secure hospital-based server through the internet via the GSM mobile network. The system eliminates the need for patients to attend outpatient clinics and allows for remote monitoring of their progress. Clinical trials are soon to be initiated, and the authors suggest that the system could be used for other orthopaedic procedures if its effectiveness is validated.

Mohammed et al. (2018) discuss the global rise in obesity and its associated health complications and costs. They review techniques for measuring obesity and body fat percentage and analyse current mobile applications and Wireless Body Area Networks designed to monitor physical activity and eating habits. The paper proposes an intelligent architecture that considers both physiological and cognitive aspects to reduce obesity and overweight. The authors suggest creating collaborative wireless networks and ensuring data security.

2.2.4 Elderly Care and Safety Monitoring

This category includes articles that focus on the safety and wellbeing of elderly patients, especially those who live independently or in long-term care facilities. These articles discuss various safety monitoring systems and technologies that can be used to ensure that elderly patients are safe and well-cared for, even when they are alone. Telemedicine is one of the technologies discussed in this category that can be used to remotely monitor elderly patients and provide timely intervention when necessary.

Singh et al. (2017) propose an enhanced fall detection system for elderly people using smart sensors worn on the body and operating through consumer home networks. By utilizing information from an accelerometer, cardio tachometer, and smart sensors, the system can successfully detect accidental falls and distinguish them from normal daily activities. The system is low cost, effective, and productive, but further development is required before it can be used in various applications. The authors suggest developing a Windows application that can support the wearable device, which should be small, unobtrusive, and in the form of a compact watch that does not label people.

Ajerla et al. (2019) develop a real-time fall detection system for patients that utilizes various body positions, including the wrist. The system communicates with an Internet of Things (IoT) device through Bluetooth Low Energy (BLE) and an analytical engine based on the Long Short-Term Memory (LSTM) model. The results indicate that combining waist and wrist positions yielded an online efficiency of 95.8%. However, the researchers did not discuss the energy consumption of the system.

Latha et al. (2020) propose the use of wireless body area networks (WBANs) for emergency conditions and Bayes' theorem for predicting such emergencies. The likelihood evidence is used to determine the probability of sending emergency messages. The paper analyses diagnosis conditions such as emergency monitoring, delay-sensitive monitoring, and general monitoring with network characteristics including data rate, cost, packet loss rate, latency, and jitter. The network model consists of 16 variables, including immediate consultation and observations related to latency, cost, packet loss rate, data rate, and jitter.
Table 2.1 provides a synthesized overview of the collected articles according to various factors including (Target Application, topology, technology, sensor, and category).

Table 2.1: Summarized of the Reviewed WBANs Monitoring System

Reference	Target Application	Topology	Technology	Sensor	Category
C. Li et al. (2017)	Cardiac monitoring system	/		SPO2	Chronic Condition Monitoring
Huzooree et al. (2017)	Real-Time Diabetes Monitoring	Scatter net, Star, Mesh	Bluetooth, Zigbee, IEEE 802.11, Wi-Fi, GPRS	glucose, Blood pressure, pulse oximeter, weighing scale, cardiovascular, thermometer	
Ferreira et al. (2017)	bioimpedance system for ubiquitous body	/	Bluetooth	Bioimpedance	
Gogate and Bakal (2018)	Cardiac Monitoring System	/	Wi-Fi	temperature, SPO2, heart rate, pulse rate, ECG	
Borzì et al. (2019)	Home monitoring for Parkinson's disease	/	Bluetooth low energy (BLE)	ECG, PPG, and IP	
Ng et al. (2019)	Electromyography monitoring system	/	Wire	Capacitive electromyography (CEMG)	
VK (2020)	Real-Time Monitoring For Palliative Patients	Star	TMAC, Zigbee MAC, SMAC	Heart rate, blood pressure	
Amine et al. (2020)	Glucose Monitoring System	Star	4G, Wi-Fi	Glucose sensor, a motion sensor and a temperature sensor	
Hernandez and Cretu (2020)	Real-time monitoring system for sleep	/	Bluetooth low energy (BLE)	ECG, accelerometer, Gyroscope, Magnetometer	
Mucchi et al. (2021)	Real-time Tele-Monitoring for Chronic Diseases	/	3G/4G/5G, WiFi, SigFox, LPWAN	blood pressure, pulse oximeter, ECG, temperature, air quality, humidity	
H. Hassan et al. (2018)	Patient Monitoring System	/	Bluetooth	Temperature, SpO2, blood pressure, ECG	Early detection, prevention and monitoring
Darwaish et al. (2019)	Cardiac Anomalies detection and prediction	Star	Bluetooth	ECG	
Yundra et al. (2019)	Hybrid Heart Detection Monitoring System	/	Bluetooth	Pulse sensor	
Grym et al. (2019)	smart wristbands for pregnancy monitoring	/	/	Act-Traker, distance, calories, heart-rate, stairs climbed, Act-intensity, sleep	
Srinivasa and Pandian (2019)	Remote Signal Monitoring System	Star	Zigbee	ECG, EEG, PPG and GSR	
Charrad et al. (2020)	Remote monitoring for heart attack assessment	/	GPRS, GSM, GPS	ECG patch	
Cesareo et al. (2020)	Long-term breathing frequency monitoring	Star	Bluetooth low energy (BLE)	ECG, PPG, and IP	
Mahmoud et al. (2020)	A real-time framework for monitoring systems	Star	LoRa	Temperature, SPO2, blood pressure	
Jafer et al. (2020)	Remote Observation of Physiological Signals	mesh	Zigbee	Heart-rate, temperature, ECG, accelerometer	
El-Rashidy et al. (2020)	Framework for Coronavirus Monitoring	Star	LoRa	Temperature, heart-rate, respiratory, SPO2, pressure	
M. M. Khan et al. (2020)	Epileptic Seizure Detector	/	Wi-Fi, GSM	Pulse meter, gyroscope sensor, accelerometer	
Kumar et al. (2021)	Skin-Health Monitoring system	Tree		Skin sensors	
S. Hassan et al. (2022)	Epileptic monitoring system	Star	Wi-Fi, Bluetooth	ECG, EMG, temperature, accelerometer	
Abubeker and Baskar (2022)	Monitoring of hospital-acquired pneumonia	/	IEEE 802.15.6	Infrared, temperature, PPG	
Soundararajan et al. (2022)	Real-Time Analyzing of Parkinson's Disease	/	Bluetooth	Accelerometer, gyro, ECG, and EMG	
Msayib et al. (2017)	Remote Monitoring for Knee Arthroplasty	P2P	GSM	flexion angle	Physical Activity Monitoring
Mohammed et al. (2018)	WBANs for Controlling Obesity	Star	GPRS, 3G, 4G,Wi-Fi	Chest strap, band, pedometer, pressure, patch	
Singh et al. (2017)	Safety Alert System for Elders	Star	Bluetooth, GSM	Accelerometer, cardio tachometer	Elderly Care and Safety Monitoring
Ajerla et al. (2019)	A Real-Time Monitoring for Fall Detection	/	Bluetooth	MetaMotionR	
Latha et al. (2020)	Telemedicine for Emergency Care	/	Wire	Non-invasive sensors	

In summary, the reviewed papers demonstrate the potential of various monitoring techniques and technologies in improving patient outcomes, reducing hospital readmissions, and lowering healthcare costs. Wearable sensors, wireless body area networks, and real-time monitoring and detection systems are some of the tools that have been developed to monitor and manage medical conditions. The accuracy and effectiveness of these systems have been demonstrated through experimental results, and they have the potential to automate monitoring tasks and provide timely intervention when necessary. However, challenges such as maintenance, accuracy in everyday use, and the need for further research and clinical evaluations remain. Nevertheless, the potential of these technologies in transforming healthcare services is promising.

Based on a synthetic study and categorization of numerous research, it is evident that there is a considerable demand for research and advancements in the field of maternal and reproductive health. This need becomes even more pronounced when considering the persisting challenges and disparities that pregnant women and new mothers continue to face.

According to the World Bank, the maternal mortality ratio in Algeria has improved from 161 in 2000 to 112 in 2017 World Health Organization et al. (2023). However, it is still higher than the regional average. The country has a maternal mortality ratio of 112 women per 100,000 live births due to pregnancy-related causes. The maternal mortality ratio is calculated by determining the number of women who die from pregnancy-related causes while pregnant or within 42 days of pregnancy termination per 100,000 live births Macrotrends (2023). Despite the improvements, many women in Algeria do not receive the care they need during and after pregnancy. Among women aged 15-49 in Algeria, around one million give birth each year. Of these women, approximately 320,000 receive fewer than four antenatal care visits, 16,000 do not deliver in a health facility, 39,000 do not receive the care they need following a major obstetric complication, and 10,000 have newborns that do not receive the necessary care for complications. These statistics highlight the need for continued efforts to improve maternal healthcare in Algeria. Sully et al. (2020)

2.3 A Detailed Overview of Pregnancy Monitoring Systems

In recent years, there has been a growing interest in utilizing wireless body area network technology for healthcare applications. One potential use case is for pregnant women with high-risk pregnancies who require intensive monitoring of both maternal and fetal vital signs. In order to explore the potential of WBANs in improving maternal and fetal health outcomes, a systematic review of relevant works in this field was conducted. The following Table 2.2 presents a summary of the identified WBANs studies for pregnancy monitoring.

Table 2.2: WBANs Studies for Pregnancy Monitoring

Reference	Target App	Topology	Technology	Sensor	Classification
Santhi et al. (2016)	Maternal Healthcare Monitoring System	Star	Bluetooth, Wi-Fi	Infant heart-beat, blood glucose, haemoglobin, temperature, pressure, ECG	Maternal monitoring
S. Gayathri et al. (2018)	Pregnant Women Health Care Monitoring System	Star	Wi-Fi	Temperature, Heart beat, Memes	
Allahem and Sampalli (2020)	Monitor Pregnant Women with a Premature Labour	Star	Wire	Sensor to monitor uterine electrohysterography (EHG)	
Sene et al. (2021)	Real-Time Monitoring of Pregnant Women	Star	802.15.4e	Blood pressure, Blood glucose, Blood type, Oxygen saturation, Temperature, Pulse	

Table 2.2 WBANs Studies for Pregnancy Monitoring

Reference	Target App	Topology	Technology	Sensor	Classification
Priyanka et al. (2021)	Pregnancy Women Health Monitoring System	Star	Wi-Fi	Heart beat, Temperature, accelerometer, Blood pressure	
Wang et al. (2019)	Remote fetal monitoring system	Star	GPRS, Bluetooth, Wi-Fi	SpO2, temperature, pressure	Fetal Monitoring
Ginting et al. (2019)	Fetal heart detection	P2P	Wi-Fi	Sensor heart rate	
Ryu et al. (2021)	Pregnancy monitoring	Star	Bluetooth Low Energy	chest, limb, abdominal	

Wireless Body Area Networks (WBANs) have emerged as a promising technology for monitoring the health of pregnant women and their fetuses. Researchers have conducted numerous studies in this area, which can be broadly categorized into maternal monitoring and fetal monitoring.

2.3.1 Maternal Monitoring

Maternal monitoring focuses on the health of the mother during pregnancy, including the monitoring of vital signs such as blood pressure, heart rate, and body temperature. WBANs can also be used to monitor maternal activity levels, sleep patterns, and stress levels. This information can help healthcare professionals identify potential health risks and intervene as necessary.

Santhi et al. (2016) propose a system that can monitor vital signs, nutrition, and other data in real-time, alerting healthcare providers to any abnormalities. The proposed system was tested using simulated and real-time protocols, and the results showed that the real-time protocol was more efficient in terms of end-to-end delay, throughput, and energy consumption.

S. Gayathri et al. (2018) also propose a wireless sensor network and IoT-based system that provides real-time data on the health of the mother and fetus, which can be viewed securely through a web page with user authentication. The ultimate goal is to create an intelligent system that can take actions and make decisions based on the data collected, minimizing the need for human interaction and increasing convenience for the end user.

Ginting et al. (2019) present a new technology for detecting fetal heart conditions using wide area network technology. The monitoring system called DOFAT sends medical data to families and healthcare centres in real-time and filters out noises, but can still detect critical information such as R-peaks with an average accuracy of around 94%.

Allahem and Sampalli (2020) discuss the global issue of premature birth and propose a framework to monitor pregnant women with a high risk of premature birth using a wireless body sensor (WBS) and a smartphone. The system monitors uterine electrohysterography (EHG) contractions and aims to detect premature labour patterns and send a warning to the pregnant woman.

Sene et al. (2021) propose a protocol called T4PW that uses biosensors and Wireless Body Area Networks (WBANs) based on the 802.15.4e TSCH standard to remotely monitor pregnant women during pregnancy and childbirth. The biosensors measure physiological parameters and the data is transmitted to a coordinator who collects and analyses it. The protocol includes a classification system based on thresholds for each biosensor to determine the health status of the pregnant woman. The experimental results demonstrate that the proposed watermarking method is robust against multiple image attacks and has satisfactory imperceptibility for real applications.

2.3.2 Fetal Monitoring

Fetal monitoring involves monitoring the health and development of the fetus. WBANs can be used to measure fetal heart rate, movement, and even oxygen levels. This information can help detect fetal distress or abnormalities and prompt medical intervention.

Wang et al. (2019) analyse the effect of remote fetal monitoring on women in late pregnancy. 160 pregnant women were randomly divided into an experimental and control group, with 80 cases in each group. The experimental group engaged in remote fetal monitoring, while the control group adopted traditional cardiac monitoring. The study found that the incidence of neonatal abnormal non-stress tests in the experimental group was significantly higher than in the control group, indicating that remote fetal monitoring could detect abnormalities earlier. The use of the Kalman filter and audio repair algorithms to preprocess collected data improved the accuracy of the data acquisition.

Priyanka et al. (2021) propose a system that uses accelerometer sensors to measure fetal kicks and other sensors to monitor the mother's blood pressure, heartbeat rate, and temperature. The data is transmitted via IoT and displayed on a mobile phone application for remote monitoring by healthcare professionals. The proposed system is cost-effective and preferred for home monitoring, unlike ultrasound scanning, which is expensive and has limitations. Additionally, the authors propose a smartphone application for automatic monitoring of a pregnant woman's well-being and fetal activity.

Ryu et al. (2021) have developed an integrated monitoring platform using flexible electronics and wireless connectivity to monitor the vital signs of pregnant women and fetuses. The system includes three sensors: a chest sensor, a limb sensor, and an abdominal sensor. The sensors integrate commercially available components and are designed to be mass-produced.

2.3.3 Discussion of Challenges

The implementation of WBANs technology in pregnancy monitoring systems faces many challenges. While there are solutions available to address some of them, others may remain unsolvable or context-specific. It is important to acknowledge and understand these challenges in order to effectively overcome them in the practical use of WBANs for pregnancy monitoring.

2.3.3.1 Topology and Energy

Network topology poses notable challenges in ensuring effective communication and reliable monitoring of pregnant women. Factors such as body postural movements, limited transmission range, energy restrictions, and diverse sensor nodes require careful consideration in designing the network topology. Mobility and frequent postural changes of pregnant women demand adaptive network architectures, while limited transmission range necessitates proximity to the base station or gateway Santhi et al. (2016).

2.3.3.2 Reliability of Network

Ensuring a reliable network is crucial in pregnancy monitoring systems to facilitate uninterrupted functioning and timely delivery of monitoring data. Achieving a long stability period and load balancing among sensor nodes are key considerations. The reliability of the network is vital for detecting vital signs and providing timely medical intervention during pregnancy monitoring. Santhi et al. (2016); Wang et al. (2019); Ginting et al. (2019); Ryu et al. (2021)

2.3.3.3 Privacy and Security

Privacy and security are significant concerns in pregnancy monitoring systems, considering the collection of sensitive personal information. Addressing these concerns is essential to protect patient confidentiality and prevent unauthorized access or tampering with healthcare information. Allahem and Sampalli (2020); Sene et al. (2021); Ginting et al. (2019); Ryu et al. (2021)

2.3.3.4 Scalability

Scalability is an essential aspect of pregnancy monitoring systems, allowing for the seamless addition or removal of devices without major changes to the network structure or operations.

Scalability is essential in healthcare settings where the number of monitored patients may vary, necessitating a network capable of handling varying levels of demand. Santhi et al. (2016); Wang et al. (2019)

2.3.3.5 Power Consumption

Efficient power consumption is a critical concern in pregnancy monitoring systems. Minimizing energy consumption during data transmission, processing, and communication among sensor nodes is necessary. Energy-efficient protocols and algorithms can optimize power usage and extend the overall network lifetime, improving the sustainability and effectiveness of pregnancy monitoring systems. Santhi et al. (2016); Wang et al. (2019)

2.3.3.6 Usability and Interoperability

Usability and interoperability are crucial considerations in pregnancy monitoring systems. User-friendly designs that can be easily set up by medical staff without extensive technical expertise are important. Seamless integration of sensors into the network, without disrupting daily routines, is crucial for user acceptance and convenience. Ensuring interoperability across multiple frequency bands and physical layers enables seamless communication between different devices and systems. Wang et al. (2019)

2.3.3.7 Signal Quality and Interference

Signal quality and interference pose significant challenges in pregnancy monitoring systems. Techniques such as advanced signal processing algorithms, adaptive filtering, and robust modulation schemes are necessary to improve signal quality and mitigate the effects of interference. Additionally, addressing interference from external sources, such as electromagnetic radiation and other wireless devices, is important for accurate and reliable monitoring of vital signs during pregnancy Sene et al. (2021); Wang et al. (2019)

2.4 Conclusion

In this chapter, a comprehensive overview of medical monitoring systems is presented. The recent advancements and progressions in WBAN technology are highlighted through the classification of numerous research papers into distinct categories. Additionally, a systematic review is conducted to examine relevant works on wireless body area networks for pregnancy monitoring. This review identifies several studies that explore the potential of WBANs in enhancing maternal and fetal health outcomes. Moreover, a comprehensive discussion addresses the challenges associated with implementing WBANs in this field.

In the following chapter, the focus will shift towards pregnancy monitoring, addressing the potential complications that can occur during pregnancy and the role of WBAN technology in their detection and prevention. A WBAN-based monitoring system specifically tailored for pregnant women will be proposed. Additionally, several scenarios will be provided to evaluate the proposed system's effectiveness and usability.

Chapter 3

Towards a Hybrid WBAN System for Pregnancy Monitoring

3.1 Introduction

Ensuring the health and well-being of women during pregnancy and childbirth is crucial for both the mother and her baby. However, despite advancements in healthcare, avoidable deaths related to pregnancy and childbirth are still a global issue, with approximately 800 women dying every day according to the UNFPA. Thus, monitoring maternal and fetal health throughout pregnancy is of utmost importance. To this end, many wearable sensors and devices have been developed to collect data related to the mother and the fetus, with the aim of reducing pregnancy-related risks.

In this chapter, a medical background on pregnancy is provided, covering the different stages of pregnancy and potential complications that can occur. Furthermore, a WBAN-based pregnancy monitoring system is then proposed and designed to observe the health and well-being of pregnant women and their unborn babies in hospital and home settings. The key components of the WBAN system are conceived and described in detail, highlighting their integration with existing technologies and medical practices. Accordingly, various scenarios are to be discussed to demonstrate the practical application of the introduced WBAN system in several monitoring situations.

3.2 Medical Background

3.2.1 Pregnancy

Pregnancy is when a woman carries a developing embryo or fetus within her body. It lasts about nine months and is divided into three trimesters. Davis (2022) The first trimester is a critical period for fetal development, and any harm during this period can result in serious disability or miscarriage. Physical and emotional changes occur throughout the pregnancy, including morning sickness, breast soreness, and moodiness. The second trimester is marked by distinct physical developments, and premature birth during this time has a chance of survival. The third trimester is when the fetus prepares for birth and the mother experiences discomfort and swelling. Pregnancy ends when the birth process begins. Huffman (2023) In Figure 3.1, all stages of pregnancy in each month are presented.

Figure 3.1: Stages of Pregnancy: Month-By-Month

3.2.2 Stages of Fetal Development

The process of fetal development is a well-organized and complex sequence that starts before a woman realizes she is pregnant and concludes with the birth of her baby. From conception to delivery, multiple detailed production steps are involved. Specifically, three main stages are distinguished, namely germinal, embryonic, and fetal. In the following, more details about each stage are provided.

3.2.2.1 Germinal Stage

The germinal stage is the first and shortest stage of human development, lasting approximately eight to nine days. It begins with fertilization, which occurs in the fallopian tube when a sperm fertilizes an egg, forming a zygote. The zygote then undergoes rapid cell division through a process called cleavage, forming a solid ball of cells called a morula. The morula then develops into a blastocyst as shown in Figure 3.2, a hollow ball of cells with an inner cell mass that will eventually become the embryo and an outer layer of cells that will form the placenta and other embryonic tissues. Finally, the blastocyst implants in the endometrium of the uterus, triggering the beginning of the embryonic stage of development. During the germinal stage, the developing organism obtains nutrients from the cell cytoplasm and secretions in the fallopian tube and uterus before obtaining nutrients from the mother's blood via the placenta. Clinic (2023); Cherry (2023)

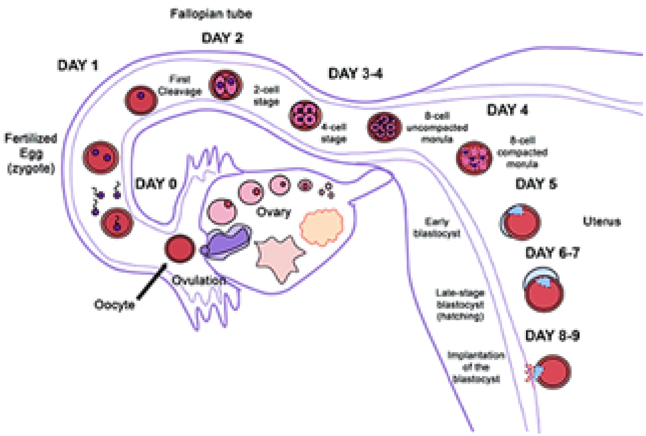


Figure 3.2: The Germinal Stage Foundation (2023)

3.2.2.2 Embryonic Stage

The embryonic stage is the second stage of prenatal development that begins after implantation of the blastocyst and lasts until the end of the eighth week of gestation, as illustrated in Figure 3.3. During this stage, the embryo undergoes rapid and significant growth, as well as the formation of all major organs and structures. The cells of the embryo continuously undergo mitosis, and distinct cell layers begin to form. The embryo undergoes gastrulation, which forms the three germ layers (the ectoderm, mesoderm, and endoderm) and the primitive gut. Neurulation also occurs during this stage, which is the formation of the nervous system. Organs begin to develop within the newly formed germ layers, with the heart being the first functional organ. The embryonic stage is essential for laying the groundwork for all the remaining stages of life. Clinic (2023); Cherry (2023)

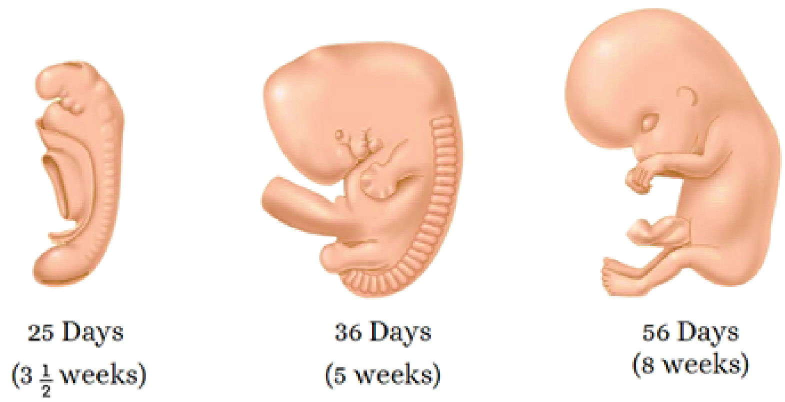


Figure 3.3: The Embryonic Stage Soffar (2021)

3.2.2.3 Fetal Stage

The fetal stage of development is the third stage of prenatal development, starting from the ninth week after fertilization and continuing until birth. During this stage, the embryo officially becomes a fetus, and its major organs and body systems continue to grow and mature. The fetus's weight and length increase significantly during this period. The fetal stage is characterized by the development of the major body organs, bones, sensory nerves, muscles, and reproductive organs. At the end of the fetal stage as shown in Figure 3.4, the fetus is ready to be born. Clinic (2023); Cherry (2023)

Figure 3.4: The Fetal stage Staff (2022)

3.2.3 Complications of Pregnancy

While pregnancy is generally a healthy process, certain women may experience health issues that can involve the mother's health, the fetus's health, or both. Such complications can cause the pregnancy to become high-risk, even if the woman was healthy prior to conception. While most pregnancies are uncomplicated, a range of complications may occur. Some of the most prevalent pregnancy complications that may arise throughout each trimester are outlined in

Table 3.1 indicating their causes and symptoms Gaillard et al. (2013); Newfield (2012); Birth Injury Help Center (2021); Cleveland Clinic (2022).

Table 3.1: Pregnancy Complications by Trimester

Trimester	**Complication**	**Causes**	**Symptoms**
First Trimester	Spontaneous Abortion	- Chromosomal abnormalities - Endocrine causes - Uncontrolled diabetes - Abnormal placental implantation.	- Lower abdominal cramps - Vaginal bleeding - Uterine contractions - Nausea or vomiting.
	Hyperemesis Gravid arum	- Rising hormone levels, specifically hCG	- Feeling nearly constant nausea - Losing appetite - Vomiting frequently - Becoming dehydrated - Feeling light-headed or dizzy
	Ectopic Pregnancy	- Inflammation and scarring of the fallopian tubes - Hormonal factors (hCG levels) - Genetic abnormalities - Birth defects	- Lower abdomen pain - A sudden onset of cramping - Severe abdominal pain - Vaginal bleeding - Increased urinary frequency - Multiple missed periods - A fever
Second Trimester	Late Miscarriages	- Issues with placenta - Cervical weakness	- Bleeding from the vagina - Strong, cramping pain - Waters break - Baby's movements have changed or not felt for a while

Table 3.1: Pregnancy Complications by Trimester

Trimester	Complication	Causes	Symptoms
	Preterm Labwe	- Bladder infection - Smoking - Chronic health condition	- Vaginal pressure - Low back pain - Frequent urination - Diarrhoea - Increased vaginal discharge - painful contractions
	Cervical incompetence	- A previous cervical trauma - A cervical cone biopsy - Other operation on the cervix	- vaginal bleeding or discharge
Third Trimester	Preeclampsia	- Genetic factors - Blood vessel problems - Autoimmune disorders	- Persistent headache - Upper abdominal pain - Unusual swelling in hands and face - Sudden weight gain - Nausea or vomiting - Shortness of breath
	Gestational diabetes	- Human placental lactogen (hPL) - Other hormones that increase insulin resistance	- Fatigue - Blurred vision - Excessive thirst - Excessive need to urinate - Yeast infections
	Placental abruption	- Advanced maternal age - Cocaine use - Diabetes - Heavy alcohol use - High blood pressure - Pregnancy with multiples	- Heavy vaginal bleeding - Severe stomach pain - Strong contractions

3.3 Proposed System

Pregnant women with high-risk pregnancies often need to be hospitalized for longer periods due to potential pregnancy-related complications. In 2020, approximately 287,000 women died from complications during pregnancy and childbirth, as per a World Health Organization (WHO) study World Health Organization (2023). Traditional maternal and childcare equipment is bulky and cumbersome. Furthermore, data transmission through cables can make them anxious, and the cable length can restrict their movements, thereby impacting the quality of monitoring.

Developing countries struggle to provide adequate healthcare to their population as they fall below the WHO's minimum threshold for the required number of doctors, midwives, and nurses per population World Health Organization (2017). Additionally, there are significant disparities in the distribution of healthcare staff between different regions. Health structures in these countries also lack adequate technical platforms, and staff members often have limited expertise and skills to diagnose and treat medical conditions properly. This deficit of healthcare workers causes several issues, especially for pregnant women, who have to travel long distances to receive medical care. The challenges mentioned earlier, make it difficult for pregnant women to follow the WHO recommendations of consulting their health providers at least 8 times during pregnancy World Health Organization (2016) to identify and manage potential problems and reduce the risk of maternal and neonatal death.

To provide a solution to the problems mentioned above and ensure continuous real-time monitoring of pregnant women (during pregnancy period and during childbirth), a hybrid wireless body area network system is proposed for monitoring pregnancy, facilitating early detection and intervention of potential complications. This approach aims to minimize the risks associated with maternal and neonatal mortality.

3.3.1 General Architecture

The proposed system architecture seamlessly integrates wearable sensors attached to pregnant women, whether they are at home or hospitalized, as shown in Figure 3.5 to provide continuous and comprehensive monitoring of their health. At home, pregnant women are fitted with wearable sensors that collect vital health data, which is then wirelessly transmitted to a smartphone and subsequently to the hospital's central monitoring unit. This unit serves as the receiver and Handler of real-time acquired data, enabling healthcare professionals to remotely monitor and analyse the health status of pregnant women from any location. Similarly, in the hospital, pregnant women also wear sensors that transmit their health parameters wirelessly to coordinators within each room. These coordinators possess wireless communication capabilities and send the data to the central monitoring unit within the hospital. By interconnecting the wearable sensors and the central monitoring unit through a secure wireless network, the architecture ensures the timely transmission of data for informed decision-making. On the other hand, in the central monitoring unit, the collected data is received, stored, and managed. Data analysis is performed to detect any anomalies or deviations from normal health parameters. In the event of complications or critical conditions, alerts and notifications are generated and communicated to the healthcare provider and family members, enabling proactive measures to be taken promptly. By integrating both home-based and hospital-based monitoring, the central monitoring unit enables continuous and comprehensive care for pregnant women, empowering healthcare providers to monitor their health status in real-time, regardless of their location, and facilitating timely interventions based on observed complications or critical events.

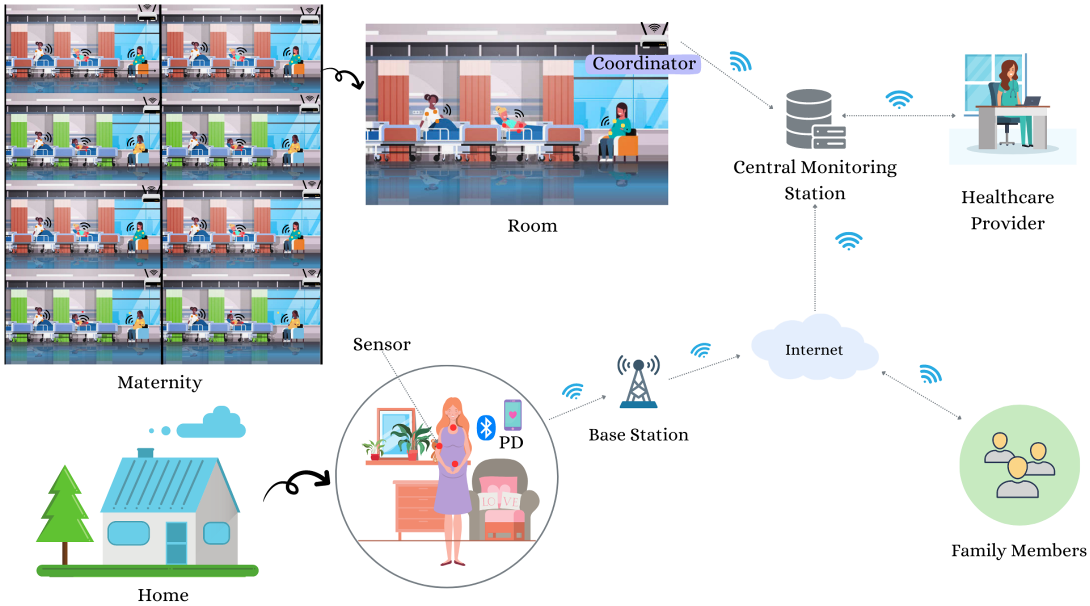


Figure 3.5: General Architecture of the Proposed System

3.3.2 Data Acquisition

The data acquisition part is primarily composed of sensors worn by patients, as shown in Figure 3.5. And the selection of sensing devices in this monitoring system is based on two issues: which parameters need to be monitored and what stage of pregnancy the women are in. For instance, in early pregnancy, it may be necessary to monitor parameters such as hormone levels and implantation bleeding. However, in the remaining stages of pregnancy, fetal movements and uterine contractions may be more critical parameters to monitor.

To address this objective, A series of interviews were conducted with midwives at Bachir Ben Nacer Hospital in Biskra to gather comprehensive insights into the complications requiring hospitalizations during pregnancy and the interventions implemented by midwives to effectively manage them. The aim of this study was to elucidate the specific complications encountered in each trimester and identify the types of sensors utilized in each case, thereby assisting in the selection of suitable monitoring techniques. By investigating these aspects, this research contributes to the understanding of obstetric care practices and informs effective approaches to managing complications during pregnancy.

In addition to the medical requirements, practical considerations such as the usability of sensors for everyday people and various moving conditions must also be considered. The selected sensors need to be easy to use and not interfere with the normal activities of the patients while still providing accurate data.

In the pregnancy monitoring system, a collection of sensors has been considered to comprehensively track and monitor various aspects of maternal and fetal health. The selected sensors include temperature sensors, heart rate sensors, glucose sensors, blood pressure sensors, and SpO2 sensors. These sensors play a crucial role in monitoring the basic vital signs and ensuring overall well-being during pregnancy. Furthermore, advanced sensors particularly designed for pregnancy monitoring have been integrated. These sensors include cervical dilation, beta-hCG, fetal movement, and abdominal sensors. The sensors used in to conceive the proposed system are listed in Table 3.2.

1. **Cervix Dilation**

   This sensor is designed for continuous monitoring of cervical dilation in pregnant women approaching labour and delivery. The sensor is attached to the cervix and consists of an electro-mechanical device encased in a plastic tube. The sensor stretches as the cervix dilates, and an active circuit or tag wirelessly transmits the diameter of the cervix to a transponder worn by the pregnant woman, which can then transmit the data to a remote data-processing agency in contact with the pregnant woman, her doctor, and hospital Verma et al. (2009). The design of this sensor is depicted in a schematic diagram shown in Figure 3.6.

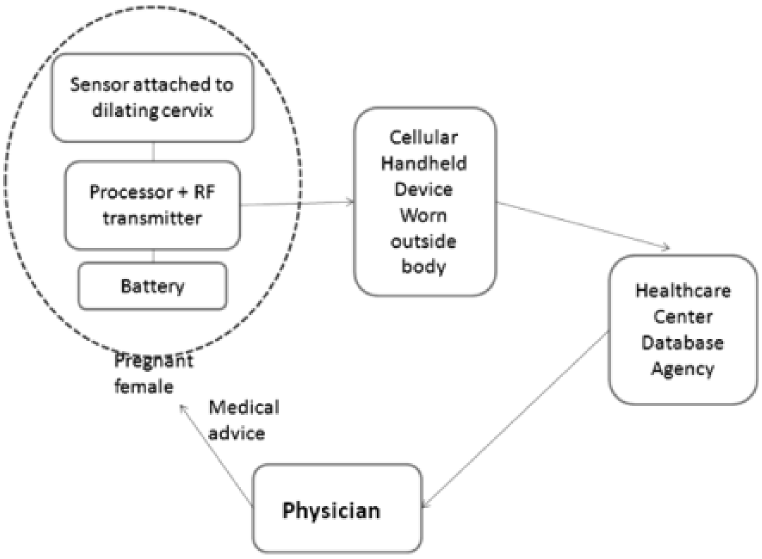


Figure 3.6: A Schematic Diagram for Monitoring Cervical Dilation. The arrows represent wireless RF links Verma et al. (2009)

2. **Beta-hCG**

   The sensor is developed for monitoring beta-hCG hormone levels, which can aid in early risk evaluation of ectopic pregnancy. The biosensor uses an electric-double-layer FET sensor and has advantages such as high sensitivity, low cost, and ease of use. The sensor is fabricated using photolithography and surface functionalization techniques and is capable of detecting proteins in high ionic strength solutions without pretreatment. The biosensor is validated using fluorescence confirmation and quantitative analysis software. The portable prototype device is connected to a computer screen to display measurement results, which can be obtained in 5 minutes by dropping a urine sample on the sensor surface. Liao et al. (2021)

3. **Fetal Movement**

   IMU sensors, including accelerometers, gyroscopes, and magnetometers, were used in the study Du et al. (2021) to detect fetal movement signals from the pregnant woman's abdomen. These sensors measured acceleration, angular velocity, and changes in the magnetic field to capture various aspects of fetal movements. Placed at each corner of a triangular shape, the IMU sensors allowed for comprehensive monitoring of fetal movement parameters such as position, duration, and relative force. IMU sensors are widely employed in diverse applications due to their accuracy and real-time motion-tracking capabilities, making them a non-invasive and practical choice for monitoring fetal movements. The device design is shown in Figure 3.7.

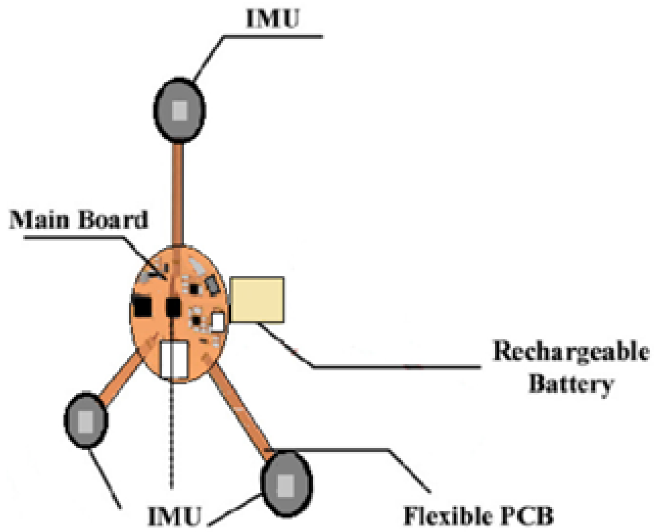


Figure 3.7: The Wearable Design Proposed to Monitor Fetal Movements Alim and Imtiaz (2023)

4. **Abdominal Sensor**

   A wireless abdominal sensor represented in Figure 3.8 was developed to measure and track Fetal Heart Rate (FHR) and uterine contractions. This sensor generates ultrasound waveforms and identifies distinct peaks that correspond to the closure of fetal heart valves, allowing for the calculation of FHR. It can also capture incidental fetal Electrocardiography (ECG) signals. Comparisons with gold-standard Doppler ultrasound systems demonstrated a strong agreement in FHR measurements. Furthermore, the sensor utilizes Electromyography (EMG) capabilities to derive uterine contractions. When compared to a gold-standard tocodynamometer, the sensor exhibited comparable performance in detecting contractions. The wireless and flexible nature of the abdominal sensor makes it a promising option for monitoring FHR and uterine contractions during labour Ryu et al. (2021).

Figure 3.8: The Abdominal Sensor Ryu et al. (2021)

Table 3.2: The sensors used in the proposed system

Trimester	**Complication**	**Sensor**	**Unit**	**Normal range**	**Abnormal range**
First Trimester	Ectopic Pregnancy	Blood pressure	mmHg	< 120/80	≥ 140/90 or higher
		Heart rate	Bpm	63.1 - 105.2	> 120 or < 60
		SpO2	%	94.3 - 99.4	< 90%
		Temperature	°C	35.55 - 37.51	> 38 or < 35
		beta-hCG sensor	IU/L	32,000 - 150,000	> 1,500
Second Trimester	Late Abortion	Blood pressure	mmHg	< 120/80	≥ 140/90 or higher
		Heart rate	Bpm	67.4 - 112.5	> 120 or < 60
		SpO2	%	92.9 - 99.3	< 90
		Temperature	°C	35.35 - 37.37	> 38 or < 35
		Fetal movement	kicks	at least 10 times over 2 hours	No fetal movements
		Cervix dilation	cm	closed	1cm
		Abdominal	Bpm, mmHg	none	> < 110 or > 160 and 4 contractions in an hour
Third Trimester	Gestational diabetes	Blood pressure	mmHg	< 120/80	≥ 140/90 mm Hg or higher
		Heart rate	Bpm	64.5 - 113.8	> 120 or < 60
		Temperature	°C	35.37 - 37.35	> 38 or < 35
		SpO2	%	93.4 - 98.5	< 90%
		Glucose	mg/dL	< 140	140 and 199

	Abdominal	Bpm, mmHg	none	< 110 or > 160 and > 8 contractions in an hour

3.3.3 Data Transmission

The proposed healthcare monitoring system for pregnant women utilizes a data transmission process consisting of two sub-processes: data transmission in the hospital setting and data transmission in the home setting to facilitate efficient communication.

3.3.3.1 Data Transmission in the Hospital Setting

Within the confines of the hospital setting, wireless sensors are strategically positioned on pregnant women to capture vital signs data. The collected data is then transmitted wirelessly to a coordinator device through the utilization of Wi-Fi technology. Wi-Fi enables the wireless transmission of large amounts of data from the sensors to the coordinator, as shown in Figure 3.5. The coordinator acts as an intermediary, facilitating the transfer of data from multiple patients to a centralized location, thereby ensuring efficient data aggregation and management. Upon successful reception, the coordinator forwards the collected data using the same technology (Wi-Fi) to the central monitoring unit, which functions as a central hub for data storage and processing. Leveraging advanced algorithms and processing techniques, the central monitoring unit analyses and interprets the collected data, thereby enabling healthcare providers to derive meaningful insights pertaining to patients' health conditions.

3.3.3.2 Data Transmission in the Home Setting

In the home setting, pregnant women wear wireless sensors designed to be compact and comfortable for continuous wear. These sensors capture vital signs data, which is then wirelessly transmitted to a smartphone employing Bluetooth Low Energy (BLE) technology. BLE is chosen for its energy efficiency, compatibility with modern devices, seamless connection establishment, and built-in security features. It enables efficient and low-power transmission of data within a Wireless Body Area Network, allowing continuous collection and transmission of maternal and fetal health data. The smartphone assumes the role of a gateway device, receiving the transmitted data from the sensors and subsequently preparing it for secure transmission to the central monitoring unit. To ensure secure and reliable transmission, the smartphone establishes a cellular connection utilizing GSM or GPRS technology. This choice of technology guarantees widespread coverage and dependable data transmission, thereby enabling patients residing in remote areas to actively participate in the WBAN system. The GSM or GPRS network provides a robust infrastructure for transmitting the collected data from the home setting to the central monitoring unit, ensuring the seamless flow of information. These technologies provide reliable and cost-effective means to transmit data over long distances.

3.3.4 Data Transmission to Healthcare Providers

Upon successful transmission to the central monitoring unit, the collected data from both the hospital and home settings is made available to healthcare providers. These healthcare providers can access the data through secure interfaces and specialized software applications. The data is presented in a structured manner, allowing healthcare providers to review and analyse it in real-time. The timely transmission of data to healthcare providers enables them to monitor patients' health status, detect abnormalities, and make informed decisions regarding necessary interventions or treatments.

3.4 Proposed Monitoring Scenarios

As described in the above sections, the proposed system can be divided into two main parts, depending on whether pregnant women are being monitored within the hospital or remotely at home. Subsequently, more specific details about the functioning scenarios for each end are provided in the following subsections.

3.4.1 Hospital-Based Pregnancy Monitoring

To study and evaluate the functionality of the proposed monitoring system in the hospital end, three main scenarios are considered, taking into account the behaviour of the deployed sensors along with their corresponding coordinators.

3.4.1.1 First scenario: Centralized data processing

In a maternity service setting, a system is deployed to monitor the pregnancy state of women using a WBAN. The first scenario operates as follows:

- Sensors are strategically positioned to collect data from pregnant women, capturing relevant information about their pregnancy state.
- Once the data is collected, it is transmitted directly to a designated coordinator present within the same room.

- The coordinator collects and accumulates the received data from all the sensors, ensuring the synchronization of updates.
- Subsequently, the coordinator transmits the collected data to a central monitoring unit, which is responsible for further processing and analysis.
- The central monitoring unit processes the data using various algorithms, techniques, and medical guidelines specific to monitoring pregnancy states.
- Upon processing, the central monitoring unit generates insights, trends, and relevant information derived from the collected data.
- Finally, the processed data, along with the generated insights, is transmitted to healthcare providers who utilize the information for monitoring the pregnancy state and making informed decisions regarding necessary medical care.

This scenario allows for efficient data collection, centralized coordination, and real-time monitoring of pregnant women's pregnancy states. By leveraging the central monitoring unit's processing capabilities, healthcare providers can receive timely and accurate information, leading to enhanced care and support for pregnant women throughout their maternity journey. Figure 3.9 illustrates the principle of the proposed scenario. Furthermore, Algorithm 1 summarizes the main steps conducted to make this first scenario function.

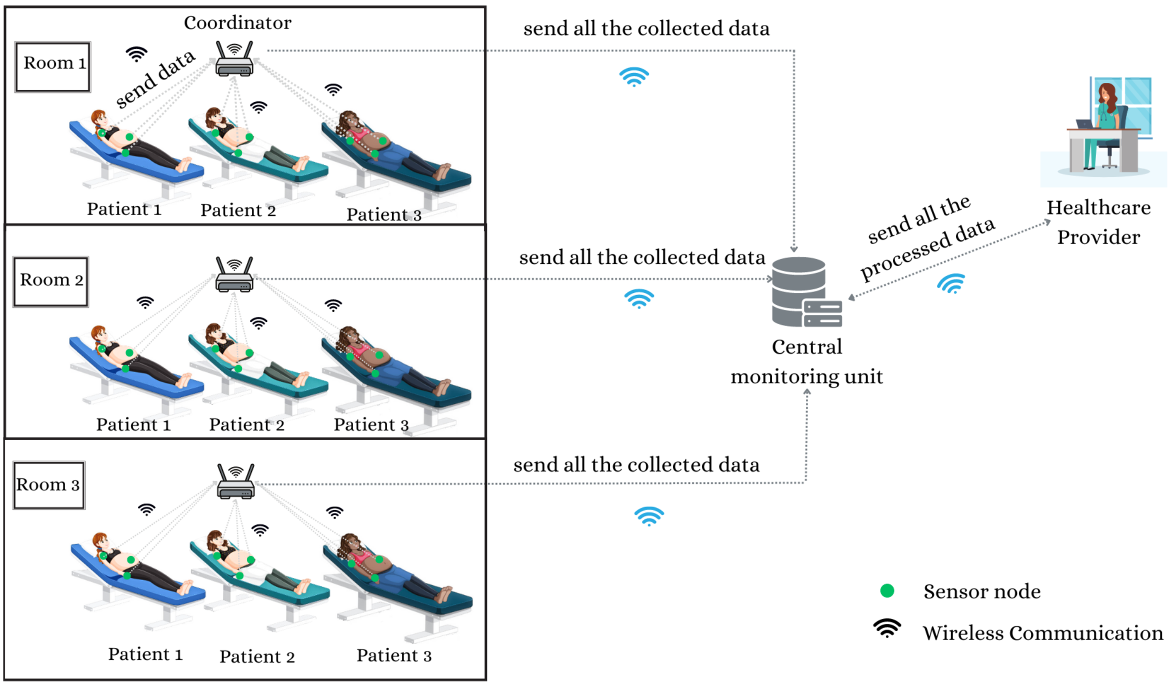


Figure 3.9: Centralized Data Processing in the First Scenario

Algorithm 1: Scenario 1

```
for each sensor in sensors do
    data = collectDataFromSensor(sensor)
    transmitDataToCoordinator(data)
end
coordinatorData = initializeEmptyArray()
while len(coordinatorData) < len(sensors) do
    receivedData = receiveDataFromSensor(); coordinatorData.append(receivedData);
end
transmitDataToCentralMonitoringUnit(coordinatorData);
processedData = processPregnancyData(coordinatorData);
transmitDataToHealthcareProviders(processedData);
```

3.4.1.2 Second scenario: Semi-Centralized data processing

Following the same above WBAN-based deployment, here are the essential operations ensured in the second proposed scenario:

- Sensors are strategically positioned to collect data from pregnant women, capturing relevant information about their pregnancy state.
- Once the data is collected, it is transmitted directly to a designated coordinator within the same room. The coordinator serves as a central hub for data management and coordination.
- The coordinator stores the collected data until an abnormal reading is detected by at least one sensor.
- When an abnormal reading is detected, the coordinator triggers an immediate action. It sends all the stored data, including the abnormal reading, to a central monitoring unit for further processing and analysis. Afterward, the coordinator resets its state to prepare for new data.
- The central monitoring unit receives the data from the coordinator and processes it using various algorithms, techniques, and medical guidelines specific to monitoring pregnancy states.
- Upon processing, the central monitoring unit generates insights, trends, and relevant information derived from the collected data.

- The processed data, along with the generated insights, is then transmitted to healthcare providers who utilize this information to monitor the pregnancy state and make informed decisions regarding appropriate actions and medical care.

- The coordinator operates on a periodic range for sending data to the central monitoring unit. However, in the event of an abnormal case being detected, all the stored data is sent immediately, even if the periodic range has not been reached. This ensures timely communication of critical information for prompt interventions and support.

This scenario enables efficient data collection, proactive detection of abnormal readings, centralized coordination, and real-time monitoring of pregnant women's pregnancy states. By leveraging the central monitoring unit and timely communication, healthcare providers can access accurate and up-to-date information to provide comprehensive care and ensure the well-being of pregnant women. Figure 3.10 illustrates the proposed scenario. Besides, the above steps are further explained and summarized in Algorithm 2.

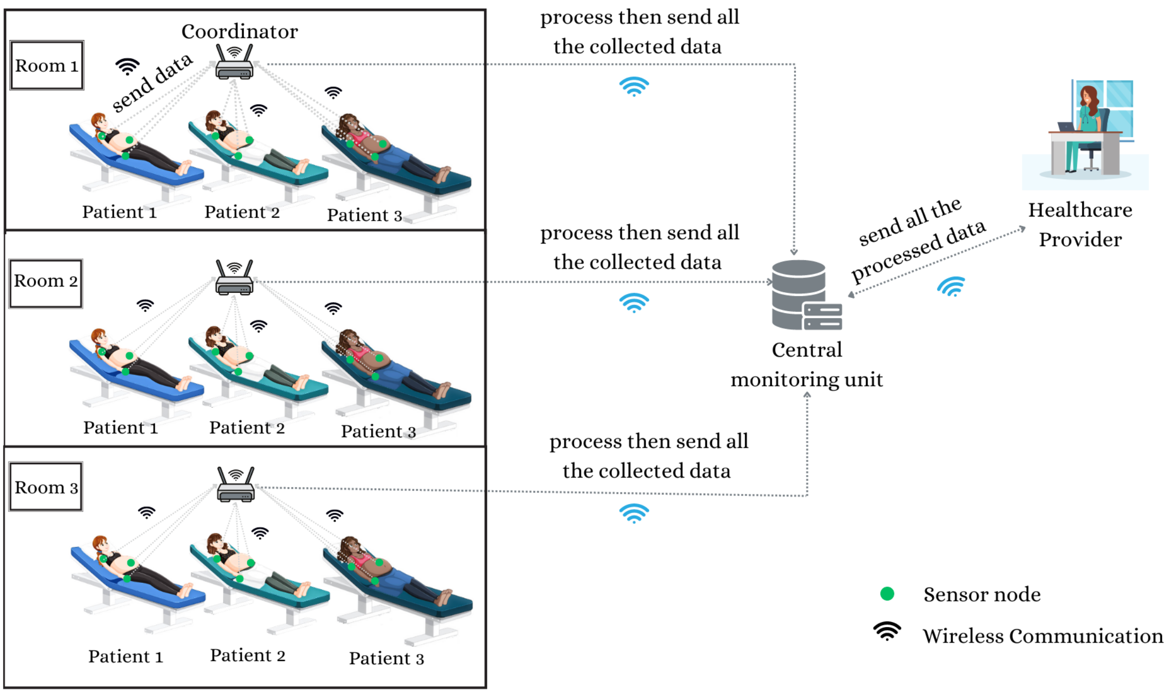


Figure 3.10: Semi-Centralized Data Processing in the Second Scenario

Algorithm 2: Scenario 2

```
for each sensor in sensors do
    data = collectDataFromSensor(sensor);
    transmitDataToCoordinator(data);
end
collectedData = initializeEmptyArray();
while true do
    for each receivedData in receiveDataFromSensors() do
        collectedData.append(receivedData);
        if isAbnormalReading(receivedData) then
            sendDataToCentralMonitoringUnit(collectedData);
            collectedData = initializeEmptyArray();
        end
    end
end
processDataFromCoordinator();
transmitDataToHealthcareProviders();
while true do
    if isPeriodicRangeReached() then
        sendDataToCentralMonitoringUnit(collectedData);
        collectedData = initializeEmptyArray();
    end
end
```

3.4.1.3 Third scenario: Decentralized data processing

In a maternity service setting, a system is deployed to monitor the pregnancy state of women using a WBAN. The third scenario operates as follows:

- Sensors are deployed to collect data from pregnant women, capturing relevant information about their pregnancy state.
- Each sensor independently processes the collected data in parallel, utilizing simultaneous processing capabilities.
- The processed data is stored within the sensors until a specific threshold is reached, signifying that a sufficient amount of data has been accumulated.
- Once the threshold is met, the sensors transmit the collected data to a designated coordinator responsible for managing the data flow.

- In the event of detecting abnormal values within the collected data, the sensors proactively send the entire history of the collected data to the coordinator, regardless of whether the threshold has been reached.
- The coordinator receives and gathers the transmitted data from all the sensors, ensuring synchronization of updates.
- Following the receipt of updates from all the sensors, the coordinator proceeds to verify the integrity and identify any abnormal cases within the collected data.
- If abnormalities are detected during the verification process, the coordinator promptly forwards the entire dataset, inclusive of all the collected data, to a central monitoring unit without waiting for updates from the remaining sensors.

This scenario is designed to enable real-time monitoring of the pregnancy state by efficiently collecting and processing data from multiple sensors. The system's ability to detect abnormal values and promptly escalate them to the central monitoring unit ensures timely interventions and enhances the overall care provided to pregnant women in the maternity service. Figure 3.11 illustrates the proposed scenario. Additionally, Algorithm 3 details the functioning principle of the current scenario.

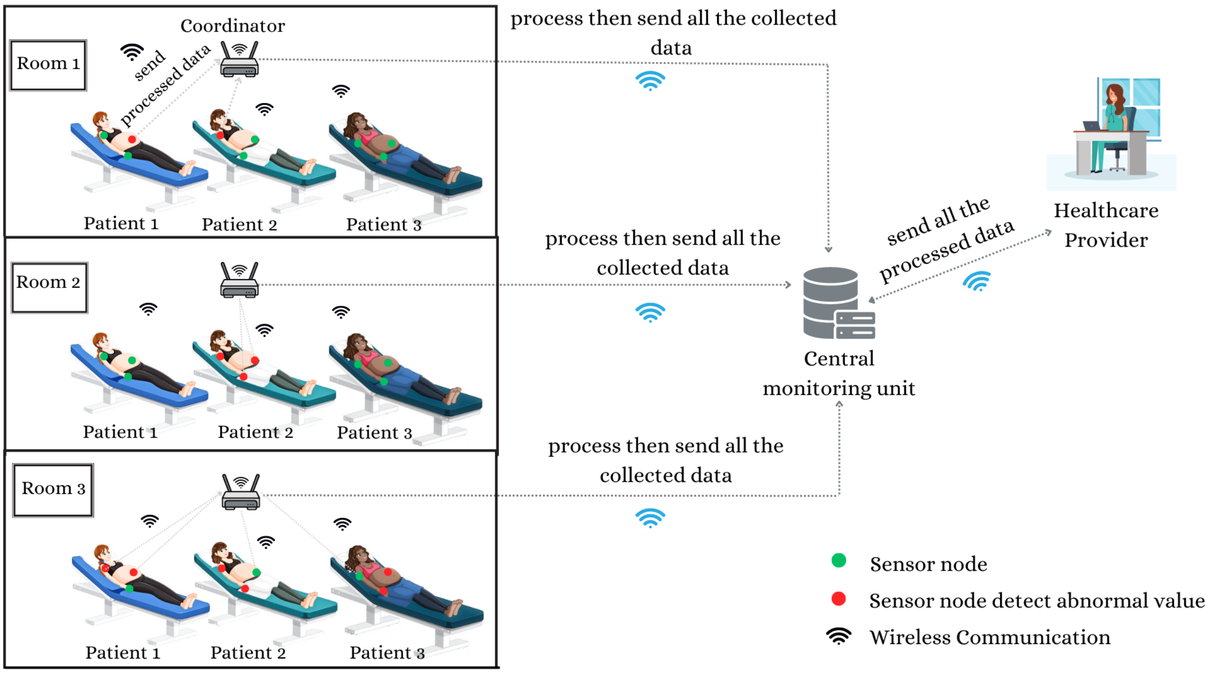


Figure 3.11: Decentralized Data Processing in the Third Scenario

Algorithm 3: Scenario 3

```
sensorData ← initializeEmptyArray();
for each sensor in sensors do
    data ← collectDataFromSensor(sensor);
    sensorData[sensor] ← data;
end
for each sensor in sensors do
    processInParallel(sensorData[sensor]);
end
threshold ← getThreshold();
while true do
    for each sensor in sensors do
        if sensorData[sensor].size() ≥ threshold then
            sendDataToCoordinator(sensorData[sensor]);
            sensorData[sensor].clear();
        end
    end
    for each sensor in sensors do
        if hasAbnormalValues(sensorData[sensor]) then
            sendDataToCoordinator(sensorData[sensor]);
            sensorData[sensor].clear();
        end
    end
    coordinatorData ← initializeEmptyArray();
    while len(coordinatorData) < len(sensors) do
        receivedData ← receiveDataFromSensor();
        coordinatorData.append(receivedData);
    end
    if hasAbnormalCases(coordinatorData) then
        sendDataToCentralMonitoringUnit(coordinatorData);
    end
end
```

3.4.2 Home-Based Pregnancy Monitoring

The wireless pregnancy monitoring system involves attaching sensors to the pregnant woman's body to collect vital signs and health-related data such as blood pressure, heart rate, fetal heart

rate, and uterine contractions. The collected data is then transmitted wirelessly to a personal device at home, which is responsible for aggregating and forwarding the data to the central monitoring unit, as depicted in Figure 3.12.
The personal device acts as a gateway for data transmission between the sensors and the central monitoring unit. It is also responsible for storing and managing the collected data and generating alerts for both healthcare providers and the woman's family members when necessary.
The central monitoring unit serves as the central database for storing and managing the collected data. It analyses the data to detect any potential complications and generates alerts for healthcare providers when necessary. With this system, healthcare providers can remotely monitor the health status of the pregnant woman and take appropriate action when necessary.

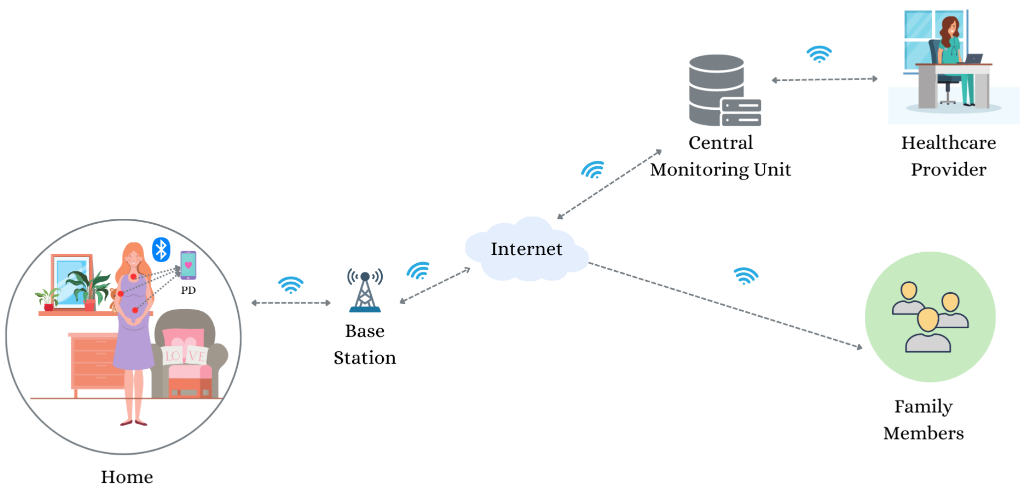


Figure 3.12: Home-Based Pregnancy Monitoring

3.5 Proposed simulation model

A simulation step is essential to study and investigate such critical monitoring systems. Therefore, this section provides more details about how the proposed pregnancy monitoring system's components are conceived and designed.

3.5.1 Sensor Node

This module is composed of 4 sub-modules down the hierarchy which are named as sensing unit, processing unit, communication unit and power unit as shown in Figure 3.13

- The sensing unit within the sensor node is responsible for capturing and measuring various physiological parameters. It detects and collects information. The sensing unit ensures accurate and reliable data acquisition from the pregnant woman's body.

- The processing unit in the sensor node handles the processing and analysis of the data received from the sensing unit. It performs computations, algorithms, and calculations to extract meaningful insights from the raw sensor data. The processing unit ensures that the data is transformed into a format suitable for transmission and further analysis.

- The communication unit within the sensor node facilitates the transmission of data to the appropriate destination. In the case of the hospital setting, the sensor node's communication unit forwards the processed data to the coordinator. The coordinator acts as an intermediate hub, receiving data from multiple sensor nodes and forwarding it to the central monitoring unit located in the hospital. In the home setting, the communication unit sends the processed data directly to the smartphone. The smartphone then serves as a bridge, transmitting the data from the home-based sensor nodes to the central monitoring unit in the hospital.

- The power unit in the sensor node provides the necessary electrical power to sustain the operation of the sensing, processing, and communication units. It not only provides the necessary electrical power, but also keeps track of the energy consumed during various tasks. In terms of energy consumption, communication is the most energy-intensive component, followed by processing, while sensing requires the least amount of energy Itani et al. (2019); Mohen et al. (2012).

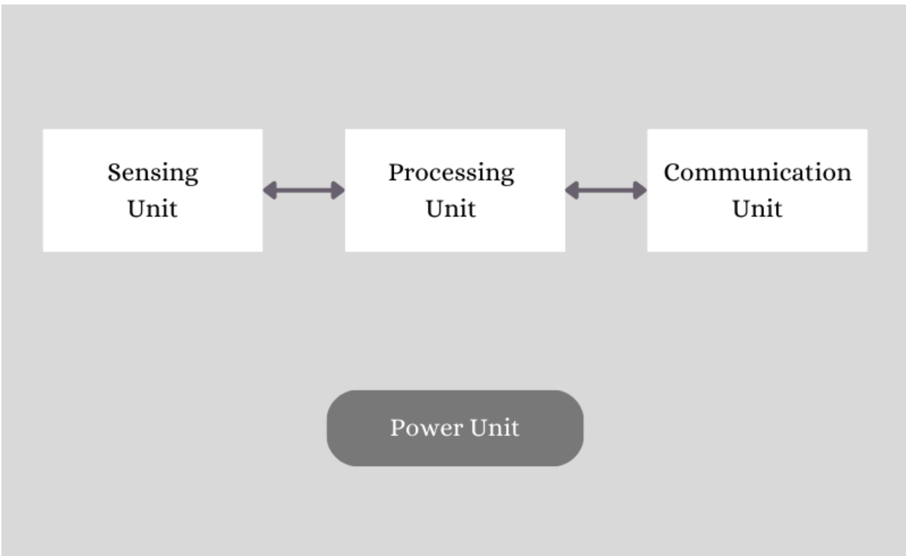


Figure 3.13: Sensor Node Design

3.5.2 Coordinator

The coordinator consists of four layers in a hierarchical structure: the application layer, network layer, MAC layer, and physical layer. Each layer is intricately linked with the layer below it (see Figure 3.14), creating a seamless flow of data transmission from the sensors to the central monitoring station.

- The application layer is closely connected to the network layer. It processes the data received from the sensors and makes decisions based on the specific requirements of each sensor. When data transmission is necessary, the application layer sends messages to the network layer, initiating the process of data encapsulation and routing.
- The network layer acts as the bridge between the application layer and the MAC layer. It encapsulates the data packets received from the application layer, adding source and destination addresses, and then forwards them to the MAC layer for further processing. Conversely, when receiving packets from the MAC layer, the network layer decapsulates them, extracting the data, and passes it to the application layer for analysis.
- The MAC layer is tightly linked with the physical layer. It encapsulates the packets received from the network layer, specifying the appropriate MAC addresses, and sends them to the physical layer for transmission. Upon receiving packets from the physical layer, the MAC layer decapsulates them and hands them over to the network layer for further routing.
- The physical layer is responsible for the actual transmission and reception of data. It establishes the connection between the coordinator and the central monitoring station. When the physical layer receives packets from the MAC layer, it ensures their reliable transmission over the communication medium to the central monitoring unit.

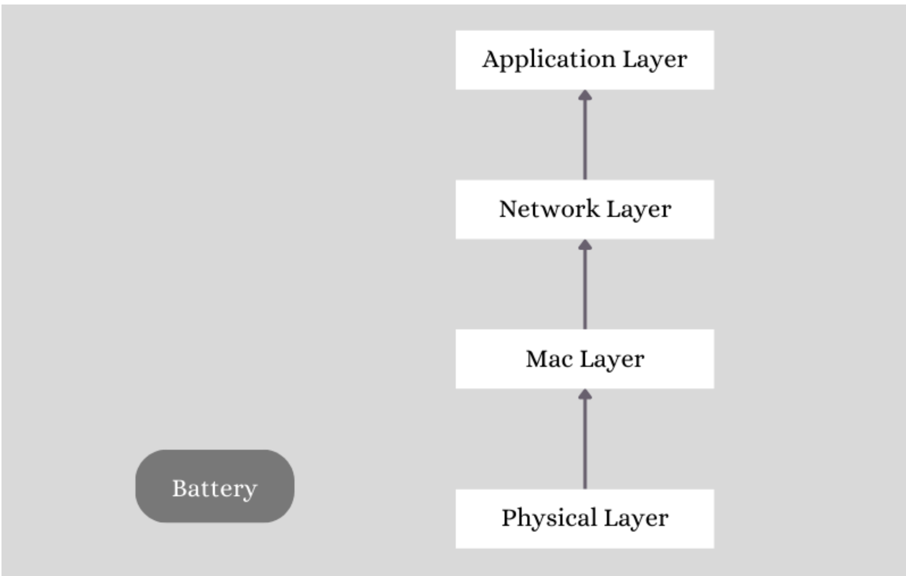


Figure 3.14: Coordinator Design

- Battery usage: Incorporating a battery into the coordinator serves the crucial purpose of ensuring uninterrupted operation of the WBAN system for pregnancy monitoring. In hospital environments, power outages or fluctuations are not uncommon, and relying solely on the hospital's power supply can lead to system disruptions. By equipping the coordinator with a battery, it gains independence from external power sources, enabling it to continue collecting and processing data without interruptions. This setup ensures reliable and continuous monitoring of pregnant women, even in the face of power supply challenges.

3.5.3 Central Monitoring Unit

The central monitoring unit in the pregnancy monitoring system serves as a centralized server, collecting and storing data from various sources. It ensures smooth data transmission, secure storage, and easy accessibility for healthcare providers. It performs tasks such as data integration, analysis, and generating valuable insights. The central monitoring unit functions as a reliable server, offering a centralized platform for healthcare providers to access real-time and historical data. It aids in informed decision-making and effective management of pregnant women's health by providing a secure and efficient communication channel.

3.5.4 The Graphical User Interface

The graphical interface is specifically designed to facilitate efficient interaction between healthcare professionals and the system in a healthcare setting. It aims to provide a comprehensive and easily understandable view of pregnant women's health data, presenting it in both graphical and textual formats. The interface ensures that the information is displayed in a clear and organized manner, enabling healthcare providers to access medical records and make informed decisions regarding patient care. Additionally, the interface includes a feature that allows the system to send SMS notifications to the healthcare provider or the patient's family in emergency situations, ensuring prompt communication during critical events.

3.6 Conclusion

This chapter provides an introduction to the topic of pregnancy and emphasizes potential complications that may arise during this period. A hybrid WBAN system is proposed for monitoring pregnancy, with the aim of early detection and intervention to enhance maternal and fetal health outcomes. The chapter also includes different scenarios of the proposed monitoring system, focusing on the monitoring of various vital signs and parameters.

In the subsequent chapter, these scenarios will be implemented using the OMNeT++ simulator to evaluate the efficiency and effectiveness of the proposed system. Simulation offers a cost-effective and efficient approach to test and refine the system. However, implementing the system in real-life situations presents challenges. Additionally, conducting experiments with pregnant women in real-life poses practical and ethical difficulties due to the sensitive and critical nature of the pregnancy period. Therefore, simulation proves to be a more feasible option.

Chapter 4

Implementation: OMNeT++ Based Simulation

4.1 Introduction

Wireless Body Area Network (WBAN) systems have emerged as a promising technology for monitoring pregnant women, providing continuous healthcare monitoring and improving maternal and fetal health outcomes. These systems utilize miniaturized sensors, strategically placed on or within the body, to collect physiological data and transmit it wirelessly to a central monitoring unit. This allows healthcare professionals to remotely monitor vital parameters, detect abnormalities, and provide timely interventions when necessary.

In this chapter, a comprehensive simulation of a wireless body area network system for monitoring pregnant women is provided using the OMNeT++ simulator. Unlike previous studies that depend on pre-built frameworks, the simulation in this study is developed from scratch, allowing for a detailed exploration of the complexities and challenges associated with designing and implementing an entire WBAN-based system. The simulation takes into account not only the communication aspects but also the behaviour and characteristics of the sensors, with the objective of creating a more realistic and precise representation of the system's performance.

4.2 OMNeT++

"OMNeT++ is an extensible, modular, component-based C++ simulation library and framework, primarily for building network simulators." OMNeT++ Community (2022) The OMNeT++ simulation environment, which has been available to the public since 1997, was initially developed with the aim of simulating communication networks, multiprocessors, and distributed systems. Rather than creating a specialized simulator, OMNeT++ was designed to be highly

versatile and adaptable to various simulation scenarios. Over the years, it has been successfully applied in a wide range of domains, including queuing network simulations, wireless and ad-hoc network simulations, business process simulations, peer-to-peer network simulations, optical switch simulations, and storage area network simulations. Varga (2010)

4.2.1 The Component Model

The OMNeT++ component model consists of four essential components: simple modules, compound modules, connections, and parameters. In the subsequent subsections, A brief introduction to each of these key components is presented. Virdis and Kirsche (2019); Varga and Hornig (2010)

4.2.1.1 Simple Modules and Compound Modules

The OMNeT++ component model includes simple modules and compound modules, as shown in Figure 4.1. Simple modules are implemented in C++ and can represent various entities such as user agents, protocol entities, network devices, or simulation-related functions. Compound modules are formed by grouping and structuring simple modules together, allowing for hierarchical organization. They are commonly used to assemble network nodes. Module types serve as templates and can be used as building blocks without affecting their functionality or usage, enabling easy reuse and modification of modules within a simulation model.

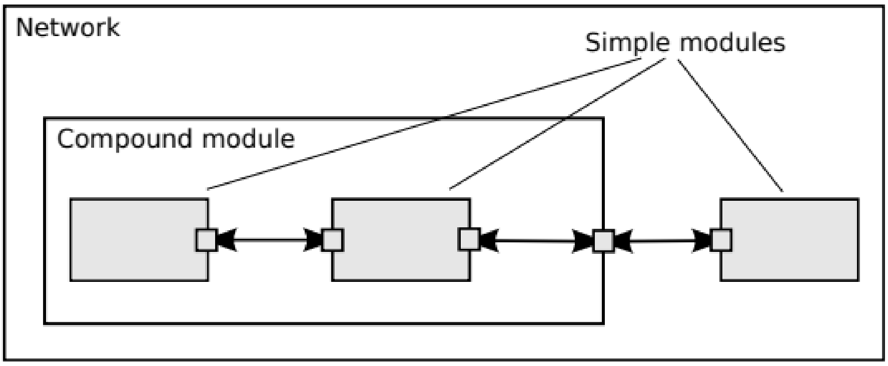


Figure 4.1: Simple and Compound Modules Varga (2019)

4.2.1.2 Connections

In the OMNeT++ component model, modules communicate through messages sent via gates. Gates include input, output, and in, out gates. Connections are established between gates and determine the flow of messages within a compound module. They can link submodules, connect submodules with their parent module, or connect gates within the parent module. Connections are limited to the scope of a compound module to ensure model reuse. Messages travel through chains of connections, with compound modules acting as intermediaries. Connections can have properties assigned to them, such as propagation delay, data rate, and bit error rate. Connection types, known as channels, can be defined with specific properties for reuse within the model.

4.2.1.3 Parameters

Modules in the OMNeT++ component model can have parameters, which serve two purposes: passing configuration data to simple modules and assisting in defining the model topology. Parameters can be of various types, including string, integer, double, boolean, and XML for accessing custom XML-based configuration files. Parameters can have default values, units of measurement, and other attributes. Volatile parameters are re-evaluated each time the simulation code reads them, allowing for dynamic behaviour. They are often used to provide stochastic input to modules. Parameters play a crucial role in configuring modules and enabling customization within the simulation model.

4.2.2 OMNeT++ File Types

An OMNeT++ model consists of the following parts: Varga (2019):

- **NED files (.ned):** NED (Network Description) files are used to define the network topology and module structure of the simulation model. They describe the modules, their parameters, gates, connections, and other properties.

- **Message files (.msg):** Message files are used to define message types and their data fields. Messages are exchanged between modules to communicate information in the simulation.

- **C++ files (.h, .cc):** OMNeT++ allows you to write custom module behaviour in C++. You can create header files (.h) to declare module classes and their methods, and implementation files (.cc) to define the behaviour of the modules.

- **Ini files (.ini):** The omnetpp.ini file is the main configuration file for an OMNeT++ simulation. It specifies global simulation settings and includes other ini files if needed.

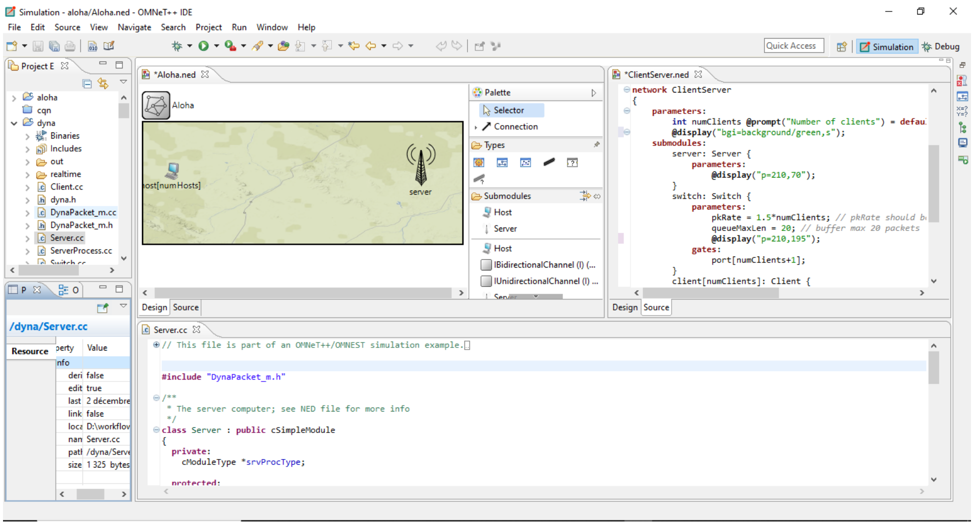


Figure 4.2: OMNET++ Simulator Interface

4.2.3 Advantages of OMNeT++

OMNeT++ offers numerous advantages as a discrete event simulator for network and system modelling. Its design objectives and features contribute to its effectiveness and popularity in academic, educational, and research-oriented environments. The following points highlight some of the key advantages of OMNeT++. Varga (2001); Kabir et al. (2014); A. R. Khan et al. (2012)

- **Hierarchical and Reusable Models:** OMNeT++ supports the development of large-scale simulation models by using a hierarchical structure and reusable components. This allows for efficient and scalable simulations.

- **Visualization and Debugging:** OMNeT++ provides tools and features for visualizing and debugging simulation models. This helps reduce the time spent on debugging and enhances the overall development process. It is particularly beneficial for educational purposes.

- **Modularity and Customization:** The simulation software is designed to be modular and customizable. It allows users to embed simulations into larger applications, such as network planning software. This flexibility enables adaptability to specific requirements and enhances the simulation capabilities.

- **Open Data Interfaces:** OMNeT++ supports open data interfaces, making it compatible with commonly available software tools. It allows for easy generation and processing of input and output files, facilitating integration with external systems.

- **Extensive Simulation Model Library:** Over the years, OMNeT++ has gained a wide range of simulation models developed by various individuals and research groups.

These models cover diverse areas such as wireless networks, sensor networks, IP networks, queuing networks, and more. Users can leverage this library to accelerate their simulation development.

- **Wide Adoption:** OMNeT++ has been successfully adopted by academic institutions, research organizations, and commercial companies like IBM, Intel, Cisco, Thales, and Broadcom. Its proven track record demonstrates its effectiveness and reliability for simulation projects.

4.2.4 Disadvantages of OMNeT++

OMNeT++ is a widely-used simulation tool for modelling communication networks and distributed systems. However, like any software, it has certain limitations that users should be aware of. C. Gayathri and Vadivel (2017); Kabir et al. (2014)

- **Limited Protocol Variety:** OMNeT++ does not offer a wide variety of pre-implemented protocols. Users may need to invest additional effort in implementing specific protocols according to their simulation requirements. This requires users to have significant background knowledge in protocol design and implementation.

- **Incomplete Mobility Extension:** The mobility extension in OMNeT++ is relatively incomplete. Simulating scenarios involving mobile nodes or scenarios requiring extensive mobility support may have limitations. Users may need to customize or develop additional functionalities to address specific mobility-related requirements.

4.3 Hardware and Software Environment

The hardware and software configuration for the simulation is as follows:

Table 4.1: Hardware and Software Configuration

Aspect	**Configuration**
Computer	Dell
Processor	Intel(R) Core™ I3 - 7020U
Processor Speed	Up to 2.30GHz
Memory	8GB
Hard Drive	1TB
Operating System	Windows 10 Pro (64-bit)
Framework	OMNeT++ 4.6

4.4 Installation and Configuration of OMNeT++

1. Download the Windows-specific archive of OMNeT++ from the official website at `https://omnetpp.org`.
2. Choose a directory for installation without any spaces in its path.
3. Copy the downloaded OMNeT++ archive to the chosen installation directory.
4. Extract the contents of the zip file.
5. Open the `omnetpp-4.6` directory and run `mingwenv.cmd` to start the MSYS bash shell.
6. Check the contents of the `configure.user` file in the `omnetpp-4.6` directory.
7. Run the commands as shown in Figure 4.3:

```
$ ./configure
$ make
```

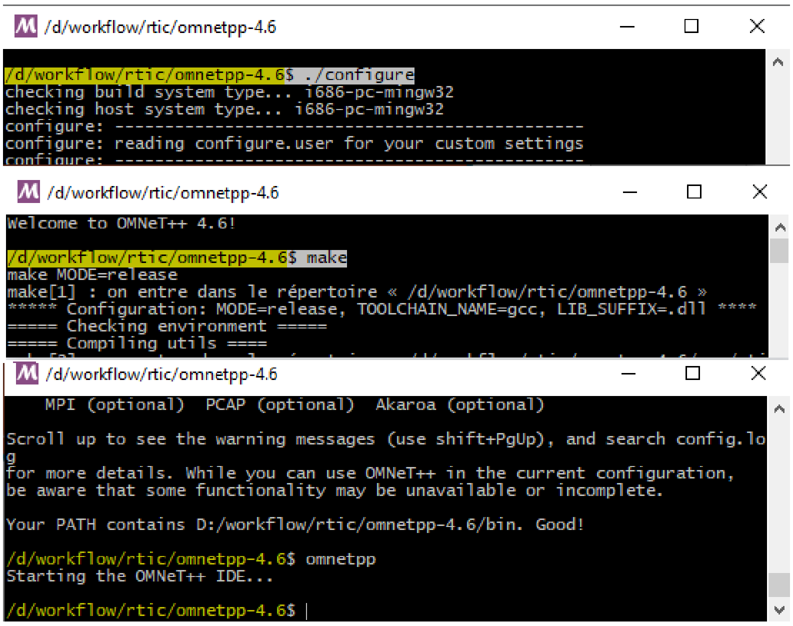


Figure 4.3: Configuring and Building OMNeT++

4.5 Simulation of the Proposed System

4.5.1 The Network

The provided screenshots 4.4, 4.5 depict the Network Description (NED) file representing the network architecture. The network comprises various components, namely a Hospital, Base

Station, Home, and Family Members. In this composition, the Hospital and Home are represented as compound modules, encapsulating multiple functionalities within themselves. On the other hand, the Base Station and Family Members are depicted as simple modules, which likely represent individual entities within the network. Communication among these modules is established, allowing for information exchange and interaction between them.

Figure 4.4: Design Model of Network Architecture

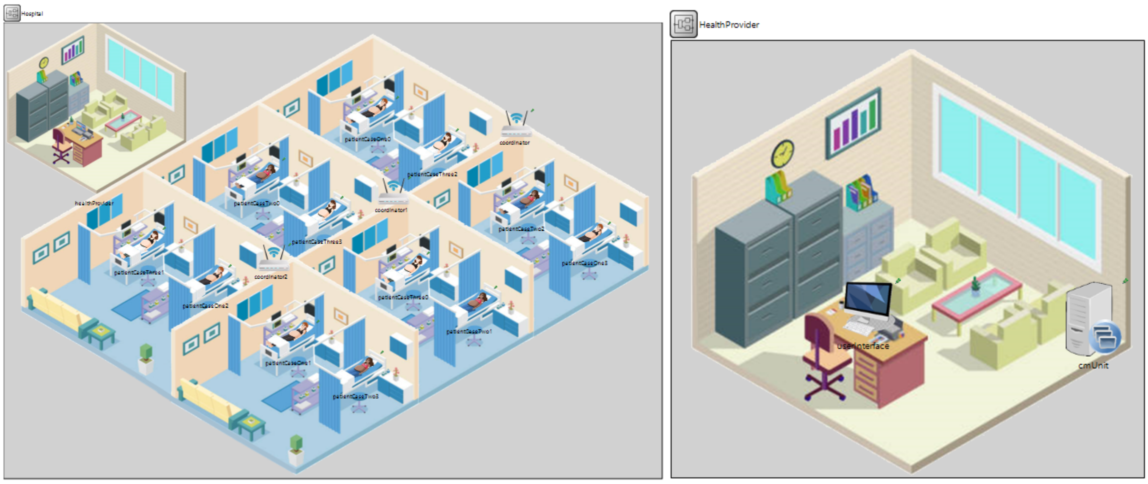
```
package pregnancy_monitoring.simulations;
import pregnancy_monitoring.cmodules.Home;
import pregnancy_monitoring.cmodules.Hospital;
import pregnancy_monitoring.smodules.BaseStation;
import pregnancy_monitoring.smodules.Family;


//
// TODO documentation
//
network Monitoring
{
    @display("bgi=background/EnvGeneral,f;bgb=1305,733");
    submodules:
        hospital: Hospital {
            @display("p=619,85;i=background/Hospital;is=n");
        }
        home: Home {
            @display("p=1065,352;i=background/home;is=n");
        }
        baseStation: BaseStation {
            @display("p=168,108;i=device/antennatower;is=vl");
        }
        family: Family {
            @display("p=512,423;i=background/famly;is=n");
        }
}
```

Figure 4.5: NED File of Network Architecture

4.5.2 Compound Modules

4.5.2.1 Hospital

The provided screenshots showcase the interior of the hospital, specifically highlighting two essential components: the maternity service 4.6a and the health provider room 4.6b where the both are compound modules. These areas can be viewed as separate but interconnected modules within the system.

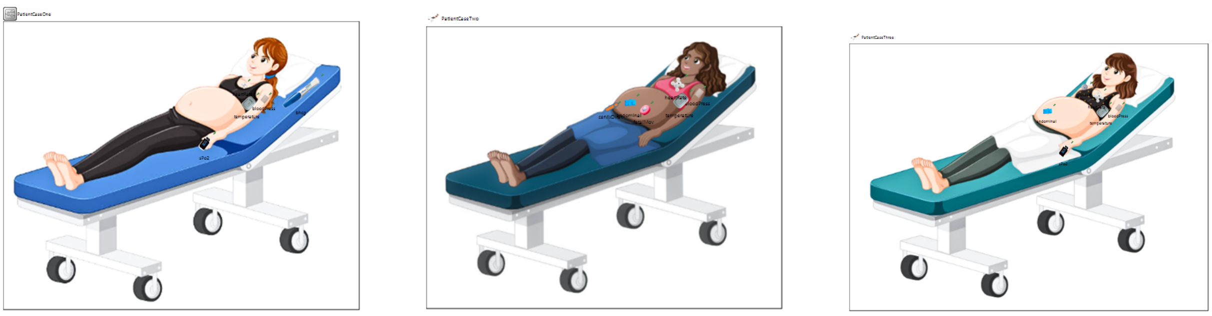


(a) Maternity Service (b) Healthcare Provider Room

Figure 4.6: The Interior of Hospital

4.5.2.2 Maternity Service

The maternity service module consists of multiple individual rooms which are compound module, each occupied by pregnant women wearing sensors and a coordinator. Notably, as highlighted in the previous chapter Table 3.2, the selection process identified three cases characterized by high pregnancy risk, who were specifically chosen to be closely monitored within the system. The different cases are illustrated in Figures 4.7a, 4.7c and 4.7b.

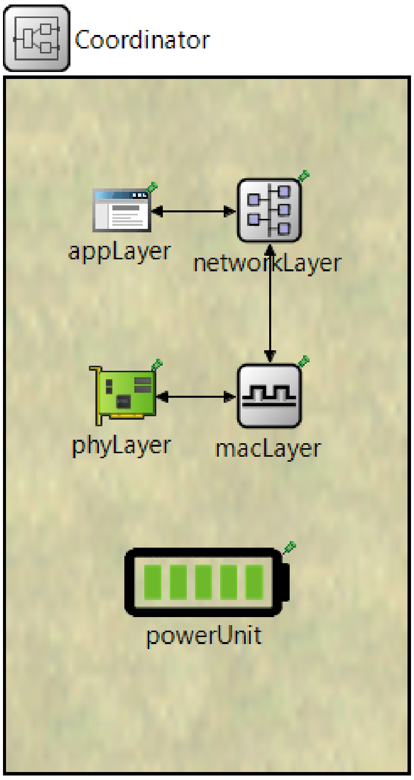


(a) First Trimester (b) Second Trimester (c) Third Trimester

Figure 4.7: The Interior of Room

4.5.2.3 Coordinator

The provided Figures 4.8a and 4.8b, illustrate the NED file design and source code for the coordinator module. These figures correspond to our conceptualization as outlined in 3.14, depicting the inclusion of four distinct submodules within the coordinator. These submodules operate as simple modules within the coordinator, contributing to its functionality at various levels of the communication protocol stack.



(a) Design

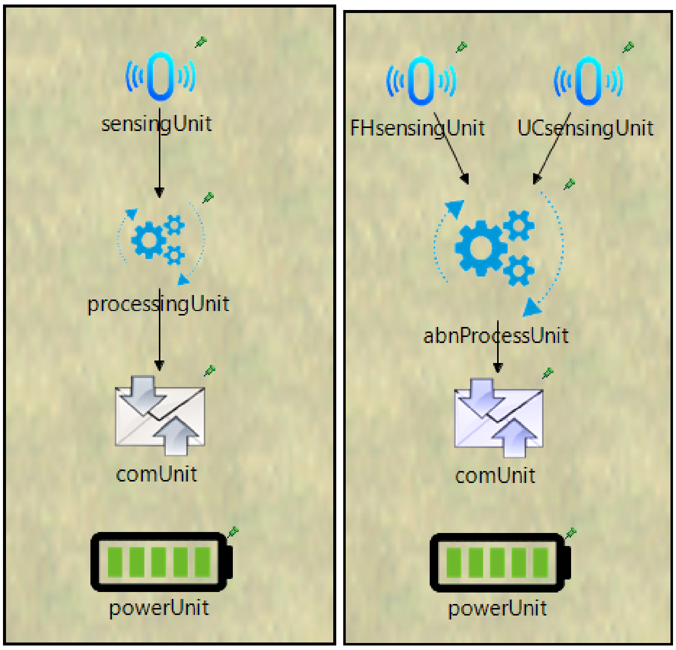
```
module Coordinator
{
    int scenario;
    double nominal @unit(mAh) = default(9000 mAh);//mAh
    double capacity @unit(mAh) = default(9000 mAh);//mAh
    double voltage @unit(V) = default(5V); // volts
    @display("bgi=background/green,s;bgb=207,326");
    submodules:
        phyLayer: PhyLayer {
            @display("p=60,160");
        }
        appLayer: AppLayer {
            @display("p=59,50");
        }
        macLayer: MacLayer {
            @display("p=147,160");
        }
        networkLayer: NetworkLayer {
            @display("p=147,50");
        }
        powerUnit: PowerUnit {
            @display("p=102,264");
        }
    connections:
        appLayer.toLower --> networkLayer.fromUpper;
        networkLayer.toUpper --> appLayer.fromLower;
        networkLayer.toLower --> macLayer.fromUpper;
        macLayer.toUpper --> networkLayer.fromLower;
        macLayer.toLower --> phyLayer.fromUpper;
        phyLayer.toUpper --> macLayer.fromLower;
}
```

(b) Ned File

Figure 4.8: The Coordinator Module

4.5.2.4 Sensor

The overall number of sensors incorporated into the system is ten. Each sensor has been meticulously designed with careful consideration of its specific characteristics and the type of data it is intended to measure. The provided screenshots 4.9a and 4.9b present the implementation of some sensors within our system.

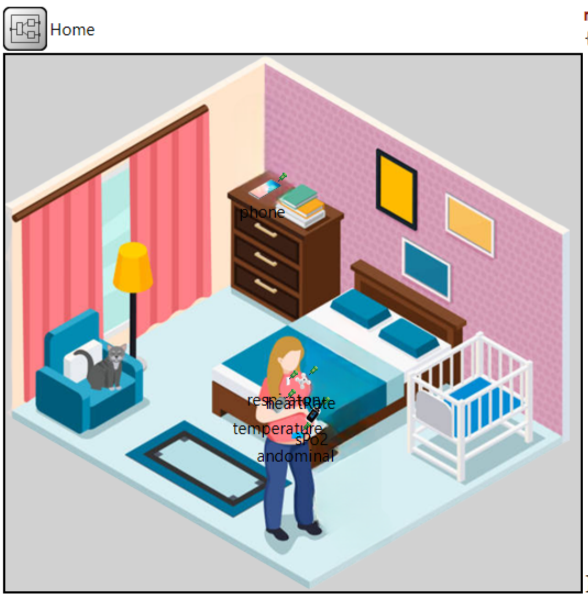


(a) Blood Pressure (b) Abdominal

Figure 4.9: The Sensor Module

4.5.2.5 Home

The provided screenshots depict the interior of the home, where the pregnant woman wears various sensors. These sensors serve as simple modules that collect and transmit data to a smartphone, which also acts as a simple module in the system.



(a) Design

```
module Home
{
    int case = 4;
    int chamber = 0;
    int PID = 0000; //patient ID
    @display("bgi=pics/pregnant_home,f;bgb=523,488");
    submodules:
        phone: Phone {
            @display("p=235,121;i=background/phone;is=s");
        }
        andominal: Andominal {
            @display("p=265,346;is=vs");
        }
        sPo2: SPo2 {
            @display("p=280,327;is=vs");
        }
        respiratory: Respiratory {
            @display("p=256,297;is=vs");
        }
        temperature: Temperature {
            @display("p=249,318;is=vs");
        }
        heartRate: HeartRate {
            @display("p=270,296;is=vs");
        }
}
```

(b) Ned File

Figure 4.10: Te interior of Home Module

4.5.3 Simple Modules

The representation details of all the simple modules utilized in the system, along with their corresponding NED files, have been listed in Table 4.2

Table 4.2: Simple Modules and Corresponding NED Files

<table>
<tr><th>Module</th><th>Ned File</th></tr>
<tr><td> Sensing Unit</td><td><pre>simple SensingUnit
{

    parameters:
    double trafficParam @unit(s);
    double initializationTime @unit(s);
    double endTime @unit(s);

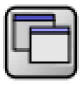
    @display("i=pics/sensingunit;is=vs");

    gates:
        output toProcessUnit;
}</pre></td></tr>
<tr><td> Processing Unit</td><td><pre>simple ProcessingUnit
{
    @display("i=pics/processingunit");
    gates:
        input fromSensUnit;
        output toCommUnit;
}</pre></td></tr>
<tr><td> Communication Unit</td><td><pre>simple ComUnit
{
    @display("i=pics/communit;is=vs");
     gates:
         input frompProcessUnit;
         input RadioIn @directIn;

}</pre></td></tr>
<tr><td> Power Unit</td><td><pre>simple PowerUnit
{
  parameters:

    double nominal@unit(mAh) = default(33000 mAh);//mAh
    double capacity@unit(mAh) = default(33000 mAh);//mAh
    double voltage@unit(V) = default(3.3 V); // volts
    double resolution @unit(s) = default(0.1s);
    double recording @unit(s) = default(1s);

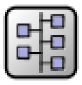
   @display("i=pics/battery");

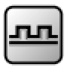
}</pre></td></tr>
<tr><td> Application Layer</td><td><pre>simple AppLayer
{
    parameters:

            @display("i=old/app");

    gates:
        input fromLower;
        output toLower;
}</pre></td></tr>
</table>

Module	Ned File

 Network Layer	simple NetworkLayer
	{
	    parameters:
	
	        @display("i=block/network");
	    gates:
	        input fromLower;
	        output toLower;
	        input fromUpper;
	        output toUpper;
	
	}

 Mac Layer	simple MacLayer
	{
	    @display("i=block/mac");
	
	    gates:
	        input fromLower;
	        output toUpper;
	        input fromUpper;
	        output toLower;
	}

 Physical Layer	simple PhyLayer
	{
	    parameters:
	    @display("i=device/card");
	
	        gates:
	            input RadioIn @directIn;
	            input fromUpper;
	            output toUpper;
	}

 Phone	simple Phone
	{
	    @display("i=pics/phone;is=vs");
	    gates:
	        input RadioIn @directIn;
	}

 Base Station	simple BaseStation
	{
	    @display("i=pics/baseStation;is=vs");
	    gates:
	        input RadioIn @directIn;
	}

 Family	simple Family
	{
	    @display("i=pics/family;is=vs");
	    gates:
	        input RadioIn @directIn;
	}

 Central Monitoring Unit	simple CMUnit
	{
	    gates:
	        input RadioIn @directIn;
	}

Module	Ned File

 User Interface	`simple UserInterface`
	`{`
	`@display("i=pics/GUI;is=vs");`
	`gates:`
	`input RadioIn @directIn;`
	`}`

4.6 Data Gathering

The **Data.h** file represented in Figure 4.11a is a C++ header file that defines the Data class. This class represents sensor data in the simulation. It inherits from the **cMessage** class and provides member variables to store information such as the type of sensor, chamber, patient ID, acquired value, and classification of the data. The header file also includes member function declarations to set and retrieve the values of these variables, as well as a function to classify the data based on predefined criteria. While Figure 4.11b illustrates, **Data.cc** file is a C++ implementation file that provides the implementation of the member functions declared in the **Data.h** header file. It contains member function definitions to set and retrieve the values of the member variables, including an overloaded function that generates random values based on the sensor type. Additionally, the implementation includes a function to classify the data based on the sensor type and value, setting the classified variable accordingly.

```
class Data: public cMessage{
    public:
        int TypeOfSensor;
        int Chamber;
        int PatientID;//patient ID
        double Value;// acquired value;
        int classified; //0= normal ; 1 = not normal;
        Data();
      virtual ~Data();
      virtual void setTypeOfSensor(int type);
      virtual void setChamber(int ch);
      virtual void setPatientID(int id);
      virtual void setValue(double val);
      virtual void setValue();
      virtual void setClassified(int clas);

      virtual int getTypeOfSensor();
      virtual int getChamber();
      virtual int getPatientID();
      virtual double getValue();
      virtual int getClassified();

     int classifyData();//0= normal ; 1 = not normal;

    private:
     Data(const Data&);
     Data& operator=(const Data&);
};
#endif /* DATA_H_ */
```

(a) Data.h

```
void Data::setTypeOfSensor(int type){ TypeOfSensor = type;}
void Data::setChamber(int ch){ Chamber = ch;}
void Data::setPatientID(int id){ PatientID = id; }
void Data::setValue(double val){Value = val;}
void Data::setValue()
{
 switch(TypeOfSensor) {
    case 1:{// set values of heart rate
        double Hrate = uniform(30, 170);
        Value = Hrate;
    break;}

    case 2:{// set values of BHCG
        double BHCG = uniform(32.000 , 200.000 );
        Value = BHCG;
        break;}

    case 3:{// set values of BloodPress
        double BloodPress = uniform(50, 180);
        Value = BloodPress;
        break;}

    case 4:{// set values of cervix dilation
        double cervixD = uniform(50, 180);
        Value = cervixD;
        break;}

    case 5:{// set values of FetalMov
        double FetalMov = uniform(0, 15);
        Value = FetalMov;
        break;}
```

(b) Data.cc

Figure 4.11: The implementation of Data Class

The **CollectData.h** file shown in Figure 4.12a defines the **CollectData** class, which is responsible for collecting and managing a collection of **Data** objects. It includes member variables such as **sommet**, which represents the number of data items collected, and an array collected to store pointers to the **Data** objects. The header file declares member functions for adding data to the collection **addData**, retrieving data from a specific index **getData**, and concatenating the data from another **CollectData** object **cooncatenateData**. By encapsulating the functionality of collecting and managing data in the **CollectData** class, it provides a convenient and organized way to handle a collection of Data objects within the program
The provided code in Figure 4.12b shown an implementation of a data collection mechanism using the **CollectData** class. The code allows for adding Data objects to the collection, retrieving Data objects based on an index, and concatenating data from another **CollectData** object. The code also keeps track of whether any abnormal data items have been added during the concatenation process.

```
#ifndef COLLECTDATA_H_
#define COLLECTDATA_H_

#include <cmessage.h>
#include <Data/Data.h>
#include <cmessage.h>

class CollectData : public cMessage{
 public:
    int sommet;

    Data *collected[2000];
    CollectData();
    virtual ~CollectData();
   virtual void addData(Data *msg);
   virtual Data *getData(int i);
   virtual int cooncatenateData(CollectData *serie);

    CollectData(const CollectData&);
       /** @brief Assignment operator is not allowed.
         */
    CollectData& operator=(const CollectData&);
};

#endif /* COLLECTDATA_H_ */
```

(a) CollectData.h

```
CollectData::CollectData() {
    {sommet = 0;}
}
CollectData::~CollectData() {
    // TODO Auto-generated destructor stub
}
void CollectData::addData(Data *msg){
    collected[sommet]= msg;
    sommet+=1;
}
Data *CollectData::getData(int i){
    if(i<sommet){
        return collected[i];
    }}
int CollectData::cooncatenateData(CollectData * serie){
    int classified = 0;
    for(int i = 0; i < serie->sommet; i++)
    {
        Data *data = new Data();
        data = serie->getData(i);
        addData(data);
        if(data->classified==1){
            classified = 1;
        }
    }
    return classified;
}
```

(b) CollectData.cc

Figure 4.12: The implementation of Collect Data Class

4.7 Configuration of Scenarios

After ensuring that the simulation environment is properly prepared, which involves defining the network topology, configuring network components, specifying simulation parameters, implementing event handlers and message processing, and ensuring the necessary dependencies are in place, the configuration of each scenario can proceed.This configuration is done through the **.ini** File Editor, which provides a user-friendly interface for customizing the simulation settings.

Figure 4.13 illustrates the form-based editing of the **.ini** file. This visual representation allows to easily configure the simulation settings by selecting options and entering values in the provided forms.

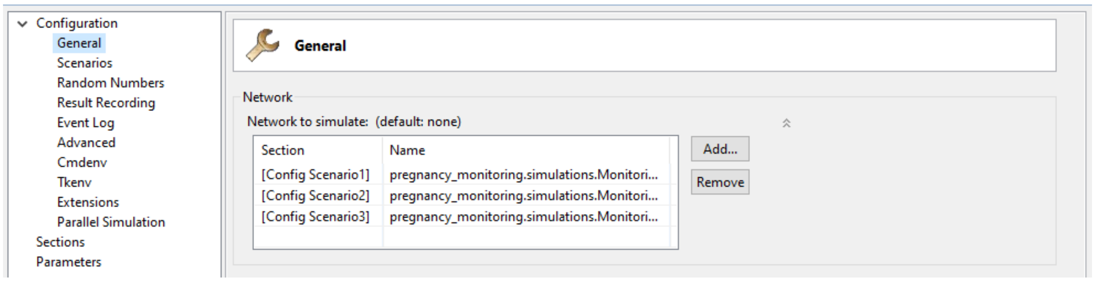


Figure 4.13: Form-based ini File Editing

The specific configurations for the different scenarios, including parameters such as network name, data sampling intervals, and simulation duration are presented in Figures 4.14, 4.15 and 4.16 which showcase the source editing of the **.ini** file for each scenario. These configurations serve as the foundation for running the simulations and analysing the results.

```
#*******************************************************
[Config Scenario1]
network = pregnancy_monitoring.simulations.Monitoring
repeat = 5
runnumber-width = 5
**.param-record-as-scalar = true
**.LifeTime.param-record-as-scalar = true
**.LifeTime.vector-recording = true
**.LifeTime.scalar-recording = true
**.*.param-record-as-scalar = true
**.result-recording-modes = +vector,+histogram
record-eventlog = true
**.energieManager.UpdateTime = 0.5min
**.energieManager.endTime = 4d
**.sensingUnit.trafficParam = 1s
**.sensingUnit.initializationTime = 1s
**.*.scenario = 1
**.heartRate.Periodic_sens = 1h
**.bloodPress.Periodic_sens = 1h
**.temperature.Periodic_sens = 1h
**.sPo2.Periodic_sens = 2h
**.bhcg.Periodic_sens = 3h
**.fetalMov.Periodic_sens = 1.5h
**.cervixDilat.Periodic_sens =2h
**.andominal.Periodic_sens = 1h
**.glucose.Periodic_sens =2h
**.respiratory.Periodic_sens =1h

#*******************************************************
```

Figure 4.14: Configuration of Scenario 1

```
#*******************************************************
[Config Scenario2]
network = pregnancy_monitoring.simulations.Monitoring
repeat = 5
runnumber-width = 5
**.param-record-as-scalar = true
**.LifeTime.param-record-as-scalar = true
**.LifeTime.vector-recording = true
**.LifeTime.scalar-recording = true
**.*.param-record-as-scalar = true
**.result-recording-modes = +vector,+histogram
record-eventlog = true
**.energieManager.UpdateTime = 0.5min
**.energieManager.endTime = 4d
**.sensingUnit.trafficParam = 1s
**.sensingUnit.initializationTime = 1s
**.*.scenario = 2
**.heartRate.Periodic_sens = 1h
**.bloodPress.Periodic_sens = 1h
**.temperature.Periodic_sens = 1h
**.sPo2.Periodic_sens = 2h
**.bhcg.Periodic_sens = 3h
**.fetalMov.Periodic_sens = 1.5h
**.cervixDilat.Periodic_sens =2h
**.andominal.Periodic_sens = 1h
**.glucose.Periodic_sens =2h
**.respiratory.Periodic_sens =1h
#*******************************************************
```

Figure 4.15: Configuration of Scenario 2

```
#*****************************************************
[Config Scenario3]
network = pregnancy_monitoring.simulations.Monitoring
repeat = 5
runnumber-width = 5
**.param-record-as-scalar = true
**.LifeTime.param-record-as-scalar = true
**.LifeTime.vector-recording = true
**.LifeTime.scalar-recording = true
**.*.param-record-as-scalar = true
**.result-recording-modes = +vector,+histogram
record-eventlog = true
**.energieManager.UpdateTime = 0.5min
**.energieManager.endTime = 4d
**.sensingUnit.trafficParam = 1s
**.sensingUnit.initializationTime = 1s
**.*.scenario = 3
**.heartRate.Periodic_sens = 1h
**.bloodPress.Periodic_sens = 1h
**.temperature.Periodic_sens = 1h
**.sPo2.Periodic_sens = 2h
**.bhcg.Periodic_sens = 3h
**.fetalMov.Periodic_sens = 1.5h
**.cervixDilat.Periodic_sens =2h
**.andominal.Periodic_sens = 1h
**.glucose.Periodic_sens =2h
**.respiratory.Periodic_sens =1h
#*****************************************************
```

Figure 4.16: Configuration of Scenario 3

4.8 Visualization of Scenarios Execution

To visualize the simulation process and the exchange of messages between the different components, we present screenshots of the scenarios in action. These screenshots capture the dynamic behaviour of the system and provide a visual representation of the communication and interactions between the modules. The screenshots below 4.17, 4.18, 4.19, 4.20 and 4.21 depict the scenarios running in the simulation environment and the exchange of messages between the various components.

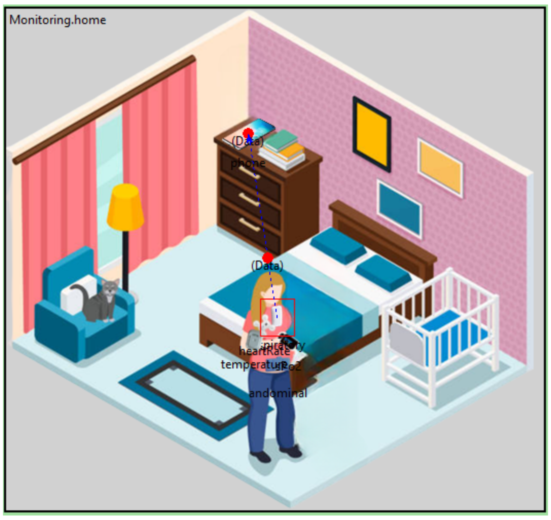


Figure 4.17: Data Transmission from Pregnant Women to Mobile Phone

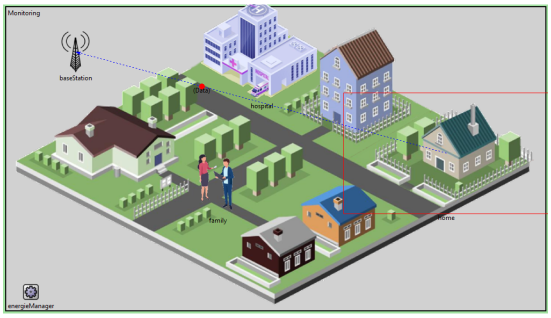


Figure 4.18: Data Transmission from Home to Base Station

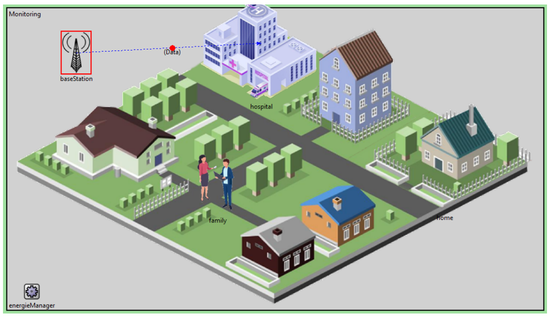


Figure 4.19: Data Transmission from Base Station to Hospital

Figure 4.20: Data Transmission from Sensor to Coordinator

Figure 4.21: Data Transmission from Coordinator to Central Monitoring Unit

4.9 Results and Discussion

The energy consumption is a crucial aspect to consider when deploying monitoring systems in healthcare settings. Efficient energy usage ensures optimal utilization of resources and prolongs the lifespan of battery-powered devices. In the context of monitoring the pregnancy state of women using a Wireless Body Area Network (WBAN) in a maternity service setting, three scenarios are considered for analysing energy consumption.

Based on the achieved experimental results, it is clear that over time, the energy consumption for the three scenarios continuously increases, as illustrated in Figure 4.22. The first scenario is considered the most energy-consuming among the three scenarios, followed by the second scenario. However, the energy consumption for the third scenario is the lowest among the experimented scenarios. This indicates that the parallel processing and independent storage of data within each sensor, along with the proactive transmission of abnormal cases, contribute to the energy efficiency of the third scenario.

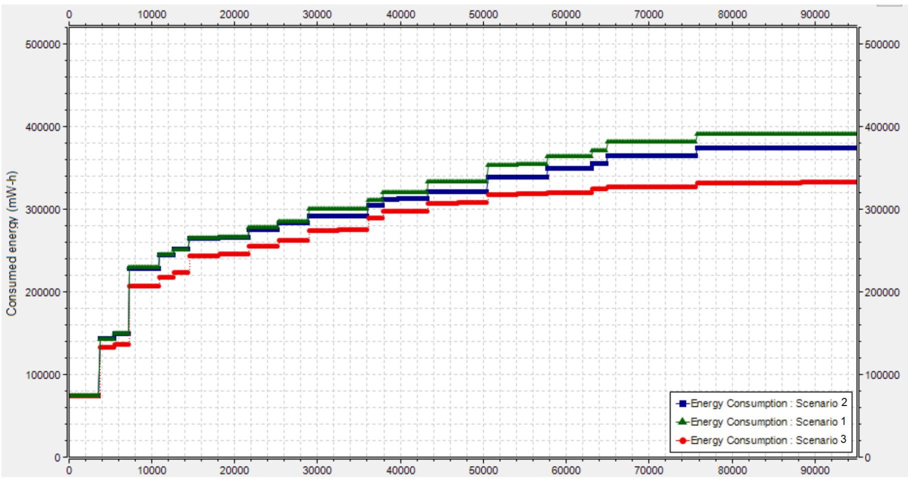


Figure 4.22: Evolution of Energy Consumption Over Time

The graphic columns demonstrate the relationship between energy efficiency and network lifetime in the three scenarios. The third scenario, with the highest network lifetime, as illustrated in Figure 4.23. This indicates that the third scenario offers the longest duration of network operation before the energy resources are depleted. The significant difference in network lifetime compared to the other scenarios suggests that the third scenario is the most energy-efficient and sustainable in terms of utilizing available energy resources effectively. The extended network lifetime implies reduced maintenance requirements and a longer duration of continuous monitoring for pregnant women.

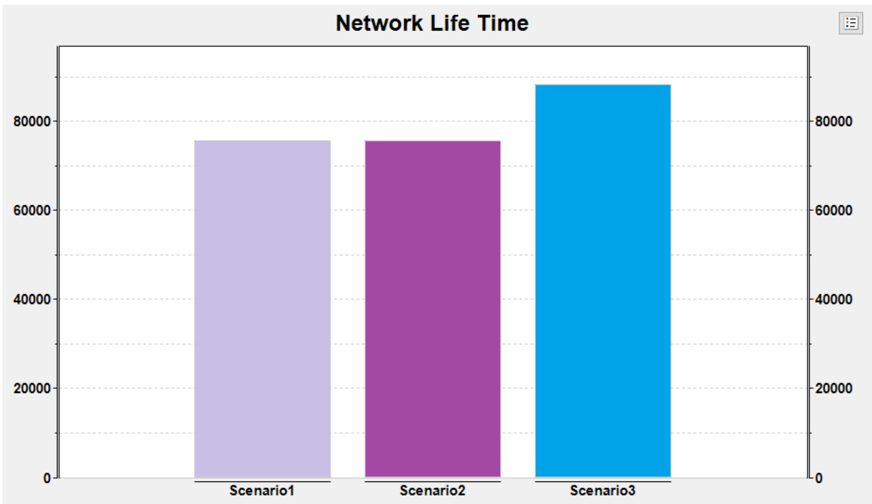


Figure 4.23: Network Life Time

The graph in Figure 4.24 represents the alive nodes over time. All three scenarios start with the same number of alive nodes, due to the initial network setup and deployment being consistent across scenarios. As time progresses, the number of alive nodes gradually decreases in all scenarios, which is expected due to the depletion of energy resources in the sensors. The observed difference lies in the rate at which the number of live nodes decreases among the scenarios. thus, scenario 1 exhibits the fastest rate of decrease, followed by Scenario 2, and then Scenario 3. This indicates that Scenario 1 experiences more rapid energy depletion compared to the other two scenarios. In contrast, Scenario 3, with its distributed processing and threshold-based transmission, shows a slower rate of decrease in the number of live nodes. The distributed processing approach reduces the load on individual nodes, allowing for more efficient energy utilization. Additionally, the threshold-based transmission strategy reduces unnecessary data transmissions, conserving energy and prolonging the lifespan of nodes.

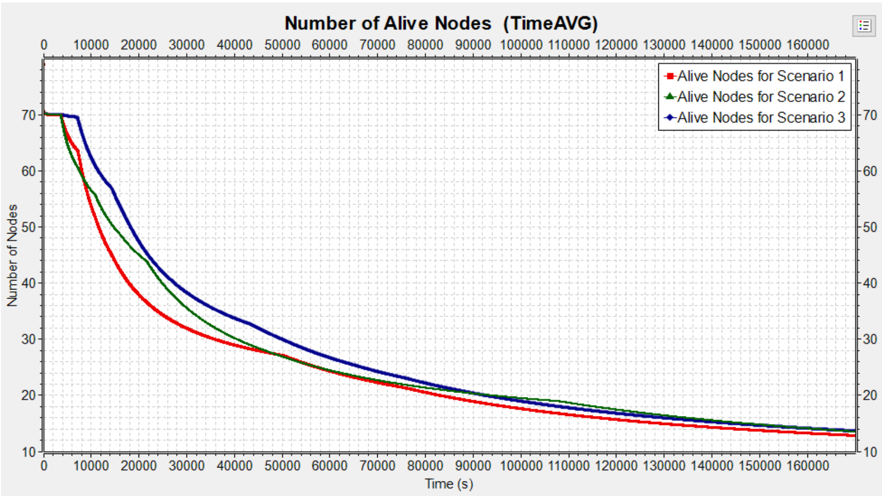


Figure 4.24: Network lifetime in terms of number of alive nodes

The column graph depicted in Figure 4.25 provides a visual representation of the total energy consumption observed during the simulation across the three scenarios. Notably, the third scenario stands out as the scenario with the lowest energy consumption, aligning with our previous analysis. This finding underscores the relative efficiency in overall energy usage within the third scenario, which can be attributed to the implementation of optimized data collection, processing, and communication mechanisms within the sensors. By adopting these measures, the energy demands associated with the scenario's operations are effectively minimized, resulting in a more efficient energy utilization pattern.

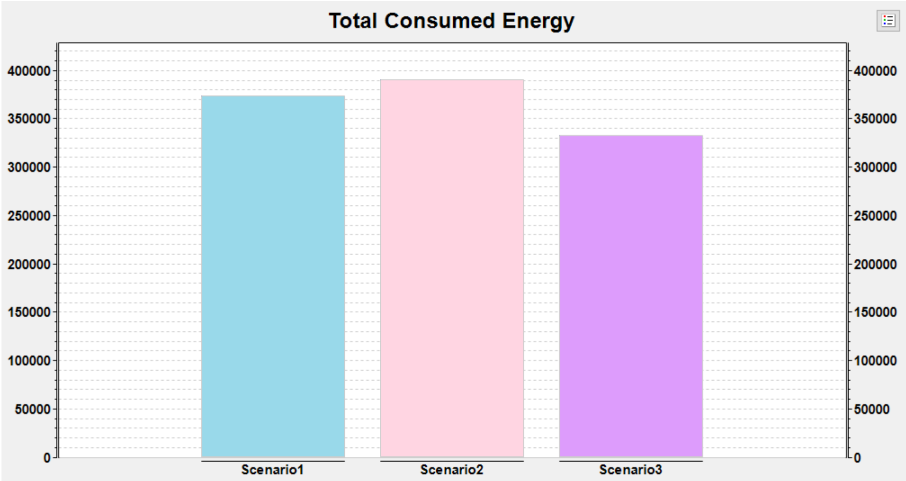


Figure 4.25: Total Network Energy Consumption

Figure 4.26 represents column graphs that correspond to the reception energy, sensing energy, transmission energy, sleep energy, and processing energy of each scenario. These graphs provide a visual representation of the energy consumption patterns in different aspects of the system. Analysing these graphs provides insights into the energy utilization and efficiency of each scenario.

In terms of reception energy, the first scenario exhibits the highest reception energy consumption, since it involves receiving data from multiple sensors and coordinating their synchronization. Scenario 2 follows with slightly lower reception energy as it also involves data reception at the coordinator. However, the third scenario demonstrates the lowest reception energy consumption, since data is received only once the threshold is met or abnormalities are detected.

Moving to sensing energy, the highest consumption is observed in the third scenario, followed by the second and first scenarios. Although there is no significant difference between the second and first scenarios, the third scenario stands out with higher energy usage during data sensing and measurement. This indicates that the sensors in the third scenario require more energy for their sensing activities.

Considering the total transmission energy, the second scenario demonstrates the highest energy consumption, as the coordinator sends all the stored data, including abnormal readings, to the central monitoring unit immediately. This leads to more frequent and potentially larger data transmissions compared to the periodic transmission in Scenario 1. Scenario 3 has the lowest transmission energy, as data transmission occurs only when a specific threshold is reached or abnormal values are detected.

In terms of sleep energy, the first and second scenarios exhibit similar levels of energy consumption, because of both scenario's similar sleep patterns. On the other hand, the third scenario consumes a higher amount of sleep energy, due to the periodic sleep cycles and waiting for updates from all the sensors.

Finally, the analysis of total processing energy reveals interesting findings. The first scenario does not involve any processing energy, because the data processing or analysis is not performed within the scenario itself. In contrast, the third scenario involves processing data by the coordinator, but the distribution of processing load among the sensors reduces the overall processing energy compared to the second scenario where the coordinator is responsible for processing all the data from sensors, which requires more computational resources and results in higher processing energy consumption.

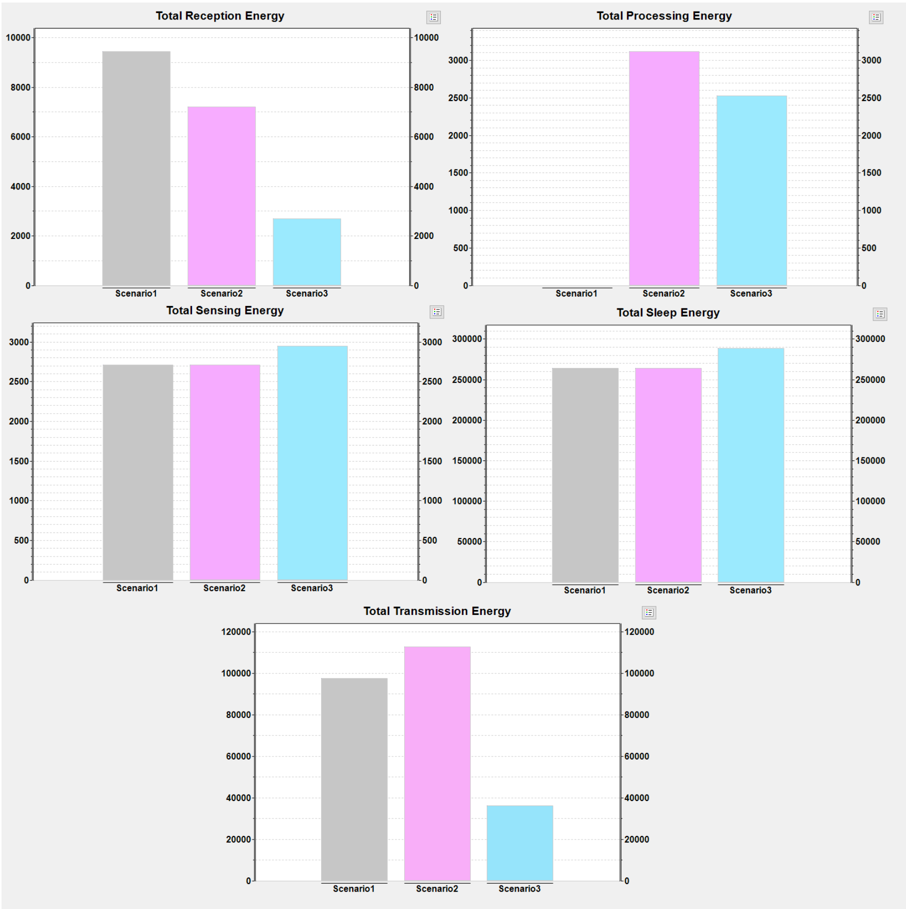


Figure 4.26: Total Energy Consumption: Reception, Processing, Sensing, Sleeping, Transmission

4.10 Conclusion

In this chapter, a customized simulation is conducted using the OMNeT++ simulator to evaluate the energy consumption of a WBAN system for monitoring pregnancy. First of all, an overview of the OMNeT++ simulator is provided, highlighting its suitability for simulating and analysing wireless communication systems.

The simulation involves the different modules used in the system and the configuration of scenarios. Moreover, detailed information are presented about each module along with the configuration settings for each scenario. These settings allow the investigation of the energy consumption characteristics for each scenario to compare their performance.

During the analysis of the simulation results, various graphs are examined, representing the energy consumption patterns of different scenarios. Due to the decentralization ensured by the third scenario, It is concluded that the third scenario; which ensures a high level of decentralized Data Processing, exhibits more efficient energy utilization compared to the other scenarios.

General Conclusion

The current work introduces a Wireless Body Area Network (WBAN) based-system designed for monitoring the health parameters of pregnant women. The primary objective of the study is to create and simulate a dependable and effective system capable of remotely monitoring the health of pregnant women, whether they are in the hospital or at home. The investigation is initiated by exploring the fundamental principles of sensors and wireless sensor networks (WSNs), with a specific focus on WBANs. This theoretical groundwork is essential for conducting a thorough examination of WBANs in the context of healthcare monitoring.

Moreover, an extensive review of existing literature and research studies is provided, involving the categorization and synthesis of their findings. This systematic analysis provides valuable insights into the diverse applications of WBAN technology in the healthcare field. In particular, WBAN pregnancy monitoring systems are thoroughly examined, including primary research and the associated implementation challenges.

To enhance the medical context, a comprehensive understanding of pregnancy is provided, encompassing different stages and potential complications. Building upon this knowledge, a WBAN pregnancy monitoring system is proposed for the sake of monitoring the health and well-being of pregnant women and their unborn babies in hospital and home settings. Detailed descriptions of the key components of the system and their integration with existing technologies and medical practices are also provided. Additionally, various scenarios are considered, simulated, and discussed to showcase the practical application of the proposed WBAN-based system in different monitoring situations.

Of significant importance, a complete simulation of a wireless body area network system for monitoring pregnant women is presented. The simulation is developed from scratch using the OMNeT++ simulator. This approach allows for an exploration of the intricacies and challenges involved in designing and implementing a WBAN system as a whole. By simulating not only the communication aspects but also the behaviour and characteristics of the sensors themselves, a more realistic and accurate representation of the system's performance is achieved.

In the study, three different scenarios are simulated in a hospital setting, along with an additional scenario in a home environment. These scenarios are designed to capture various configurations and operational procedures for WBAN-based pregnancy monitoring. The diversity in settings

provided a comprehensive analysis of the system's performance across different contexts.
Upon analysing the results, it is inferred that the third scenario demonstrates superior energy consumption compared to the other scenarios. This finding suggests that the design of the third scenario, involving distributed processing, threshold-based transmission, and minimal reception energy, is more energy-efficient for monitoring the pregnancy state of women using the proposed WBAN-based system. The simulation results reinforce the potential benefits of adopting such a configuration to reduce energy consumption while ensuring effective monitoring. These insights contribute to the optimization and refinement of WBAN systems for maternity services, promoting energy efficiency and overall system performance.

Future Work:

The proposed WBAN system introduces several perspectives that highlight potential areas for further research and development in the field. These directions aim to advance and optimize WBAN technologies, enhancing their performance, security, and efficiency. In the following sections, various aspects that can be explored to accomplish these goals within WBAN systems are discussed.

- Explore optimization techniques to further enhance the energy efficiency of the proposed system.
- Focus on security and privacy measures to safeguard sensitive medical data.
- Continue advancements in data processing algorithms, transmission scheduling, and sensor activation for improved energy efficiency.
- Implement routing algorithms that adapt to changing topology and signal conditions caused by user mobility.
- Implement techniques to adjust transmission power based on distance and signal conditions to reduce packet loss in mobile scenarios.
- Implement Machine learning algorithms to identify patterns of abnormal behaviour for early detection of health issues or anomalies.
- Validate simulation results through real-world implementation and data collection.

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