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An Improved Packet Switching Technique for Mitigating Gateway Failures in Wireless Body Area Networks

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ABSTRACT

Wireless Body Area Networks (WBANs) have gained attention as a promising technology for healthcare applications. However, one of the key challenges in WBANs is the reliability of the gateway device which serves as a bridge between the WBAN and the external network. This research has proposed a technique for the gateway failure problem which occurs when a default gateway fails to transmit packets to the medical server due to unforeseen circumstances such as loss of network, and power interruption during continuous packet transmission. This research has proposed a method called redundant gateway architecture (RGA) in which a backup gateway is introduced as an aide for the default gateway and automatically continues the task of packet transmission whenever the default gateway is out of service until it's back to function. RGA uses a failover mechanism to detect gateway failures. We evaluate the RGA in real-time with ECG, temperature sensor, pulse sensor, ESP8266, and ESP37 microcontrollers and the results show that the proposed architecture can effectively handle gateway failures in WBANs with a high delivery ratio and low latency. The RGA architecture demonstrated superior performance compared to other methods, particularly in terms of packet delivery ratio, attributed to its ability to minimize packet loss throughout the routing process. This has enhanced the reliability of WBAN data and enabled the seamless delivery of healthcare services.

1. Introduction

Wireless Body Area Networks (WBANs) have emerged as an advanced technology that has significantly transformed the healthcare field and pervasive surveillance. The purpose of these networks is to effectively incorporate wearable or implantable sensors and devices into a wireless communication system, thereby establishing a fluid ecosystem for continuously monitoring health and transferring data in real time. WBANs have become increasingly significant due to their capacity

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to observe essential physiological indicators, monitor health metrics, and facilitate uninterrupted data gathering from individuals [1]. These networks offer useful insights for healthcare practitioners and researchers [2,21,22].

The fundamental principle underlying WBANs involves establishing connections between sensors and equipment positioned on or within the human body. This arrangement creates a network that functions close to the individual. The proximity of WBANs allows for the collection of detailed health data, such as heart rate, temperature, blood pressure, and other relevant metrics, in real time [1]. WBANs have emerged as a significant technological advancement in the field of personalized and remote healthcare [7]. These networks can revolutionize healthcare delivery, disease management, and the overall quality of life. WBANs offer the potential for safer and more efficient medical practices, as well as a more comprehensive comprehension of human physiology.

Gateways in WBANs serve as intermediates that enable communication between the body-worn devices and external networks or systems. They function as the intermediary that links the personal domain of the human physique to the wider digital environment. Gateways play a crucial role in healthcare applications by facilitating the transmission of essential patient data to medical professionals and databases, enabling its analysis and supporting informed decision-making. Nevertheless, the consistent and dependable transmission of data in WBANs is sometimes hindered by the ongoing issue of gateway failures. The failure of a gateway can have significant consequences, as it interrupts the smooth transmission of data. This interruption for example has the potential to pose risks to patient health [3].

Gateway failures in WBANs can arise from a variety of sources, encompassing hardware malfunctions, network interruptions, and environmental obstacles. Common causes of gateway malfunction include hardware issues such as component failures, overheating, and power supply problems. These factors have the potential to render gateways inoperable [4]. Various factors connected to networks, including as signal interference, signal loss, and network congestion, have the potential to disrupt the communication link between the gateway and WBAN devices [5]. Frequently, these disturbances result in the occurrence of packet loss or delays in the transfer of data. Gateways can experience performance and longevity issues due to environmental concerns, including exposure to severe environments, dampness, and physical trauma. The occurrence of gateway failures also can be attributed to power management issues, especially when battery-powered gateways encounter rapid battery depletion or employ ineffective power management measures. Addressing the various factors contributing to gateway failure in WBANs requires a comprehensive strategy that includes hardware resilience, network optimization, proactive maintenance, environmental factors, security measures, and resource-efficient designs.

One of the strategies employed to mitigate power consumption in medical sensors and enhance the longevity of gateway devices within healthcare monitoring systems is the technique of minimizing radio interface activation and optimizing interface switching in order to decrease the duty cycle. Doudou, Rault & Bouabdallah [9] have proposed a new communication architectural approach by using dual radio. However, the drawback of this method is the cost of periodic scanning of medical sensors for ZigBee gateway in terms of delay and power consumption.

Fog computing or cloudlet is one of the methods introduced to improve data reliability and network congestion management. In this approach, the gateway is equipped with an algorithm that communicates and fetches data directly from cloudlet instead of the cloud. The aim of introducing cloudlet is to reduce the amount of time required to retrieve WBAN data from cloud. The cloud is claimed to be far, congested, and interfered which leads to the unreliability of WBAN data [10].

The research focus on gateway failures in WBANs has been limited, primarily due to several key factors. Firstly, gateway devices in WBANs are typically stationary, often serving as base stations or desktop computers situated in static positions. Additionally, these gateways connect to the internet via Ethernet cables, ensuring robust and secure network connections. Furthermore, their immobility and reliance on wired connections make them less susceptible to failures caused by issues like battery power drainage, which is commonly associated with mobile and battery-powered devices within WBANs.

However, as a result of the need for user mobility, the utilization of mobile gateways has become increasingly favoured as a gateway device. This is primarily due to the fact that mobile gateways have become an integral aspect of human existence and may fulfil additional functions beyond packet transmission. Individuals can readily relocate themselves without encountering limitations on their mobility [11,12]. With this, the design paradigm has been shifted from using a fixed base-station computer such as desktops to mobile gateways such as Microcontroller, Arduino, and Raspberry pi [13].

This research presents a novel approach to address the issue of network downtime by introducing a backup gateway. The proposed solution involves the implementation of a redundant gateway architecture (RGA) that enables seamless packet transmission resumption in the event of a default gateway failure. The proposed method is aimed to improve the reliability, packet delivery ratio (PDR), and throughput of WBAN system.

The first part of this paper introduces the paper, while the second part describes the research methodology, and the result analysis of the proposed method is discussed in part three. While the fourth part concludes the paper.

2. Methodology

The implementation of several gateway devices within WBAN constitutes a redundant gateway architecture, which is a network design approach. The objective of this architecture is to guarantee the robustness of the network, its ability to handle faults, and the uninterrupted transfer of data in the case of a breakdown in the gateway. In this research, a redundant gateway architecture (RGA) involves the strategic placement of two or more gateway devices. The gateway devices function as access points and are tasked with the aggregation, management, and transmission of data between the body-worn sensors/devices and external networks or systems.

The issue of redundancy arises when one of the gateways experiences a failure. Redundant gateways are specifically engineered to function in a state of standby or idle until their activation becomes necessary. In the event of a loss or disruption in the primary gateway, a backup gateway assumes the role of data aggregation and forwarding automatically. The transition is generally smooth, with end devices in the WBAN potentially unaware of the switch.

RGA is designed to incorporate failover mechanisms for the purpose of detecting gateway failures. In order to detect the failure of the primary gateway, various methods are utilized, including the analysis of heartbeat signals and the continuous monitoring of gateway status. Upon the detection of a failure, the backup gateway is promptly activated, thereby facilitating the redirection of data flow through it.

The proposed RGA is developed and implemented in real-time scenarios. A desktop application is also developed and written in C# in Microsoft Visual Studio IDE to collect sensor data in real-time. Figure 1 and Figure 2 depict the circuit and hardware configuration of node 1 and node 2, respectively. These nodes are equipped with the Max30100 Pulse sensor, Max30102 Heart rate sensor, ECG sensor, and LM35 Temperature sensor.

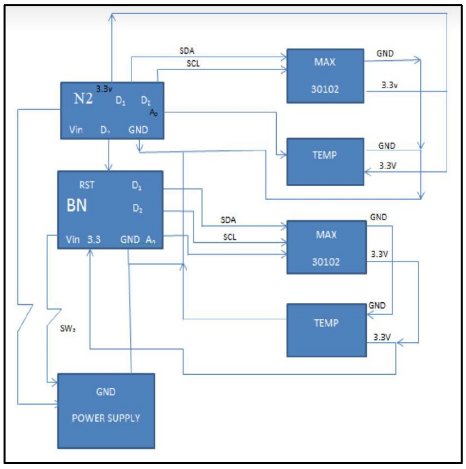

Fig. 1. Node 1 circuit set up and arrangement

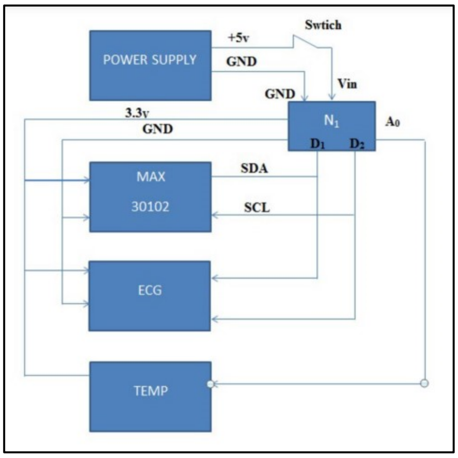

Fig. 2. Node 2 circuit set up and arrangement

The WBAN consists of two (2) microcontrollers as follows: ESP8266 used for bio-signal data acquisition from the sensors and ESP32 for packets relay to the server. The formal is economical and powerful enough to get sensor readings easily, while the latter supports faster Wi-Fi processing with less lag [14]. Both microcontrollers have better interoperability since they are digital hardware device, unlike sensor which is an analogue device and needs Analogue to Digital Device (ADC) to convert its data into digital [15,16].

The designed mesh network used in this research consists of the following nodes and hardware:

i. Node 1: this node has 2 sensors - ECG module and pulse oximeter (Max30100) sensor - as shown in Figure 3 and one microcontroller ESP8266 as shown in Figure 3.

Fig. 3. Node1 system architecture

ii. Node 2: this node is responsible for data reception and merging its own sensor data into incoming data and then forwarding it to the mesh server. It comprises of three (3) sensors; pulse sensor Max30100, temperature sensor LM35, and heart rate sensor Max30102 as shown in Figure 4.

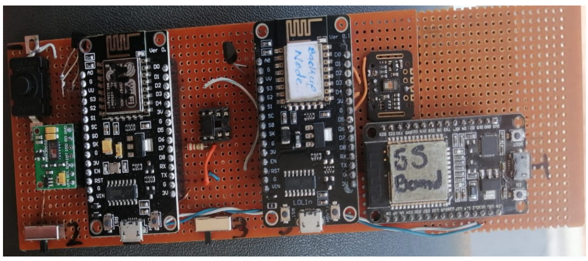

Fig. 4. Node 2 system architecture

iii. Backup Node: this node has a similar function with node 2. It becomes active when the default microcontroller gateway in node 2 becomes unavailable due to power shortage or disconnection. This node is shown in Figure 4 and is equipped with the same sensors as node2.
iv. Server Board: The microcontroller ESP32 is placed in this setup board. The mesh network is a close loop network which only support intra-communication and can only communicate inside a network [17]. However, to send bio-signal readings of medical sensors outside the mesh network to an outer network such as a medical server, an additional hardware must be introduced. The research deployed ESP32 Wroom Board for taking the serial data and send it to the server. The data is received via a serial communication cable, and then forwarded to the server in real-time. This board is also shown in Figure 4.

The attainment of the desired results was achieved by using the Wi-Fi Mesh Network Methodology. This methodology entails the deployment of many ESP boards, referred to as nodes, which are networked by Wi-Fi. This interconnected network enables the efficient transmission and reception of data across large indoor and outdoor spaces. The ESP Wi-Fi mesh is self-healing which means the network can be built and maintained autonomously [18]. The ESP Wi-Fi Mesh network distinguishes itself from conventional Wi-Fi networks by enabling nodes to establish connections with adjacent nodes. Nodes are mutually responsible for relaying each other's transmissions. The utilization of an ESP Wi-Fi Mesh network enables the attainment of a significantly expanded coverage area, as the nodes are capable of establishing interconnectivity or interoperability without necessitating proximity to the central node. Similarly, ESP Wi-Fi Mesh exhibits a reduced vulnerability to network overload due to the absence of a single central node that limits the number of nodes allowed on the network. This is made possible by the interconnected nature of the nodes [19].

WBAN application involves continuous acquisition and transmission of data from a patient. The circuit boards labelled as node1 and node2 were utilized for measurement purposes. These circuit boards, when separated, are composed of a total of five distinct sensors, as previously indicated. However, the pulse sensor Max30100 are used twice, once in each node1 and node2. Basically, both sensors are collecting the same bio-signal readings. Also, the heart rate sensor Max30102 is similar with pulse sensor in terms of data acquisition and parameter. As such, all these three sensors are represented as a single sensor node during packet transmission to avoid data redundancy.

Three (3) sensors which collect data are: Pulse sensor Max30100, Temperature sensor LM35, and ECG sensor. The backup gateway is implemented together with node2 circuit board which is also equipped with all the three (3) sensors mentioned above in node2. It starts functioning automatically immediately the default microcontroller fails due to battery drainage. Both the default microcontroller and backup microcontroller are running on battery. This research objective aims to provide an alternative means for a medical sensor to send its bio-signal readings to the server when the default gateway fails due to power drainage.

In order to assess the proposed RGA, an initial step was taken to ascertain the transmission type of each sensor packet, thereby determining whether the packets were classified as normal or urgent. Subsequently, a comparison was made between the acquired data and the actual readings obtainable in a hospital environment, with the intention of establishing the validity of the data. Finally, the packet delivery ratio was measured during the transition period between default and backup gateways.

The following Figures 5, 6 and 7, depict the recorded sensor readings obtained from both node 1 and node 2. The sensors run for 37min on battery to collect various data from the three sensors. The reason of choosing 37min to run the application for data collection is to prevent excessive data redundancy. Within 37min, 1478 packets have been received from all the sensors. These data are enough to determine the main objective of this research since we are focusing mainly on packet transmission.

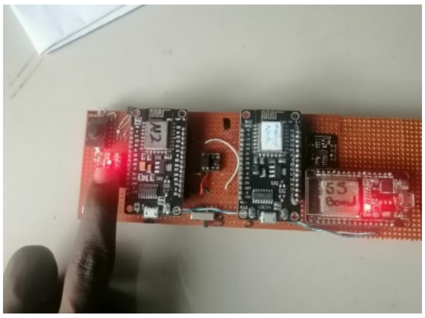

Fig. 5. Max30100 sensor taking readings

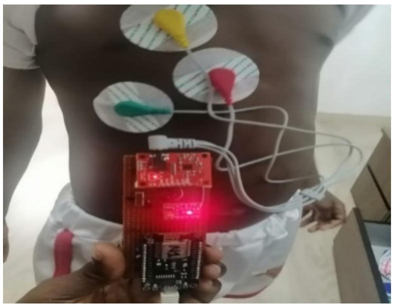

Fig. 6. ECG sensor taking readings

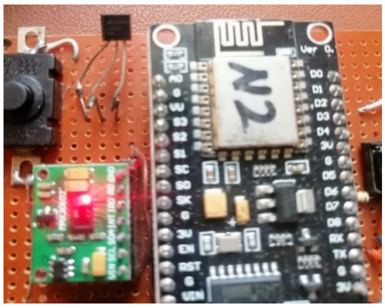

Fig. 7. LM35 sensor taking readings

The server application was started by running the codes in MS Visual Studio. The desktop server application is launched, connects to the available network either through Ethernet cable or wireless connection such as Wi-Fi by selecting a secure available SSID. For security reason, the internet connection of the server application is predefined and preconFigured with the sensor nodes of each patient within the same network.

Figure 8 shows the server interface which display the sensor readings. The desktop app is mainly accessible by an authorized medical practitioner, ambulance department, patient, and family members to evaluate and assess various patient data and take actions. The username and password are provided to the authorized users as a level of user authentication. The server app is also a real-time app which displays bio-signal readings of patients in live.

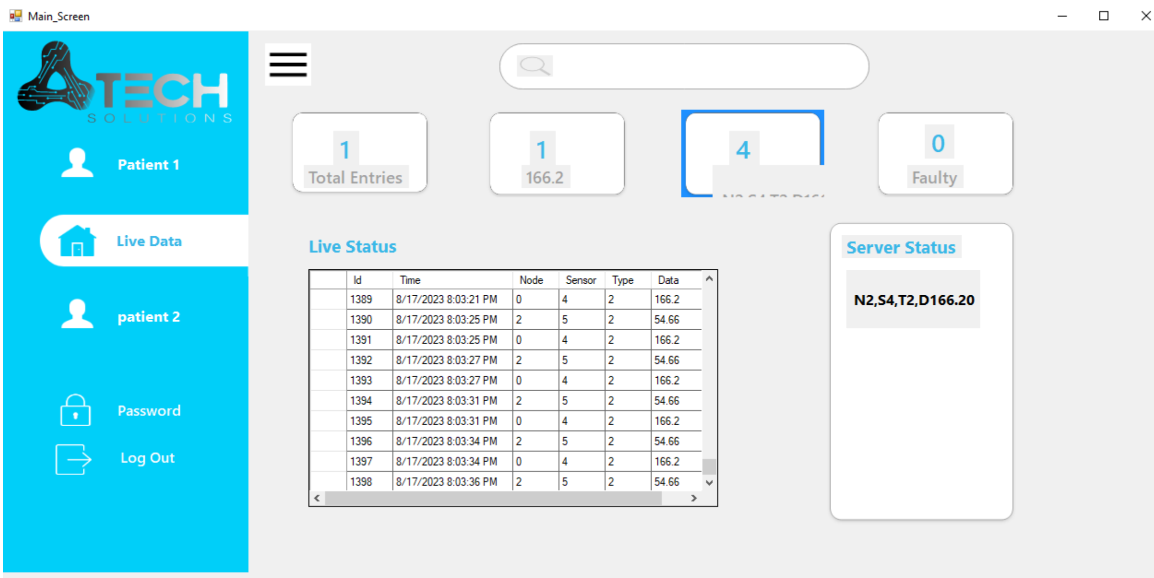

Fig. 8. Sensor bio-signal reading

The subsequent formulas provided are the appropriate equations that will be utilized to compute the efficiency of this metric:

i. Packet Delivery Ratio: The performance metric used to measure the effectiveness of this gateway failure technique algorithm is packet delivery ratio which is a very important metric to measure the performance of routing protocol in any sensor network either WSN or WBAN [20]. The performance of the protocol is contingent upon a range of parameters selected for the simulation. The primary parameters encompass packet size, the number of nodes, transmission range, and the network's structural configuration. The metric referred to as the packet delivery ratio is derived by dividing the aggregate quantity of data packets that have successfully reached their designated destinations by the total number of data packets transmitted from their respective sources. In simple terms, the packet delivery ratio signifies the proportion of packets received at the destination compared to those initially dispatched from the source. Enhanced performance is correlated with higher packet delivery ratios. This mathematical relationship is denoted as Eq. (1), elucidating the mathematical representation that underscores the correlation between the packet delivery ratio and the overall protocol performance.

$$Packet\ Delivery\ Ratio = \frac{\sum(Number\ of\ successfully\ delivered\ packets)}{\sum(Total\ number\ of\ packets\ sent\ from\ source\ node)} \times 100 \quad (1)$$

ii. Average End-to-End Delay: The concept of end-to-end delay refers to the time it takes for a packet to travel through the network, starting from where it originates and ends at its intended destination. In order to determine the average end-to-end delay, it is necessary to calculate the mean duration of the complete voyage for all messages that have been effectively transmitted. It is noteworthy that the end-to-end delay is partially determined by the packet delivery ratio. As the spatial separation between the data source and its intended destination expands, the probability of packet loss also escalates. The calculation of the average end-to-end delay encompasses a comprehensive analysis of various potential delays that may occur within the network. This includes pauses due to buffering, time taken for the route to be discovered, the delay caused by retransmissions at the Medium Access Control (MAC) layer, and the combined impact of how long it takes for the signal to travel as well as being transmitted. This entire concept can be expressed in a more mathematical way as Eq. (2).

$$D = \frac{1}{n}\sum_{i=1}^{n}(Tr_i - Ts_i) \times 1000\ [ms] \quad (2)$$

where
D = Average E2E delay
i = packet identifier
Tr_i = reception time
Ts_i = send time
n = number of packets successfully delivered

iii. Packet Loss: Packet loss is the ratio of the number of packets arrived at the destination to the number of packets originated from the source. It is shown mathematically in Eq. (3) as follows:

$$PL = \frac{nSentPackets - nReceivedPacket}{nSentPackets} \tag{3}$$

where
nReceivedPackets = Number of received packets
nSentPackets = Number of sent packets

iv. Packet Loss Ratio: Packet loss ratio is the ratio of the number of packets that never reached the destination against the number of packets sent from the source. The Eq. (4) shows its mathematical representation.

$$PLR = \frac{nSentPackets - nReceivedPackets}{nSentPackets} \times 100 \tag{4}$$

where
nReceivedPackets = Number of received packets
nSentPackets = Number of sent packets

v. Average Throughput: This is measured in packets per unit as Time Interval Length (TIL). Mathematically it can be expressed as shown Eq. (5).

$$Average\ Throughput = \frac{receivedSize}{stopTime - startTime} \times \frac{8}{1000} \tag{5}$$

where
receivedSize = Store received packet’s size
stopTime = Simulation stop time
startTime = Simulation start time

3. Result Analysis

For simplicity, the server interface is configured for two patients. The server application is scalable, and more patients can be added along the line. The bio-signal readings of patient 1 goes under patient 1 page, and the same applies to patient 2. The live data depicts a summary of all the incoming bio-signal readings sent to the server. The total entry field shows the total number of packets received by the server. The emergency field shows a packet whose value has exceeded the threshold value of each sensor and needs attention from the medical practitioner. The normal field shows the packets within a threshold of each sensor node, while the faulty field shows extreme and abnormal data which are outside range of expected result. The server status column shows the real-time packet transmission to the server which displays the current node. Each node is determined to represent a patient. Since there are two different nodes, the server is configured for two patients.

The application was run for 37 minutes to continuously collect data from a patient from 17/08/2023 19:28 to 17/08/2023 20:05. Each sensor has a separate threshold that determines the normal data from abnormal or extreme data. The body temperature sensor is usually within 36.5 ^{0}C – 37^{0}C, while ECG and pulse sensor threshold values are between 60 – 100bpm based on a patient's age and health status. Table 1 below shows the thresholds of each sensor participating in the transmission.

Table 1
Threshold of sensor nodes

Sensors	Threshold	Normal data	Abnormal data
LM35	37	36.5 – 37	> 37
Max30100	100	60 – 100	>100
ECG	100	60 – 100	>100

The determination of the quantity of normal and urgent packets for each sensor in the continuous transmission setup is accomplished by examining the data type, which is designated as 1 for urgent data and 2 for normal data, as depicted in Figure 9. In general, 10% of data transmitted packets are abnormal data which required immediate medical practitioner intervention. The 10% extreme data received from sensors is expected since the patients used to collect data in this research are in good state of health.

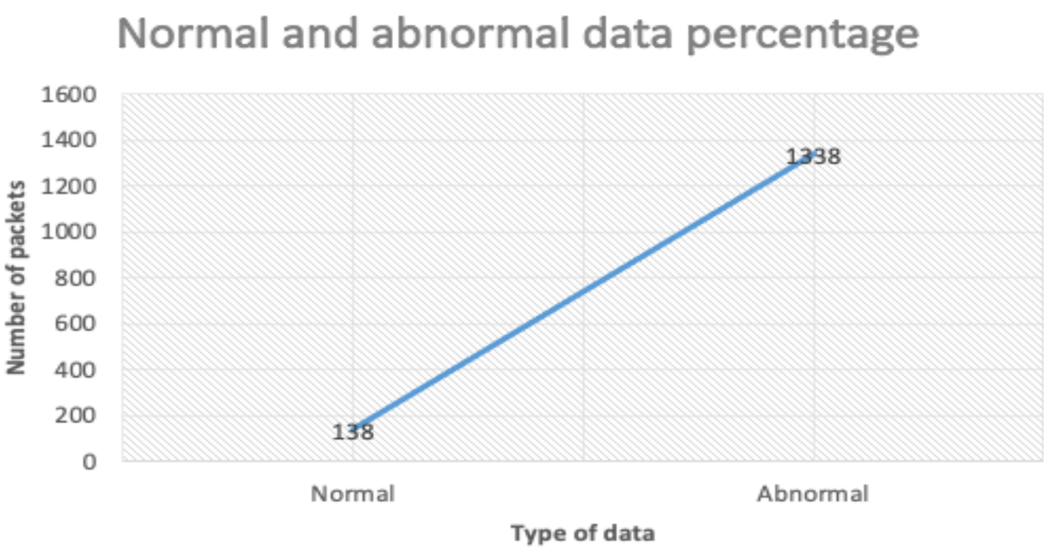

Fig. 9. Normal and abnormal data ratio

However, when considering individual sensors, Figure 10 illustrates the proportion of individual packets in relation to normal and anomalous data. It is noticed that pulse rate has a lowest abnormal data i.e., data above its threshold throughout the transmission period. The noticeable reason for this is the patient condition during the data collection. The patient was in a rest state and has a stable pulse throughout the transmission. This reversibly affects the electric activity in the heart measured through the ECG which happens to have 40 packets throughout the transmission. However, the temperature of the patient is not stable which amounts to abnormal packets of 4% throughout the transmission. In the same way, more packets are received from pulse sensor due to transmission interval and quick pulse value of the patient.

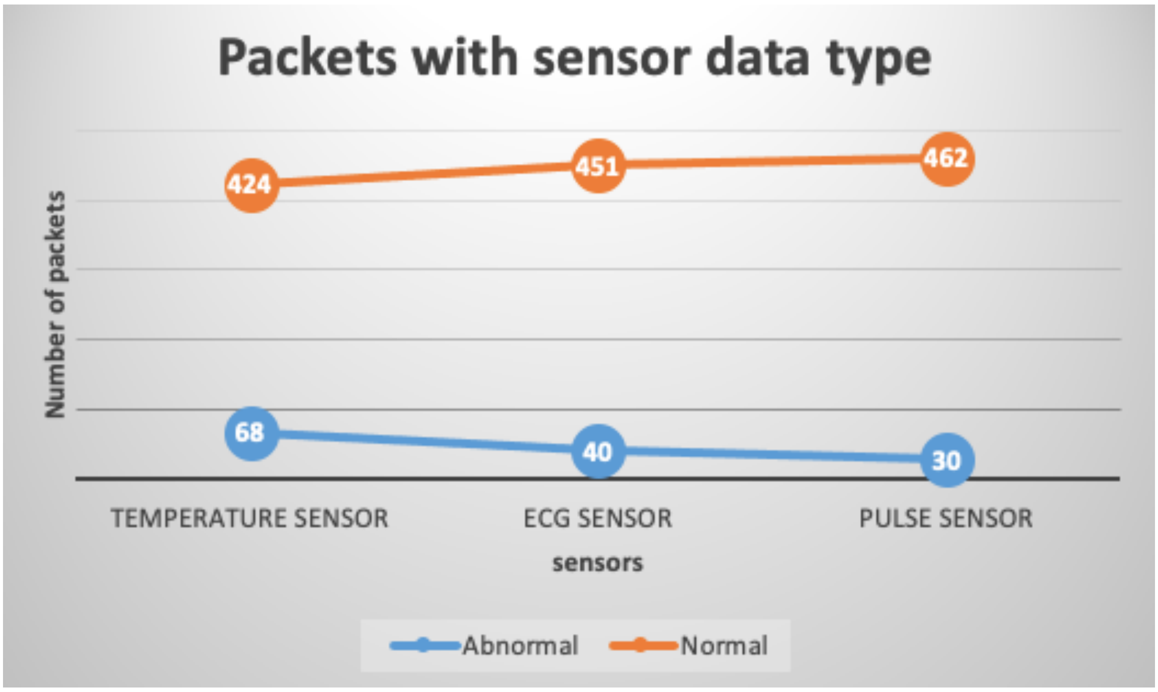

Fig. 10. Packets with sensor types

Now, to measure the effectiveness of our proposed RGA with the implementation of backup microcontroller, the transmitted packets are checked whether there's a break in packet transmission or not during the gateway switching technique. Figure 11 illustrates that a total of 55 packets were lost within a time span of 120 seconds during the transition of the microcontroller from its default state to the backup state, namely in the communication between the sensor and the gateway. The red circle in the figure illustrates the missing packets during gateway switching in transmission. The packets were transmitting perfectly until there's an interruption of gateway switching. The efficiency of the proposed gateway switching routing protocol is assessed by systematically altering multiple parameters associated with each sensor.

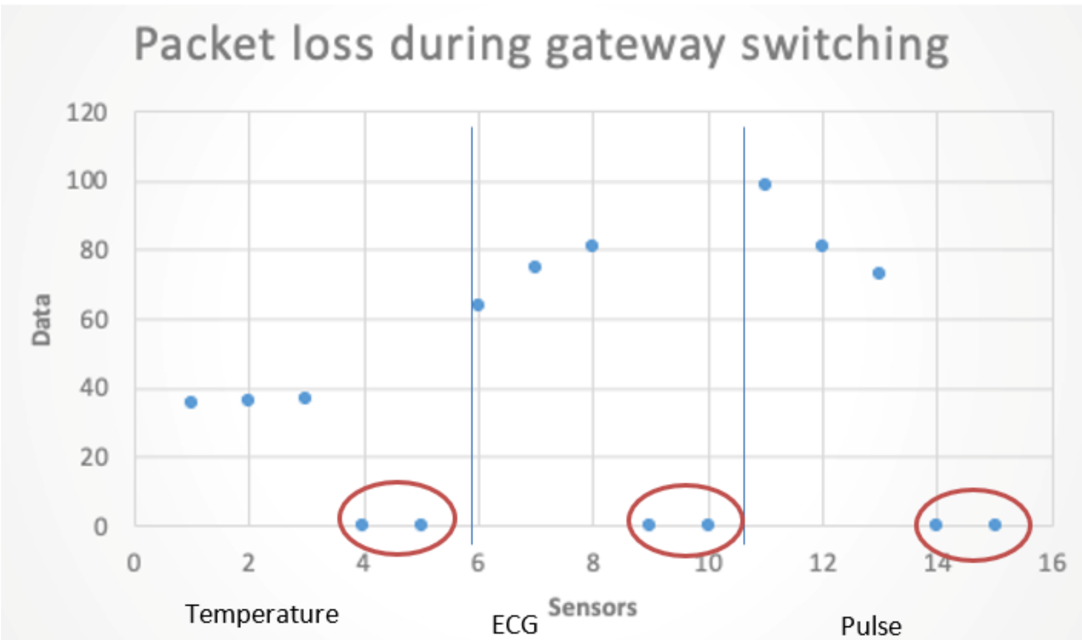

Fig. 11. Packet loss during gateway failure

Table 2 shows various parameter used while varying number of connections.

Table 2
Parameters for gateway failure transmission

Parameters	Value
Protocols	Gateway failure routing protocol (GFRP)
Type	Reactive
Number of sensor nodes	1, 2, 3
Real-time transmission period	37min
Traffic type	Constant Bit Rate (CBR)
Transmission range	2m
Mobility model	Random waypoint
Node speed	20m/s
Pause time	0s
Interface type	Queue
MAC protocol	802.11Ext
Packet size	16 KB

The performance of the proposed research is demonstrated in Table 3, considering the modifications made to various variables based on the aforementioned parameters and formulas.

Table 3
Performance of the gateway failure routing protocols with different connections

Varying sensor	Packet loss	Average E2E Delay	PDR	Average throughput	Packet Loss Ratio
Temperature sensor	19	42	96.13%	67	0.35
ECG sensor	18	40	96.34%	69	0.33
Pulse sensor	18	40	96.34%	69	0.33
Temp, ECG, Pulse	55	89	96.41%	115	0.04

In comparison with the existing works, the PDR achieved with our proposed RGA is compared with the methods experimented by Vaishali, Khairnar and Kotecha [20] as shown in Table 4. The survey work by Vaishali, Khairnar and Kotecha [20] has simulated all the listed routing protocols by varying various parameter metrics to determine the most suitable protocol for each scenario. Our proposed RGA outperformed other existing routing protocols especially in terms of packet delivery ratio due to low packet loss during packet routing.

Table 4
Performance comparison of methods

Methods	Packet loss	Average E2E Delay	PDR	Average throughput	Packet Loss Ratio
AODV	1285	129.825	92.3664	266.87	6.789
DSR	313	142.524	1.2919	198.33	1.909
GPSR	280	90.00	1.989	140.89	1.190
GSRA	55	89	96.41%	115	0.04

4. Conclusions

In summary, the research shows a routing architecture that offers an alternate routing solution in the event of gateway failure. This research introduces an innovative strategy to tackle the problem of network downtime through the implementation of a backup gateway. The suggested approach entails the deployment of a redundant gateway architecture (RGA) that facilitates uninterrupted resumption of packet transmission in the case of a failure in the default gateway. The proposed approach is designed to enhance the dependability, packet delivery ratio (PDR), and throughput of the Wireless Body Area Network (WBAN) system. This is achieved by incorporating a backup ESP8266 gateway device to assume transmission responsibilities in case of packet failure. The system was tested with various live, normal, abnormal, and extreme data. A total of five (5) distinct sensors were utilized in this research, including one (1) LM35 temperature sensor, two (2) Max30100 pulse sensors, one (1) heart rate sensor, and one (1) ECG sensor. In the same way, three (3) microcontrollers are used to handle the sensors' data which are: three (3) ESP8266 which collects data directly from sensors and one (1) ESP32 which Wi-Fi enabled and sends packets directly to the desktop application server. The data was collected in real-time and compared with existing routing protocols. The proposed RGA outperformed the existing ones in terms of packet delivery ratio. In future, we will work on packet aggregation technique to improve the congestion of big-signal readings during congested continuous transmission environment.

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