Comparison of Bluetooth Low Energy (BLE), Wi-Fi, Serial and 5G in IoMT

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Abstract: With the inception of Industry 4.0, incorporating technologies like the Internet of Things (IoT) into healthcare has become essential. This integration is commonly referred to as the Internet of Medical Things (IoMT). The IoMT is the connection of medical devices using wired or wireless data transmission technology to allow data exchange with the goal of improving the overall healthcare delivery. Despite the numerous advantages that IoMT brings into the healthcare process, there are potential performance challenges that may occur if factors such as data quality and reliability of the IoT devices in different environmental settings are not properly considered. The purpose of this paper is to analyse the performance of connected medical IoT devices that are used for heartrate monitoring based on the aforementioned factors. The setup of the IoMT consists of sensor nodes, which transmit the Electrocardiogram (ECG) data through a multi-protocol gateway to a central server for further data processing. This paper presents the performance analysis of the comparison of four communication technologies: Serial (UART), Bluetooth Low Energy (BLE), Wi-Fi, and 5G NR for real-time ECG monitoring applications, while taking notice of environmental factors that may affect performance. The sensor data transmission is evaluated based on round trip time (RTT) latency, ensuring a desirable throughput and minimal or no data loss. The data readings were taken at varying distances (0.1m to 17m) and sampling rates (300Hz and 1000Hz). The experimental results show that while Serial communication achieves the lowest latency (3.96ms - 4.37ms), Wi-Fi demonstrates consistent Gateway-Server performance (40ms - 60ms RTT), 5G excels in short-range communication (1.8ms - 2.0ms Sensor Node-Gateway RTT), and BLE provides balanced performance (4.86ms - 7.57ms latency). Wi-Fi performed better in long-range scenarios (43.48ms - 66.23ms RTT) and maintaining stable performance at longer ranges while 5G shows superior performance in short-range, high-frequency scenarios.

1 INTRODUCTION

In healthcare, the Internet of Medical Things (IoMT) has emerged as an evolutionary paradigm which leverages connected network devices to enhance the patient's journey through the hospital, which includes patient care, monitoring and medical diagnosis, and decision making (Dimitrov, 2016). IoMT systems rely on various network communication technologies to allow exchange of data between the medical devices and the server or monitoring system.

This paper focuses particularly on, Bluetooth Low Energy (BLE), Wi-Fi, 5G, and UART serial communication technologies. Bluetooth Low Energy (BLE) is widely used in IoMT because it of its low power consumption capability and works well with smartphones and tablets. It is especially useful for short-distance communication in wearable medical device (Girolami et al., 2020). Wi-Fi has a high advantage of fast data transfer within local networks (Pahlavan and Krishnamurthy, 2021). It is also good for sending large amounts of medical data, such as high-resolution medical images or continuous streams of vital signs. The fifth-generation cellular network technology, or 5G, promises extremely low latency and high bandwidth, which makes it perfect for real-time monitoring both locally and remotely (Varga et al., 2020). Because of its dependability and simplicity in short-range wired connections between medical devices and local gateways, UART Communication, despite not being a wireless technology remains essential in the Internet of medical things

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(Huang and Sheng, 2024).

Ensuring optimal performance of networked medical device setups is critical, as it directly affects the timeliness and quality of healthcare delivery provided by IoMT systems. A number of factors, including data quality, energy efficiency, dependability, and transfer speed, significantly affect how effective IoMT solutions are.

1.1 Problem Statement

Even though there have been many advancements in IoMT and its related communication technologies, a significant number of challenges still remain, particularly in the area of ECG heart rate monitoring. Data loss, latency, and throughput issues may jeopardize the quality and reliability of vital sign monitoring, resulting in delayed or inaccurate medical interventions. Even minor data loss during ECG monitoring may result in the oversight of crucial events such as arrhythmias or other cardiac problems. High latency in data transmission may result in delays in detecting rapid changes in heart rate or rhythm, which is critical in emergency situations. Inadequate throughput may limit the frequency of ECG signal sampling, lowering the granularity of heart rate data and perhaps missing essential short events (Kwon et al., 2018).

While there are many interesting researches which have sought to address various aspects of IoMT performance, there remains a critical need for solutions that simultaneously achieve minimal data loss, desirable sampling frequency, ultra-low latency, and high throughput in ECG heartrate monitoring applications.

1.2 Purpose and Objectives

The objectives of this paper are to address the identified issues by developing and evaluating an IoMT solution which is designed for ECG heart rate monitoring:

- To compare the performance of the proposed setup across different communication technologies (BLE, Wi-Fi, 5G, and UART);
- To evaluate impact of sampling frequency on performance of the system.

The rest of this paper is organized as follows: Section 2 reviews related work. Section 3 describes the proposed system setup. Section 4 presents the evaluation results and analysis. Finally, conclusion, recommendations and future work in Section 5.

2 RELATED WORKS

The Internet of Medical Things (IoMT) has garnered significant attention in recent years due to its potential to revolutionize healthcare delivery. This section provides an overview of existing research on IoMT, network communication technologies, and the analysis of performance in networked IoT/IoMT systems.

IoMT research has expanded rapidly, covering various aspects of healthcare technology integration. (Dimitrov, 2016) provided a comprehensive overview of IoMT, highlighting its potential to improve patient outcomes and reduce healthcare costs. The study emphasized the importance of interoperability and data security in IoMT systems identifying the fact that ensuring seamless communication between diverse medical devices and systems remains a significant challenge. Building on this foundation, (Alshehri and Muhammad, 2020) proposed a framework for IoMT that addresses key challenges in data collection, transmission, and analysis. Their work highlighted the need for efficient communication protocols and robust data analytics in IoMT applications.

Most research on network communication technologies for IoMT has focused on optimizing performance for medical applications. Several key technologies have emerged as prominent in IoMT research. (Al-Shareeda et al., 2023) conducted a comprehensive review of BLE applications in healthcare, noting its advantages in power efficiency and widespread adoption in consumer devices. (Vellela, 2024) explored an IoT-based framework for patient monitoring in intensive care units, addressing challenges related to quality of life of patients. (Ahad et al., 2019) discussed the potential of 5G in revolutionizing IoMT, particularly in enabling real-time remote monitoring and telesurgery applications. While less prominent in recent literature, UART remains relevant in certain IoMT applications. (Deb et al., 2022) demonstrated its use in a low-cost ECG monitoring system.

Performance analysis of networked IoT and IoMT systems has been a critical area of research. (Vismaya et al., 2024) proposed a comprehensive 5G-based framework for IoT network performance analysis, considering security issues and long-range patient monitoring and care. Focusing specifically on healthcare, (Rahmani et al., 2018) presented a fog computing-based approach for analysing and optimizing IoMT network performance.

Several studies have proposed frameworks and approaches for measuring IoT network performance, with potential applications in IoMT. (Arafat et al., 2024) developed a Quality of Service (QoS) aware

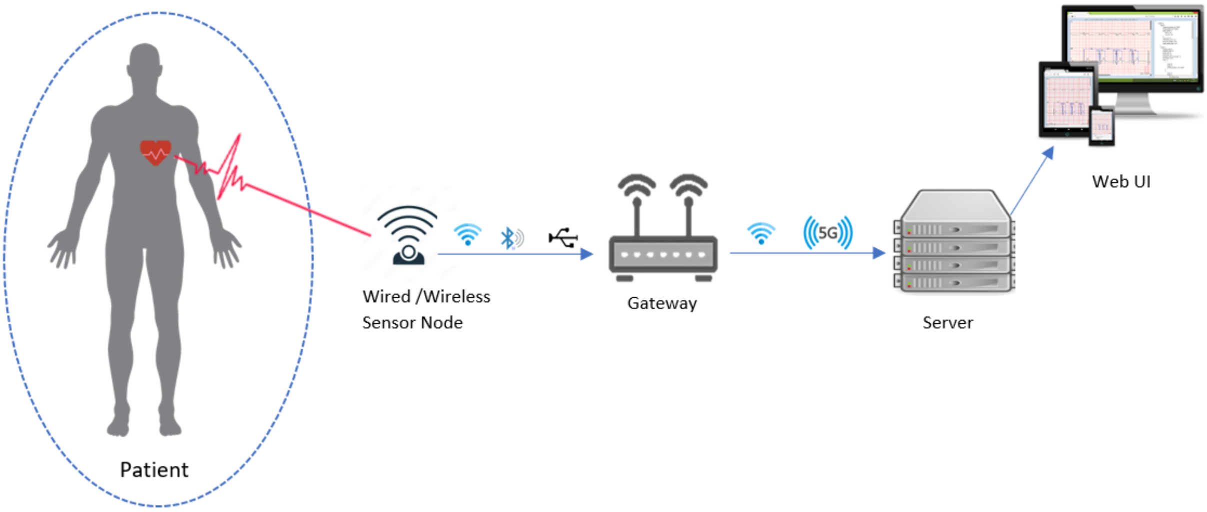

Figure 1: Setup of transmission of ECG data through a multi-protocol Gateway to Server.

framework for IoMT networks, which is adapted for smart healthcare. (Razzaque et al., 2016) reviewed requirements for middleware IoT, many of which are applicable to IoMT. (Varga et al., 2020) presented a comprehensive review of latency in IoT networks, with a focus on industrial IoT 5G-enabled applications. (Hameed and Koo, 2024)explored the impact of active reconfigurable intelligent surfaces to improve throughput optimization in IoT networks. These related works highlight the dynamic nature of IoMT research and the ongoing efforts to improve network performance for medical applications. While significant progress has been made, there remain ample opportunities for innovation in addressing the unique challenges posed by IoMT systems.

3 PROPOSED SYSTEM

Figures 1 and 2 depict the architecture and block diagram of the setup respectively. The proposed system consists of sensor nodes for measuring vital data of patients (i.e., ECG). In the experimental setup, an ECG sensor is attached to the vital positions of a person to read the heart rate signals. These signals are transmitted through microcontroller boards that are capable of either wired or wireless communication. This is followed by a wired or wireless transmission of the sensor data to the multi-protocol gateway for processing of the data and forwarding from the gateway to a central server which houses the central data storage. Visualization of stored data and live data from ongoing measurements can be viewed on the web interface and also used for further analysis.

As shown in Table 1, the proposed model consists of a setup with AD8232 ECG sensor electrodes placed on a patient.

Wired / Wireless Sensor Node: Selected microcontroller units (MCU) with different communication technologies (UART (Arduino Nano Every), Bluetooth BLE (Arduino Nano 33 BLE), Wi-Fi (ESP8266) via a wireless access point), are used to send the ECG data to the gateway.

Multi-protocol Gateway: Raspberry Pi 5 is used as the gateway which is connected to RM520N-GL 5G USB TO M.2 B KEY dongle to allow for 5G communication between the gateway and server.

Server System: Another Raspberry Pi 5 connected to an RM520N-GL 5G USB TO M.2 B KEY dongle, or a computer connected to the 5G network acts as the server to receive and process the data from the gateway and display the real time heart rate signals on a web user interface.

The sensor data transmission is evaluated mainly based on the latency using sampling frequencies (300Hz and 1000Hz) as input parameter. Ensuring minimal data loss, maintaining desirable sampling frequency (>100Hz), and achieving ultra-low latency are crucial for accurate heart rate monitoring (Kwon et al.,2018). For this reason, the 300Hz and 1000Hz were chosen to test how the setup can handle the ECG data transmission and guarantee these sampling rates without data loss or low throughput.

4 EVALUATIONS

As shown in Table 2, the experiment was done in two variations with fixed sampling frequencies of 300Hz and 1000Hz and varied distances. This is to sys-

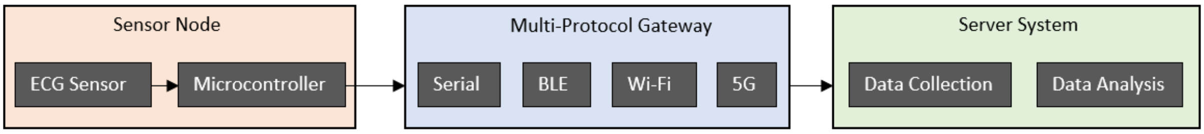

Figure 2: Block diagram of transmission of ECG data from sensor node to server.

Table 1: System Components and Specifications.

Component	Hardware	Config	Purpose
ECG Sensor	AD8232	12-bit ADC	Data acquisition
Micro controller	Arduino Nano Every, ESP8266 NodeMCU, Arduino Nano 33 BLE	ATMega 4809 microcontroller, Wi-Fi: IEEE 802.11 b/g/n, Bluetooth 5.0	Serial, Wi-Fi, BLE transmission
5G Device	RM520N-GL 5G USB TO M.2 B KEY dongle	5G Sub-6 GHz module	5G transmission
Gateway	Raspberry Pi 5	Multi-protocol support and data processing	Sensor data transmission
Server	Raspberry Pi 5	Data storage and analysis	Analysis and storage

tematically evaluate the communication protocols at different stages of the IoT healthcare system. This approach isolates and analyses performance characteristics of both edge (sensor node to gateway) and backhaul (gateway to server) communications independently. Table 3 shows the specifications of the test environment. The experiment was done indoors in a lab with 5G antenna and a 5GHz Wi-Fi router mounted at the same place to the wall 3.7m from the ground. the room is divided into 3 partitions by partial concrete walls (2m height).

The first part of testing involved sensor node to gateway edge communication where the testing protocols used were UART (Arduino Nano Every), Wi-Fi (ESP8266) and BLE (Arduino Nano 33 BLE). The test configurations in this part were made up of the following distance variations as test points: (a) Baseline measurement: fixed minimal distance, which is the starting point, (b) Measurement without obstacles: Distances: 1m, 2m, 5m, 10m and (c) Measurement with obstacles (Wall): Distances: 2.4m, 3.4m, 5.4m, 6.4m

Table 2: Experimental Parameters and Settings.

Parameter	**Values**	**Description**
Distances	0.1-17m	Multiple points
Sampling Rates	300Hz, 1000Hz	Fixed intervals
Duration	10 minutes	Per configuration
Environment	Indoor controlled	Temperature: 22±2°C

The second part of the experimental tests was gateway to server backhaul communication, both Raspberry Pi 5 devices with in-built Wi-Fi and connected to RM520N-GL 5G USB TO M.2 B KEY dongle as test protocols. The ECG sensor was connected to Arduino Nano Every to the gateway via UART for this test. Distance test points measured were

Test points: (a) Partition A: 6m (facing 5G antenna and Wi-Fi router), 9m (left), 10m (right), (b) Partition B: 7.5m (facing 5G antenna and Wi-Fi router) and (c) Partition C: 17m (facing 5G antenna and Wi-Fi router)

Table 3: Test Environment Specifications.

Parameter	Configuration
Room Dimensions	25m x 25m
Antenna / Wi-Fi Router Height	3.7m
Wall Material	Concrete
Internal Partitions	Concrete

For each communication protocol, each distance, and each sampling rate, other data such as, timestamps, sample indices for each ECG data, is generated alongside the ECG sensor data to help track the performance of the IoMT devices. In order to determine data loss, throughput and latency performance of the system, the communication devices attach sequence numbers to each ECG data point generated with the timestamp each data point was received. This is then transmitted in bulks of 50 to the gateway. The gateway periodically pings the sensor node and records the time it receives a response to determine the roundtrip time. Same process happens between the gateway and the server devices.

The data loss rate is calculated by comparing the total expected samples from the sensor node with what the gateway received (gateway sequence) vs what the server received (server sequence) in the dataset. The difference, divided by the total expected and multiplied by 100, gives the percentage of data loss. Latency is calculated for different stages:

- Sensor Node to Gateway (SnG): Time difference between sensor node timestamp and Gateway received time. T.response: Time of response receipt and T.request: Time of initial request;

$$RTT.SnG = T.response - T.request \quad (1)$$

- b. Gateway to Server: Uses the Roundtrip (RTT) Latency from the gateway data, where T.proc: Server processing delay, T.Sresp: Server response time and T.Greq: Gateway request time;

$$RTT.GS = (T.Sresp - T.Greq) - T.proc \quad (2)$$

- End-to-End Latency (E2E): Time difference between Arduino timestamp and Server processed time;

$$E2E = RTT.SnG + RTT.GS \quad (3)$$

5 ANALYSES

Tables 4 and 5 depict the comparisons after analysis is done on the collected data. First, we observed no data losses for experiments. This is due to implementation of techniques such as connection intervals specifically for BLE communication and sending the data in bulk and in batches to ensure all ECG sensor data generated are transmitted by the communication devices.

5.1 Edge Communication Performance (Sensor Node to Gateway Analysis)

For the roundtrip time measurement without obstacles, serial communication shows the lowest latency (3.96ms at 300Hz, 4.37ms at 1000Hz), which is expected as it's a direct connection. BLE and Wi-Fi show higher latencies, with Wi-Fi generally having slightly higher latencies than BLE. Wi-Fi is about 1.5ms higher than serial and BLE is about 1.3ms higher than serial.

The 1000Hz configurations generally show slightly higher latencies than the 300Hz configurations especially at longer distances. Generally, latency increases with distance for both 300Hz and 1000Hz frequencies. The presence of obstacles tends to increase latency compared to no obstacles. The highest latencies are observed at the greatest distances (10m), particularly with obstacles present. The table compares end-to-end latency across different methods and frequencies:

- Wi-Fi has the highest average latency, followed closely by BLE, while serial communication has the lowest latency;
- For Wi-Fi and BLE, the 1000Hz frequency shows slightly higher latency than 300Hz, but the difference is small;
- Serial communication shows the least variation in latency between frequencies;

Table 4: Communication Latency Comparison at Different Distances Without Obstacles and Sampling Rates.

Distance	**Serial (ms) 300Hz**	**Wi-Fi (ms) 300Hz**	**BLE (ms) 300Hz**
Starting point	3.96	5.48	5.24
1m	N/A	6.06	5.45
2m	N/A	6.47	6.02
5m	N/A	8.07	7.48
10m	N/A	10.51	10.04
Distance	**Serial (ms) 1000Hz**	**Wi-Fi (ms) 1000Hz**	**BLE (ms) 1000Hz**
Starting point	4.37	5.74	4.86
1m	N/A	6.21	5.22
2m	N/A	6.20	6.04
5m	N/A	8.44	7.97
10m	N/A	10.99	9.78

Table 5: Wi-Fi and BLE Latency Comparison at Different Distances With Obstacles and Sampling Rates.

Distance	**300Hz (ms)**		**1000Hz (ms)**	
	Wi-Fi	**BLE**	**Wi-Fi**	**BLE**
2.4m	7.97	7.24	7.59	7.73
3.4m	8.44	7.91	8.43	7.59
5.4m	9.61	9.07	9.43	8.83
6.4m	10.22	9.65	10.74	9.64

Like BLE, Wi-Fi latency generally increases with distance. Obstacles tend to increase latency compared to no obstacles. There's high variability in latency, especially at longer distances. The 1000Hz frequency often shows higher latency than 300Hz, particularly with obstacles. The highest latencies are observed at 6.4m and 10m distances.

5.1.1 Baseline Performance Analysis

The initial testing at the starting point of measurement revealed distinct performance characteristics for each protocol. Serial communication established the baseline for optimal performance, achieving a mean latency of 3.96ms (±0.06ms at 95% confidence interval) at 300Hz sampling rate. This performance saw a slight degradation to 4.37ms (±0.07ms) when increasing to 1000Hz sampling rate, representing only a 10.4% increase despite more than tripling the data rate. Bluetooth Low Energy demonstrated remarkable performance for a wireless protocol, with mean latencies of 5.24ms (±0.09ms) at 300Hz and 4.86ms (±0.08ms) at 1000Hz. Notably, BLE showed improved performance at the higher sampling rate, suggesting effective packet bundling and transmission optimization. WiFi performance established the baseline for IP-based communication, with mean latencies of 5.48ms (±0.11ms) at 300Hz and 5.74ms (±0.12ms) at 1000Hz. The relatively small latency increase of 4.7% between sampling rates indicates robust scalability for higher data rates.

5.1.2 Distance Impact Analysis

The impact of distance on the wireless protocols revealed some important patterns for healthcare deployment planning. BLE demonstrated a linear degradation rate of approximately 0.48ms per meter ($R^2 = 0.982$) at 300Hz sampling rate. This predictable degradation allows for reliable performance estimation in hospital environments. WiFi showed a similar linear pattern but with a steeper degradation rate of 0.503ms per meter ($R^2 = 0.975$) at 300Hz. The difference in degradation rates became more pronounced at 1000Hz sampling rate where BLE had 0.492ms/m ($R^2 = 0.978$) and WiFi had 0.525ms/m ($R^2 = 0.971$)

5.1.3 Obstacle Effects

The introduction of concrete walls created significant but predictable impacts on wireless performance. At 2-meter distance BLE latency increased by 20.3% (±1.2%) and WiFi latency increased by 23.2% (±1.4%). This difference in obstacle impact becomes particularly relevant for hospital deployments where multiple walls may separate sensors from gateways.

5.2 Backhaul Communication Performance (Gateway to Server Analysis)

Table 6 shows the performance comparison between Wi-Fi and 5G and these are the key observations: As observed in the first set of experiments, both Wi-Fi and 5G show excellent performance with no observable data loss across all distances and sampling rates. Both technologies maintain the target sampling rates (300Hz and 1000Hz) with no data loss. There's no significant difference between Wi-Fi and 5G in terms of maintaining the desired sampling rate.

Table 6: Wi-Fi and 5G Latency Comparison at Different Distances.

Distance	**Wi-Fi (ms)**		**5G (ms)**	
	300Hz	**1000Hz**	**300Hz**	**1000Hz**
6m	78.64	44.32	204.53	213.64
7.5m	60.16	47.82	181.21	163.53
9m	65.19	62.02	172.75	169.39
10m	66.23	44.84	187.91	160.68
17m	43.48	54.16	290.63	202.81

End-to-end round trip time latency measurements gave the following results. At 300Hz sampling frequency, Wi-Fi had an initial high latency (78.64ms) at 6m which showed at 7.5m to 60.16ms. It then became relatively stable (60ms - 66ms) at 9m and 10m distances. Its best performance was at maximum distance (43.48ms at 17m). At 1000Hz sampling frequency, it had a consistent performance range (44-62ms) with more stable latency across the distances. The average RTT improvement of 39.8 percent compared to 300Hz.

5G also had moderate latency (204.53ms) at 6.0m initially at 300Hz sampling frequency. It could be observed that there was a progressive improvement until 9m (172.75ms) but performed quite poorly beyond 10m with a significant decline in performance (290.63ms) at maximum distance. At 1000Hz sampling frequency, higher initial latency (213.64ms) was recorded at 6m which improved with distances 7.5m to 10m. It had 30.2 percent lower RTT at 17m compared to 300Hz.

Wi-Fi consistently outperforms 5G in terms of Gateway-Server RTT across all distances and sampling rates. Wi-Fi RTT remains relatively stable (mostly under 70ms) even at longer distances. 5G shows higher RTT values (160ms-290ms) and more variation with distance.

Increasing the sampling rate from 300Hz to 1000Hz doesn't significantly impact the performance of either technology in terms of data loss or throughput. There's a slight increase in Arduino-Gateway RTT for both technologies at 1000Hz, but it's minimal. Wi-Fi maintains consistent performance across different distances. 5G shows more variation in Gateway-Server RTT as distance increases, particularly noticeable at 17m.

5.2.1 Protocol Comparison

The backhaul testing revealed substantially different performance characteristics compared to edge communication. At the 6-meter baseline position the average performance of 5G was 300Hz: 204.53ms (±3.21ms) and 1000Hz: 213.64ms (±3.45ms), whiles average Wi-Fi performance was 300Hz: 78.64ms (±1.89ms) and 1000Hz: 44.32ms (±1.56ms)

6 DISCUSSION

6.1 Clinical Implications

The performance characteristics revealed in this experiment have some implications for different types of medical monitoring scenarios. It is, therefore, important to understand these implication to help with protocol selection for specific healthcare applications.

6.1.1 Critical Care Applications

In critical care settings, where immediate detection of life-threatening arrhythmias is essential, these results indicate that protocol selection can significantly impact the reliability of the system. For instance, in ventricular fibrillation detection, where every millisecond impacts survival rates, the measured latency differences become clinically significant.

The consistent communication of UART of sub-4ms latency makes it ideal for bedside monitoring equipment where physical connections are feasible. The average latency of 3.96ms ensures that rhythm analysis algorithms receive data with minimal delay, which can be crucial for real-time detection of dangerous arrhythmias.

BLE's performance (5.24ms average) makes it a viable wireless alternative for critical care applications, particularly important for maintaining mobility of the patient while ensuring timely data transmission. The stability of BLE performance, which is indicated by its low coefficient of variation (3.44%), provides the reliability necessary for critical care monitoring.

6.1.2 General Ward Monitoring

For general ward monitoring, where patients require continuous observation but with quite flexible timing requirements, these results obtained support more flexible protocol selection. The measured Wi-Fi latencies (5.48ms to 10.51ms depending on distance) fall well within acceptable ranges for routine vital sign monitoring, where updates every 50-100ms are typically sufficient.

6.1.3 Remote Monitoring Considerations

The backhaul communication results obtained indicates suitability for remote monitoring implementations. The measured 5G latencies (204.53ms to 290.63ms) prove suitable for non-critical remote monitoring applications while requiring careful consideration for any critical care implementations requiring real-time response.

6.2 Implementation Recommendations

Based on our findings, we propose the following implementation strategies for different healthcare scenarios:

For critical care environments, we recommend for primary monitoring, serial connections are used where possible, because provided the most reliable and lowest latency data transmission. For mobile monitoring, BLE implementations with redundant receivers may be used to maintain coverage. For maximum distance, maintaining BLE sensor-to-gateway distances under 5m can ensure latency remains below 7.5ms. And for sampling rate, 300Hz provides optimal balance of data resolution and system performance.

For general ward monitoring, our results suggest Wi-Fi is suitable to be used as a primary protocol for its broader coverage and acceptable latency characteristics. For access point placement, a maximum 10m separation from the gateway to maintain sub-10ms latency is suitable. And for sampling rate, both 300Hz and 1000Hz are viable depending on the specific monitoring needs.

7 CONCLUSION

This paper investigated the performance characteristics of different data transmission methods (Serial, Wi-Fi, and BLE comparison and Wi-Fi and 5G comparison) for an ECG monitoring system. We find that for the Serial, Wi-Fi, and BLE comparison, all the communication technologies maintain data integrity with no data loss. The system achieves expected throughput based on the target sampling frequencies accurately. Latencies are within expected ranges, with serial being fastest, followed by BLE, then Wi-Fi. For the Wi-Fi and 5G comparison, the experiment demonstrates that while both Wi-Fi and 5G are viable options for ECG monitoring systems, their optimal use cases differ. At distance 0.1 to 1m, the best options are Serial (3.96ms) or BLE (4.86ms) which consistently gave low latency. This is critical for real-time monitoring which can be suitable for Critical Care Units. Wi-Fi and 5G are best suited for mid-range to long-range monitoring.

There were some limitations of this experiment which has help to suggest the directions for future research. Our testing environment, while controlled, represents a simplified version of actual hospital environments. Specific limitations include limited interference sources compared to active hospital environments, single-story testing versus multi-floor hospital scenarios, and absence of dynamic obstacles (moving equipment and people).

The technical aspect of the experiment also had some constraints including RTT-based latency measurements versus true end-to-end timing and limited number of simultaneous devices tested. While our results align with theoretical requirements for medical monitoring, additional validation would strengthen the clinical relevance such as testing with standardized ECG datasets from PhysioNet, validation in active hospital environments, and long-term stability assessment in clinical settings.

In future work, we plan to implement a corresponding digital twin of this physical setup and a probe to properly monitor the performance and particularly to obtain a more accurate latency calculation of the system. There will also be power consumption analysis and testing of the characteristics of ECG signals during rest vs exercise (for wearable devices) to determine how both may affect performance of the system. And to investigate performance under higher network load conditions.

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REFERENCES

Ahad, A., Tahir, M., and Yau, K. L. (2019). 5g-based smart healthcare network: Architecture, taxonomy, challenges and future research directions. *IEEE Access*, PP:1–1.

Al-Shareeda, M., Ali, M., Manickam, S., and Karuppayah, S. (2023). Bluetooth low energy for internet of things: review, challenges, and open issues. *Indonesian Journal of Electrical Engineering and Computer Science*, 31:1182–1189.

Alshehri, F. and Muhammad, G. (2020). A comprehensive survey of the internet of things (iot) and edge computing in healthcare. *IEEE Access*, PP:1–1.

Arafat, M. Y., Pan, S., and Bak, E. (2024). Qqar: A q-learning-based qos-aware routing for iomt-enabled wireless body area networks for smart healthcare. *Internet of Things*, 26:101151.

Deb, S., Islam, M. R., Robaiatmou, J., and Islam, M. T. (2022). Design and implementation of low-cost ecg monitoring system for the patient using smart device. In *International Conference on Inventive Computational Sciences (ICICCS)*.

Dimitrov, D. V. (2016). Medical internet of things and big data in healthcare. *Healthcare Informatics Research*, 22(3):156–163.

Girolami, M., Mavilia, F., and Delmastro, F. (2020). Sensing social interactions through ble beacons and commercial mobile devices. *Pervasive and Mobile Computing*, 67:101198.

Hameed, I. and Koo, I. (2024). Enhancing throughput in iot networks: The impact of active ris on wireless powered communication systems. *Electronics*, 13:1402.

Huang, W. and Sheng, G. (2024). Analysis and research on uart communication protocol. In *2024 4th Asia-Pacific Conference on Communications Technology and Computer Science (ACCTCS)*, pages 768–771.

Kwon, O., Jeong, J., Kim, H. B., Kwon, I. H., Park, S. Y., Kim, J. E., and Choi, Y. (2018). Electrocardiogram sampling frequency range acceptable for heart rate variability analysis. *Healthcare Informatics Research*, 24(3):198–206.

Pahlavan, K. and Krishnamurthy, P. (2021). Evolution and impact of wi-fi technology and applications: A historical perspective. *International Journal of Wireless Information Networks*, 28:3–19.

Rahmani, A. M., Gia, T. N., Negash, B., Anzanpour, A., Azimi, I., Jiang, M., and Liljeberg, P. (2018). Exploiting smart e-health gateways at the edge of healthcare internet-of-things: A fog computing approach. *Future Generation Computer Systems*, 78:641–658.

Razzaque, M. A., Milojevic-Jevric, M., Palade, A., and Clarke, S. (2016). Middleware for internet of things: A survey. *IEEE Internet of Things Journal*, 3(1):70–95.

Varga, P., Peto, J., Franko, A., Balla, D., Haja, D., Janky, F., and Kozma, G. (2020). 5g support for industrial iot applications—challenges, solutions, and research gaps. *Sensors*, 20(3):828.

Vellela, S. S. (2024). Iot based icu patient monitoring system. *International Journal for Modern Trends in Science and Technology*, 10.

Vismaya, O., Kumar, A., and Syethima, K. (2024). 5g enabled iot network and security in healthcare.