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Entitled

Simulation of Wireless Body Area Networks (WBAN) with Castalia Framework and Omnet++

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Abstract

This thesis focuses on the simulation of a Wireless Body Area Network (WBAN), employed for monitoring human physiological parameters such as body temperature, blood oxygen saturation, and blood pressure through a network of sensors deployed on the human body. The simulation framework was established using OMNeT++ in conjunction with the Castalia platform, enabling the evaluation of the network under various scenarios.

The study involved configuring the simulation environment, specifying the number and types of nodes (including sensor nodes and a central sink node), and setting up the necessary applications for data acquisition and transmission. Network performance was assessed using two primary metrics: transmission delay and packet delivery ratio.

The obtained simulation results demonstrated that network performance varies according to the chosen scenario and number of sensors, providing valuable insights into the impact of network design on efficiency. These findings contribute to the optimization of WBAN deployment in real-world healthcare contexts, particularly in applications requiring high accuracy and responsiveness.

Résumé

Ce mémoire porte sur la simulation d’un réseau de capteurs corporels sans fil (WBAN), utilisé pour surveiller les paramètres physiologiques humains tels que la température corporelle, la saturation en oxygène du sang et la pression artérielle, au moyen d’un réseau de capteurs placés sur le corps humain. Le cadre de simulation a été mis en place à l’aide d’OMNeT++ en conjonction avec la plateforme Castalia, permettant l’évaluation du réseau selon différents scénarios de transmission.

L’étude comprend la configuration de l’environnement de simulation, la définition du nombre et du type de nœuds (y compris les nœuds capteurs et le nœud central), ainsi que l’installation des applications nécessaires à l’acquisition et à la transmission des données. La performance du réseau a été évaluée selon deux métriques principales : le délai de transmission et le taux de livraison des paquets.

Les résultats obtenus ont montré que la performance du réseau varie en fonction du scénario choisi et du nombre de capteurs, offrant ainsi des perspectives utiles sur l’impact de la conception du réseau sur son efficacité. Ces résultats contribuent à l’optimisation du déploiement des WBAN dans les contextes médicaux réels, notamment dans les applications nécessitant une grande précision et une réactivité élevée.

الملخص

تركز هذه المذكرة على محاكاة شبكة المنطقة الجسدية اللاسلكية (WBAN)، التي تُستخدم لمراقبة المؤشرات الفسيولوجية للإنسان مثل درجة حرارة الجسم، تشبع الدم بالأوكسجين، وضغط الدم، وذلك باستخدام شبكة من الحساسات المثبتة على جسم الإنسان. تم إعداد بيئة المحاكاة باستخدام OMNeT++ بالتكامل مع إطارCastalia ، مما أتاح تقييم أداء الشبكة تحت سيناريوهات نقل مختلفة.

شمل العمل تكوين بيئة المحاكاة، وتحديد عدد وأنواع العقد (بما في ذلك عقد الاستشعار والعقدة المركزية)، بالإضافة إلى إعداد التطبيقات اللازمة لجمع البيانات وإرسالها. تم تقييم أداء الشبكة اعتمادًا على مؤشرين أساسيين: زمن التأخير ونسبة إيصال الحزم.

أظهرت نتائج المحاكاة أن أداء الشبكة يختلف حسب السيناريو المختار وعدد الحساسات، مما يوفر رؤى مهمة حول تأثير تصميم الشبكة على كفاءتها. وتسهم هذه النتائج في تحسين نشر WBAN في السياقات الصحية الواقعية، خاصةً في التطبيقات التي تتطلب دقة واستجابة عالية.

Dedication

To my mother, who has always given me strength with her love, patience, and prayers.
To my father, who believed in me and taught me to persevere no matter how difficult things were.
To my brothers and sisters, thank you for standing by me, for your support, and for always making me smile, even during the toughest days.
To my fiancé, who has stood by me through everything. You have been my comfort, my support, and my push forward when I needed it most. Thank you for always being there.
To my colleague at work, who has supported and understood me during times of hardship—I truly appreciate you.
To my dear friends, who have been a source of moral support during difficult times and a source of genuine smiles during moments of stress—I proudly dedicate this work to you.
You are truly a part of this achievement.

Akila Zehani

Dedication

To the soul of my dear father — may Allah have mercy on him — whose memory continues to inspire me every day. Your absence is deeply felt, but your guidance and values remain my compass.

To my beloved mother, whose endless sacrifices, prayers, and unconditional love have been my strongest source of strength.

To my brothers and sisters, who stood by me with love, laughter, and unwavering encouragement through every challenge.

To my supportive colleagues, who showed me kindness and understanding during moments of pressure.

To my dear friends, thank you for lifting my spirits, for believing in me, and for reminding me that I'm never alone.

This work is dedicated to all of you — for being part of my journey, for your presence, and for the light you brought into every step of this path.

Chima Laouidji

Acknowledgement

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A special thank you goes to our dear parents for their constant support, prayers, and patience. They have always been our greatest source of strength. We also thank our families for their love and encouragement.

Content

List of Figures

List of table

List of Acronyms

- **WBAN**: Wireless Body Area Network
- **WLAN** : Wireless Local Area Network
- **WPAN** : Wireless Personal Area Network
- **WMAN** : Wireless Metropolitan Area Network
- **WWAN** : Wireless Wide Area Network
- **ECG** : Electrocardiogram
- **EEG** : Electroencephalogram
- **EMG** : Electromyogram
- **IEEE**: Institute of Electrical and Electronics Engineers
- **ISO** : International Organization for Standardization
- **OMNeT++**: Objective Modular Network Testbed in C++
- **MAC** : Medium Access Control
- **QoS** : Quality of Service
- **BAN** : Body Area Network
- **PS** : Personal Server
- **UWB** : Ultra Wideband
- **TDMA**: Time Division Multiple Access
- **CSMA** : Carrier Sense Multiple Access

General Introduction

Wireless Body Area Networks (WBANs) are among the most important modern innovations in healthcare technology. They enable remote monitoring of a patient's health status using a set of small sensors that can be worn on the body or implanted inside it. These sensors collect vital physiological data such as temperature, blood pressure, and more, and send them to a central unit for processing or storage.

This technology has greatly improved the quality of healthcare, especially for elderly individuals and patients with chronic diseases, as it provides continuous monitoring without the need to stay in medical centers.

Based on this, the aim of this thesis is to study the performance of a WBAN by simulating it using the OMNeT++ and Castalia, under a variety of transmission scenarios. The focus is on measuring key performance indicators such as Energy consumption, delay and packet delivery ratio in order to analyze the impact of each scenario.

This thesis is structured into two main chapters:

- **Chapter I: Theoretical Background of WBANs**

  This chapter covers the basic concepts of Wireless Body Area Networks, including their components, areas of application, technical challenges, and the different protocols used to manage them.

- **Chapter II: Simulation Environment Setup and Performance Analysis**

  This chapter focuses on the practical side of the project. A WBAN is built using OMNeT++ and Castalia, with several simulation scenarios designed and tested. It includes the implementation steps, results extraction, and performance analysis based on specific metrics such as delay and packet delivery ratio, to accurately assess the effect of each scenario and draw conclusions.

Chapter I: wireless body area network

I.1 Introduction

With the advancement of networking and communications technologies, wireless body area networks (WBANs) have emerged as an innovative solution for monitoring human health, particularly through the use of small, wearable or implantable sensors. These networks enable the collection of vital data—such as heart rate and body temperature— and **enable the transmission** to medical devices or monitoring centers.

In this chapter, we provide an overview of wireless body area networks (WBANs), defining their purpose and distinguishing them from other networks such as Wireless Local Area Networks (WLANs) and Wireless Personal Area Networks (WPANs). We also discuss the key challenges facing WBANs, their infrastructure, the protocols and standards used, and tools used in their development. In addition, we highlight some notable testbeds and research projects in this field.

I.2 Definition of WBANs

Wireless Body Area Networks (WBANs) are networks consisting of mini-sensors that are wearable (non-invasive) or implanted in the human body (invasive) that are comfortable and do not interfere with the normal activities of the human being.[1]

Each sensor node is usually capable of detecting one or more physiological characteristics from the human body or its environment. The sensors collect different information in order to monitor the health status regardless of its location; if an emergency is detected, an alert will be generated by the computer system to inform the patient and/or medical staff. The sensor node stores and then transmits the measured data - via a wireless network - to a central processing device known as a personal server (PS: Personal Server). Although WBAN is relative to WPAN, WBAN offers a closer interconnection (2-5 meters) with more stringent technical requirements such as high reliability, energy efficiency and extreme security, especially safety for human body.[1]

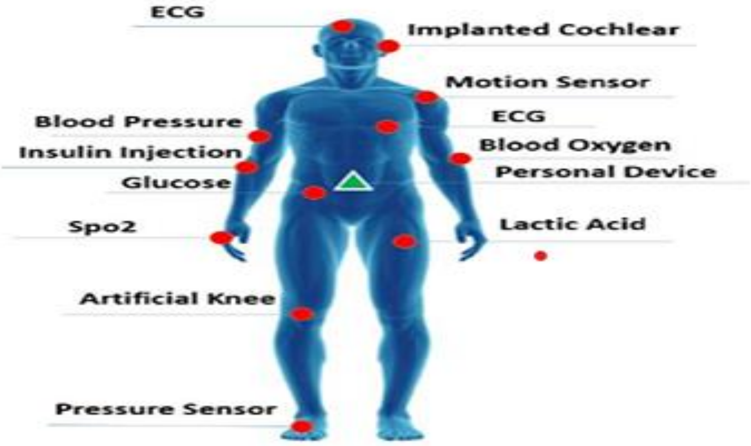


Figure I.0-1 WBAN network.[2]

I.3 Differences between WBANs and other types of wireless networks

Wireless Body Area Networks (WBANs) differ from other wireless networks like **WPAN (Wireless Personal Area Network)** and **WLAN (Wireless Local Area Network)** in several key aspects, including their **application scope, power consumption, and communication range**. Below we present a comparison based on some factors

I.3.1 Application WBANs

- **WBAN** :
  - Primarily used for health monitoring (e.g., heart rate, glucose levels, body temperature).
  - Designed for medical, fitness, and sports applications.
  - Operates within a very short range (within a range of approximately 2 to 5 meters) around the human body.
  - Example1 : Wearable ECG monitors

Figure I.0-2 Wearable ECG monitors [3]

- Example2 implantable glucose sensors.

Figure I.0-3 implantable glucose sensors [4]

- **WPAN** :
  - Connects personal devices like smartphones, smartwatches, and wireless earbuds.
  - Use Bluetooth or ZigBee for short-range communication (up to 10 meters).
  - Example: Wireless headphones syncing with a phone.

Figure I.0-4 Wireless headphones syncing with a phone [5]

- **WLAN** :
  - Provides broad wireless coverage (homes, offices, campuses).
  - Supports multiple devices (laptops, smartphones, IoT devices) over longer distances (100+ meters).
  - Example: Wi-Fi networks in universities or offices.

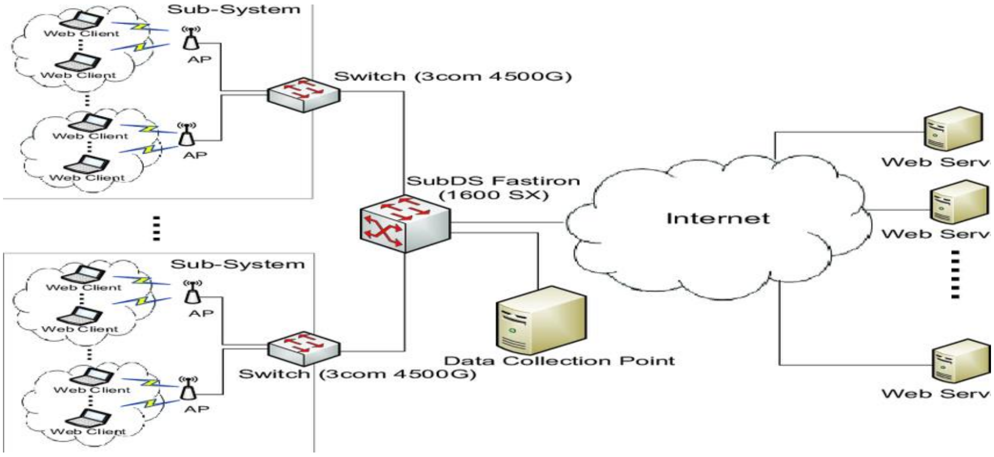


Figure I.0-5 Wi-Fi networks in universities or offices. [6]

I.3.2 Power Consumption and Device Size

- **WBAN** :
  - Use ultra-small, low-power sensors (wearable or implantable).
  - Extremely energy-efficient due to medical constraints (long battery life required).
- **WPAN** :
  - Also, low-power, but devices are external (easier to recharge/replace).
  - Example: Bluetooth devices with rechargeable batteries.

- **WLAN** :
  - Higher power consumption (devices like routers and laptops use more energy).
  - Less strict size constraints (e.g., Wi-Fi access points).

I.3.3 Communication Range and Network Architecture

- **WBAN** :
  - Very short range (~2 meters).
  - Simple star or point-to-point topology for body-centric communication.
- **WPAN** :
  - Up to 10 meters.
  - Supports star, tree, or mesh topologies (e.g., Bluetooth mesh networks).
- **WLAN** :
  - Long-range (hundreds of meters).
  - Use infrastructure mode (access points) for wider coverage.

I.4 Main challenges in WBANs

WBAN is an emerging technology, and there are many issues that need to be resolved both technically and ethically such as privacy. Some of the most important challenges or problems that are needed to be resolved immediately are shown in table 1.[7]

Table 1 challenges in WBANs

Challenges	Challenges in WBAN
Range	WBANs operate within a very short range (a few meters), which requires adaptive communication techniques such as dynamic routing and power control to maintain reliable data transmission.
Power Consumption	Need for constant power to function properly and difficult to change power source especially if it's transplanted inside human body

Security	Due to low power and less processing, it’s difficult to add sophisticated security mechanism to WBAN
Quality of Service	One of the major challenges in WBAN is to improve the quality of service
Scalability	Addresses the challenge of connecting more devices and suggests efficient communication protocols and network management strategies.
Interference and Communication Reliability	Discusses interference from other devices and suggests advanced modulation techniques and frequency allocation schemes.

I.5 Practical applications of WBANs

The Three-Tier Architecture of WBAN

Wireless Body Area Networks (WBANs) are commonly structured into three functional layers. Each layer plays a distinct role in the process of data acquisition and communication.

Tier 1: Sensor Layer

This layer includes sensors placed on or implanted in the body. These sensors are responsible for measuring physiological parameters and monitoring physical activity. Typical components are:

- Inertial sensors (motion and orientation tracking)
- ECG sensors (heart signal monitoring)
- PPG sensors (pulse measurement using light)
- Activity trackers (physical movement detection)

Tier 2: Personal Server Layer

This layer manages communication between the sensors and external systems. It collects data from Tier 1 and sends it to the medical infrastructure. It generally involves:

- On-body devices (e.g., smartwatches)
- Off-body devices (e.g., smartphones)

Tier 3: Medical Server Layer

This layer is responsible for long-term storage, analysis, and medical follow-up. It is typically located remotely, such as in a hospital or cloud system. It includes:

- Telemedicine platforms
- Internet connectivity

▪ Medical record servers

▪ Health professionals

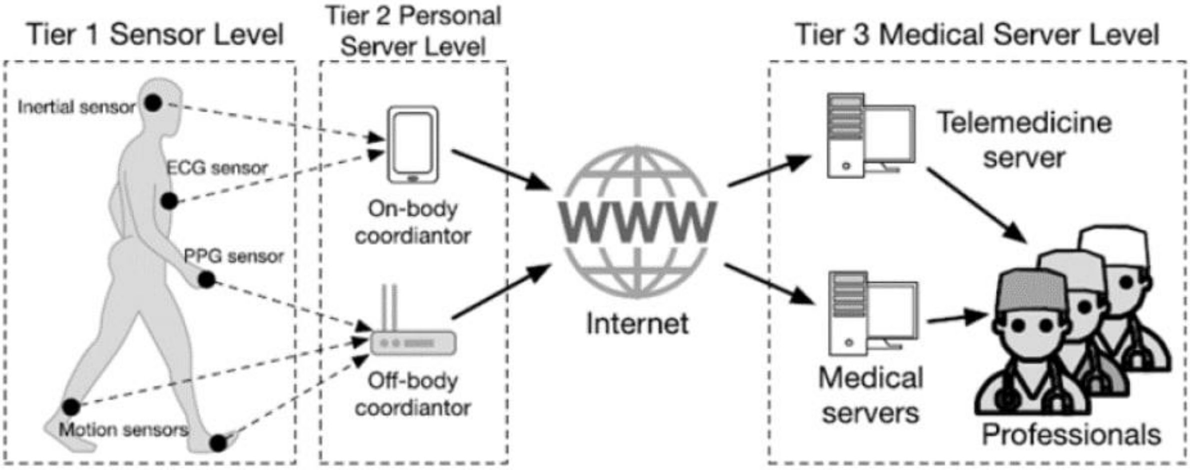


Figure I.0-6 general WBAN architecture

Wireless Body Area Networks (WBANs) use miniature sensors placed on or inside the human body to monitor physiological parameters and transmit data wirelessly. Their applications span several fields, including healthcare, sports, military, and daily life.

I.5.1 Healthcare Applications

- **Remote Monitoring:** WBANs enable continuous tracking of vital signs such as heart rate, blood pressure, and body temperature, which improves chronic disease management and post-operative care.[8][9]
- **Telemedicine:** These systems support remote healthcare delivery by transmitting biometric data to physicians, especially in remote areas.[8]
- **Implantable and Wearable Devices:** Devices like smartwatches, smart clothing, and implantable sensors allow internal monitoring and real-time alerts in case of medical emergencies.[8][10]

I.5.2 Sports and Rehabilitation

- Monitoring athletes' performance to optimize training, prevent injuries, and personalize fitness routines.[9]
- Supporting patient progress tracking during physiotherapy and improving rehabilitation quality.[9]

I.5.3 Military Applications

- Real-time monitoring of soldiers' vital signs and location to enhance decision-making and emergency response.[8][9]
- Supporting secure coordination and communication in the field.[10]

I.5.4 Lifestyle and Entertainment

- Tracking physical activity, calorie consumption, and sleep cycles for healthier daily routines.[10]
- Enhancing gaming and virtual reality experiences using real-time physiological and motion data.[10]
- Assisting elderly or disabled individuals with fall detection and automated alerts.[9][10]

I.6 Architecture

To understand how Wireless Body Area Networks (WBANs) operate, it is essential to explore their architecture. This includes analyzing the key components that form the network, their roles, and how they interact to ensure reliable data acquisition and communication.

I.6.1 Basic components of WBANs

Wireless Body Area Networks (WBANs) are composed of multiple integrated components that cooperate to monitor, transmit, and analyze physiological data, and in some cases, external environmental factors such as temperature or movement. These components are essential for ensuring efficient, real-time, and reliable operation of WBAN systems, especially in medical and health-related applications.

I.6.1.1 Data Types Generated by WBAN Sensors

Wireless Body Area Networks (WBANs) generate various types of data depending on the sensors used. These include: Physiological signals like ECG (heart activity), EMG (muscle activity), EEG (brain activity), blood pressure, body temperature, oxygen saturation (SpO_2), and glucose levels. Motion-related data such as accelerometer and gyroscope signals, useful for tracking physical activities and posture. Specialized data including audio (e.g., heart sounds) and image/video streams from devices like capsule endoscopes. These data types are mainly time series, scalar values, or multimedia, and are crucial for health monitoring and real-time decision-making. [11]

I.6.1.2 Sensor Nodes

Sensor nodes are the fundamental elements of WBANs, responsible for collecting physiological signals such as heart rate, blood pressure, temperature, glucose level, and brain activity. These nodes are classified into:

- In-body sensors: Implanted within the body to monitor internal parameters (e.g., pacemaker status, glucose level).
- On-body sensors: Worn on the skin or embedded in clothing, such as ECG (Electrocardiogram) or SpO_2 (Peripheral oxygen saturation) sensors.[12]

Figure I.0-7 Sensor Nodes [13]

I.6.1.3 Actuators

Actuators are specialized components that perform actions based on sensing data. For example, they may administer medication automatically or trigger alarms in case of abnormal readings, enabling a responsive healthcare system.[14]

I.6.1.4 Central Control Unit (CCU)

Also known as the coordinator node, the CCU manages communication within the WBAN. It collects data from all sensors and actuators, processes the information locally, and forwards it to the upper layer, typically the medical server (Tier 3), for storage and further analysis. The CCU may be implemented in devices such as smartphones or smartwatches, and it also handles power management and scheduling of sensing tasks. [12]

I.6.1.5 Communication Gateway

The Communication Gateway connects the Wireless Body Area Network (WBAN) to external systems like healthcare servers or cloud platforms. Unlike the Central Control Unit (CCU), which collects and processes data from sensors inside the WBAN, the Gateway sends this data outside the network using wireless technologies such as Bluetooth, Wi-Fi, GSM, 3G, 4G, or Ultra-Wideband (UWB). This allows remote monitoring and access to the data from outside the WBAN. In short, the CCU handles data inside the network, while the Gateway links the WBAN to external systems.[12]

I.6.1.6 Control Center

Tier 3 includes cloud services or remote servers where data is stored and analyzed. The control center enables real-time visualization, long-term storage, and medical decision support. It can also alert medical personnel or caregivers in emergency situations.[14]

I.6.1.7 Network Architecture

WBAN typically adopts a star topology, where all sensor nodes communicate directly with the CCU, or a multihop topology, where data is relayed between nodes to reach the coordinator. These structures are chosen to optimize energy consumption and reduce latency.[14]

I.6.2 Types of nodes in WBANs (primary nodes, secondary nodes)

In Wireless Body Area Networks (WBANs), nodes are generally classified into two main types based on their role within the network: primary and secondary nodes. This classification is essential for understanding the network’s architecture.

I.6.2.1 Primary Node (Hub/Coordinator)

The primary node, also known as the *hub* or *sink*, serves as the central controller of the WBAN. It collects data from other nodes, manages intra-network communication, and acts as a gateway to external systems. It is typically a mobile device such as a smartphone or smartwatch, with greater processing power and energy resources than other nodes.[15]

I.6.2.2 Secondary Nodes

Secondary nodes include all nodes in the network other than the coordinator, and are divided into:

- **End Nodes (Sensor/Actuator Nodes):** These nodes monitor physiological parameters such as heart rate and temperature or perform actions like administering medication. They can be implanted inside the body or worn externally.[15]

- **Relay Nodes:** These nodes are used to extend communication range within the network. They forward data from end nodes to the hub, especially in large-scale or complex network topologies.[16]

I.6.3 Network topology (star, mesh, etc.)

In this section, we describe the most used topologies for the deployment of WBANs. We distinguish the following topologies: point-to-point, star, mesh and tree.

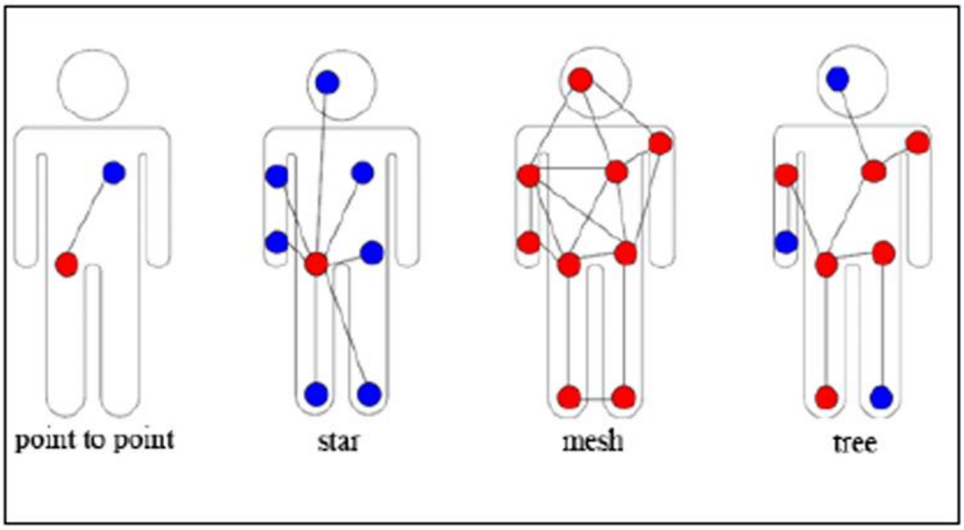


Figure I.0-8 Topologies of WBANs [17]

I.6.3.1 Point-to-Point Topology

This is the simplest topology in networks. This topology is intended for a single link, for example between a data collector and a sensor node. The main advantage of this topology is its simplicity, which often allows the use of a simple protocol, low latency and high throughput. Disadvantages include its limited functionality and low coverage. [17]

I.6.3.2 Star Topology

A topology in which all nodes are connected through a central node is a star topology. These nodes can only send or receive a message to or from the single central node. They are not allowed to exchange messages directly with each other. To date, this topology is the most proposed and used for WBAN networks. This topology has advantages that can be summarized by the simplicity, the low energy consumption of the nodes and the lower communication latency between the nodes and the central node. On the other hand, its major drawback is the vulnerability of the central node because the entire network is managed by a single node. [17]

I.6.3.3 Mesh Topology

A topology with complete connectivity between the nodes is a mesh topology. A node wanting to transmit a message to another node out of its transmission range, can use an intermediate node to send its message to the destination node. The advantage of using the mesh topology is the ability to scale the network, with redundancy and fault tolerance and good coverage. On the other hand, the disadvantages of such a topology are the high energy consumption induced by multi-hop communication as well as the latency created by the passage of messages through several nodes before reaching the destination node.

The use of a mesh topology is a primary consideration in all situations in which reliability and flexible communication are prioritized over energy efficiency and network lifetime. [17]

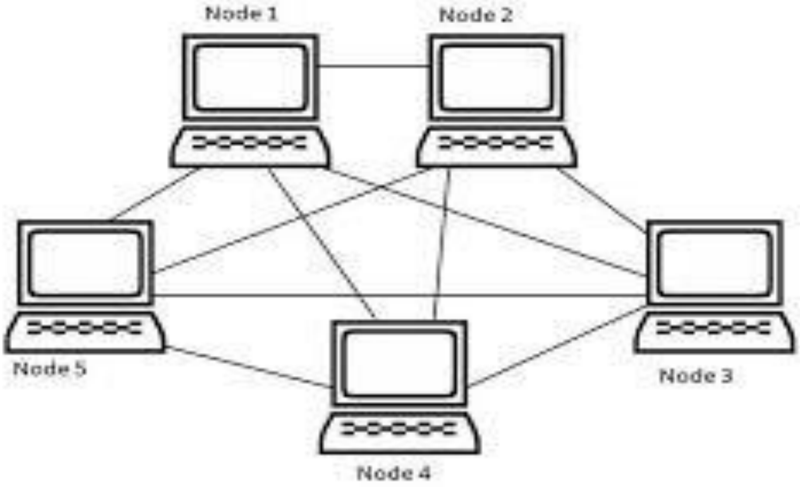


Figure I.0-9 Data flow between nodes in Mesh Topology [18]

I.6.3.4 Tree Topology

A tree topology contains a vertex with a branch structure below. The connections between the nodes are structured hierarchically, which means that each node can be a child to a higher-level node and a parent to a lower-level node. This topology divides the network into subparts so that it becomes easier to manage. It has good fault tolerance, good coverage, high bandwidth and low latency. However, the parent nodes can consume a lot of energy. [17]

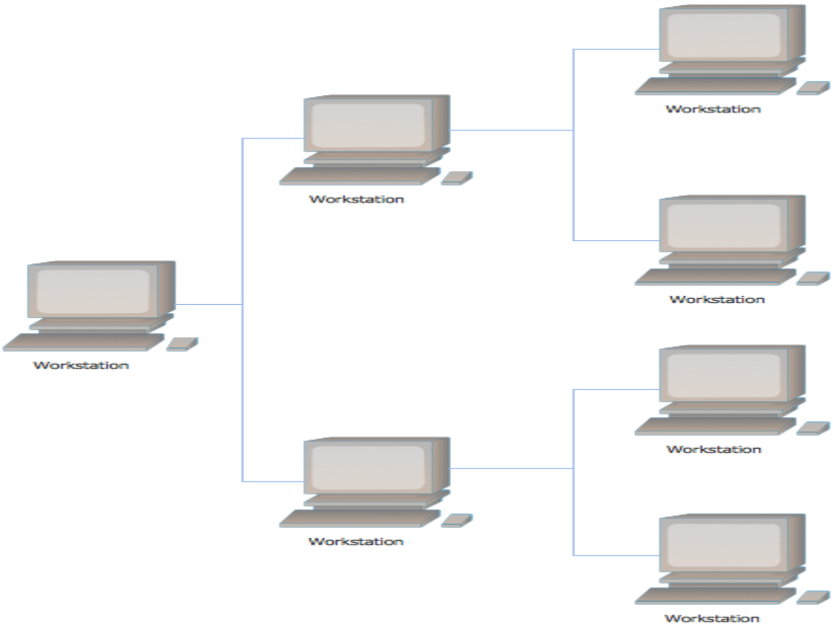


Figure I.0-10 Data flow between nodes in tree Topology [19]

I.6.4 Communication between nodes (Single-hop vs. multi-hop)

In Wireless Body Area Networks (WBANs), data exchange between nodes typically follows one of two main communication strategies: **single-hop** or **multi-hop**. Each approach has its own characteristics in terms of energy efficiency, latency, and reliability.

I.6.4.1 Single-hop Communication

In single-hop communication, each sensor node sends its data **directly** to the central coordinator (hub), usually forming a **star topology**.

- **Advantages** :
  - Simple network design and easier to manage.
  - Low communication delay since data is sent directly.
- **Limitations** :
  - Higher energy consumption for distant nodes.
  - Connection quality may be affected by body movements or posture changes

I.6.4.2 Multi-hop Communication

In multi-hop communication, data is **forwarded through intermediate nodes** before reaching the coordinator.

- **Advantages** :
  - Reduces energy consumption, as nodes transmit over shorter distances.
  - More stable under movement, since data can take alternate routes.
- **Limitations** :
  - Requires more complex routing and time synchronization.
  - May introduce slight delays due to multiple transmissions.

Table 2 differences between single-hop and multi-hop communication in wireless sensor networks

	Single-Hop Communication	**Multi-Hop Communication**
Distance	Limited to small distances	Can transmit over larger distances
Efficiency	Simple and efficient	Less efficient
Real-Time Transmission	Good for real-timetransmission	May have more delay due to forwarding through multiple nodes
Energy Consumption	Low	Higher
Processing Power	Low	Higher
Complexity	Simple	More complex

I.7 Protocols & Standards

I.7.1 Protocols used in WBANs

Wireless Body Area Networks (WBANs) are a type of short-range wireless network used to connect medical and non-medical sensors around the human body. To provide reliable and efficient communication, several wireless technologies are used, each differing in terms of speed, power consumption, and coverage range.

I.7.1.1 Bluetooth

Bluetooth is a short-range wireless communication technology that operates under the IEEE 802.15.1 standard. It is widely used in WBANs due to its low power consumption and ease of integration into portable devices. It operates in the 2.4 GHz ISM band and uses frequency hopping across 79 channels at a rate of up to 1600 hops per second to minimize interference. A typical Bluetooth network consists of a group called a *Piconet*, where one device acts as the master and can connect with up to seven slave devices. This setup can be expanded into a Scatternet by linking multiple Piconets together through shared nodes. Bluetooth devices can support data rates of up to 3 Mbps and offer coverage ranging from 1 to 100 meters, depending on the device class and transmission power (ranging from 1 mW to 100 mW). One of Bluetooth's key features is its ability to maintain communication even in Non-Line-Of-Sight (NLOS) conditions, which is particularly useful in dynamic environments like the human body.

Thanks to these characteristics, Bluetooth is well-suited for short-range data transmission in WBAN applications, such as sending sensor data to a smartphone or a personal computer, without requiring complex infrastructure or high energy consumption.

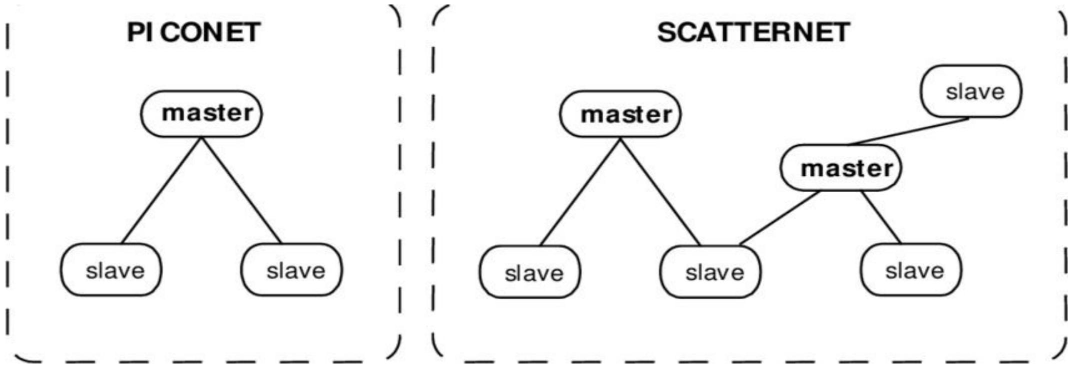


Figure I.0-11 Bluetooth Piconet and Scatternet network [20]

I.7.1.2 ZigBee

ZigBee is a wireless communication standard based on IEEE 802.15.4, primarily designed for low-power and low-data-rate applications such as sensing and control networks. It is highly suitable for WBAN environments due to its minimal energy consumption, which supports long battery life. A typical ZigBee network consists of three types of devices: a **coordinator** (which initiates and manages the network), **routers** (which relay data), and **end devices** (usually sensors that stay in sleep mode most of the time and wake up only to transmit or receive data).

ZigBee operates over three frequency bands: 868 MHz, 915 MHz, and 2.4 GHz—the latter being the most commonly used. However, the 2.4 GHz band is also shared with WiFi, leading to potential interference. ZigBee supports **star**, **tree**, and **mesh** topologies, enabling multi-hop communication that extends the effective coverage. Although its data rate is limited to 250 kbps, making it less suitable for real-time or high-throughput WBAN applications, it is still an excellent choice for scenarios such as **health monitoring, fitness tracking, assisted living, and environmental sensing**, typically within a range of **50–70 meters**.

Figure 1 describes a ZigBee network topology which typically includes three types of devices or nodes:

Coordinator: One coordinator exists in each network. It starts the network and handles management functions as well as data routing functions. These functions require that the coordinator always be powered. Therefore, this type of node is recommended to be main-powered.

Routers: In most cases, routers are also main-powered. They help carry data across multi-hop ZigBee networks including a variable number of routers and, in some cases, are without routers, thus, transforming the network into a point-to-multipoint.

End Devices: These are devices that are battery-powered due to their low-power consumption. They sleep most of the time and wake up regularly to collect and transmit data. Devices such as sensors are configured as end devices. They are connected to the network through the routers.

The type of node is assigned during the commissioning process. The main-powered requirement for coordinators can be a limiting factor for ZigBee, especially if minimizing power consumption is actively targeted for each and every device. [21]

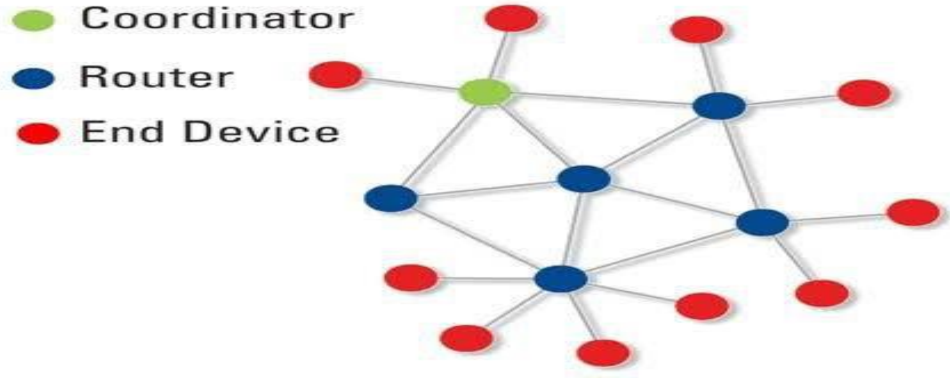


Figure I.0-12 ZigBee network architecture with three types of nodes. [21]

I.7.1.3 WiFi

WiFi is one of the most widely used wireless communication technologies, based on the IEEE 802.11 standard. It includes multiple variants (such as 802.11 a/b/g/n) and operates in the 2.4 GHz and 5 GHz ISM bands, offering a typical coverage of up to 100 meters in ideal conditions. Its high data transfer rates make it especially suitable for applications like video streaming and real-time transmission of medical data.

In the context of WBANs, WiFi can be used to connect sensor nodes to a central device or the internet via an access point or in ad hoc mode. Some advanced implementations even allow direct communication between sensors and smartphones or computers without any intermediary device.

However, the main drawback of WiFi is its high energy consumption, which limits its use in wearable sensors that require long battery life. For this reason, WiFi is often reserved for WBAN applications that prioritize data rate over power efficiency

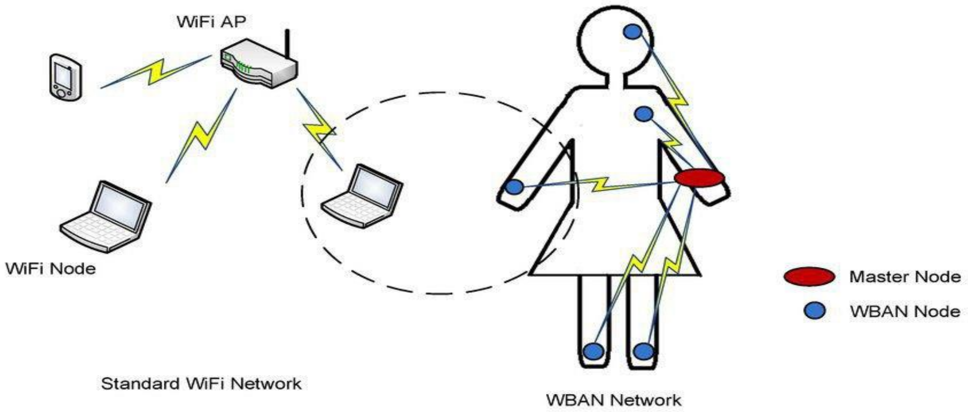


Figure I.0-13 Illustrative representation of the use of Wi-Fi technology in WBANs [22]

I.7.1.4 IEEE 802.15.6 WBAN

IEEE 802.15.6 is the latest addition in WPAN which is known as WBAN standard that provides various medical and non-medical applications and supports communications inside and around the human body. This standard supports communication inside and outside of human body which can be used for different medical and non-medical applications such as e-Healthcare monitoring, sports, environment etc. IEEE 802.15.6 standard is classified by three physical layer standards.

Each standard uses different frequency bands for data transmission with data rate 10 Mbps maximum. First one is Narrowband (NB) which operates within the range of 400, 800, 900 MHz and 2.3, 2.4 GHz bands. The Human Body Communication (HBC) is another standard which operates at range of 50 MHz. The Ultra-Wideband (UWB) technology operates between 3.1 GHz to 10.6 GHz which supports high bandwidth in short range communication.

I.7.2 Comparison between different protocols

To select an appropriate communication protocol for Wireless Body Area Networks (WBANs), it is essential to understand how each option performs in terms of data rate, range, energy consumption, and suitability for medical use. Table 3 provides a comparison of commonly used protocols including Bluetooth, ZigBee, Wi-Fi, and IEEE 802.15.6 based on these key features.

Table 3 Comparison between different protocols

Feature	**Bluetooth**	**ZigBee**	**Wi-Fi**	**IEEE 802.15.6**
Data Rate	≤3 Mbps	≤250 kbps	≤600 Mbps	≤10 Mbps
Range	1–100 m	10–100 m	~100 m	≤5m
Power Use	moderate	Very Low	High	Ultra-Low
Topology	Piconet/Scatternet	Mesh/Star	AP/Ad hoc	Star/multi-hop
Interference Resistance	Moderate	Low	Low	High
Medical Suitability	Limited	Basic Monitoring	Non-Critical	Optimized

I.7.3 International standards for WBANs

International standards for Wireless Body Area Networks WBANs are crucial for ensuring interoperability, reliability, and efficiency in healthcare and consumer electronics applications. Here are some key international standards:

I.7.3.1 IEEE 802.15.6

A detailed description of IEEE 802.15.6 standard, including its architecture, physical layers, and frequency bands, has been previously presented in Section I.7.1.4.

I.7.3.2 ISO/IEEE 11073

Description: Although not exclusively a WBAN standard, ISO/IEEE 11073 is a family of standards for medical device communication. It provides guidelines for interoperability between medical devices, which can be relevant for WBAN applications involving medical sensors.

Features: Focuses on ensuring that medical devices can communicate effectively, which is essential for WBANs used in healthcare monitoring.[23]

I.7.3.3 ISO/IEC 180006

Description: This standard pertains to RFID Radio Frequency Identification) technology, which can be integrated into WBANs for identification and tracking purposes.

Features: While not directly a WBAN standard, it can be used in WBAN applications requiring RFID capabilities.[24]

I.7.3.3 ISO/IEC 27001

Description: Although not specific to WBANs, this standard provides guidelines for information security management systems. It is relevant for ensuring the security of data transmitted through WBANs.

Features**:** Ensures confidentiality, integrity, and availability of sensitive health data.

I.8 Framework

This section explains how to build and secure Wireless Body Area Networks (WBANs). First, it covers the basic design principles, then describes the simulation tools and development approaches used. Next, it explains the process of gathering, analyzing, and sending sensor data.

Finally, it presents security solutions for protecting private health information. Together, these components show how WBANs work in actual healthcare settings." .

I.8.1 Theoretical framework for designing WBANs

The design of (WBANs) is based on a set of theoretical principles aimed at ensuring reliable, low-power, and secure communication within and around the human body. This framework includes several core elements that contribute to meeting the performance requirements that define the network's effectiveness in healthcare applications and other uses.

I.8.1.1 Network Architecture

WBANs typically rely on a star topology, where all sensor nodes communicate directly with a central coordinator. This topology is energy-efficient and allows for easy organization of communication within the network, making it ideal for vital applications that require continuous and reliable connectivity.

I.8.1.2 Node Roles

In WBANs, nodes are generally classified into two main types: coordinators (or aggregators), which manage data flow and ensure coordination between different nodes in the network, and sensors, which collect data from the surrounding environment. The coordinator manages network access efficiently using access control protocols to regulate interactions between nodes and external systems.

I.8.1.3 Communication Protocols

Medium Access Control (MAC) protocols are crucial in WBANs as they help organize channel usage and minimize collisions in environments with multiple wireless devices. Techniques such as priority-based scheduling and adaptive time-slot allocation are effective tools for ensuring real-time data transmission requirements are met.

I.8.1.4 Interference and Reliability

To reduce interference between multiple networks in the same environment, the framework relies on techniques like adaptive channel allocation and optimized transmission timing, which help minimize interference and enhance reliability. These methods are essential in multi-network environments where interference is more likely.

I.8.1.5 Security and Data Privacy

Given the sensitive nature of health-related data collected in WBANs, these networks focus on implementing lightweight encryption and authentication mechanisms to ensure data confidentiality and integrity. Advanced encryption techniques are used to maintain security on resource-constrained devices, enhancing user privacy protection.

I.8.1.6 Flexibility and Compatibility

The design of WBANs must be flexible enough to adapt to a wide range of devices, ensuring compatibility with various sensor devices and health monitoring systems. This flexibility allows the network to scale easily and ensures seamless integration with new technologies without compromising performance.

I.8.2 Tools and methodologies used in developing WBANs

Wireless Body Area Networks (WBANs) are specialized wireless sensor networks designed for monitoring, communication, and data collection from sensors placed on or inside the human body. The development of WBANs involves a range of tools and methodologies spanning simulation environments, algorithmic approaches, and physical layer characterization.

I.8.2.1 Simulation Tools and Platforms

Simulation is a critical methodology for WBAN development, allowing researchers to model, test, and validate network protocols, topologies, and performance under realistic conditions without the need for immediate hardware deployment. Common tools include :

- **MATLAB/Simulink**: Widely used for modeling hardware design, simulating communication channels, and analyzing signal path loss and strength. MATLAB provides a communication toolbox and Simulink offers a GUI for block diagram creation, supporting both linear and nonlinear system modeling.[26][28]

- **OMNeT++**: A modular, C++-based discrete event simulator that supports WBAN modeling through extensions like INET, Castalia, and MiXim. It allows for detailed protocol and mobility modeling, though native routing and heterogeneous traffic support may require additional modules.[25][28]
- **NS-2 and NS-3**: Network simulators that enable protocol and network behavior analysis for WBANs, with NS-3 offering improved flexibility for WBAN research.[28]

- **QualNet**: Suited for network-centric WBAN systems, allowing for the building, testing, and deployment of realistic network models.[26]
- **OPNET Modeler**: Enables simulation of WBAN applications and services, integration with cloud technologies, and analysis of system architecture and protocol efficiency.[26]
- **MoBAN**: Specifically designed for WBANs, supporting extensive mobility modeling and intra/extra WBAN service assessment.[28]
- **J-Sim**: A Java-based discrete event simulator with a user-friendly GUI, supporting WBAN protocol simulation and custom scripting.[30]

I.8.2.2 Algorithmic Methodologies

Several advanced algorithms are employed to optimize various aspects of WBAN operation, including energy efficiency, routing, load balancing, and network lifetime:

- **Cuckoo Search-Based Algorithms**: Used for adaptive band selection and optimal relay node assignment, improving network efficiency.[26]
- **Artificial Bee Colony**: Focuses on unconstrained data transmission, offering low energy consumption and high reliability.[26]
- **Energy-Aware Opportunistic Routing**: Balances network load and reduces overhead, enhancing overall performance.[26]
- **Cost and Energy-Aware Routing Protocols**: Select optimal routing paths to maximize power efficiency and reliability.[26]
- **Particle Swarm Optimization (PSO)**: Applied for computational problem-solving, increasing packet transmission success rates and minimizing specific absorption rates.[26]
- **Genetic Ant Colony Algorithms**: Optimize relay node selection to reduce energy consumption.[26]
- **Hybrid PSO-Genetic Approaches**: Used for workflow scheduling and maximizing network lifetime.[26]

I.8.2.3 Physical Layer Characterization and Measurement

Understanding the physical behavior of WBANs is crucial for reliable operation:

- **Path Loss and Delay Spread Analysis**: Characterization of electromagnetic wave propagation and antenna behavior near the human body using RF measurements and numerical simulations (e.g., Finite-Difference Time-Domain (FDTD), Method of Moments (MoM)) [26].

- **Antenna and Node Position Optimization**: Determining optimal on-body positions for sensors and characterizing antenna performance in various environments (anechoic, reverberation, real-world).[27]
- **RF Exposure Assessment**: Use of distributed exposimeters to measure personal radio-frequency exposure in real-life scenarios.[27]
- **Mobility and Channel Modeling**: Incorporating realistic mobility models and channel conditions into simulations to reflect actual WBAN usage environments.[28]

I.8.3 Data management in WBANs

Data management in WBANs encompasses the systematic handling of physiological and activity-related data collected from wearable or implantable sensors. This includes data **collection**, **processing**, and **transmission**, all optimized for energy efficiency, accuracy, and reliability.

I.8.3.1 Data Collection

- **Wearable sensors:** Devices like accelerometers and temperature sensors convert physical signals into electrical ones. These are suitable for continuous, non-invasive monitoring.
- **Implanted sensors:** Used for internal measurements (e.g., glucose or ECG monitoring), offering high precision for chronic conditions.
- **Edge devices:** Perform preliminary data filtering (e.g., downsampling, anomaly removal) before transmission, minimizing bandwidth and energy usage.[29],[30]

I.8.3.2 Data Processing

- **Time-series transformation:** Algorithms such as Gramian Angular Field (GAF) convert 1D signals into 2D images for input into deep learning models like DenseNet, boosting human activity recognition accuracy.[30]
- **Adaptive sampling and filtering:** These techniques reduce energy usage while preserving important information.
- **Hybrid models:** Combining statistical techniques with AI (e.g., CNN + LSTM) improves feature extraction and adaptability in real-time monitoring.[30],[31]

I.8.3.3 Data Transmission

- **Routing protocols:** Energy-aware and opportunistic routing schemes reduce overhead and extend network lifespan.[32]

- **Beamforming with AI**: mmWave systems enhanced by machine learning (e.g., GANs) improve transmission quality in dynamic environments.[34]
- **Efficient physical layer protocols**: Protocols like Enhanced ShockBurst (ESB) provide high-speed, low-power communication, while simulations using FDTD/MoM help optimize antenna design.[33]

I.8.4 Security framework for WBANs

Wireless Body Area Networks (WBANs) handle highly sensitive medical data, making security a critical requirement. Given their constraints in power, processing, and memory, WBANs demand lightweight, efficient, and layered security mechanisms. This section outlines a comprehensive, structured security framework that integrates encryption, authentication, key management, privacy preservation, and threat mitigation—tailored specifically to WBAN environments.

I.8.4.1 Encryption Techniques

To ensure data confidentiality and integrity in WBANs, lightweight encryption algorithms are used:

AES (Advanced Encryption Standard): A symmetric encryption standard suitable for WBANs due to its reliability and low overhead.[36]

PSRSA (Partial Simplified RSA): A lightweight RSA variant optimized for energy-constrained devices. It provides NIST AAL-3 level security by combining encryption with message authentication codes (E-MAC).[35]

XOR-based Encryption: Used in dynamic keying schemes where encryption keys are generated from reference frames, ensuring fast and energy-efficient encryption.[41]

I.8.4.2 Authentication and Authorization

Authentication prevents unauthorized access to data and devices:

TOKEN-PSRSA Protocol: Uses periodic token-based rekeying and E-MAC for mutual authentication between nodes.[35]

LIMAP (Lightweight Multilayer Authentication Protocol): Combines Elliptic Curve Cryptography (ECC) with custom hash functions for two-layer authentication, minimizing computation overhead.[39]

Hash-based Schemes: Utilize one-way hash functions and XOR operations to validate device identity while preserving anonymity.[40]

I.8.4.3 Key Management

Due to the dynamic nature of WBANs, efficient key management is essential:
Token-Based Rekeying: Keys are regularly refreshed using shared tokens, reducing the impact of key compromise.[37]

Reference Frame-Based Key Generation: Keys are derived from pre-agreed reference frames and synchronized sequence numbers, eliminating the need for costly key exchanges.[41]

I.8.4.4 Privacy Preservation

WBANs require strict privacy protections due to the sensitive nature of health data:

Identity Masking: Nodes periodically change their identifiers (pseudonyms) to prevent tracking.[40]

Data Anonymization: Personally identifiable information (PII) is removed or masked before transmission.[38]

I.9 Testbed

To understand the role of testbeds in WBAN development, it is important to first define what a testbed is and highlight its significance in bridging theoretical design and practical application.

I.9.1 Definition of a testbed and its importance in developing WBANs

The following subsection provides a precise definition of a testbed, outlining its structure, purpose, and key characteristics in system evaluation.

I.9.1.1 Definition of a testbed

Testbeds, as indicated previously, are composite abstractions of systems and are used to study system components and interactions to gain further insight into the essence of the real system. They are built of prototypes and pieces of real system components and are used to provide insight into the workings of an element(s) of a system. The important feature of a testbed is that it only focuses on a subset of the total system. That is, the important aspect that we wish to study, refine, or develop is the aspect implemented in the testbed. All other aspects have stubs that provide their stimulus or extract their load but are not themselves complete components, just simulated pieces. The testbed provides a realistic hardware-software environment with which to test components without having the ultimate system. The testbed provides a means to improve the understanding of the functional requirements and operational behavior of the system. It supplies measurements from which quantitative results about the system can be derived. It provides an integrated environment in which the interrelationships of solutions to system problems can be evaluated. Finally, it provides an environment in which design decisions can be based on both theoretical and empirical studies.[40]

I.9.1.2 Importance of Testbeds in Developing WBANs

Testbeds play a crucial role in the development and validation of Wireless Body Area Networks (WBANs). While simulations provide valuable insights into network performance, testbeds offer real-world environments where theoretical models and protocols can be tested under realistic conditions, including human body movement, interference, and hardware limitations.

They allow researchers to evaluate energy consumption, latency, reliability, and data accuracy using actual sensor nodes and wireless communication modules. This practical validation helps bridge the gap between simulation results and real deployment, making testbeds essential for developing robust and efficient WBAN applications, especially in healthcare and emergency monitoring systems.[41],[42]

I.9.2 Examples of Testbeds Used in WBANs

Testbeds play a crucial role in evaluating WBAN systems under realistic conditions. Here are some practical examples of testbeds used in WBAN development:

I.9.2.1 ASE-BAN Testbed

The ASE-BAN is modular wireless body area network testbed (a controlled experimental platform for testing and evaluating wireless body area networks) designed for real-life experiments. It consists of multiple sensors including those monitoring the autonomic nervous system, and integrates hardware like the Human ++ UniNode. It has been widely used in WBAN performance evaluations and real-time health monitoring scenarios.[43]

I.9.2.2 WBAN Sensor Prototype Testbed

This prototype was developed to assess WBAN vulnerability to wireless security attacks. It includes a basic sensor node with an antenna, a data rate of up to 250 kbps, and a 3V battery. It was used in experiments to identify security risks and define secure zones in WBAN deployments.[44]

I.9.4 Comparison between different testbeds

Table 4 Comparison between different testbeds

Testbed	Type	Focus	Advantages	Limitations
ASE-BAN	Physical	Real-world WBAN deployment	Real sensor nodes, modular design, physiological data	Limited scalability, cost of hardware
WBAN Sensor Prototype	Physical	Security testing in WBANs	Tests under real conditions, security vulnerability	Limited protocol flexibility, basic configuration

I.10 Simulators

Most Commonly Used Network Simulators

- **OMNeT++:** A powerful open-source network simulator widely used in academic research due to its flexible graphical interface and support for various types of networks (wired, wireless, ad hoc). It is particularly effective for simulating protocols and analyzing performance metrics such as energy consumption, packet loss, delay, jitter, and throughput.[47][46]
- **GNS3:** More of an emulator than a pure simulator, GNS3 allows running real network operating systems (e.g., Cisco IOS) for building realistic test environments. It is ideal for practical connectivity and configuration testing but is less suitable for statistical or protocol-level simulations.[48]
- **NS2 / NS3:** Open-source network simulators commonly used in academic research for protocol-level simulation. NS3, not to be confused with GNS3, is designed specifically for simulating wireless and sensor networks, and supports scripting in both C++ and Python.[49]
- **BNS Framework**

  Although not a physical testbed, the BNS (Body Network Simulator) framework is an advanced simulation tool built as an extension to the Castalia simulator. It provides a flexible environment to test various WBAN protocols, channel models, and patient mobility patterns, making it suitable for realistic and repeatable evaluations.[45]

I.11 Projects

Examples of WBAN Simulation Projects with Realistic Parameters

- **BNS Framework (OMNeT++/Castalia)**

Enables realistic WBAN simulations by modeling body-specific radio propagation, temperature effects, and healthcare protocols (IEEE 802.15.6, ISO/IEEE 11073) for eHealth scenarios.[50]

- **Body-to-Body Network Simulator (WSNet/OMNeT++)**

Uses real mobility and radio effects (LOS/NLOS) to simulate human motion and analyze path loss, fading, and interference in dynamic WBAN/BBN environments.[51]

- **Power-Aware Routing Protocols (OMNeT++)**

Focuses on testing routing strategies (e.g., temperature-based, cross-layer) under multi-user health monitoring conditions to improve latency, lifetime, and efficiency.[52]

I.12 Conclusion

In this part of the thesis, we tried to explain the main points about WBANs, including how they work, their structure, and the tools and protocols used to design them. This information will help us later to create a correct and useful simulation project in the next chapters.

Chapter II: Simulation Environment Setup and Performance Analysis

II.1 Introduction

This chapter demonstrates the experimental implementation of Wireless Body Area Network (WBAN) systems by developing a realistic simulation environment utilizing OMNeT++ discrete-event simulator integrated with the Castalia platform. It includes the stages of network design, node configuration, scenario setup, and application assignment for sensor nodes. Performance evaluation metrics are also used to measure the effectiveness of the network under different conditions. Finally, the results are analyzed and compared in order to draw meaningful conclusions and recommendations.

II.2 Selecting Compatible Versions of Castalia and OMNeT++

In order to ensure a stable and functional simulation environment, it is essential to select compatible versions of both Castalia and OMNeT++. This section provides an overview of each platform, explains the compatibility requirements between their versions, and details the steps needed to install and configure the simulation tools correctly.

II.2.1 Overview of the Castalia Platform

Castalia is a simulation platform specifically designed for low-power wireless networks such as Wireless Sensor Networks (WSNs) and Body Area Networks (BANs). Built on top of the OMNeT++ framework, it offers a flexible and accurate environment for testing communication protocols and distributed algorithms under realistic wireless conditions.[53][55]

Main Features:

- **Realistic Wireless Channel Modeling:**

  Castalia uses real-world experimental data to model the wireless channel. It supports node mobility, time-varying signal attenuation, and calculates interference based on the Received Signal Strength Indicator (RSSI) [53][54]

- **Accurate Radio Behavior:**

  The simulator models radio behavior using real parameters such as Signal-to-Interference-plus-Noise Ratio (SINR), packet size, and modulation type (e.g., PSK, FSK). It also supports multiple transmission power levels and models power consumption during state switching.[53][54]

- **Flexible Sensing and Physical Process Modeling:**

  Castalia allows users to simulate different sensor types and physical processes, including noise, bias, and power usage.[53]

- **Support for Protocols and Network Dynamics:**

It includes support for various MAC and routing protocols, and allows easy integration or modification of algorithms due to its modular structure.[53][55]

- **Parametric and Modular Design:**

Built using OMNeT++'s NED language, Castalia is highly modular and configurable, enabling users to define or extend simulation components easily.[53][55]

- **Output and Visualization Tools:**

The platform includes tools to process simulation results and generate graphs automatically from output files.[53]

Typical Use Cases:

- Testing and evaluation of communication protocols in WSNs and BANs.
- Simulation of radio and sensor behavior in realistic wireless environments.
- Analysis of energy consumption and protocol performance under different conditions.

II.2.2 Overview of the OMNeT++ Simulator

OMNeT++ is a modular, extensible, and component-based C++ simulation framework designed primarily for simulating communication networks [56]. It supports various network types including wireless sensor networks (WSNs), body area networks (BANs), Internet-based systems, and queuing models [57].

Key Features

- **Modular Architecture:**

OMNeT++ simulations are built from reusable modules written in C++. These modules can be simple or compound and are structured using the NED (Network Description) language [56].

- **Discrete Event Simulation:**

The simulator operates using a discrete event kernel, processing events in chronological order and handling time progression, message passing, and event scheduling efficiently [57].

- **User Interfaces:**

It offers both a graphical user interface (GUI) and a command-line interface. The GUI, based on the Eclipse IDE, supports editing, compiling, executing, and visualizing simulations [56].

- **Extensibility and Integration:**

OMNeT++ supports integration with model frameworks like INET (for Internet protocols) and Castalia (for sensor networks), making it suitable for domain-specific simulations [58].

- **Simulation Files:**

- . Ned files: Define module connections and network layout.
- .msg files: Specify message types.
- .cc / .h files: Contain the logic of simulation components.

Summary

OMNeT++ is a powerful and flexible simulation platform for designing, testing, and analyzing communication systems. Its modular design, ease of use, and broad community support make it widely used in academic and research environments.[56][57]

II.2.3 Compatibility Requirements Between the Two Versions

While setting up the simulation environment, it was found that **Castalia 3.2 is only compatible with OMNeT++ 4.6**, as mentioned in the official documentation [Castalia-Doc]. This is because newer versions of OMNeT++ introduced major changes in file structure and how simulations are handled, which can cause errors if unsupported versions are used. For this reason, **OMNeT++ 4.6** was selected to ensure Castalia works correctly. [58]

II.2.4 Installing and Setting Up the Working Environment

Steps to Install Castalia 3.2 with OMNeT++ 4.6

1. **Download OMNeT++ 4.6**

OMNetT++ 4.6 has been downloaded from the official website.:

https://omnetpp.org

After downloading, extract the archive, then open the mingwenv.cmd file located inside the OMNeT++ directory.

Execute the following commands in the terminal:

```
. /Setenv
. /Configure
make
```

2. **Download Castalia 3.2**

Download Castalia 3.2 from the official repository:

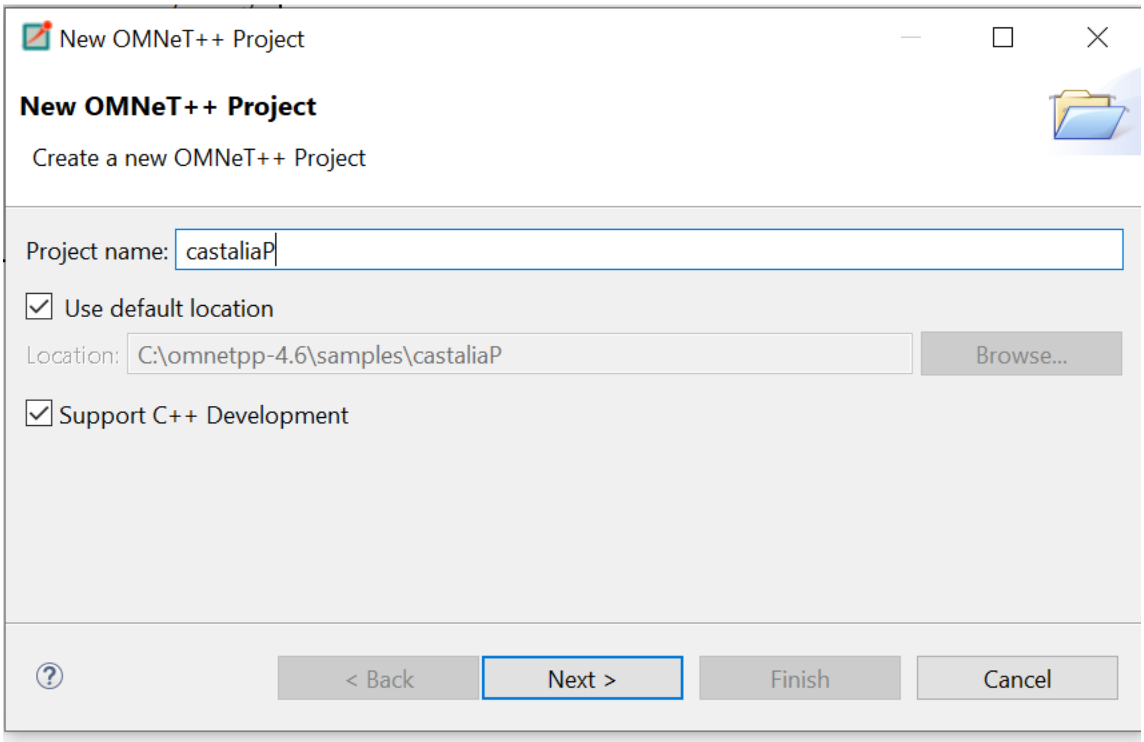
https://github.com/boulis/Castalia

3. **Extract and Copy the Project**

After downloading, extract the Castalia-3.2 folder.

Copy this folder into the OMNeT++ directory, for example:

~/omnetpp-4.6/Castalia-3.2



New OMNeT++ Project

New OMNeT++ Project

Create a new OMNeT++ Project

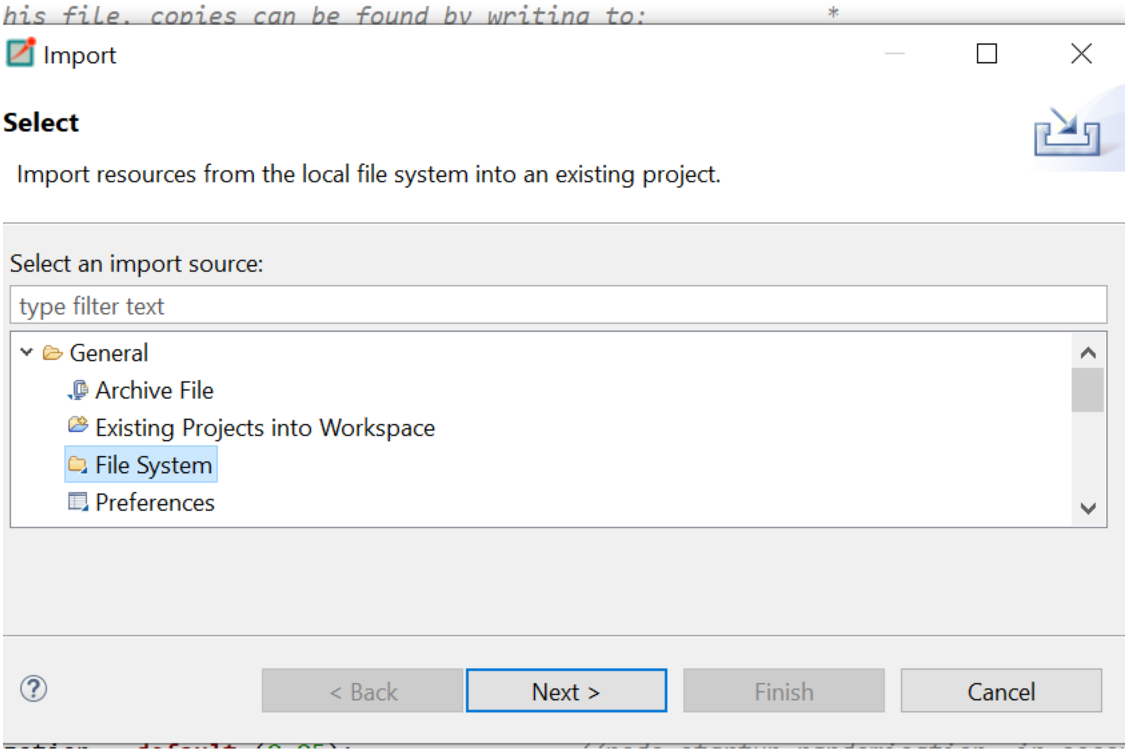
Project name: castaliaP

☑ Use default location

Location: C:\omnetpp-4.6\samples\castaliaP

☑ Support C++ Development

Figure II.0-1 Castalia_Folder_Structure



Import

Select

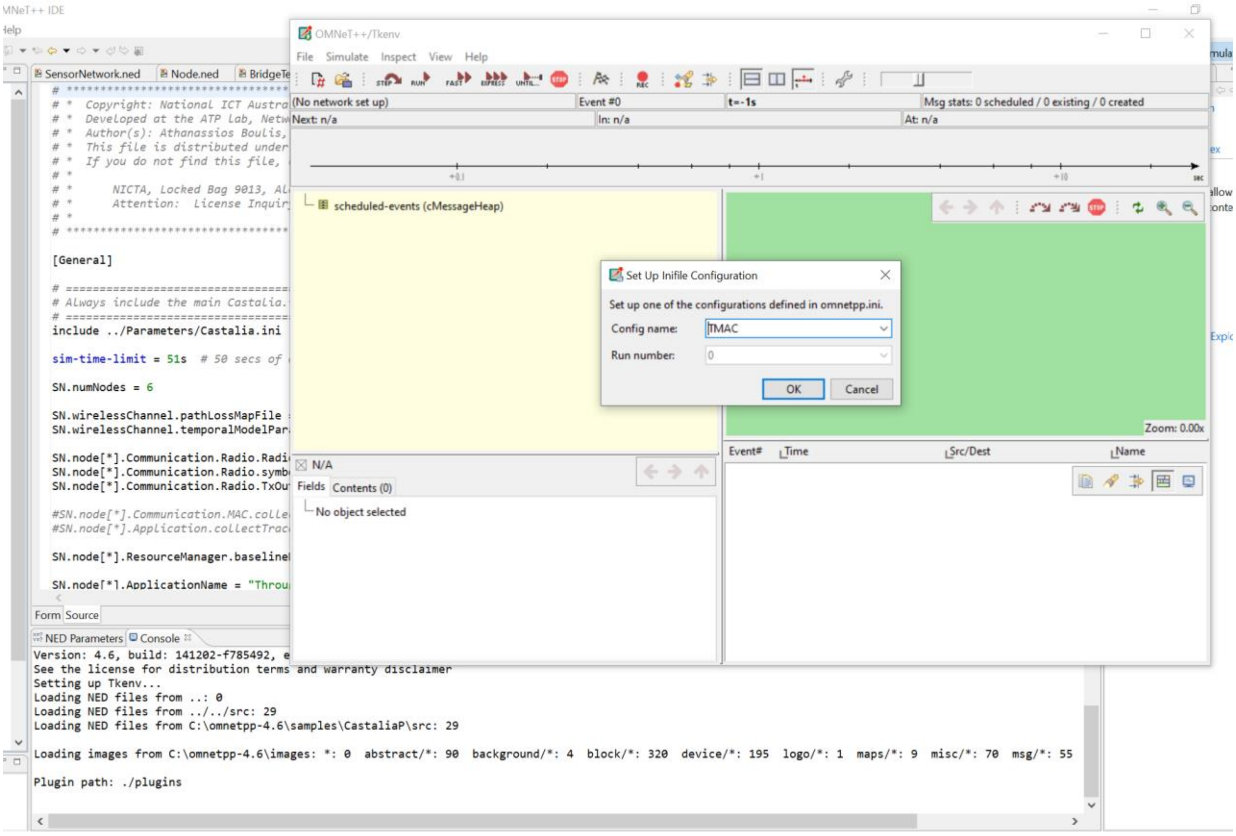
Import resources from the local file system into an existing project.

Select an import source:

type filter text

- General
  - Archive File
  - Existing Projects into Workspace
  - File System
  - Preferences

Figure II.0-2 OMNeT_IDE_Overview



```
# *********************************
# *  Copyright: National ICT Austra
# *  Developed at the ATP lab, Netw
# *  Author(s): Athanassios Boulis,
# *  This file is distributed under
# *  If you do not find this file,
# *
# *      NICTA, Locked Bag 9013, Al
# *      Attention:  License Inquir
# *
# *********************************

[General]

# =================================
# Always include the main Castalia.
# =================================
include ../Parameters/Castalia.ini

sim-time-limit = 51s  # 50 secs of

SN.numNodes = 6

SN.wirelessChannel.pathLossMapFile
SN.wirelessChannel.temporalModelPar

SN.node[*].Communication.Radio.Radi
SN.node[*].Communication.Radio.symb
SN.node[*].Communication.Radio.TxOu

#SN.node[*].Communication.MAC.colle
#SN.node[*].Application.collectTrac

SN.node[*].ResourceManager.baseline

SN.node[*].ApplicationName = "Throu
```

(No network set up) | Event #0 | t=-1s | Msg stats: 0 scheduled / 0 existing / 0 created

Next: n/a | In: n/a | At: n/a

Set Up Inifile Configuration

Set up one of the configurations defined in omnetpp.ini.

Config name: TMAC

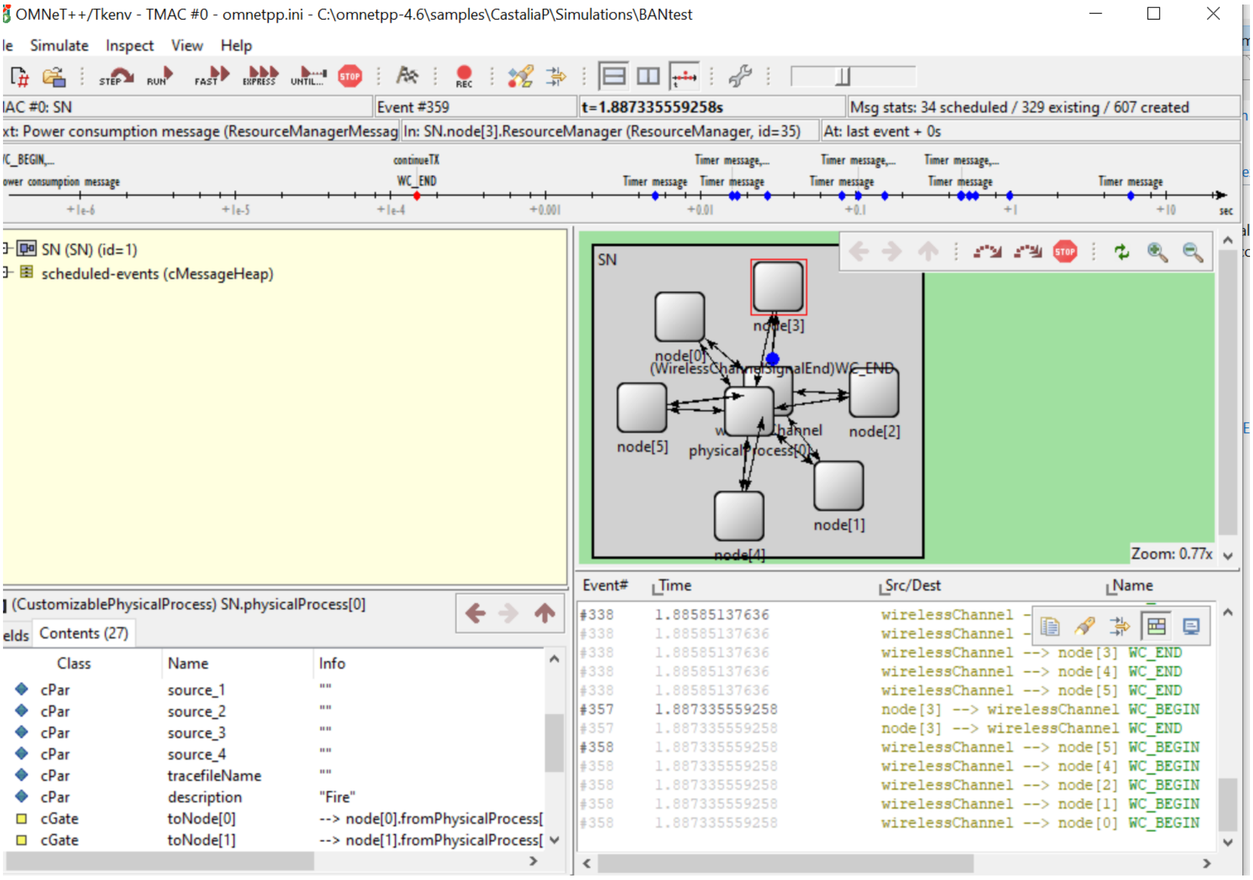
Run number: 0

```
Version: 4.6, build: 141202-f785492, e
See the license for distribution terms and warranty disclaimer
Setting up Tkenv...
Loading NED files from ..: 0
Loading NED files from ../../src: 29
Loading NED files from C:\omnetpp-4.6\samples\CastaliaP\src: 29

Loading images from C:\omnetpp-4.6\images: *: 0  abstract/*: 90  background/*: 4  block/*: 320  device/*: 195  logo/*: 1  maps/*: 9  misc/*: 70  msg/*: 55

Plugin path: ./plugins
```

Figure II.0-3 Simulation_Configuration_Settings



IAC #0: SN | Event #359 | t=1.887335559258s | Msg stats: 34 scheduled / 329 existing / 607 created

xt: Power consumption message (ResourceManagerMessag | In: SN.node[3].ResourceManager (ResourceManager, id=35) | At: last event + 0s

(CustomizablePhysicalProcess) SN.physicalProcess[0]

elds | Contents (27)

	Class	Name	Info
◆	cPar	source_1	""
◆	cPar	source_2	""
◆	cPar	source_3	""
◆	cPar	source_4	""
◆	cPar	tracefileName	""
◆	cPar	description	"Fire"
☐	cGate	toNode[0]	--> node[0].fromPhysicalProcess[
☐	cGate	toNode[1]	--> node[1].fromPhysicalProcess[

```
Event#    Time              Src/Dest                         Name
#338      1.88585137636     wirelessChannel -
#338      1.88585137636     wirelessChannel -
#338      1.88585137636     wirelessChannel --> node[3] WC_END
#338      1.88585137636     wirelessChannel --> node[4] WC_END
#338      1.88585137636     wirelessChannel --> node[5] WC_END
#357      1.887335559258    node[3] --> wirelessChannel WC_BEGIN
#357      1.887335559258    node[3] --> wirelessChannel WC_END
#358      1.887335559258    wirelessChannel --> node[5] WC_BEGIN
#358      1.887335559258    wirelessChannel --> node[4] WC_BEGIN
#358      1.887335559258    wirelessChannel --> node[2] WC_BEGIN
#358      1.887335559258    wirelessChannel --> node[1] WC_BEGIN
#358      1.887335559258    wirelessChannel --> node[0] WC_BEGIN
```

Figure II.0-4 Simulation_Results_Visualization

II.3 WBAN Network Design

This part outlines the network configuration adopted for the simulation. It includes the specification of node types and numbers, the chosen simulation scenarios, the applications implemented on each node, and the criteria used to assess network performance.

II.3.1 Defining the Number and Types of Nodes

In setting up the simulation environment for the WBAN using Castalia and OMNeT++, the number and types of nodes were defined based on the project scenarios. The network consists of five (5) nodes distributed as follows:

- One central node (Sink): assigned number 0, it is the main element in the network. Its function is to receive data from the sensor nodes, then process or forward it to an external system.
- Four sensor nodes (1 to 4): represent sensors attached to the human body to monitor health data such as temperature, blood pressure, blood sugar level, and oxygen saturation (SpO2). These nodes periodically collect data and send it to the central node.

II.3.2 Setting Up the Applications Used

Each node in the network uses an application called *UnifiedHealthMonitoringApp*, which is responsible for reading sensor values, analyzing them, and deciding whether to send data based on the scenario type. Node 0 (Sink) only receives data and stores the results in CSV files.

II.3.3 Defining the Evaluation Metrics

Three main metrics were used to evaluate the network's performance:

- Energy consumption: the amount of energy used by each node during the simulation.
- Delay time: the time between sending a packet from the sensor and receiving it at the Sink.
- Packet delivery ratio: the number of received packets compared to the number of sent packets.

II.4 Executing the Simulation

This section covers the step-by-step execution of the simulation, from setting up the environment to analyzing the extracted results.

II.4.1 Setting Up the Simulation Framework

OMNeT++ (version 4.6) was used alongside the Castalia framework, which is a specialized tool for simulating wireless networks, especially WBANs. Castalia provides a flexible environment for configuring nodes, setting up protocols, and defining communication properties.

II.4.2 Preparing the Configuration Files

Before running the simulation, the configuration file WBAN*App.ini* was prepared to specify: Other configuration files for the physical layer, MAC, and radio were included via *include* directives in the *.ini* file and .ned.

The full content of the main configuration files used in the simulation is provided below for completeness and reproducibility.

Table 5 WBAN Simulation Parameters and Scenario Definitions

Parameter	Value	Notes
Topology	One hop star	Nodes 1..4 transmit directly to node 0 (Sink)
Sink / Hub Node	node [0]	SN. Node [0]. Application.isSink = true and MAC.isHub = true
Number of Nodes	5	SN. Num Nodes = 5

Radio Parameters File	BANRadio.txt	SN. node [*]. Communication. Radio. RadioParametersFile
MAC Protocol	BaselineBANMac (IEEE 802.15.6 draft)	SN. node [*]. Communication.MACProtocolName = "BaselineBANMac"
Routing Protocol	BypassRouting (no routing)	No actual routing (1-hop)
Simulation Time	3600s	sim-time-limit = 3600s
Path Loss File	pathLossMap.txt	SN. wirelessChannel.pathLossMapFile
Temporal Model File	TemporalModel.txt	SN. wirelessChannel.temporalModelParametersFile
Tx Output Power	-15dBm	SN. node [*]. Communication.Radio. TxOutputPower = "-15dBm"
Initial Energy per Node	100000	SN. node [*]. ResourceManager.initialEnergy = 100000
Baseline Node Power	0	SN. node [*]. ResourceManager.baselineNodePower = 0
PHY Data Rate	1024	SN. node [*]. Communication.MAC.phyDataRate = 1024
RSSI Symbols	16	SN. Node [*]. Communication.Radio. SymbolsForRSSI = 16
Sensor Types per Node	node [1]: temperature node [2]: blood_pressure node [3]: glucose node [4]: spo2	Defined via SensorManager.sensorTypes
Application Name	WBANApp	SN. node [*]. ApplicationName = "WBANApp"
Sink Flags	node [0]: true, others: false	Set via Application.isSink

Scenarios Defined	Scenario1-AlwaysSend Scenario2-ThresholdOnly Scenario3-ThresholdAndPeriodic	Three different application configurations
Sample Intervals (per scenario)	node[1]: 20s node[2]: 30s node[3]: 40s node[4]: 15s	Repeated across all scenarios
Thresholds (Scenario 2 & 3)	temp: 36.5–38.5 bp: 100–140 glucose: 70–140 spo2: 90–97	Each sensor has different min/max threshold values
Periodic Forcing (Scenario 3)	forceSendPeriod = 10	Forces nodes to send data every 10 samples even if no threshold exceeded

- **WBANApp.ini file :**
  The complete code of our protocol is in Annex-A-
- **WBAN App.ned file :**
- The complete code of our protocol is in Annex-B-

This is File Interaction Diagram in WBAN Simulation using Castalia

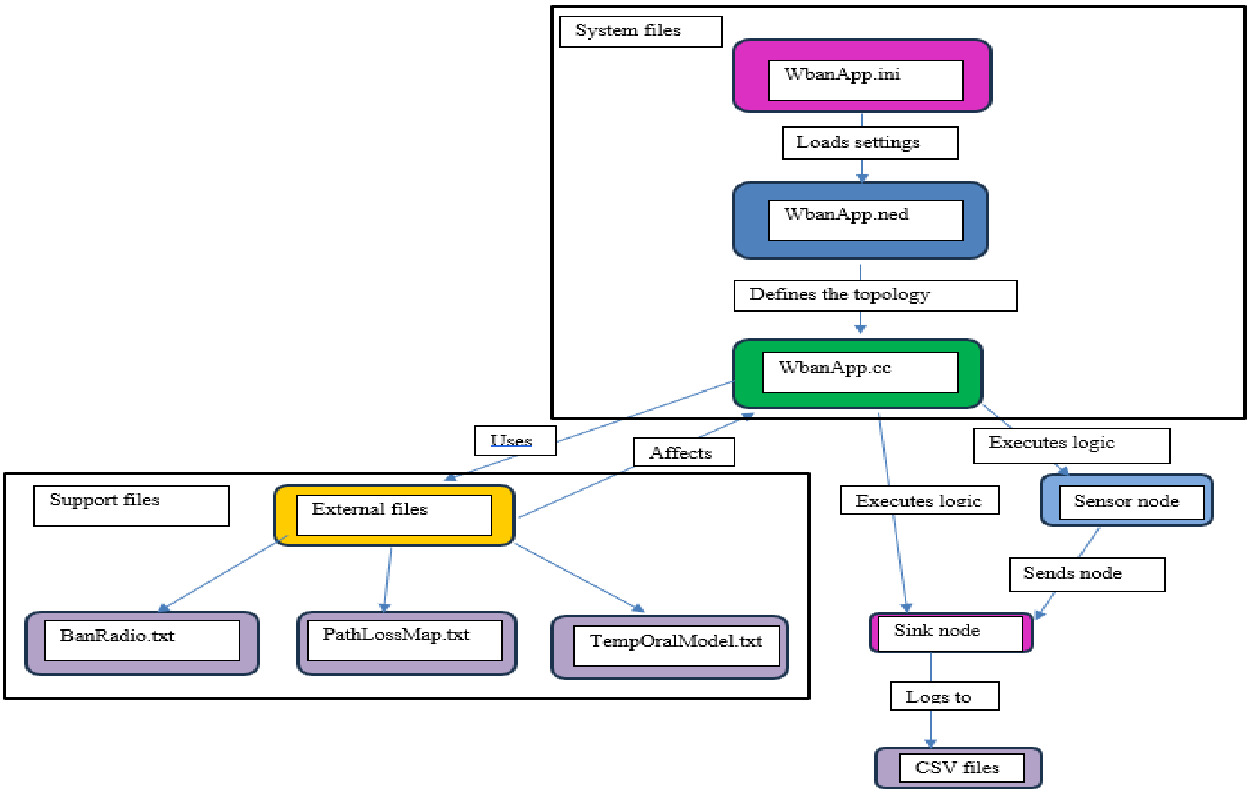


Figure II.0-5 File Interaction Diagram in WBAN Simulation using Castalia

II.4.3 Collecting and Analyzing the Results

During the simulation, the central node (Sink) receives data from different sensors and automatically records it in separate CSV files according to the sensor type.

Each file contains detailed information including:

- The time the packet was received
- Sending node number
- Measured value
- Status type (normal, alert, emergency)
- Delay time
- Reception signals (RSSI and LQI)

This data is later used to plot graphs and analyze network performance in terms of energy consumption, delay, and packet delivery ratio.

II.5 Results Presentation and Analysis

To begin the analysis, we first explain how data is generated and transmitted within the WBAN simulation, focusing on the core functions responsible for sending and receiving sensor data.

II.5.1 Translation of the Functions handleSensorReading and from NetworkLayer in a WBAN Application

In a Wireless Body Area Network (WBAN), nodes are divided into two types:

- Sensor Nodes: These nodes capture readings from the body (such as temperature, blood pressure, oxygen levels, etc.).
- Sink Node: This node receives all data from the sensors and either analyzes or stores it.

First: handleSensorReading

Execution Location:

This function is executed only in sensor nodes.

Functionality:

- Generates a random sensor reading (temperature, blood pressure, glucose, SpO2, etc.).
- Analyzes whether the value is "normal," "warning," or "emergency."
- Based on the activated scenario, it decides whether to send this reading to the Sink node or not.

If it is decided to send the reading:

- A data packet is created.
- Information such as the value, sensor type, and node number is populated.
- The packet is sent to the Sink node.
- Transmission information is printed to the console.

Who Sends?

The sensor node is responsible for sending data to the Sink node.

Second: fromNetworkLayer function

Execution Location:

This function is executed only in the Sink node.

Functionality:

- Receives packets sent from sensor nodes.
- Extracts:
  - Sensor type.
  - Sent value
  - Time of transmission.
  - Sending node number.
- Calculates the delay between sending and receiving the packet.
- Prints this information to the console.
- Stores results in a CSV file specific to each sensor type (e.g., temperature.csv, glucose.csv, etc.).

Who Receives?

The Sink node receives data from the sensor nodes.

- Relationship Between the Two Functions:

The handleSensorReading function in sensor nodes generates and sends data packets to the Sink node, while the fromNetworkLayer function in the Sink node receives these packets, processes them, and stores the relevant information.

- Example :

Node 1 (Temperature Sensor) generates a reading of 37.5°C.
This reading is considered normal in Scenario 1 (constant transmission).
The packet is sent to Node 0.
Node 0 receives the packet and prints:

```
[15.2] Sink RECV: temperature = 37.50 | From: 1 | Delay: 0.02s | Seq: 5
```

The result is stored in the file temperature.csv.

II.5.2 Tools Used in the Practical Part

- **Castalia and OMNeT++:**
  OMNeT++ version 4.6, together with the Castalia framework, was used to simulate the WBAN network under different scenarios. This setup was selected due to its flexibility and its support for modeling wireless medical sensor networks.
- **CSV Files:**
  These files were used to store simulation results (such as measured values, timestamps, and node IDs) in an organized format, making performance analysis easier and more accurate.
- **Python Language:**
  Python was used within the Google Colab environment to analyze the simulation output, such as calculating delay rates and generating performance-related plots and graphs.

II.5.3 Presenting Results

We simulated three different scenarios to study the performance of the WBAN network. Each scenario represents a specific data transmission method.

Scenario1-AlwaysSend

Is based on periodic transmission, bellow an extract of the results obtained

```
[15.014759069498] Node 4 SENT: spo2 = 82.43 (Alert), Seq=1
[15.074754352125] Sink RECV: spo2 = 82.43 | From: 4 | spo2 | Delay: 0.06s Seq: 1
[20.003672223318] Node 1 SENT: temperature = 37.55 (Normal), Seq=1
```

```
[20.195421439226] Sink RECV: temperature = 37.55 | From: 1 | temperature | Delay: 0.19s Seq: 1
[30.014972901817] Node 4 SENT: spo2 = 91.39 (Normal), Seq=2
[30.036943178518] Node 2 SENT: blood_pressure = 143.58 (Alert), Seq=1
[40.00380820262] Node 1 SENT: temperature = 37.19 (Normal), Seq=2
[40.034811546446] Sink RECV: temperature = 37.19 | From: 1 | temperature | Delay: 0.03s Seq: 2
[40.04175752708] Node 3 SENT : glucose = 140.67 (Alert), Seq=1
[40.044925322291] Sink RECV: glucose = 140.67 | From: 3 | glucose | Delay: 0.00s Seq: 1
[45.015186734136] Node 4 SENT: spo2 = 80.37 (Alert), Seq=3
[45.153318680605] Sink RECV: spo2 = 80.37 | From: 4 | spo2 | Delay: 0.14s Seq: 2
[60.003944181922] Node 1 SENT: temperature = 35.63 (Alert), Seq=3
[60.015400566455] Node 4 SENT: spo2 = 80.81 (Alert), Seq=4
[60.038478965927] Node 2 SENT: blood_pressure = 102.43 (Normal), Seq=2
[60.193500844249] Sink RECV: temperature = 35.63 | From: 1 | temperature | Delay: 0.19s Seq: 3
[60.196021053158] Sink RECV: blood_pressure = 102.43 | From: 2 | blood_pressure | Delay: 0.16s Seq: 1
```

During the simulation, several messages were recorded to represent the activity and behavior of the network nodes. Below is a brief explanation of the main elements shown in the simulation results:

- **Node X SENT:**
  This indicates that node X (à sensor) has sent à data reading at a specific moment. Each sensor sends its health data (such as temperature, blood pressure, etc.) at different time intervals depending on the applied scenario.
- **Sink RECV:**
  This means that the central node (Sink) has received the data sent by one of the sensor nodes. The received message includes the measured value, the ID of the sending node, and the reception time.
- **Delay:**
  Represents the time difference between when the data was sent and when it was received, usually measured in seconds (s). This is a key metric in evaluating network performance.
- **Seq (Sequence Number):**
  A unique number assigned to each data packet, both at sending (SENT) and receiving (RECV). It is used to track the order of messages and to detect any data loss or delay.

- **Sensor Readings:**
  Each sensor in the network (temperature, blood pressure, glucose, SpO2...) generates independent readings. These values are recorded in CSV files, organized by sensor type, to allow for detailed analysis later.

The following graphs show the sensor data trends over time, allowing for a visual analysis of how each physiological parameter evolved during the simulation.

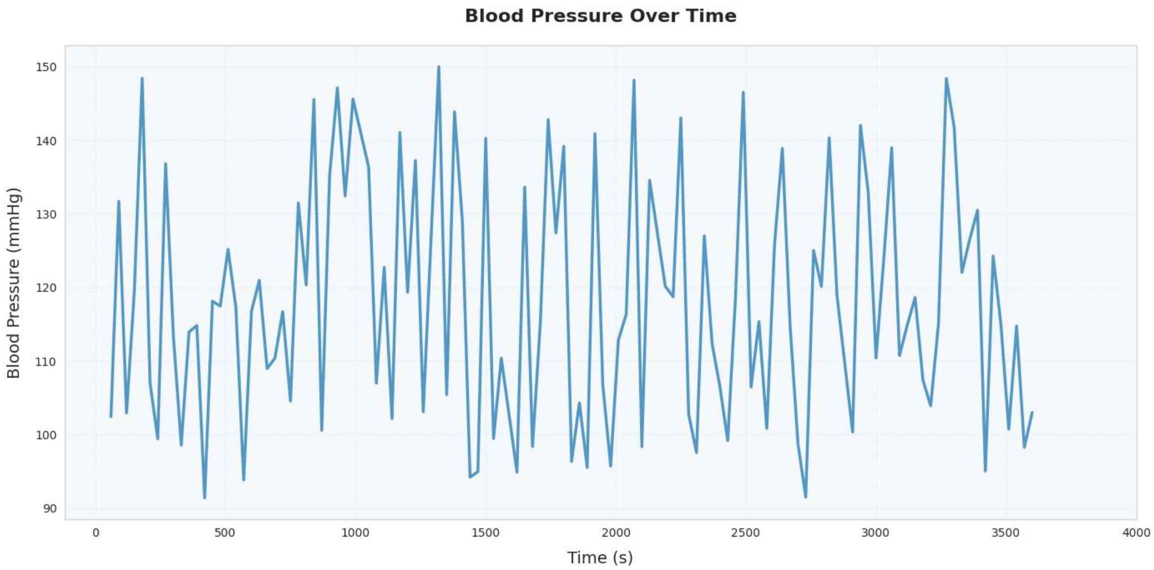


Figure II.0-6 Temporal Analysis of Blood Pressure Dynamics in Wireless Body Area Networks

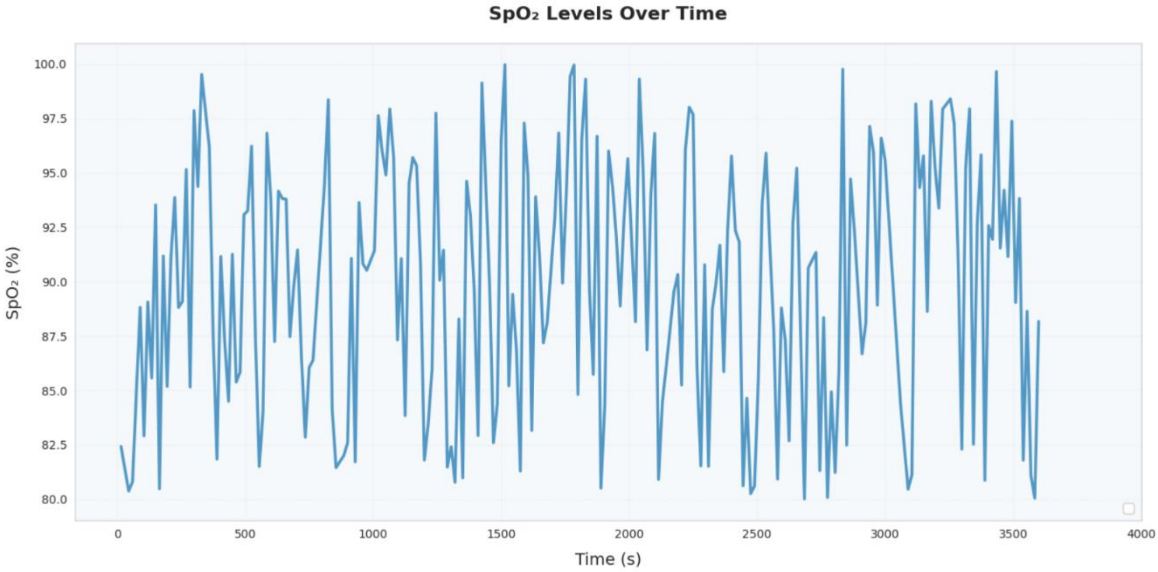


Figure II.0-7 Temporal Variation of Blood Oxygen Saturation (SpO₂) Levels in WBAN Monitoring

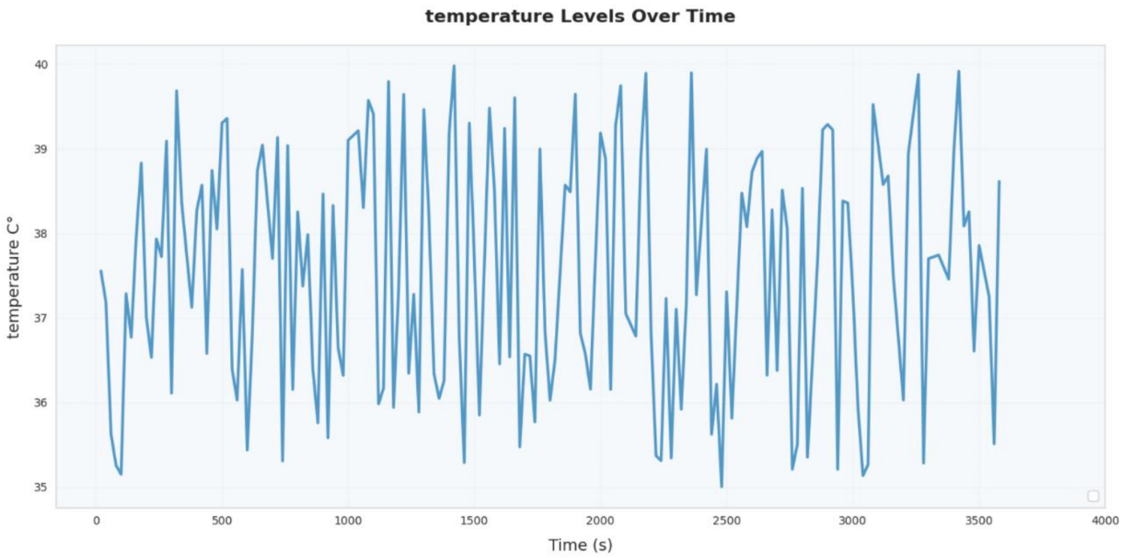


Figure II.0-8 Temporal Dynamics of Body Temperature Variations in WBAN Monitoring Systems

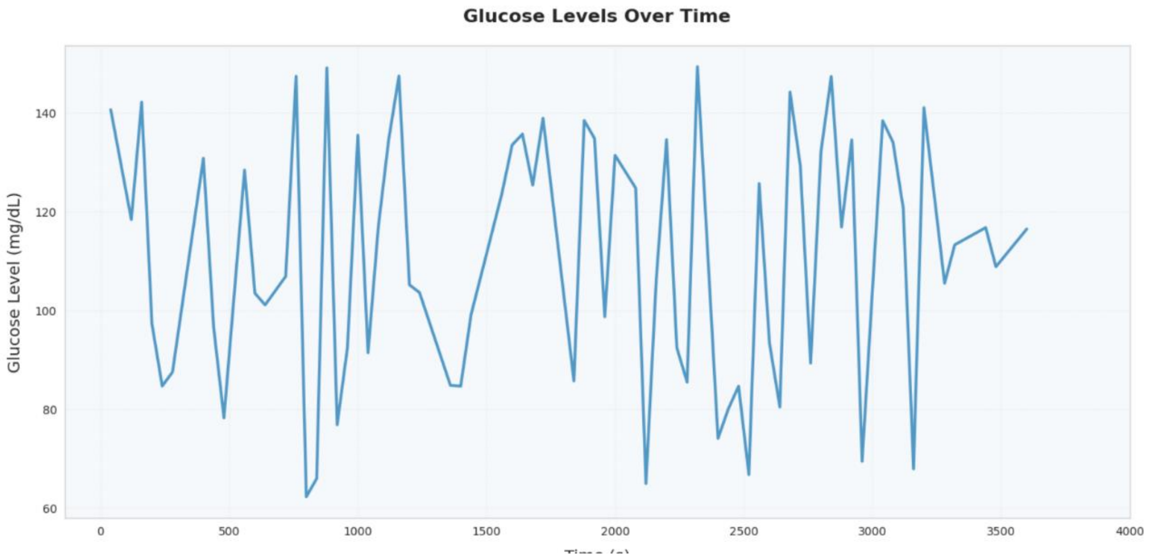


Figure II.0-9 Temporal Evolution of Glucose Levels in WBANs

- **Delay Variation Between Sending and Receiving in WBAN**

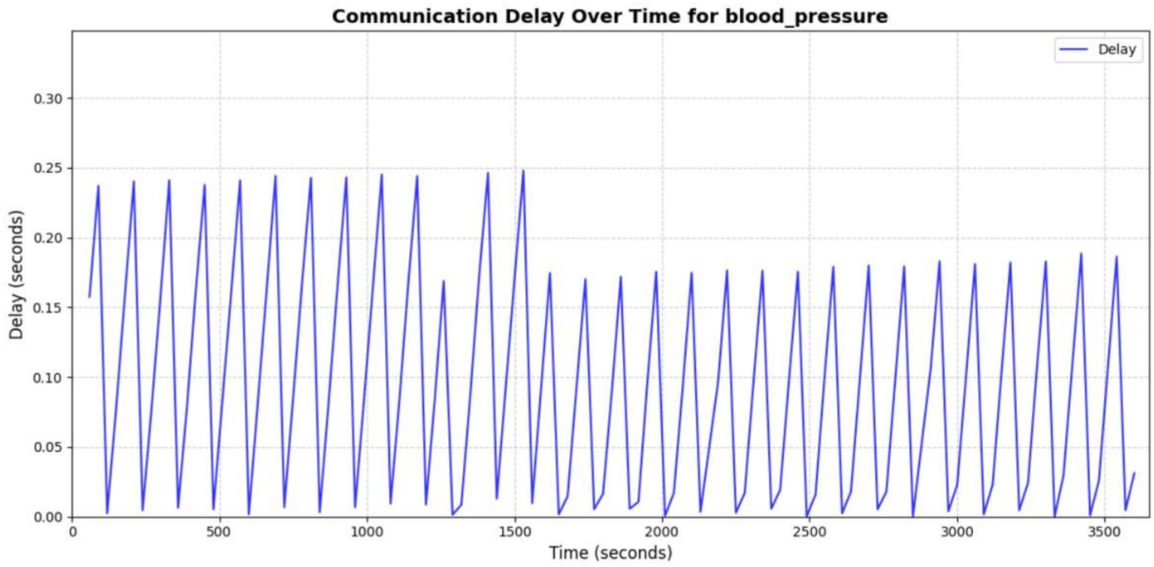


Figure II.0-10 Temporal Analysis of Blood Pressure Data Transmission Delay in WBANs

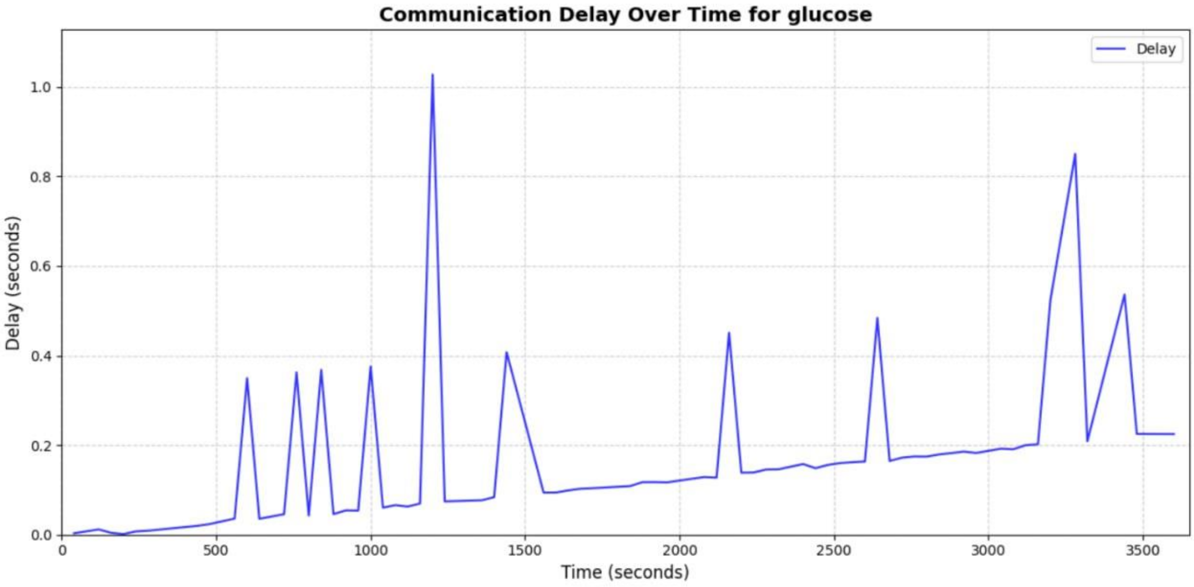


Figure II.0-11 Communication Delay Over Time for Glucose

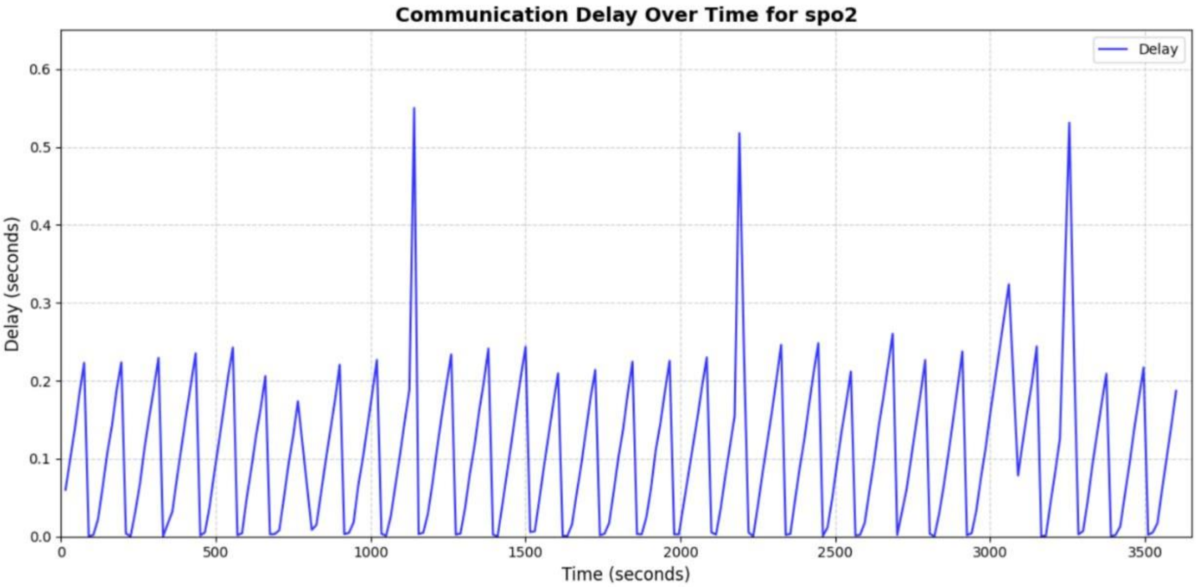


Figure II.0-12 Communication Delay Over Time for spo2

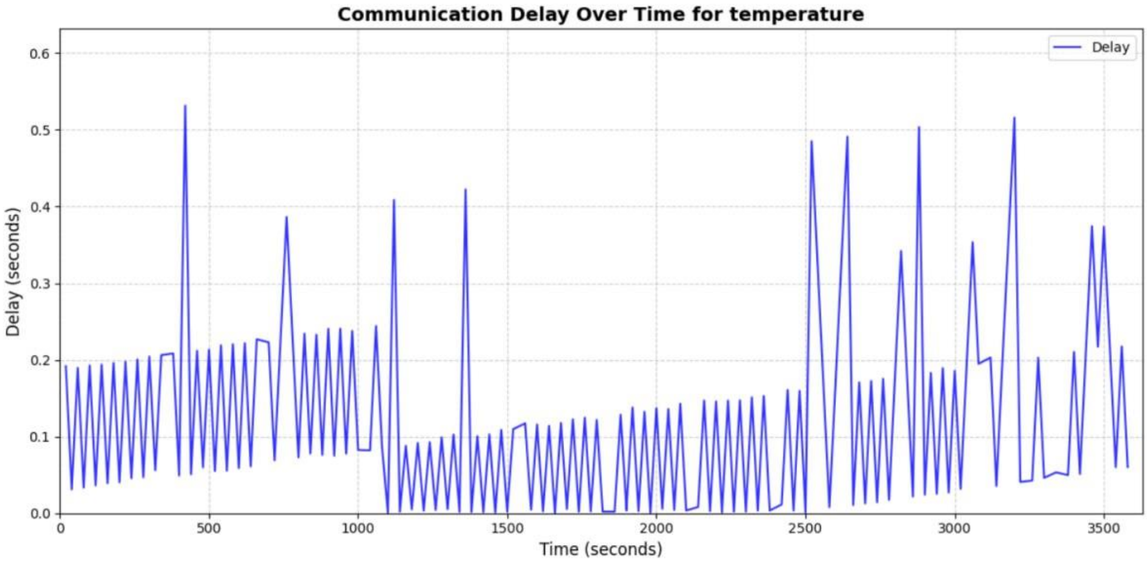


Figure II.0-13 Communication Delay Over Time for Temperature

Scenario2-ThresholdOnly

After executing **the second scenario,** which is based on threshold-triggered transmission, the following results were recorded. These results reflect the behavior of the nodes under this condition.

```
[15.014759069498] Node 4 SENT: spo2 = 82.43 (Alert), Seq=1
[15.074754352125] Sink RECV: spo2 = 82.43 | From: 4 | spo2 | Delay: 0.06s Seq: 1
[30.036943178518] Node 2 SENT: blood_pressure = 143.58 (Alert), Seq=1
[30.116016770645] Sink RECV: blood_pressure = 143.58 | From: 2 | blood_pressure | Delay:
0.08s Seq: 1
```

```
[40.04175752708] Node 3 SENT : glucose = 140.67 (Alert), Seq=1
[40.044565324452] Sink RECV: glucose = 140.67 | From: 3 | glucose | Delay: 0.00s Seq: 1
[45.015186734136] Node 4 SENT: spo2 = 80.37 (Alert), Seq=2
[45.154398695995] Sink RECV: spo2 = 80.37 | From: 4 | spo2 | Delay: 0.14s Seq: 2
[60.003944181922] Node 1 SENT: temperature = 35.63 (Alert), Seq=1
[60.015400566455] Node 4 SENT: spo2 = 80.81 (Alert), Seq=3
[60.196020861371] Sink RECV: temperature = 35.63 | From: 1 | temperature | Delay: 0.19s Seq: 1
```

Explanation of Observations in Scenario 2

- **Node X SENT:**
  This message indicates that the sensor node (Node X) transmitted data only when the measured values exceeded predefined thresholds. The transmissions occurred at different time intervals depending on each case.
- **Sink RECV:**
  This shows that the central node (Sink) successfully received the data sent by the sensor.
- **Delay:**
  Refers to the time between the moment the packet was sent by the sensor and the moment it was received by the Sink. It is a key metric used to evaluate network performance.
- **Seq (Sequence Number):**
  Both the SENT and RECV messages include a sequence number, which helps track each packet and verify whether any data was lost or delayed.
- **Graphical Results:**
  In this scenario, graphical plots were generated for only two sensors. These graphs highlight when the threshold values were exceeded and data was transmitted, showing the behavior of each sensor under this transmission condition.

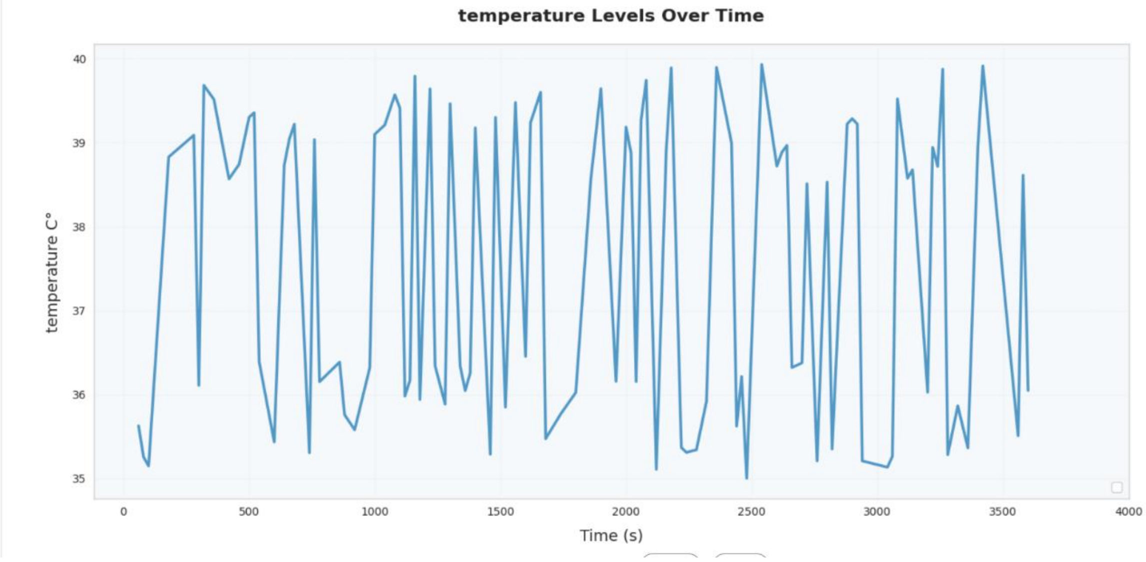


Figure II.0-14 Temperature Levels Over Time

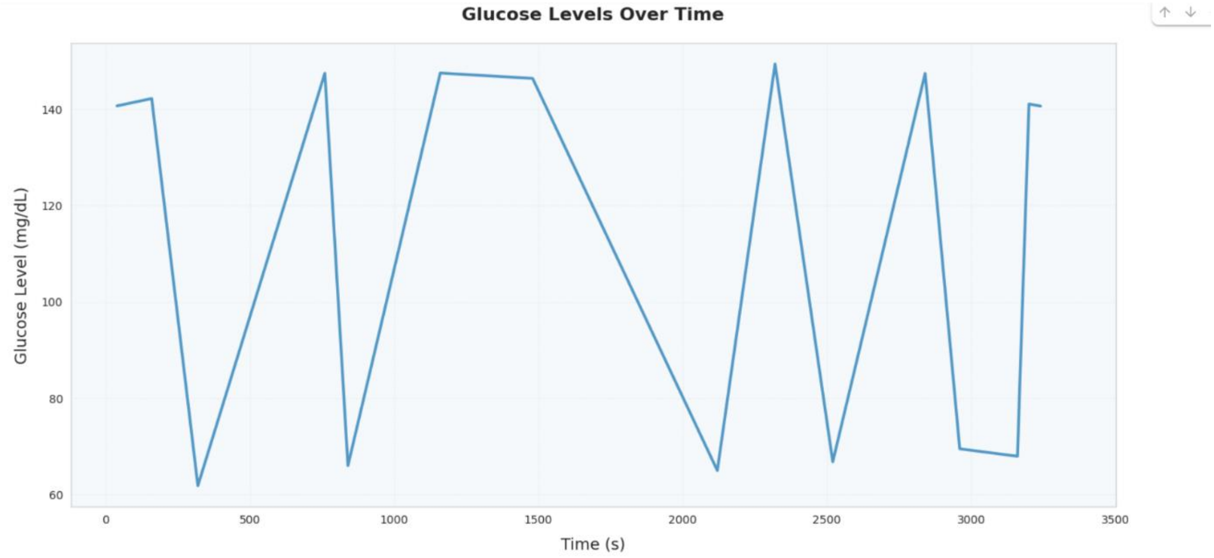


Figure II.0-15 Glucose Levels Over Time

Scenario3-ThresholdAndPeriodic

The simulation results in **the third scenario** showed the effectiveness of this pattern in balancing emergency transmission with regular periodic transmission, according to the following results:

```
[15.014759069498] Node 4 SENT: spo2 = 82.43 (Emergency), Seq=1
[15.074754352125] Sink RECV: spo2 = 82.43 | From: 4 | spo2 | Delay: 0.06s Seq: 1
[30.036943178518] Node 2 SENT: blood_pressure = 143.58 (Emergency), Seq=1
[30.116016770645] Sink RECV: blood_pressure = 143.58 | From: 2 | blood_pressure | Delay: 0.08s Seq: 1
[40.04175752708] Node 3 SENT: glucose = 140.67 (Emergency), Seq=1
```

```
[40.044565324452] Sink RECV: glucose = 140.67 | From: 3 | glucose | Delay: 0.00s Seq: 1
[45.015186734136] Node 4 SENT: spo2 = 80.37 (Emergency), Seq=2
[45.154398695995] Sink RECV: spo2 = 80.37 | From: 4 | spo2 | Delay: 0.14s Seq: 2
[60.003944181922] Node 1 SENT: temperature = 35.63 (Emergency), Seq=1
[60.015400566455] Node 4 SENT: spo2 = 80.81 (Emergency), Seq=3
[60.196020861371] Sink RECV: temperature = 35.63 | From: 1 | temperature | Delay: 0.19s
Seq: 1
[60.515680083925] Sink RECV: spo2 = 80.81 | From: 4 | spo2 | Delay: 0.50s Seq: 3
[75.015614398774] Node 4 SENT: spo2 = 84.96 (Emergency), Seq=4
```

- **Node X SENT:**
  This message indicates that sensor node X transmitted data either when the measured values exceeded predefined emergency thresholds or at regular periodic intervals. This hybrid transmission model ensures responsiveness to critical events while maintaining regular monitoring.
- **Sink RECV:**
  This shows that the central node (Sink) successfully received the data sent by the respective sensor. Each received message includes relevant metadata such as the sensor ID, data type, measured value, delay, and sequence number.
- **Delay:**
  The delay refers to the elapsed time between the moment the data was transmitted by the sensor and the moment it was received by the Sink. In this scenario, variations in delay help evaluate the impact of mixing emergency and periodic transmissions on network performance.
- **Seq (Sequence Number):**
  Each SENT and RECV message contains a sequence number, which helps in tracking individual packets and detecting possible data loss, duplication, or latency.
- **Graphical Results:**
  In this scenario, graphs were generated for several sensors to visually represent the behavior of the network under a combined transmission approach. These plots clearly show when emergency thresholds were exceeded and when regular periodic data was sent, allowing for a better understanding of how each sensor behaved under mixed transmission conditions.

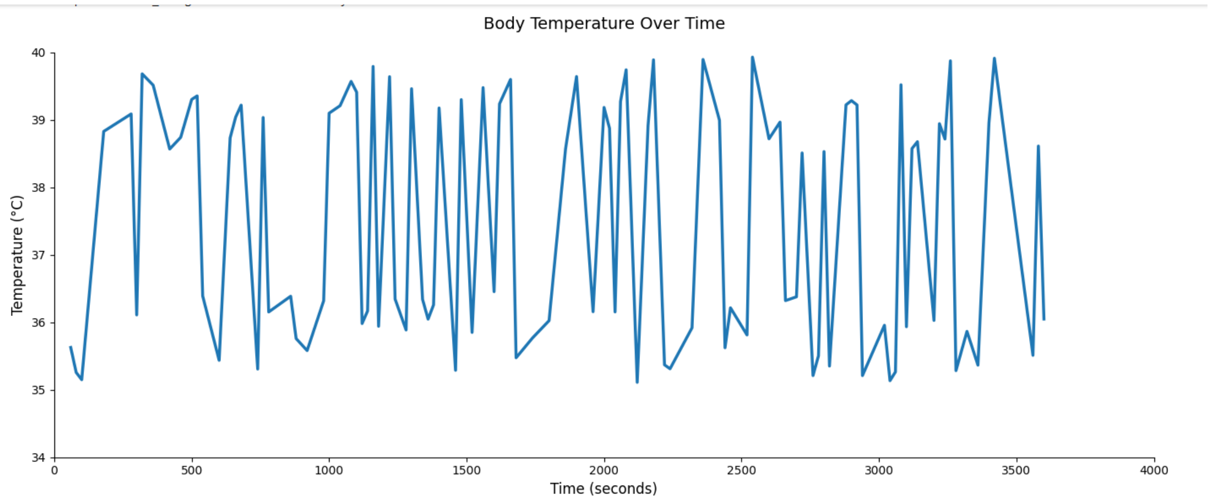


Figure II.0-16 Body Temperature Over Time

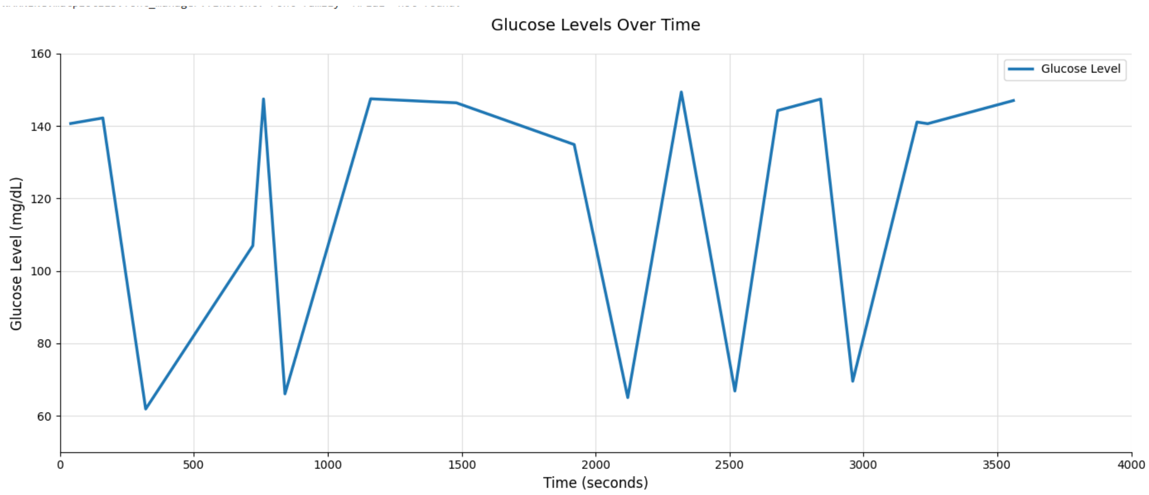


Figure II.0-17 Glucose Levels Over Time

II.5.4 Comparing Different Scenarios

- **Scenario 1 : Continuous Transmission**

This scenario is characterized by continuously sending all sensor readings regardless of their values, providing a complete and accurate dataset. It is ideal for research and clinical studies that require high precision. However, it suffers from high energy consumption and significant pressure on network capacity, which may limit its effectiveness in long-term applications.

- **Scenario 2 : Transmission Only During Emergencies**

This model focuses on efficiency by sending data only when values exceed specified thresholds, ensuring excellent energy savings and making it ideal for early warning systems and emergency monitoring. However, it may result in the loss of some data between thresholds and may not capture important gradual changes in the patient's condition.

- **Scenario 3 : Hybrid Model**

This scenario effectively combines the advantages of the previous two models by sending data immediately during emergencies while maintaining periodic transmission of important readings. This provides an optimal balance between data accuracy and energy conservation, making it the best choice for most daily medical monitoring applications, although it requires more complex implementation than the other models.

The following graph shows the variation of glucose values sent by the sensors in a WBAN network during the simulation period, under three different transmission scenarios:

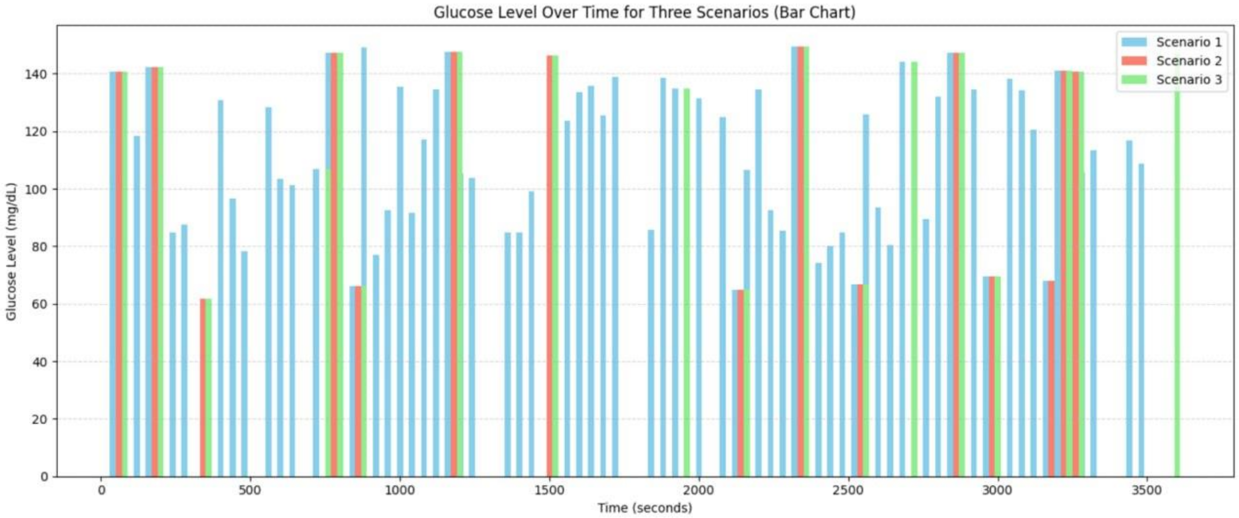


Figure II.18 Comparative analysis of glucose levels (mg/dL) across different transmission scenarios in wireless body area networks (WBANs)

The chart illustrates the variation of glucose levels over time across three different transmission scenarios:

- **X-axis**: Time (in seconds)
- **Y-axis** : Glucose level (mg/dL)

Bar Colors :

- **Light blue**: Scenario 1 (Always Send) – continuous transmission of every reading.
- **Red**: Scenario 2 (Threshold Only) – transmission only when the reading exceeds a certain threshold.
- **Light green**: Scenario 3 (Threshold or Periodic) – transmission either when the threshold is exceeded or after every 10 readings.

Each bar represents a single glucose reading sent from sensor node 3 (which measures glucose levels) to the sink node (node 0).

[Config Scenario1 – AlwaysSend]

In this scenario, every reading is transmitted without any condition.

This is reflected in the large number of light blue bars present throughout the chart.

[Config Scenario2 – ThresholdOnly]

Here, readings are only transmitted if they exceed or fall below a certain threshold.

The threshold values are not explicitly defined in the configuration file; they may be set within the code or follow default settings.

As a result, the red bars appear only when abnormal glucose levels are detected.

[Config Scenario3 – ThresholdAndPeriodic]

In this configuration, a reading is transmitted if it exceeds the threshold or after every 10 readings, regardless of value.

- **Purpose of the Chart :**

  To compare the transmission behavior under the three scenarios by addressing the following questions :

  - Are all readings being transmitted?
  - Are normal readings being ignored?
  - Is there a balance between energy efficiency and monitoring accuracy?

- **Conclusion from the Chart :**

  - **Scenario 1** generates a high volume of data, ensuring continuous monitoring but resulting in greater energy consumption.
  - **Scenario 2** transmits fewer readings, which conserves energy but may miss critical health events if the threshold is not exceeded.
  - **Scenario 3** offers a balanced approach by combining threshold-based transmission with periodic updates, maintaining efficient energy usage while ensuring ongoing monitoring.

- **Comparison of Simulation Scenarios Based on Communication Delay and Packet Collisions**

  To assess the network performance under different simulation scenarios, both total communication delay and the number of packet collisions were analyzed for each sensor type. The number of collisions is determined as follows:

Collisions=Sent Sequence-Received Sequence

Table 6 Comparative Analysis of Total Communication Delay and Packet Collisions for Each Sensor Type Across Three Simulation Scenarios

Sensor Type	Total Delay (Scenario 1)	Collisions (Scenario 1)	Total Delay (Scenario 2)	Collisions (Scenario 2)	Total Delay (Scenario 3)	Collisions (Scenario 3)
SpO2	23.262	17	15.184	10	15.651	9
Blood Pressure	10.942	5	4.061	0	4.096	0
Glucose	12.349	19	1.644	7	2.002	6
Temperature	20.285	15	13.385	9	12.655	8

- **Energy Consumption Estimation**

To estimate the energy consumed during transmission and reception processes, the fundamental physics equation is applied:

Energy (J) = Power (W) × Time (s)

Where :

- E is energy (in joules),
- P is power (in watts),
- t is time (in seconds).

Given the low power nature of Wireless Body Area Networks (WBANs), energy values are expressed in microjoules (µJ). Note:

$$1J=1{,}000{,}000\mu J, 1mW\cdot s=1mJ=1{,}000\mu J$$

$$\text{Energy } (\mu J) = \text{Power } (mW) \times \text{Time } (s)$$

Transmission and Reception Time Calculation

For the purposes of our estimation:

- **Packet size** : 100 bytes = 100×8=800 bits
- **Data rate**: 1024 bits/s (as configured in omnetpp.ini: SN.node[*]. Communication.MAC.phyDataRate = 1024)

The time required to transmit a single packet is:

$$t=\text{Number of bits/Bitrate}=1024800\approx 0.78125\text{seconds}$$

Power Consumption Parameters:

The transmission (TX) and reception (RX) power values are obtained from the BANRadio.txt configuration file:

- **Transmission power**: PTX=2.93 mW

- **Reception power** : $P_{RX}=3.10\,\text{mW}$

Using the energy equation :

- **Transmission energy** :

$$E_{TX}=2.93\,\text{mW}\times 0.78125\,\text{s}\approx 2.290\,\text{mJ}=2290\,\mu\text{J}$$

- **Reception energy** :

$$E_{RX}=3.10\,\text{mW}\times 0.78125\,\text{s}\approx 2.422\,\text{mJ}=2422\,\mu\text{J}$$

Table 7 Estimated Energy Cost per Communication Activity in Wireless Sensor Nodes

Process	Power Consumption (µJ)
Transmission (TX)	2290 µJ
Reception (RX)	2420 µJ

Scenario-Based Energy Consumption (µJ):

The table below summarizes the energy consumed in three different simulation scenarios, for four types of physiological sensors. Values are reported separately for transmission and reception operations.

Table 8 Energy Consumption During Transmission and Reception for Each Sensor Type Under Three Different Simulation Scenarios

Sensor Type	**Scenario 1 TX (µJ)**	**Scenario 1 RX (µJ)**	**Scenario 2 TX (µJ)**	**Scenario 2 RX (µJ)**	**Scenario 3 TX (µJ)**	**Scenario 3 RX (µJ)**
SpO_2	549600	539660	336630	331540	336630	333960
Blood Pressure	27480	278300	87020	91960	89310	94380
Glucose	206100	171820	50380	36300	54960	43560
Temperature	412200	399300	251900	244420	251900	246840

Scenario 1 (Always-On Transmission) results in the highest energy consumption across all sensor types.

Scenario 2 (Threshold-Based Transmission Only) significantly reduces energy consumption but may overlook critical information.

Scenario 3 (Threshold Combined with Periodic Transmission) represents a balanced approach, offering a trade-off between accuracy and energy efficiency.

SpO_2 and Temperature sensors consume more energy than other sensors due to their high sampling frequency and fast transmission rates.

II.6 Conclusion

This chapter focuses on the practical aspect of studying wireless body area networks (WBANs) by simulating a realistic network environment using OMNeT++ and Castalia tools. The study included network design, node configuration, selection of different data transmission scenarios, and performance analysis based on indicators such as latency and packet delivery rate. The results showed that network performance varies depending on the applied scenario and the number of nodes used, emphasizing the importance of choosing the optimal design to achieve the desired efficiency in real-world applications, especially in healthcare. These findings provide valuable insights for the future development and improvement of WBANs.

General Conclusion

In this memorandum, Wireless Body Area Networks (WBAN) were studied from both theoretical and practical perspectives. The first chapter addressed the fundamental principles of these networks, including their components and applications in medical, sports, and military fields, as well as the technical challenges such as energy consumption and security. Additionally, the protocols and standards used in WBAN, such as Bluetooth, ZigBee, and IEEE 802.15.6, were analyzed, comparing their performance and effectiveness. The second chapter focused on the practical aspect by simulating a WBAN using OMNeT++ and Castalia tools. A virtual network was designed, consisting of sensor nodes and a central unit (Sink) to monitor vital signs such as temperature, blood pressure, glucose levels, and heart rate. Three different data transmission scenarios were tested (periodic transmission, emergency transmission, and hybrid model), and performance was analyzed based on metrics like latency and packet delivery rate. The results showed that the hybrid model provides an optimal balance between data accuracy and energy efficiency, making it the best choice for real-world medical applications. In conclusion, WBANs represent a promising technology for enhancing remote healthcare, especially for chronic patients and the elderly. However, there are still challenges that require further research, such as improving energy efficiency and enhancing security. Future studies could include developing artificial intelligence algorithms for real-time data analysis or integrating WBAN with fifth-generation (5G) technologies to improve response speed and network reliability. Ultimately, this memorandum represents a step toward a deeper understanding of WBANs and their applications, highlighting the importance of simulation in optimizing their performance prior to actual deployment.

Annex

Anexx-A-: WBANApp.ini file

```
[General]
include ../Parameters/Castalia.ini
sim-time-limit =   3600s
SN.numNodes = 5
SN.wirelessChannel.pathLossMapFile=
"../Parameters/WirelessChannel/BANmodels/pathLossMap.txt"
SN.wirelessChannel.temporalModelParametersFile=
"../Parameters/WirelessChannel/BANmodels/TemporalModel.txt"

SN.node[*].Communication.Radio.RadioParametersFile = "../Parameters/Radio/BANRadio.txt"
SN.node[*].Communication.Radio.symbolsForRSSI = 16
SN.node[*].Communication.Radio.TxOutputPower = "-15dBm"
SN.node[*].ResourceManager.baselineNodePower = 0
#SN.node[*].ApplicationName = "Application"
SN.node[0].Application.isSink = true

SN.node[*].Communication.MACProtocolName = "BaselineBANMac"
SN.node[*].Communication.MAC.phyDataRate = 1024
SN.node[0].Communication.MAC.isHub = true
SN.node[*].Communication.Routing.collectTraceInfo = true
SN.node[*].ResourceManager.initialEnergy = 100000
SN.node[*].Application.priority = 1
# Sink
SN.node[0].ApplicationName = "WBANApp"
SN.node[1..4].Application.isSink = false

SN.node[1].SensorManager.sensorTypes = "temperature"
SN.node[1].Application.isSink = false

SN.node[2].SensorManager.sensorTypes = "blood_pressure"
SN.node[2].Application.isSink = false
```

```
SN.node[3].SensorManager.sensorTypes = "glucose"
SN.node[3].Application.isSink = false

SN.node[4].SensorManager.sensorTypes = "spo2"
SN.node[4].Application.isSink = false
# ==============================
# Config 1:
[Config Scenario1-AlwaysSend]
SN.node[*].ApplicationName = "WBANApp"
SN.node[0].Application.isSink = true

SN.node[1].Application.sampleInterval = 20
SN.node[2].Application.sampleInterval = 30
SN.node[3].Application.sampleInterval = 40
SN.node[4].Application.sampleInterval = 15
[Config Scenario2-ThresholdOnly]
SN.node[*].ApplicationName = "WBANApp"

SN.node[1..4].Application.isSink = false
SN.node[1..4].Application.scenario = 2

SN.node[1].Application.tempThresholdLow = 36.5
SN.node[1].Application.tempThresholdHigh = 38.5
SN.node[2].Application.bpThresholdLow = 100
SN.node[2].Application.bpThresholdHigh = 140
SN.node[3].Application.glucoseThresholdLow = 70
SN.node[3].Application.glucoseThresholdHigh = 140
SN.node[4].Application.spo2ThresholdLow = 90
SN.node[4].Application.spo2ThresholdHigh = 97

SN.node[1].Application.sampleInterval = 20
SN.node[2].Application.sampleInterval = 30
SN.node[3].Application.sampleInterval = 40
SN.node[4].Application.sampleInterval = 15
```

```
[Config Scenario3-ThresholdAndPeriodic]
SN.node[*].ApplicationName = "WBANApp"

SN.node[1..4].Application.isSink = false
SN.node[1..4].Application.scenario = 3

SN.node[1].Application.tempThresholdLow = 36.5
SN.node[1].Application.tempThresholdHigh = 38.5
SN.node[2].Application.bpThresholdLow = 100
SN.node[2].Application.bpThresholdHigh = 140
SN.node[3].Application.glucoseThresholdLow = 70
SN.node[3].Application.glucoseThresholdHigh = 140
SN.node[4].Application.spo2ThresholdLow = 90
SN.node[4].Application.spo2ThresholdHigh = 97

SN.node[1].Application.sampleInterval = 20
SN.node[2].Application.sampleInterval = 30
SN.node[3].Application.sampleInterval = 40
SN.node[4].Application.sampleInterval = 15

SN.node[1..4].Application.forceSendPeriod = 10
```

Annex-B-: WBANApp.ned file

```
package node.application.WBANApp;

import node.application.iApplication;

simple WBANApp like iApplication {
    parameters:

        string applicationID = default("WBANApp");
        bool collectTraceInfo = default(true);
        int priority = default(1);  //
        int packetHeaderOverhead = default(8);    // in bytes
        int constantDataPayload = default(2);    // in bytes
        double sampleInterval = default(1000);    // ms
```

```
        bool isSink = default(false);
        int scenario = default(1);
        int forceSendPeriod = default(5)
        @class(WBANApp);

        double tempThresholdLow = default(36.5);
        double tempThresholdHigh = default(38.5);
        double bpThresholdLow = default(100);
        double bpThresholdHigh = default(140);
        double glucoseThresholdLow = default(70);
        double glucoseThresholdHigh = default(140);
        double spo2ThresholdLow = default(90);
        double spo2ThresholdHigh = default(97);

    gates:
        input fromCommunicationModule;
        output toCommunicationModule;
        input fromSensorDeviceManager ;
        output toSensorDeviceManager ;
        input fromResourceManager ;
}
```

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