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Design and Performance Analysis of a Point-to-Point LoRa-Based Wearable Health Monitoring System in Line-of-Sight (LOS) and Indoor Environments

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***Abstract*—This research presents the design and performance evaluation of a Long Range (LoRa)-based wearable health monitoring system for real-time transmission of physiological data, namely heart rate, blood oxygen saturation (SpO_2), and body temperature. The system integrates a MAX30105 sensor with an ESP32-C3 microcontroller and an SX1276 LoRa module to enable low-power, long-range communication for Internet of Medical Things (IoMT) applications. Testing is conducted under Line of Sight (LOS) and indoor conditions to examine the effect of distance and propagation characteristics on Received Signal Strength Indicator (RSSI), transmission delay, and data transfer speed (bps). Pearson correlation, linear regression, and one-way Analysis of Variance (ANOVA) are applied to quantify distance-performance relationships and compare both environments. Results show that increasing distance degrades performance in a near-linear pattern, with decreasing RSSI and transfer speed and increasing delay. Stable communication is maintained up to 500 m under LOS, whereas indoor performance deteriorates earlier due to attenuation and multipath propagation. Although ANOVA indicates no statistically significant difference in the average performance of successfully received packets ($p > 0.05$), practical evaluation reveals that indoor environments impose a shorter effective range with higher packet loss. The novelty lies in implementing a compact point-to-point LoRa wearable platform based on ESP32-C3 and SX1276 for real physiological payload transmission, combined with statistical performance evaluation under practical LOS and indoor scenarios without relying on Long Range Wide Area Network (LoRaWAN) infrastructure. These findings demonstrate that LoRa is a viable and energy-efficient communication solution for wearable health monitoring, particularly in remote and infrastructure-limited IoMT applications.**

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I. INTRODUCTION

THE development of Internet of Things (IoT) technology has significantly transformed modern health monitoring systems [1]. In medical services, real-time monitoring of patients' physiological conditions is increasingly required to support mobility without compromising comfort or data accuracy. Vital parameters such as heart rate, blood oxygen saturation (SpO_2), and body temperature are essential indicators for early detection of health disorders and timely clinical decision-making [2, 3]. Recent biomedical studies further emphasize that wearable monitoring platforms enable continuous physiological observation for telemedicine and remote patient care, improving clinical responsiveness and long-term health management [4, 5].

To support continuous monitoring, Long Range (LoRa) wireless communication has emerged as a promising solution. It has long transmission range, low power consumption, and robustness under varying environmental conditions. These characteristics make it suitable for wearable health monitoring applications that require energy-efficient and reliable wireless connectivity [6–8].

Several studies have applied LoRa in IoT-based healthcare systems. For instance, a Smart Textile LoRa-enabled healthcare application has demonstrated effective transmission up to 350 m using Photoplethysmography (PPG)-based sensors and temperature monitoring [9]. Other works have reported that increasing distance and physical obstructions significantly reduce Received Signal Strength Indicator (RSSI) and transfer speed while increasing transmission delay, especially under Non-Line-of-Sight (NLOS) conditions [10–13]. While these studies confirm the impact of environmental conditions on LoRa performance, most focus on generic propagation analysis, outdoor scenarios, or Long Range Wide Area Network (LoRaWAN)-based architectures rather than wearable point-to-point wearable implementations.

Although LOS and indoor LoRa comparisons have been reported, a clear research gap remains for wearable Internet of Medical Things (IoMT) systems that transmit real physiological payloads using compact point-to-point LoRa devices without gateway infrastructure. Existing works rarely analyze how actual biomedical payload size, continuous transmission behavior, and low-power wearable hardware such as the ESP32-C3 combined with SX1276 affect RSSI, delay, and transfer speed in realistic LOS and indoor deployments. Consequently, results from conventional LoRa propagation studies cannot be directly generalized to wearable health monitoring applications.

Therefore, the research designs and evaluates a LoRa-based wearable health monitoring system integrating a MAX30105 sensor to measure heart rate, SpO_2, and body temperature. The system employs an ESP32-C3 microcontroller and an SX1276 LoRa module operating in point-to-point mode without LoRaWAN infrastructure. Performance testing is conducted under LOS and indoor environments, focusing on RSSI, delay, and transfer speed as indicators of communication reliability for continuous physiological monitoring. RSSI reflects received signal strength and determines communication range and stability, with lower RSSI increasing packet loss and latency [14, 15]. Delay represents the transmission time influenced by distance, attenuation, and LoRa parameters such as spreading factor [6, 14]. Meanwhile, transfer speed reflects data transfer efficiency and is closely related to channel conditions and signal quality. Optimizing LoRa parameters has been shown to improve transfer speed and reduce latency, supporting real-time monitoring even in dynamic environments [16–18].

The research novelty lies in the implementation of a compact wearable point-to-point LoRa platform using real physiological payload transmission with ESP32-C3 and SX1276, combined with statistical performance evaluation under LOS and indoor propagation conditions without relying on LoRaWAN or gateway infrastructure. The research contributes by developing a low-power wearable IoMT device. It also experimentally evaluates LoRa performance in LOS and indoor environments, applies Pearson correlation, linear regression, and one-way Analysis of Variance (ANOVA) to model performance degradation, and demonstrates a practical communication framework suitable for telemedicine, disaster response, and home-based patient monitoring.

II. Research Method

The research is conducted to design and test a health monitoring system based on a wearable device using LoRa communication. Testing was carried out over two weeks in May 2025 on the campus grounds and in laboratory rooms to represent two environmental conditions: LOS and indoor. The system is designed to measure three key human body parameters, heart rate, SpO_2, and body temperature, in real time and wirelessly transmit the data to a receiver using the LoRa SX1276 module.

A. System Design

The LoRa-based health monitoring system is designed with two main units: the transmitter and the receiver. The transmitter unit functions as a wearable device worn by the user to capture physiological data in real time, while the receiver unit serves as a station that displays the measurement results. Both devices communicate in a point-to-point configuration using the LoRa SX1276 module, without requiring an Internet connection, allowing the system to operate even in areas without Wi-Fi or cellular coverage.

The system wiring design illustrates the configuration and connections between the main components on both the transmitter and receiver sides. On the transmitter side, the MAX30105 sensor is connected to the ESP32-C3 SuperMini microcontroller via the I2C communication lines (Serial Data (SDA) and Serial Clock (SCL)). The microcontroller then sends the collected data to the LoRa SX1276 module through the Serial Peripheral Interface (SPI). The data are also displayed locally on a 0.96-inch SSD1306 OLED, which is connected in parallel via the I2C lines. The system is powered by a 3.7 V Li-Po battery, which is connected to a 5 V step-up converter to stabilize the voltage, along with a TP4056 module for charging regulation and overvoltage protection. A manual switch is added to disconnect the power when the device is not in use, enhancing energy efficiency. On the receiver side, the ESP32-C3 SuperMini microcontroller receives data from the LoRa SX1276 module and displays it on a 1.3-inch SSD1306 OLED. The wiring scheme employs a modular design to facilitate easier debugging and system maintenance. Flexible jumper cables are used to connect components to maintain signal stability and reduce electromagnetic interference.

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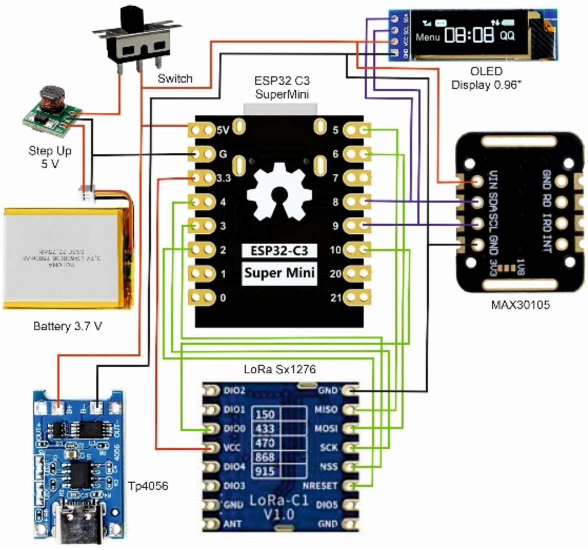

Fig. 1. Transmitter system wiring design.

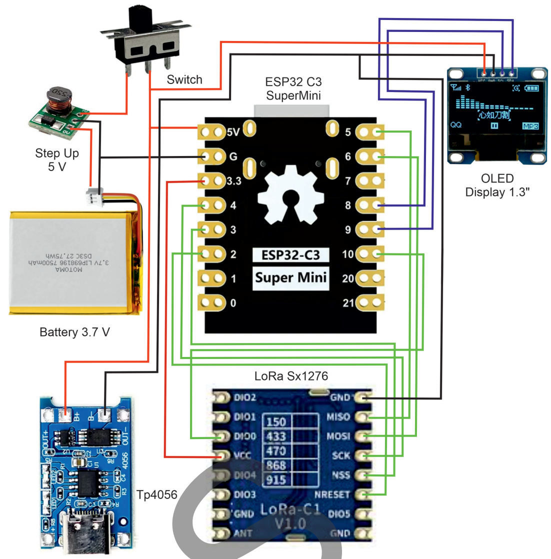

Fig. 2. Receiver system wiring design.

Overall, the wiring design ensures stable system integration, low power consumption, and a compact form factor to support the portability of the wearable device. The interconnection between the MAX30105 sensor, ESP32-C3 microcontroller, LoRa SX1276 module, and OLED display is carefully arranged to minimize signal interference and voltage drops, which are critical for maintaining reliable sensor readings and communication performance. Power management is also considered in the wiring layout by utilizing a LiPo battery and charging module to support continuous operation with minimal energy consumption. Complete wiring diagrams for both the transmitter and receiver systems are presented in Figs. 1 and 2, illustrating the detailed connections among sensors, microcontrollers, communication modules, and power supplies. These diagrams provide a clear representation of how data acquisition, processing, and transmission are integrated within the system. By employing a modular and well-organized wiring configuration, the system becomes easier to assemble, test, and expand for future development, such as the integration of additional sensors or Internet connectivity. This design approach enhances system reliability while maintaining the flexibility required for real-world wearable health monitoring applications.

In addition to the electronic system design, the research also develops a three-dimensional (3D) physical model of the wearable device using SolidWorks. The 3D design is created to visualize the internal layout of all components, including the sensor module, microcontroller, LoRa communication module, battery, and display, before physical assembly. This approach helps to ensure that all components can be arranged efficiently within a limited space while maintaining proper sensor placement and accessibility. Furthermore, the 3D model is used to estimate the overall device dimensions and evaluate ergonomic aspects related to user comfort during continuous use. Considerations, such as device thickness, wrist placement, and component alignment, are taken into account to minimize discomfort and ensure stable contact between the sensor and the user's skin. By utilizing a 3D design approach, potential mechanical issues can be identified early, reducing the need for repeated hardware modifications. This design strategy supports the development of a compact, wearable, and user-friendly health monitoring device that is suitable for real-world IoMT applications.

The 3D model of the transmitter is designed to resemble a smartwatch, with the MAX30105 sensor positioned on the index finger to ensure optimal PPG signal readings. The microcontroller, LoRa module, and battery components are arranged vertically within the casing to minimize size and maintain weight balance. The casing material is designed for 3D printing using PLA filament, offering sufficient rigidity while remaining lightweight.

The receiver is designed as a larger, portable monitoring module, with a 1.3-inch OLED screen on the front to display heart rate, SpO_2, body temperature, signal strength (RSSI), delay, and transfer speed. Component layout on the receiver is optimized for easy access during testing, including the placement of the power port, LoRa antenna, and reset button. The resulting 3D designs of both the transmitter and receiver are shown

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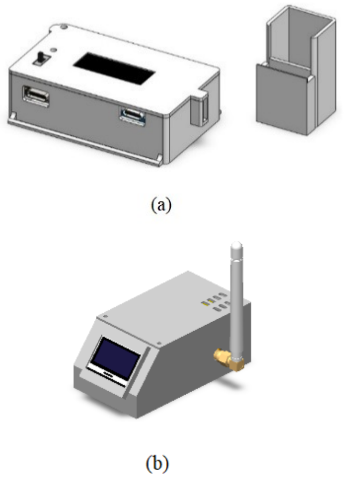

Fig. 3. 3D Design of the (a) transmitter and (b) receiver system.

in Fig. 3, illustrating the external appearance of the devices.

B. System Block Diagram

The LoRa-based health monitoring system integrates electronic components for real-time acquisition, processing, and wireless transmission of biometric data. It consists of two main units: a transmitter and a receiver. The transmitter, worn as a device, continuously measures physiological parameters, heart rate, SpO_2, and body temperature, using an integrated sensor module. Data are processed by a microcontroller and transmitted via a LoRa module. The receiver captures the incoming data, decodes it through a microcontroller, and displays it in real time on a visual interface, enabling remote monitoring. This block-based architecture separates sensing, processing, communication, and display, simplifying analysis, testing, and future expansion, such as cloud storage or IoMT integration.

Data obtained from the MAX30105 sensor, including heart rate, SpO_2, and body temperature, is processed by the ESP32-C3 SuperMini microcontroller. The microcontroller then transmits the data wirelessly via the LoRa SX1276 module to the receiver. On the receiver side, another ESP32-C3 receives the data and displays it directly on an SSD1306 OLED screen, allowing real-time monitoring of the user's condition. The overall system design is illustrated in Fig. 4.

The MAX30105 sensor functions as the input block of the system by detecting three key physiological parameters (heart rate, SpO_2, and body temperature), which are then forwarded as digital signals to the ESP32-C3 SuperMini microcontroller on the transmitter side for processing. The microcontroller reads and formats the sensor data before transmitting it wirelessly through the LoRa SX1276 module using the SPI, enabling long-range communication with low power consumption. The transmitted data are received by another ESP32-C3 microcontroller on the receiver side via a corresponding LoRa module, forming a point-to-point communication architecture without relying on an Internet connection. Finally, the received data are displayed in real time on a 1.3-inch SSD1306 OLED screen at the receiver, while the transmitter also provides local data visualization on its OLED display, allowing users to directly monitor their physiological conditions from the wearable device.

C. System Flowchart

The algorithm used is designed to manage the acquisition, transmission, and reception of physiological data via LoRa communication in real time. The system consists of two main components, namely the transmitter and the receiver, which operate synchronously to ensure stable data delivery from the wearable device to the receiving unit. On the transmitter side, the algorithm initiates sensor data acquisition, processes the physiological parameters, and transmits the formatted data packets through the LoRa module at predefined intervals. On the receiver side, the algorithm continuously listens for incoming data, decodes the received packets, and displays the physiological information in real time, thereby ensuring continuous and reliable monitoring.

The LoRa communication in this system is implemented using the SX1276 module operating in point-to-point mode without relying on LoRaWAN infrastructure. The transmitter and receiver are configured at a carrier frequency of 915 MHz to provide long-range communication with low power consumption suitable for wearable applications. The transmission power is set to 20 dBm to maximize coverage while maintaining stable operation for battery-powered devices. On the transmitter side, the system begins by initializing serial communication, the MAX30105 sensor, and the OLED display. The LoRa SX1276 module is then configured with fixed parameters, including a Spreading Factor (SF) of 7, a bandwidth of 500 kHz, a coding rate of 4/5, and a preamble length of 6, selected to balance communication range, transfer speed, and transmission reliability. This configuration also optimizes the time-on-air, which is important for real-time physiological monitoring. Cyclic Redundancy Check (CRC) is enabled to ensure data integrity during wireless transmission. After configuration, the system enters the main process in which the MAX30105 sensor continuously acquires physiological parameters, namely heart rate,

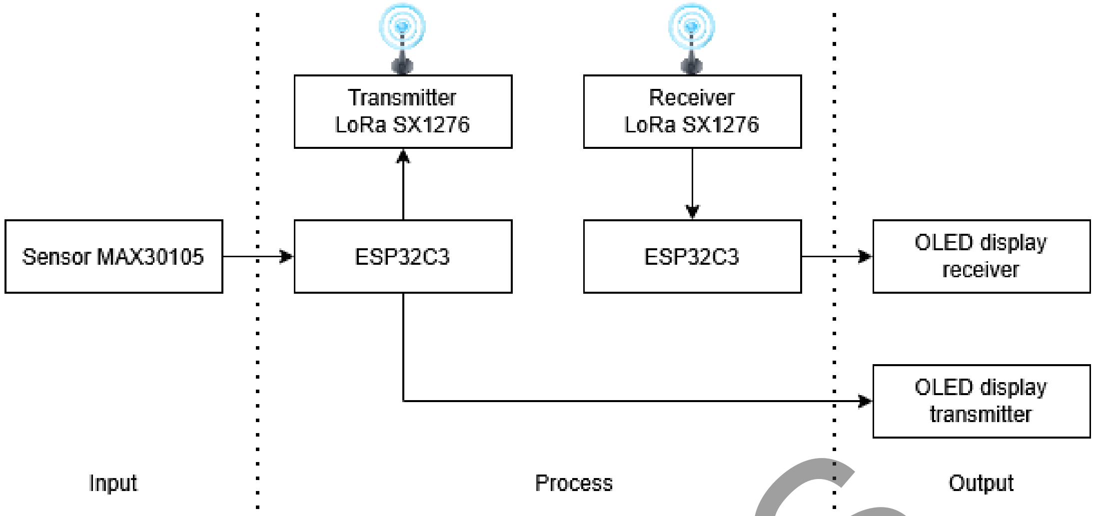

Fig. 4. Block diagram of the Long Range (LoRa) SX1276-based health monitoring system.

SpO_2, and body temperature. Data packets are transmitted periodically at 500 ms interval, enabling near real-time monitoring of the user's condition. The communication operates without acknowledgment (ACK) and retransmission mechanisms so that performance evaluation reflects the actual channel behavior without protocol-level recovery. The system is powered by a 3.7 V LiPo battery. Although low-power features of the ESP32-C3 are enabled, no deep-sleep mode is applied to maintain continuous sensing and transmission during the experiments.

Data are collected in buffers of 50 samples, and the average value is calculated to reduce signal fluctuations caused by noise. The processed data are then transmitted via the LoRa SX1276 module to the receiver. During transmission, the system also measures communication parameters, such as transmission time, transfer speed, and RSSI, to analyze network performance under various environmental conditions. The transmitted data are also displayed on the transmitter's OLED screen to provide visual feedback to the user.

On the receiver side, the system operates similarly. After initialization and LoRa configuration, the device waits for data packets from the transmitter. Received packets are parsed to separate physiological information from communication parameters. The system then calculates the data reception interval to determine delay, data size, transfer speed, and RSSI.

The calculated physiological parameters, including heart rate, SpO_2, and body temperature, are displayed in real time on the OLED screen to provide immediate feedback to the user. This process is executed repeatedly in a continuous loop, enabling uninterrupted monitoring of the user's physiological condition during system operation. The looping mechanism ensures that new sensor data are continuously acquired, processed, and transmitted without requiring manual intervention. The overall flowchart of the transmitter and receiver processes is presented in Figs. A1 and A2 in Appendix, illustrating the complete workflow from sensor data acquisition, LoRa-based transmission, packet reception, and result visualization.

D. Data Acquisition and Analysis Method

Data acquisition is conducted experimentally using the previously designed LoRa-based wearable health monitoring system. Data are obtained directly from the MAX30105 sensor installed on the transmitter unit. This sensor measures three primary physiological parameters: heart rate, SpO_2, and body temperature. The measured values are processed by the ESP32-C3 SuperMini microcontroller, which then transmits the data wirelessly via the LoRa SX1276 module to the receiver device.

On the receiver side, another ESP32-C3 microcontroller receives the data and displays it in real time on an SSD1306 OLED screen, allowing each data packet to be monitored continuously during testing. The system is tested under two different environmental conditions: LOS in open areas and indoor conditions, as shown in Figs. 5 and 6. Tests are conducted at various distances until data transmission can no longer be received by the receiver.

Fig. 7 shows the final prototype of the LoRa-based wearable health monitoring system, consisting of a transmitter and a receiver unit. The transmitter is designed as a compact wearable device integrating a MAX30105 sensor for measuring heart rate, SpO_2,

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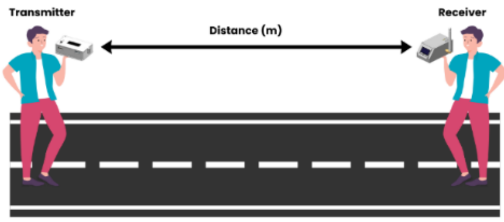

Fig. 5. Illustration of data acquisition under Line-of-Sight (LOS) conditions.

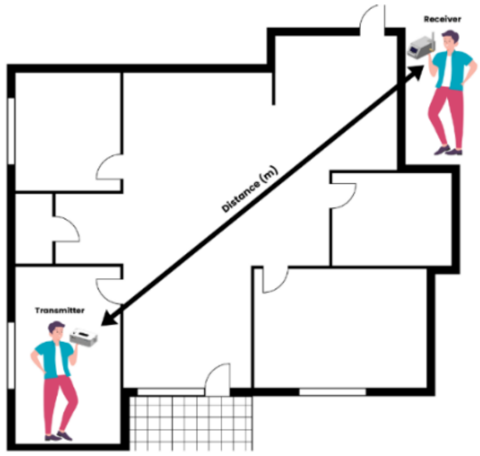

Fig. 6. Illustration of data acquisition under indoor conditions.

and body temperature, along with an ESP32-C3 SuperMini microcontroller for local data processing. The processed physiological data are transmitted wirelessly using the LoRa SX1276 module, which enables long-range communication with low power consumption. The receiver unit functions as a data acquisition and visualization device, employing an ESP32-C3 SuperMini and a LoRa SX1276 module to receive data from the transmitter via point-to-point LoRa communication. The received physiological parameters are displayed in real time on a 1.3-inch OLED screen, allowing direct monitoring of the user's condition. This prototype demonstrates the practical feasibility of the proposed system for wearable health monitoring applications under various testing environments.

At each distance point, data transmission is performed repeatedly to obtain multiple samples for statistical analysis. For every test distance, five data packets are transmitted and recorded, and the measured values of RSSI, delay, and transfer speed are averaged to represent the performance at that distance. This averaging process helps to reduce random fluctuations and provides a more reliable representation of LoRa

Fig. 7. Transmitter and receiver devices used for testing.

communication behavior under each testing condition.

The transmission interval is set to 500 ms between consecutive packets, enabling near real-time data delivery while maintaining stable channel conditions during the experiment. As a result, each distance point requires approximately 5 seconds of measurement time before moving to the next location. This fixed interval ensures consistency in packet generation and minimizes temporal bias during data collection. During testing, packet loss is also observed at longer distances, where some transmitted packets cannot be received by the receiver due to signal attenuation and environmental interference. In such cases, only successfully received packets are included in the averaging process, while unreachable distances are marked as "no data received." This approach allows the evaluation to reflect the practical communication limits and reliability of the LoRa-based wearable system under both LOS and indoor environments.

Next, data analysis is conducted in two main stages. The first stage aims to evaluate the relationship between distance and LoRa communication performance under each testing condition (LOS and indoor), focusing on parameters such as signal strength (RSSI), transmission delay, and transfer speed. Pearson correlation is used to determine the strength of the relationship between distance and performance parameters, while simple linear regression models the decline in performance relative to transmission distance. All statistical analyses are performed using MATLAB to ensure consistent calculations and graphically visualize the results.

The second stage focuses on a comparative analysis between LOS and indoor conditions to assess how environmental differences affect LoRa communication performance. This situation involves comparing graphs

TABLE I
DATA FROM LINE OF SIGHT (LOS) TESTING.

Distance (m)	Delay (ms)	RSSI (dBm)	Transfer Speed (bps)
0	13	−48	14153.9
100	14	−54	13142.9
200	16	−68	12077.3
300	18	−76	10222.2
400	25	−83	7680.0
500	30	−90	6133.3
600	Data are not received		

Note: Received Signal Strength Indicator (RSSI).

of each parameter (distance vs. RSSI, distance vs. delay, and distance vs. transfer speed) and performing one-way ANOVA to determine the significance of mean differences between conditions. Boxplot is also employed to visualize data distribution and identify variations in transmission performance under the two testing scenarios.

III. RESULTS AND DISCUSSION

A. Data Transmission Testing Under Line of Sight (LOS) Conditions

Testing under LOS conditions is conducted in an open area with no physical obstructions between the transmitter and receiver. The purpose of this test is to evaluate LoRa communication performance under ideal conditions, where radio wave propagation is not hindered by obstacles such as walls or building structures. During the test, the transmitter is configured to periodically send data from the MAX30105 sensor, including heart rate, SpO_2, and body temperature, to the receiver using the LoRa SX1276 module with fixed configuration parameters (spreading factor 7, bandwidth 500 kHz, and coding rate 4/5).

Data are collected through controlled experimental measurements conducted at incremental distances, starting from 0 meters until reliable data reception is no longer possible. The distance between the transmitter and receiver is increased gradually at intervals of 100 meters for LOS testing, while shorter intervals are applied for indoor testing to account for environmental constraints. At each distance point, three key performance parameters are recorded, namely RSSI, transmission delay, and data transfer speed. These parameters are selected to represent signal quality, latency, and data transfer speed, which are critical indicators of LoRa communication performance in wearable health monitoring systems. The detailed results of the LOS testing are presented in Table I.

In general, the results indicate that increasing transmission distance gradually reduces RSSI and transfer speed, accompanied by increased delay. At short distances (0–200 meters), the signal is very strong, with RSSI values above −68 dBm and delays below 16 ms. The results indicate stable and efficient communication. However, beyond 300 meters, significant signal degradation occurs, with delay increasing to around 30 ms and transfer speed dropping below 7 kbps. At 600 meters, the connection can no longer be maintained, as data packets are no longer received at the receiver.

To gain a deeper understanding of the relationship between transmission distance and communication performance under LOS conditions, Pearson correlation and simple linear regression analyses are conducted on the three main parameters: RSSI, delay, and transfer speed. The correlation analysis is used to measure the strength of the relationship between distance and each performance parameter, while linear regression is employed to model the trend of parameter changes with increasing distance. This approach allows for the quantitative identification of signal degradation, increased latency, and reduced transmission speed with increasing transmission distance in the LoRa communication system [19]. The results of the Pearson correlation analysis are presented in Fig. 8.

The Pearson correlation analysis under LOS conditions reveals a very strong relationship between transmission distance and the three observed performance parameters. Based on the correlation coefficients, there is a very strong positive correlation ($r = 0.951$) between distance and delay, indicating that as transmission distance increases, data transmission time also increases. Conversely, the relationships between distance and transfer speed and between distance and RSSI show very strong negative correlations, with $r = -0.987$ and $r = -0.993$, respectively. This indicates that increasing distance significantly reduces signal strength and transfer speed.

Overall, these results confirm the basic characteristics of LoRa communication, which tends to experience transmission quality degradation as distance increases, particularly for RSSI and transfer speed. The very high correlations suggest that distance is a dominant factor affecting network performance degradation in the Line-of-Sight scenario, although performance remains acceptable for real-time health monitoring applications up to approximately 400 meters. The results of the simple linear regression analysis are presented in Fig. 9.

Under LOS conditions, the regression analysis shows that distance has a strong impact on LoRa communication performance. The first regression model describes the relationship between distance and transfer speed as an inverse relationship, indicating that each additional meter of distance reduces the transfer speed by approximately 2080 bps. The high coefficient of

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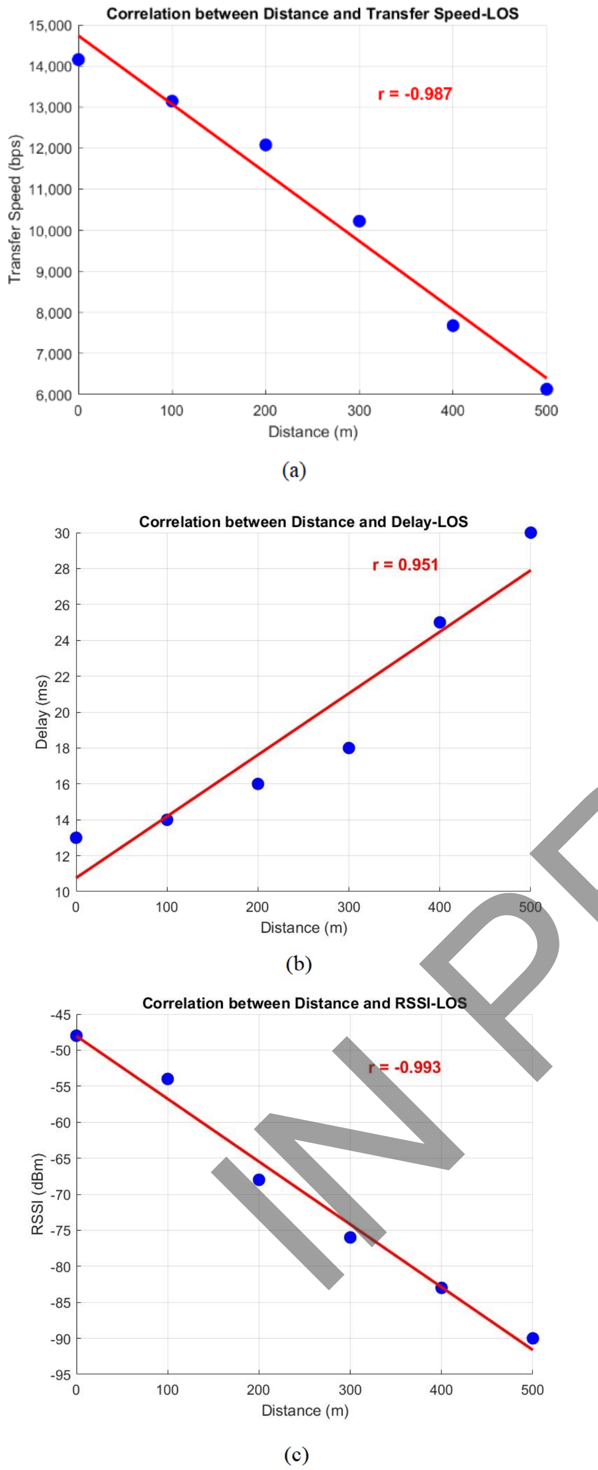

Fig. 8. Pearson correlation graphs under Line of Sight (LOS) conditions: (a) distance vs. transfer speed, (b) distance vs. delay, (c) distance vs. Received Signal Strength Indicator (RSSI).

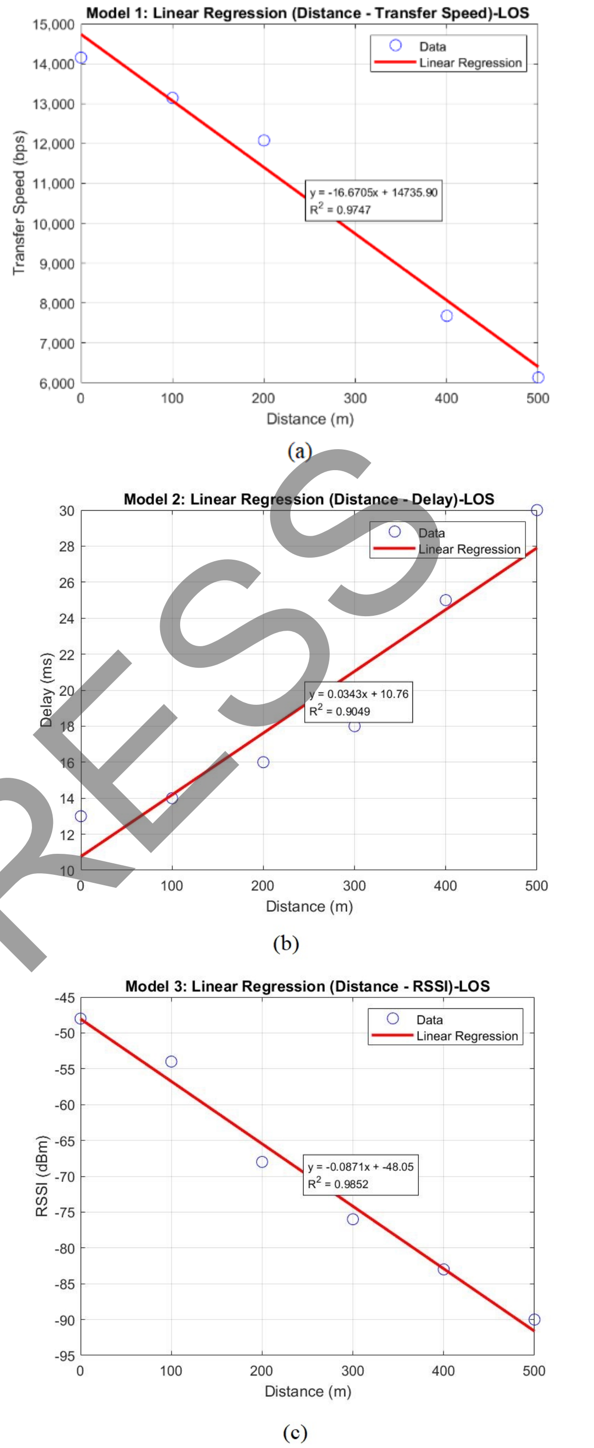

Fig. 9. Simple linear regression under Line of Sight (LOS) conditions: (a) distance vs. transfer speed, (b) distance vs. delay, (c) distance vs. Received Signal Strength Indicator (RSSI).

determination (R^2) suggests that nearly all variations in transfer speed can be explained by distance, meaning that transfer speed decreases consistently as transmission distance increases.

The second model represents the relationship be-

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tween distance and delay, showing a strong positive correlation. The increasing distance causes a linear increase in delay. This result is logical, as longer distances between transmitter and receiver increase signal propagation time and the likelihood of retransmissions due to signal attenuation, leading to reduced network latency performance.

The third model shows the relationship between distance and RSSI. It confirms a very strong negative correlation between distance and received signal strength. The linear decrease in RSSI reflects significant path loss, where signal energy diminishes as it propagates through free space.

Overall, the three analytical models demonstrate that under LOS conditions, transmission distance plays a dominant role in determining LoRa communication performance. As the distance between the transmitter and receiver increases, the transfer speed decreases due to reduced signal quality, while transmission delay increases as a result of longer propagation time and potential retransmissions. In addition, RSSI shows a consistent weakening trend with increasing distance, reflecting the effects of path loss in open-space environments. These results indicate that although LOS conditions provide a more stable propagation environment compared to indoor scenarios, distance remains a critical limiting factor that directly impacts the reliability and efficiency of LoRa-based data transmission for wearable health monitoring applications.

B. Data Transmission Testing Under Indoor Conditions

Testing under indoor conditions is conducted to evaluate LoRa communication performance in enclosed environments with various physical obstacles, such as walls, furniture, and building structures. This scenario represents the use of the wearable health monitoring system indoors, such as in hospitals, clinics, or healthcare facilities, where radio signals experience attenuation and multipath effects. The device configuration for this test is made identical to the LOS scenario, using the LoRa SX1276 module with fixed parameters, spreading factor 7, bandwidth 500 kHz, and coding rate 4/5, to allow for an objective comparison between the two testing conditions.

Data for the indoor test are collected at incremental distances from 0 to 300 meters, with 50-meter intervals. At each distance, three main parameters, RSSI, delay, and transfer speed, are observed to assess the impact of distance on communication performance indoors. The detailed results of the indoor testing are presented in Table II.

Based on the initial results, LoRa performance under indoor conditions declines more rapidly compared to the LOS tests. RSSI values drop significantly beyond 150 meters, while delay increases sharply, reaching 63 ms at a maximum distance of 250 meters. In addition, transfer speed decreases consistently from 14153.9 bps (14.2 kbps) at 0 meters to approximately 3144.8 bps (3.1 kbps) at 250 meters, and the connection is lost at 300 meters. These findings indicate that physical obstacles and signal reflections in enclosed environments have a substantial impact on the stability of LoRa communication.

TABLE II
DATA FROM INDOOR TESTING.

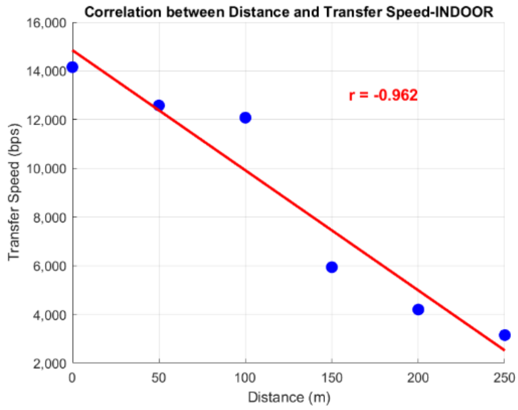
Distance (m)	Delay (ms)	RSSI (dBm)	Transfer Speed (bps)
0	13	−48	14153.9
50	15	−54	12576.0
100	15	−68	12077.3
150	31	−80	5935.5
200	47	−88	4193.3
250	63	−90	3144.8
300	Data are not received		

Note: Received Signal Strength Indicator (RSSI).

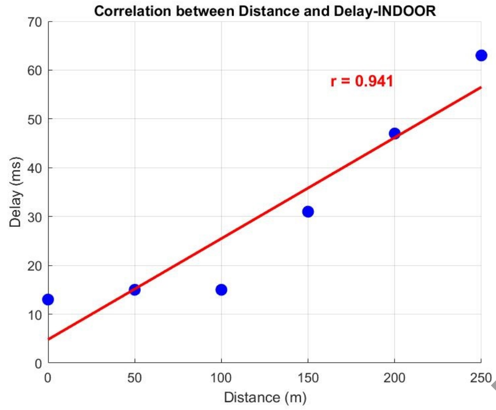
The relationship between transmission distance and communication performance parameters is illustrated in Figs. 10 and 11. The Pearson correlation analysis under indoor conditions indicates that the relationship between distance and LoRa communication performance parameters remains very strong, although the correlation values are slightly lower compared to the LOS tests. The correlation coefficients show a very strong positive relationship (r = 0.941) between distance and delay, indicating that transmission delay increases as distance grows. Conversely, the relationships between distance and transfer speed and between distance and RSSI are very strong negative correlations, with r = -0.962 and r = -0.981, respectively. These results indicate that as transmission distance increases in an enclosed environment, signal degradation becomes more pronounced and transfer speed decreases.

Compared to LOS conditions, these correlations show that environmental factors have a greater impact on transmission stability. Physical obstacles such as walls and furniture lead to increased signal attenuation and multipath effects, causing RSSI to drop more rapidly and delay to fluctuate more. Nevertheless, the correlations remain very strong, indicating that the LoRa communication system can still maintain a consistent linear relationship between distance and transmission performance in indoor scenarios, making it suitable for health monitoring applications within a limited range. The results of the simple linear regression analysis are presented in Fig. 11.

The performance testing of LoRa communication under indoor conditions is conducted to analyze the



(a)



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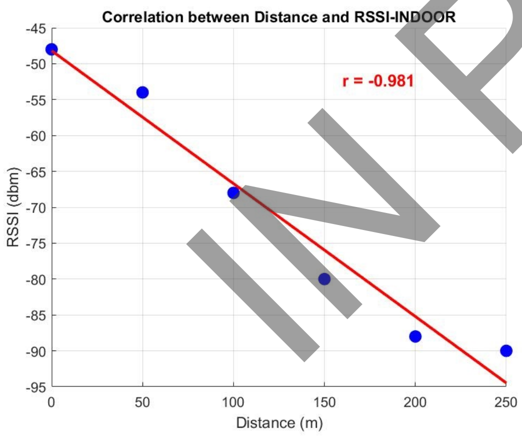
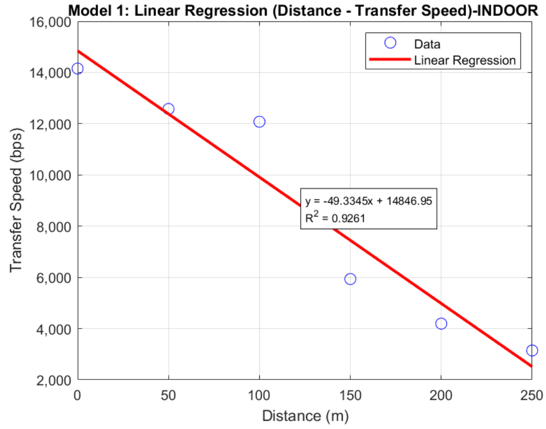
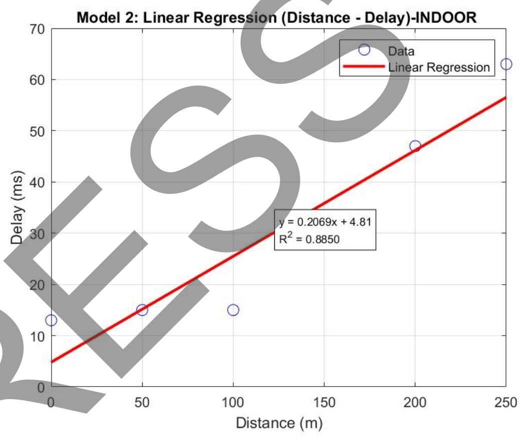


(c)

Fig. 10. Pearson correlation graphs under indoor conditions: (a) distance vs. transfer speed, (b) distance vs. delay, (c) distance vs. Received Signal Strength Indicator (RSSI).



(a)



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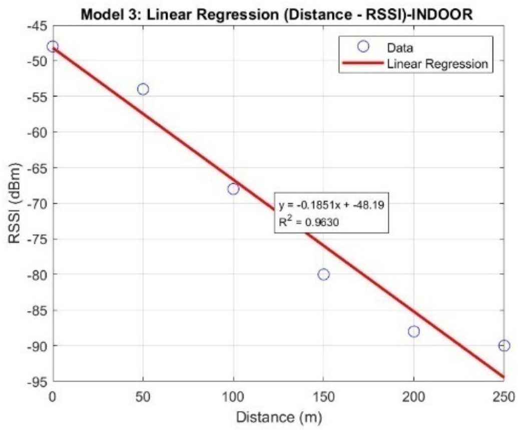

(c)

Fig. 11. Simple linear regression under indoor conditions: (a) distance vs. transfer speed, (b) distance vs. delay, (c) distance vs. Received Signal Strength Indicator (RSSI).

effect of distance on three main parameters: data transfer speed, transmission delay, and RSSI. Based on the linear regression results between distance and transfer speed, the negative slope indicates that as the distance between the transmitter and receiver increases, the transfer speed decreases linearly at an average rate of approximately 6170 bps per meter. The high coefficient

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of determination (R^2) demonstrates a strong relationship between distance and transfer speed, which is primarily attributable to signal attenuation and increased interference in indoor environments.

The relationship between distance and delay shows that transmission delay increases with distance. It has an average rate of approximately 0.206 ms per meter. This increase in delay is influenced by retransmissions and longer signal propagation times due to reduced signal quality in indoor environments.

Meanwhile, the linear regression between distance and RSSI indicates that signal strength consistently decreases with distance, at an average rate of about 0.185 dBm per meter. The very high coefficient of determination (R^2) shows a strong correlation between distance and signal degradation. It is primarily caused by path loss and physical obstacles such as walls and furniture in indoor settings.

Overall, the regression analysis indicates that increasing distance significantly impacts LoRa communication performance in indoor environments. Greater distances lead to decreased transfer speed, increased delay, and reduced RSSI in a linear manner. All three regression models have coefficients of determination above 0.88, indicating very strong linear relationships and stable testing results, accurately representing LoRa signal propagation characteristics under indoor conditions.

C. Comparative Analysis of LOS and Indoor Conditions

After conducting separate tests under LOS and indoor conditions, the next step is to analyze and compare LoRa communication performance between the two scenarios. The purpose of this analysis is to determine the extent to which the environment affects system performance parameters, including delay, RSSI, and data transfer speed. The overall comparison of performance between LOS and indoor conditions for delay, RSSI, and transfer speed is shown in Fig. 12.

Based on the delay versus distance graph, indoor conditions show a sharp increase in delay as distance increases, particularly beyond 100 meters, where delay rises to over 60 ms. In contrast, under LOS conditions, the increase in delay is slower and more stable, with a maximum of around 30 ms at 500 meters. This comparison indicates that physical obstacles and multipath propagation in indoor environments cause significantly longer data transmission times compared to open areas with a direct line of sight.

In the RSSI versus distance graph, RSSI decreases with distance under both conditions, but the decline is much more pronounced indoors. At around 200 meters, the indoor signal weakens to nearly −90 dBm, whereas under LOS conditions, the signal remains relatively

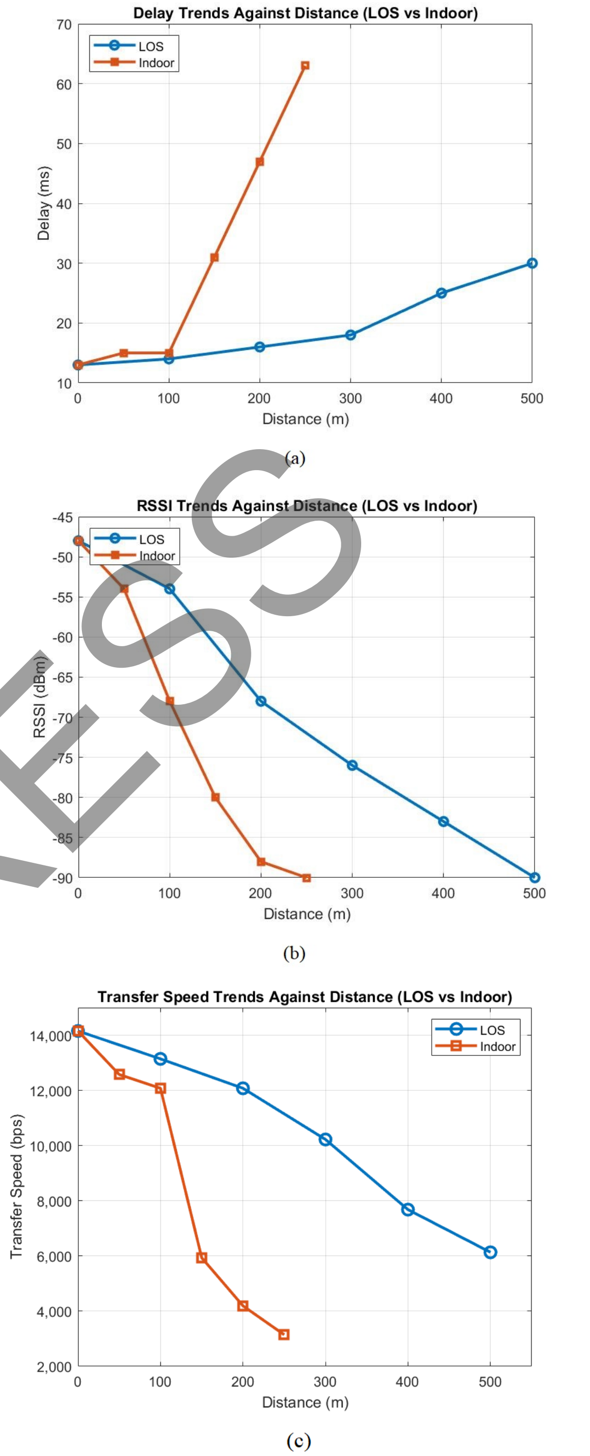

Fig. 12. Performance comparison between Line of Sight (LOS) and Indoor conditions: (a) delay, (b) Received Signal Strength Indicator (RSSI), (c) transfer speed.

strong at approximately −70 dBm at the same distance. This result demonstrates that walls and obstacles in indoor environments greatly affect LoRa signal attenuation, reducing the effective communication range compared to open areas.

Similarly, the transfer speed versus distance graph follows the same pattern as RSSI. Under LOS conditions, transfer speed gradually decreases from around 14 kbps to 6 kbps at 500 meters, whereas indoors, it drops sharply to below 3 kbps at less than 300 meters. This result indicates a strong correlation between RSSI and data transfer speed. Weaker signals result in lower achievable transfer speed. These trends describe the general behavior of LoRa communication under different propagation environments. However, beyond the average values shown in the graphs, it is also important to consider measurement variability and experimental limitations.

Although the presented results are based on averaged values at each distance, each measurement point represents the mean of five consecutive transmissions. This averaging approach reduces short-term fluctuations caused by noise and instantaneous channel variations. However, since the number of samples per distance is limited, small-scale fading and transient interference effects may not be fully captured. Consequently, the observed trends primarily reflect large-scale propagation behavior rather than small-scale fluctuations.

Further analysis is performed using one-way ANOVA and Boxplot. ANOVA is used to test the significance of mean differences in parameters between the two conditions, ensuring that observed variations are truly influenced by environmental factors rather than random fluctuations. Boxplot is used to visualize data distribution, medians, and extreme values for each parameter, providing an intuitive view of performance patterns under LOS and indoor conditions. The results of the ANOVA and Boxplot comparison for transfer speed are presented in Fig. 13.

Based on the ANOVA results in Fig. 13, the F-value is 0.65 with a p-value of 0.4393. Since the p-value is greater than 0.05, there is no statistically significant difference in data transfer speed between LOS and indoor conditions. This indicates that, in general, environmental conditions (LOS or indoor) do not have a meaningful impact on LoRa transfer speed in this test. The observed variation is likely due to factors other than the tested environmental conditions.

The Boxplot shows that the distribution of transfer speed under LOS tends to have a higher median compared to indoor conditions, although both conditions exhibit a wide and overlapping interquartile range. This suggests that while LOS appears slightly better on average, the large variability makes the difference statistically insignificant, consistent with the ANOVA results. The comparison of ANOVA and Boxplot results for delay is presented in Fig. 14.

The one-way ANOVA test yields F = 1.64 with a p-value of 0.2286 (> 0.05), indicating that the difference in mean delay between the two conditions is not statistically significant. Nevertheless, the larger variation in delay under indoor conditions suggests potential interference and signal reflections that affect transmission stability. Overall, the LoRa system still demonstrates stable and sufficiently reliable performance for real-

ANOVA Table

Source	SS	df	MS	F	Prob>F
Groups	1.06951e+07	1	1.06951e+07	0.65	0.4393
Error	1.64879e+08	10	1.64879e+07		
Total	1.75574e+08	11			

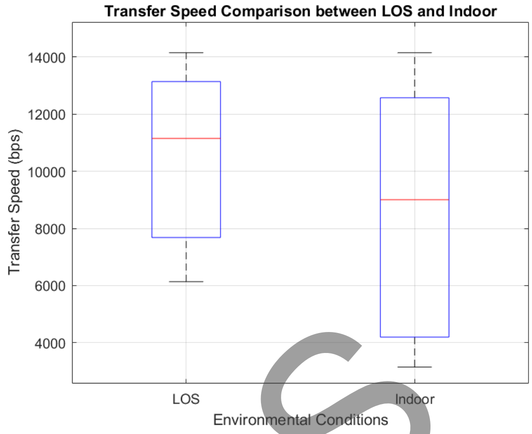

Fig. 13. ANOVA and Boxplot comparison of transfer speed: Line of Sight (LOS) versus indoor.

ANOVA Table

Source	SS	df	MS	F	Prob>F
Groups	385.33	1	385.333	1.64	0.2286
Error	2342.67	10	234.267		
Total	2728	11			

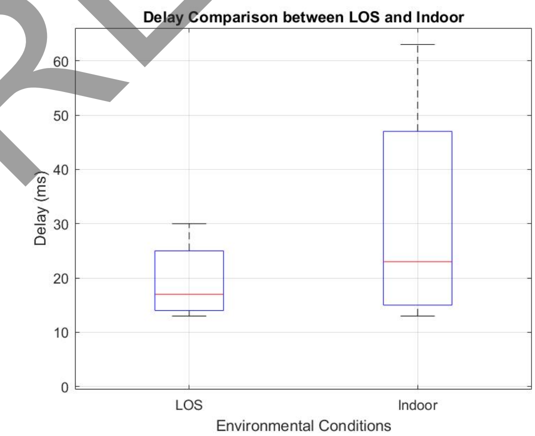

Fig. 14. ANOVA and Boxplot Comparison of Delay: LOS vs. Indoor.

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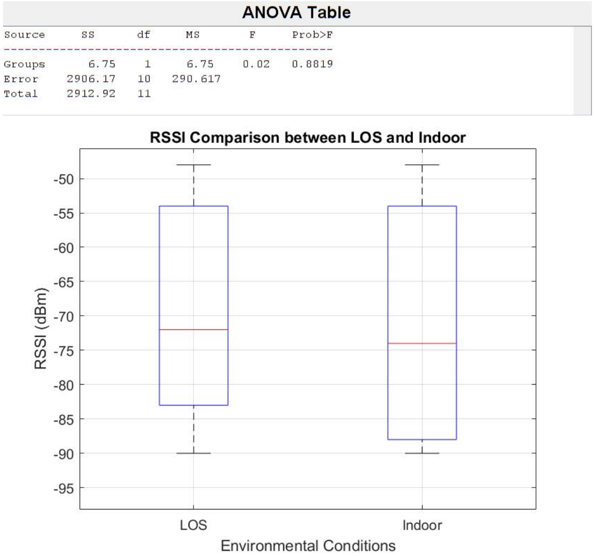

ANOVA Table

Source	SS	df	MS	F	Prob>F
Groups	6.75	1	6.75	0.02	0.8819
Error	2906.17	10	290.617		
Total	2912.92	11			

Fig. 15. Analysis of Variance (ANOVA) and Boxplot Comparison of RSSI: LOS vs. Indoor.

time health monitoring applications.

The Boxplot analysis shows that delay values indoors tend to be higher and more widely distributed compared to those observed under LOS, indicating the influence of physical obstacles on transmission time. The median delay indoors is approximately 23 ms, whereas the median delay under LOS is around 17 ms. The comparison of ANOVA and Boxplot results for RSSI is presented in Fig. 15.

Based on the ANOVA analysis shown in Fig. 15, the F-value is 0.02 with a p-value of 0.8819. Since the p-value is greater than 0.05, the statistical test indicates no significant difference in the average RSSI values between LOS and indoor conditions for the successfully received packets. It means that, at comparable short distances where packets are still delivered, the measured RSSI levels between LOS and indoor environments are statistically similar.

However, this result must be interpreted carefully from an engineering perspective. The ANOVA comparison only includes distances where data packets are successfully received, introducing survivorship bias. In the indoor scenario, communication fails completely at 300 m, whereas under LOS conditions the system continues to operate up to 500 m. As a result, the ANOVA analysis ignores the range beyond 250 m for indoor tests, where no packets are received. Therefore, it does not reflect the actual difference in effective communication range between the two environments.

This behavior is further illustrated by the Boxplot, which shows overlapping RSSI distributions at short ranges, but does not capture the early connection failure observed in indoor conditions. While LOS and indoor RSSI may appear similar at close distances, the indoor environment experiences stronger attenuation and multipath effects that cause the link to collapse much earlier. Consequently, although the statistical averages of surviving packets are not significantly different, the physical communication performance is substantially worse indoors in terms of coverage, robustness, and usable range.

Therefore, the ANOVA results should be understood as describing packet behavior only within the operational region, not the full system capability. From a practical deployment perspective, LOS provides a much larger and more reliable communication range for wearable LoRa health monitoring, while indoor environments impose strict limitations due to obstruction and propagation loss that cannot be fully represented by the p-value alone.

D. Discussion

Overall, the comparative analysis between LOS and indoor conditions demonstrates that LoRa communication performance experiences noticeable degradation in the presence of physical obstructions, particularly in terms of delay and transfer speed. Indoor environments introduce additional attenuation and multipath effects caused by walls, furniture, and reflections, which increase transmission delay and reduce achievable transfer speeds. Although the ANOVA results indicate that the average differences between LOS and indoor conditions are not statistically significant (p-value $>$ 0.05), this statistical outcome should be interpreted carefully from an engineering perspective. The ANOVA comparison only considers successfully received packets at overlapping distances, which introduce survivorship bias. In practice, the indoor system fails to deliver packets beyond 250 m, while LOS communication remains operational up to 500 m. Therefore, even if the mean values at short ranges appear similar, the effective communication range and reliability are significantly worse in indoor environments.

This behavior is also supported by the Boxplot analysis, which shows a wider dispersion of delay, RSSI, and transfer speed under indoor conditions. The larger variance indicates that indoor transmission is less stable and more sensitive to environmental changes. While LOS links benefit from predictable propagation, indoor links are affected by dynamic obstacles and signal reflections that cause fluctuations in RSSI and transfer speed. Consequently, although average metrics may appear comparable at short distances, indoor deployments suffer from earlier performance collapse and higher uncertainty in real operation.

Compared with previous studies, the observed behavior is consistent with reported LoRa propagation characteristics. For example, studies on indoor and outdoor LoRa performance show that RSSI and transfer speed degrade faster indoors due to shadowing and multipath propagation, while LOS links maintain longer effective ranges [10, 11]. Similar findings are reported in multi-gateway LoRa performance evaluations, where indoor environments exhibit reduced coverage and higher latency compared to outdoor deployments [14, 18]. The research results confirm these trends in the context of wearable health monitoring, demonstrating that environmental conditions strongly influence IoMT communication reliability.

Beyond experimental validation, the research demonstrates strong potential for real-world implementation. The LoRa-based wearable device enables continuous physiological monitoring without relying on Internet infrastructure, making it suitable for rural areas, disaster response, and field medical operations. With stable LOS communication up to 500 m and low power consumption, the system supports emergency monitoring and mobile healthcare services. Furthermore, the ability to transmit heart rate, SpO_2, and temperature data in near real-time supports telemedicine and hospital patient management, allowing healthcare providers to monitor patients remotely, reduce workload, and improve response time in both clinical and home-care environments.

Although statistical analysis using ANOVA indicates no significant difference between LOS and indoor conditions for successfully received packets at short ranges, engineering analysis reveals that indoor environments impose a hard physical limit on effective communication range. While short-range performance may appear comparable, indoor links fail much earlier than LOS, highlighting that environmental obstacles critically affect the reliability and coverage of LoRa-based wearable systems.

Several limitations should be acknowledged in the research. The experiments are conducted using fixed LoRa parameters, a single hardware configuration, and a limited number of samples at each transmission distance within specific indoor and outdoor environments, which may reduce statistical sensitivity to detect subtle performance differences. In addition, environmental factors, such as building materials, furniture layout, human movement, terrain conditions, minor obstructions, and electromagnetic interference, may introduce variability in signal propagation, thereby affecting RSSI, delay, and transfer speed. Consequently, the results may not fully represent all practical propagation scenarios.

Future developments may include adaptive transmission power control, multi-hop networking, and cloud-based integration to improve scalability and robustness for broader IoMT applications. Future work may also focus on optimizing the communication reliability and scalability of the proposed system by implementing adaptive transmission power control, adaptive LoRa parameter optimization (e.g., spreading factor and bandwidth), and multi-hop networking to extend communication coverage in complex environments. Integration with cloud-based IoMT platforms and mobile applications can also be explored to enable remote data storage, visualization, and real-time clinical monitoring. In addition, future studies should evaluate the system under larger datasets, more diverse indoor and outdoor environments, different building structures, longer testing durations, and statistical variability analyses, such as confidence intervals or error bars, to provide a more comprehensive evaluation of LoRa communication performance and to further validate its robustness and practical applicability for continuous wearable health monitoring.

IV. CONCLUSION

The research successfully designs and evaluates a LoRa-based wearable health monitoring system capable of transmitting heart rate, SpO_2, and body temperature data in real time using point-to-point communication. Experimental results demonstrate that transmission distance significantly affects communication performance. Under LOS conditions, stable communication is maintained up to 500 m, with RSSI decreasing from approximately -48 dBm to -90 dBm, transfer speed reducing from about 14153.9 bps (14.1 kbps) to 6133.3 bps (6.1 kbps), and delay increasing to around 30 ms. In contrast, indoor communication degrades earlier, where reliable transmission is limited to about 250 m due to stronger attenuation and multipath propagation, resulting in higher delay and lower transfer speed. The novelty of this research lies in the implementation of a compact point-to-point LoRa wearable platform using ESP32-C3 and SX1276 for real physiological payload transmission, combined with both statistical and engineering-based performance evaluation under LOS and indoor propagation scenarios without relying on LoRaWAN infrastructure.

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AUTHOR CONTRIBUTION

Conceived and designed the point-to-point LoRa-based system, R. A. and G. B. S.; Collected the data for the point-to-point LoRa-based system/network, R. A.; Contributed data and analysis tools for the wearable health monitoring system, R. A. and I. N.; Performed the analysis for the wearable health monitoring system, R. A. and I. N.; Wrote the paper, I. N. and G. B. S.; Formatted the paper and checked the grammar and language, I. N. and G. B. S.; and Supervised the paper, I. N. and G. B. S.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of the research are available within the article.

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APPENDIX

The Appendix can be seen in the next page.

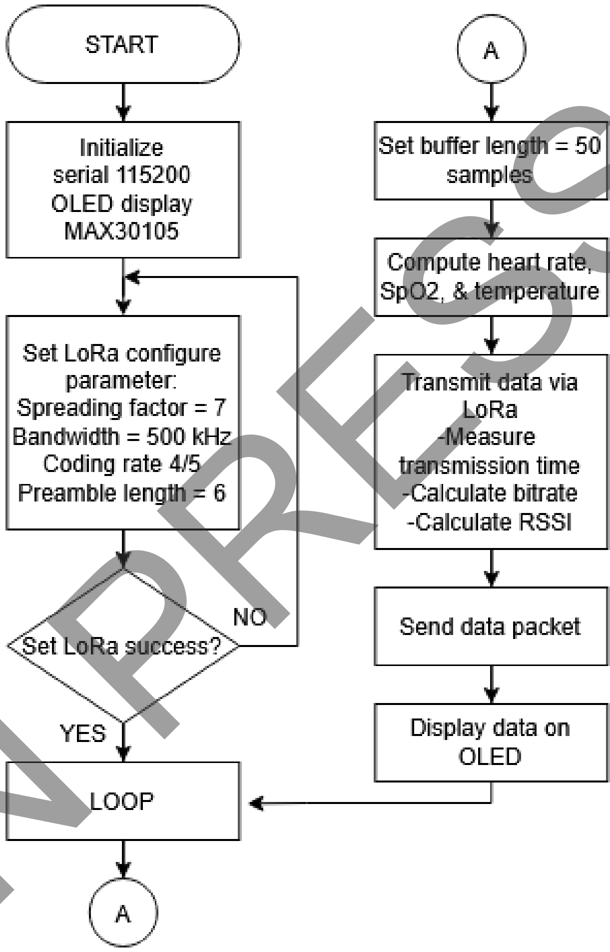

Fig. A1. Transmitter system flowchart.

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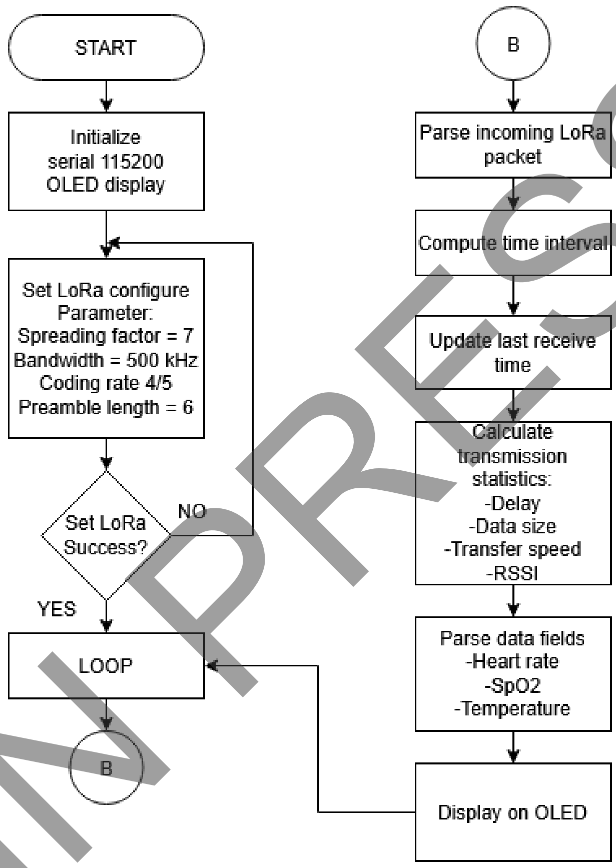

Fig. A2. Receiver system flowchart.