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Applications and Challenges of BLE in Healthcare IoT Systems

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Abstract

Bluetooth Low Energy (BLE) has emerged as a fundamental technology for enabling wireless communication in healthcare-focused **Internet of Things (IoT)** systems. Designed for low power consumption and capable of supporting mesh networking, BLE is especially well-suited for battery-operated medical wearables and resource-constrained health monitoring devices. Its energy-efficient characteristics make it ideal for continuous patient monitoring, remote diagnostics, and mobile health applications.

This paper investigates the use case of BLE in healthcare and explores the role of BLE in facilitating seamless communication between medical devices in both clinical and home care environments.

Despite its benefits, BLE presents several performance limitations that can impact its deployment in healthcare settings, such as limited range, signal interference. Drawing on recent research and technical literature, this paper analyses the practical challenges of deploying BLE in healthcare IoT and discusses mitigating these during implementation.

Contents

Chapter 1

Introduction

1.0.1 Paper Outline

This paper is structured as follows. Chapter 2 examines practical healthcare applications of BLE, including wearable monitoring systems and indoor positioning. Chapter 3 evaluates potential challenges, particularly wireless interference in healthcare environments, drawing on recent studies.

My analysis reveals that while theoretical concerns exist about BLE performance in dense wireless environments, practical studies demonstrate remarkable resilience with packet delivery ratios exceeding 99.99% in realistic healthcare settings.

Building on these findings, this paper proposes practical testing guidelines for healthcare organizations implementing BLE solutions, addressing the gap between research studies and real-world deployment requirements.

1.0.2 Bluetooth and BLE Background

BLE, like Bluetooth BR/EDR (Bluetooth Classic), operates on the 2.4 GHz ISM band[3]which is available for unlicensed use. However, BLE is specifically designed for low power consumption and mesh networking, which is not available to Bluetooth Classic.

At the protocol level, BLE uses its **Generic Attribute Protocol (GAP)** to define device roles and connections, it also has an **Attribute Protocol (ATT)**, and **Generic Attribute Profile (GATT)**(built on ATT) to structure and exchange that data. [3].

BLE also supports two device configurations: **Single-mode** (BLE only) and **Dual-mode** (BLE + BR/EDR). Some IoT implementations also use **Bluetooth Mesh**, which enables many-to-many communication via message flooding. Table 1.1 summarizes these options.

Configuration	Description	Communication
Single-mode	BLE only; low-power IoT use.	With Single-mode and Dual-mode (not only BR/EDR).
Dual-mode	Supports both BR/EDR and BLE.	With all Bluetooth devices.
Mesh (BLE Mesh)	Many-to-many topology using flooding.	Scalable IoT messaging across nodes.

Table 1.1: BLE Configurations and Mesh Networking

Bluetooth technology is also exceptionally well-documented, with a comprehensive specifications maintained by the **Bluetooth Special Interest Group** (Bluetooth SIG). These specifications include a wide range of optional **profiles**, some specifically for healthcare devices, which allow for a standardized way of implementing Bluetooth into the technology.

Chapter 2

Healthcare Applications of BLE

2.1 Use Cases in Healthcare

BLE-enabled devices can be found in many healthcare devices in hospitals and home care environments. Several discuss the successful implementation of such devices.

2.1.1 Use in Healthcare Equipment

Blood Oxygen Monitoring

One such paper proposes a design for a wearable **blood oxygen saturation (SpO2)** monitoring system[1] that uses Bluetooth technology to wirelessly communicate the results of SpO2 to an Android smartphone where users health data is stored and also receives commands from the Android device on when to start monitoring[1].

The Bluetooth core specification allowed the BLE module to interface with the main host controller of the blood oxygen saturation monitoring device and a connection to the client paired mobile-phone. On the monitoring device side the BLE module establishes a serial connection with the main controller at a baud rate of 115200 with a maximum buffer of 128 Bytes.

On the mobile-phone side, APIs for connecting to Bluetooth devices were used[1]. Both on the monitoring device and mobile-phone side algorithms for computing the blood oxygen value (monitoring device) and storing the data (mobile device) are also able to be implemented between the Bluetooth communication.

This paper conclusively demonstrates the feasible and appropriate use of BLE in a healthcare product and demonstrates seamless communication between both the controller and mobile device. The wearable in this case also demonstrates not just clinical application but use for the everyday person out and about and continuous monitoring.

Blood pressure Measurement

Another paper from the National Taiwan University of Science and Technology on a Bluetooth based blood pressure measurement system where a homemade blood pressure measuring device is used in conjunction with Bluetooth to transmit results to a smartphone [6]. The paper highlights both the convenience of Bluetooth and its advantage of its low power qualities.

The design of the system consists of

- A homemade blood pressure monitor with a low power Bluetooth System-on-Chip CC2541 to accommodate a blood pressure measurement algorithm and Bluetooth transmission[6].
- A mobile application with a user interface to control the blood pressure monitor and display blood pressure measurements[6].

The paper reasons using BLE over **Adaptive Network Topology (ANT)** and **ZigBee** (a wireless communication protocol, similar to Wi-Fi and Bluetooth designed for low-power, low-data-rate applications) because of its low energy consumption qualities, and describes it as ”suitable for small-scale electronic products such as medical instruments, health management device or remote controller.”[6]. The authors further leverage the Bluetooth SIG Blood pressure profile for the design of the transmission packets[6]to allow the blood pressure monitor to be flexible with the devices it is compatible with.

In terms of accuracy, the System-on-Chip produced low error margins of -1.13 ± 0.52 beats in pulse rate[6], and 0.69 ± 1.63 mmHg and 0.20 ± 1.02 mmHg for systolic blood pressure (SBP) and diastolic blood pressure (DBP)[6], respectively. In clinical trial the results showed slightly higher errors, with an average difference of 2.66 ± 2.71 mmHg for systolic blood pressure (SBP) and 3.42 ± 4.42 mmHg for diastolic blood pressure (DBP), but these values remain within acceptable limits.

While the paper thoroughly demonstrates the convenience and low power advantages of BLE and the use of Bluetooth SIG profiles, it does not investigate how the other systems in the environment may have an effect on the performance of this device where wireless interference could be high.

2.1.2 Locational Positioning in Healthcare Environments

As well as patient monitoring BLE enabled deceives offer other applications in the healthcare sector such as contact tracing and other locational positioning through **Received Signal Strength Indicator (RSSI)**.

Contact Tracing

The outbreak of COVID-19 brought new safety challenges, heightening the need for innovative solutions to ensure staff protection and efficient resource management.

For instance, an article by Curtis et al conducted a pilot study exploring the feasibility of using BLE wearable tags to quantify healthcare worker proximity networks and close patient contacts[2]. The study aimed to develop and pilot automated contact tracing by utilizing a BLE system architecture consisting of wearable tags with anonymity identification number communicating over BLE to fixed receivers at patient room doors where the data will be sent over LoRa to and an edge gateway device then onto a cloud server via Wifi or Ethernet[2].

The pilot study was a success in presenting a new form of contact tracing in a clinical environment when dealing with infections diseases but was tested on a small scale with a total of 27 nursing staff and 3 medical staff[2] with a maximum of 11 and any given time but as stated by the authors a larger participant size would be tested with in further studies[2].

Regardless of the small scale, the architecture implements multiple wireless technologies with BLE being the main technology for contact tracing. These tags demonstrates robust interoperability with complementary wireless technologies, creating seamless multi-layer communication architecture.

Hospital Guidance System

Furthermore BLE has been integrated in with augmented reality to help patients with disabilities navigate hospitals. A study by Mizan et al describes a system which uses BLE tags placed throughout the hospital to generate and spread signals which are then used to determine the location of a user based on the strongest RSSI signal their mobile phone picks up.

This features allows the user to select a destination in the hospital and the application will calculate the current position of the user and display the directions to the users desired location[7]. The algorithm used to calculate the current locations specifically filters through crossover signals and chooses the strongest signal for location mapping. The system was evaluated indoors using 4 BLE tags for transmission and worked with positive results[7].

This particular study highlights the versatility of BLE and shows that it can be used for more than just data transfer. The study doesn't explicitly address scalability issue if reproduced with a larger number of tags or higher interference in general but avoids this being an issue by design.

Chapter 3

Potential Challenges BLE in Healthcare Environments

Some challenges that BLE might face in a healthcare environment such as a hospital can range from latency constraints, range limitations, battery and power management but most importantly reliability of data transmission. This reliability of data transmission might be heavily effected by interference from other BLE devices and other devices using the 2.4 GHz ISM band.

3.1 Addressing Challenges Drawing from Recent Studies

3.1.1 Interference and Wireless Coexistence

Hospital Environments

To evaluate whether Bluetooth's known challenges are present in healthcare, it is important to analyse its performance in realistic settings. In their 2016 study, Kalaa et al. examined BLE performance in various environments, including a hospital ICU by testing probability of transmission failure relative to the a systems interference detection threshold[4].

The study analyses the BLE Data Channel Selection algorithm's ability to adapt to interference by examining how it selects among the 37 available data channels when faced with competing wireless technologies over multiple environments including a hospital ICU[4]. The researchers used a National Instruments PXIe-5644R spectrum analyser to conduct comprehensive surveys of the 2.4 GHz ISM band.

For the hospital ICU environment, they surveyed it for a duration of 3 hours and 21 minutes during a typical working week. The spectrum analyser captured power measurements across the entire 2.4 GHz ISM band (2.40-2.48 GHz) by dividing it into 1992 discrete frequency bins, each spanning 40 kHz. Complete spectrum sweeps were performed every 4 milliseconds[4].

In their study they found when the interference detection threshold approaches the environment's noise floor, the likelihood of having available data channels declines, eventually reaching a point where no channels remain available[4]. They also established that BLE channel selection focused on using channels less prone to interference[4]. They also observed that only in extreme cases of interferences (when the observed noise floor is close to the system's interference detection threshold) the probability of failure was near total[4].

Wireless Coexistence

Another study exploring coexistence with other radio-based protocols on the 2.4 ISM band by La et al. (2018) examined these coexistence conditions in densely deployed BLE-based body area networks (BANs).

The testbed they used in this study consisted of multiple BANs deployed independently and in close range to each other. Each BAN consisted of wearable sensors and a gateway. The sensors will transmit their data to the gateway which is then responsible for processing or forwarding. The gateways they used used a wired connection as they were only interested in the sensors[5].

The researchers tested BLE coexistence in two setups (Table 3.1):

Setup	**Configuration**
Dense BLE-based BANs	One gateway + 3 BLE nodes $(\approx 0.3mfromgateway).Upto4BANsplaced0.5\text{–}2mapart.$
Dense Heterogeneous BANs	One gateway + 3 BLE nodes + 3 ZigBee nodes. ZigBee uses time-slotted channel hopping over 16 frequencies. Max 24 devices in small area.

Table 3.1: Dense BAN Setups [5]

In their results they found that BLE exhibits remarkable resilience in dense coexistence scenarios, specifically BLE maintained exceptional performance metrics even under severe interference conditions, with packet delivery ratios consistently exceeding 99.99% regardless of interference levels[5].

These findings also indicate that BLE's adaptive frequency hopping mechanisms and robust retransmission protocols effectively mitigate the theoretical coexistence challenges, making it a viable solution for critical healthcare applications despite the crowded 2.4 GHz spectrum. Another property La et al noted was that BLE was able to maintain its power efficiency throughout their experiment.

A study by Natarajan et al. revealed more nuanced coexistence behavior through systematic analysis of BLE with LR-WPAN(IEEE 802.15.4) and WiFi (IEEE 802.11b).Based on their mathematical and experimental methodologies where they cross examined BLE being the affected by LR-WPAN and WiFi network and also being the interfering network[8]. This Study also found that at short interval packet interferences the reliability of BLE was around 60% but when adaptive frequency hopping was used, improved it to about 85%[8].

3.1.2 Discussion

These studies demonstrate that BLE shows remarkable resilience in practical healthcare environments, despite theoretical challenges in busy wireless settings. The research also reveals the complexity of testing BLE performance comprehensively. Multiple interfering technologies and diverse BLE-enabled devices create varied performance scenarios. This diversity makes it difficult to test every possible deployment situation.

3.2 Mitigation of Challenges

3.2.1 Proposed Implementation Strategies

While these studies demonstrate BLE's theoretical resilience, practical deployment success depends heavily on proper consideration of the environment it is being deployed in. Based on the strategies the previous studies discuss I propose the following guidelines for the implementation of healthcare IoT.

Scale

Before implementation, clearly define the intended healthcare setting (home, clinic, or hospital), the scale of deployment (number of devices, patients, and staff), and the criticality of use (wellness tracking vs. life-critical monitoring).

Healthcare environments also often contain multiple wireless technologies operating in the same frequency spectrum (e.g., Wi-Fi, ZigBee, LoRa, and other BLE devices). Without careful planning, this can lead to interference and degraded or performance.

Bluetooth Profiles

Leveraging standardized Bluetooth SIG profiles (e.g., Heart Rate, Blood Pressure, Glucose) ensures interoperability across devices and reduces development complexity. The blood pressure monitoring system by Lin et al[6] illustrates how adopting the Blood Pressure Profile enables accurate measurements and seamless integration with mobile applications. Failing to use standard profiles can limit compatibility and complicate device integration.

Hardware Choice and Configuration

Selecting appropriate hardware and configuration is critical for maintaining reliable BLE performance in healthcare deployments. These results emphasize that hardware with robust receiver sensitivity, combined with adaptive frequency hopping and retransmission protocols, can effectively mitigate interference challenges demonstrated by Natarajan et al.

Other Competing Technologies

Deployments should consider surrounding wireless architectures and implement strategies such as strategically placed gateways, spectrum coordination, or multi-radio gateways. Curtis et al[2] demonstrate that BLE can coexist robustly with complementary wireless systems when integrated thoughtfully into multi-layer architectures. Proper planning ensures reliable data transmission even in complex hospital environments.

Chapter 4

Conclusion

In this paper, I have discussed how BLE has been implemented in healthcare IoT systems across diverse environments, from wearable health monitoring devices to indoor navigation and clinical contact tracing. These case studies illustrate the versatility of BLE as a communication standard capable of supporting both patient-focused and operational applications in hospitals and home-care settings.

I also examined potential challenges facing BLE in healthcare deployments, including interference from other 2.4 GHz technologies, scalability in dense environments, and the advantages of utilizing packet loss prevention features in Bluetooth.

To bridge the gap between research and practice, I proposed mitigation strategies for healthcare IoT implementations. These include careful planning of deployment scale, adoption of standardized Bluetooth SIG profiles for interoperability, hardware selection with high receiver sensitivity, spectrum coordination with competing wireless systems, and configuration of adaptive connection parameters. Together, these strategies ensure that BLE can be deployed reliably and efficiently in healthcare environments without compromising patient safety or system performance.

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