The role of Bluetooth Low Energy (BLE) in the Internet of Things

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Introduction

The International Telecommunication Union (ITU) first introduced the concept of the Internet of Things (IoT) in 2005, which can be described as a network of physical devices that have technologies such as built-in sensors with the purpose of processing and transferring data (Kopetz and Steiner, 2022; IBM, 2024). IoT has grown into a global technological phenomenon over the past few years, integrating itself in a plethora of fields and industries. Today it is a part of most people's everyday lives, and it is ever growing to the point that it is probably used in many of our daily activities which we may not even recognise or expect (Greengard, 2021). We can refer to devices that are a part of the IoT as smart objects; these smart objects require some kind of connectivity technology to be used such as Wi-Fi, Bluetooth Classic, Bluetooth Low Energy (BLE), Zigbee, Long-Range Wide-Area-Networks (LoRaWAN), NB-IoT, Z-Wave, Sigfox, RFID, and LTE-M. This essay explores Bluetooth Low Energy (BLE), a key connectivity technology first introduced in Bluetooth 4.0 and used in Bluetooth 5.0 and 5.2, which is essential for low-power, cost-effective wireless communication in devices like PCs, tablets, smartphones, and wearables (Liu *et al.*, 2021, p.012021). Its efficiency makes it crucial for the growing IoT. The essay will also compare BLE to other technologies like LoRaWAN, Wi-Fi and Zigbee.

Discussion: Background and related work

Bluetooth technology, developed to create a universal standard for short-range wireless communication, was named after Viking King Harald "Bluetooth" Gormsson to represent technological consolidation. Bluetooth 1.0 (1999) had interoperability and security issues; Bluetooth 2.0 (2004) brought Enhanced Data Rate (EDR) and multitasking; and Bluetooth 3.0 (2009) featured Alternate MAC/PHY (AMP) enabling dynamic frequency selection. Bluetooth 4.0 (2010) introduced Bluetooth Low Energy (BLE), which is designed for low power consumption and long battery life, making it perfect for IoT devices (Liu *et al*., 2021). Bluetooth 5.0 and 5.2 improved BLE's range, battery efficiency, data speed, and coverage, while limitations such as limited range and connectivity concerns remain (Collotta *et al*., 2018; Wang and Liang, 2021).

BLE uses Gaussian Frequency Shift Keying (GFSK) for modulation and operates on the 2.4 GHz ISM band. By changing the carrier signal's frequency, GFSK modifies data while using less power and noise. Due to longer inter-frame intervals and TX-RX exchanges, Bluetooth 5.0's 2M PHY architecture doubles the symbol rate and boosts efficiency, but it does not double transmission efficiency.The primary characteristics of BLE are as follows:

- Range: Dependent on route loss and antenna type, with a maximum range of about 33 metres in ideal circumstances.
- Latency: The duration of data transmission that is impacted by scan windows, advertising intervals, and scan intervals. Among the initiatives to lower latency are novel finding methods.
- Power Consumption: Deep sleep modes and enhanced broadcast and scan mechanisms enable BLE's low power consumption, which enables devices to operate on tiny batteries for months or even years.

BLE's Cyclic Redundancy Check (CRC) maintains data integrity by adding a redundancy code to data frames that is examined upon reception for mistakes. While it contributes to reliable data transmission, discovered flaws can result in retransmission delays (Liu *et al*., 2021, p.012021).

BLE is used in a variety of IoT-related applications. Beacon technology is a significant application in which BLE beacons broadcast messages to adjacent devices via geolocation services, alerting users to local recipients. Another application, bleach, which serves as a "black box" for data flow. BLE facilitates frictionless transactions in mobile payments when coupled with payment apps, allowing shops to employ beacons for both promotions and payment processing. Latest BLE-IoT capabilities include faster rates of up to 2 Mbps, a 200-metre range, and longer battery life. BLE v5 can handle larger payloads (up to 255 bytes), LE advertising extensions for packet exchange, and LE audio for dual device connections. It also includes GATT caching for faster reconnections, a slot availability mask to prevent LTE interference, and improved security (Al-Shareeda *et al.*, 2023, p.1183-1184).

BLE enables Bluetooth-enabled devices to combine the advantages of low-power IoT applications, which has led to the widespread use of BLE beacons. Numerous IoT use cases, such as enhanced shopping experiences, museum guides, indoor tracking, assistance for disabled people, energy-efficient businesses, smart home management, and more, have been made possible by their simple connection with smartphones. The adoption of BLE has been driven by major tech companies like Google, Apple, Facebook, and LINE. This has resulted in the development of creative applications like context-aware notifications, indoor navigation, and user activity monitoring. BLE, designed for low power IoT applications, differs from Bluetooth Classic by focusing on minimal power consumption and one-to-many communication. BLE beacons use specific advertising channels and can operate in various custom profiles. Signal strength and range can vary due to environmental factors and density of beacons, impacting signal detection and accuracy. (Jeon *et al.*, 2018, p.811-814).

The BLE 2.4-GHz spectrum comprises 40 channels, with advertising on channels 37, 38, and 39. Beacons broadcast on these channels at regular intervals, carrying tiny data payloads that do not require device pairing. Popular profiles that make use of this data include Apple's iBeacon which focuses on long battery life and is primarily used with iOS devices, needing dedicated apps for interaction and Eddystone, developed by Google, provides additional versatility with different frame types (URL, UID, TLM) and is cross-platform compatible, including Android and Chrome. While iBeacon works well for iOS-based devices, Eddystone's adaptability makes it appropriate for a broader range of applications (Jeon *et al.*, 2018, p.814-815).

BLE has gained popularity in the IoT industry due to its low energy consumption and dependable data transmission. However, it confronts various challenges, including unsafe pairing methods, protocol compatibility, limited battery life, and system scaling issues. Battery monitoring is hampered by occasional updates and different data formats, whilst distance estimate suffers from unreliable signals in packed situations, necessitating stronger algorithms. Excessive network requests cause scalability issues, although performance can be improved by optimising request processing and batching. Furthermore, existing security solutions are computationally intensive, emphasising the need for more scalable and efficient alternatives. Despite these challenges, continued advancements in pairing techniques, encryption, and security measures are likely to make BLE a highly secure and efficient alternative for future IoT applications. (Al-Shareeda *et al.*, 2023, p.1187; Jeon *et al.*, 2018, p.824-826).

LoRaWAN

Long-range (LoRa) technology is commonly utilised in IoT for low-power wide-area networks (WAN) due to its large coverage and good signal handling using the chirp spread spectrum. LoRaWAN handles device connections in a star topology and adapts to network changes, addressing issues like signal interference and transmission collisions through software upgrades and improved network designs. LoRaWAN has undergone substantial improvements since its v1.0 release in 2015, with v1.0.4 (2020) delivering enhanced security, roaming, and features over previous versions (Jouhari *et al.*, 2023, pp. 1851-1852). LoRaWAN and BLE serve different IoT needs: LoRaWAN is well-suited for large-scale, long-range applications such as smart cities and environmental monitoring, with a localization precision of around 0.62 metres (Khan *et al*., 2021). BLE, which is intended for short-range communication (up to 100 metres), is extremely power-efficient and suited for indoor applications like asset tracking and proximity sensing. Thus, the decision between LoRaWAN and BLE is determined by specific range, accuracy, and power efficiency requirements (Jouhari *et al*., 2023, p. 1865).

Wi-Fi and Zigbee

As IoT expands, devices require reliable wireless connection. According to Natgunanathan *et al*. (p.1826, 2023) Bluetooth Mesh (BT Mesh), built on BLE, announced in 2017 improves on conventional technologies such as ZigBee and Wi-Fi by providing higher coverage, dependability, and efficiency. It supports huge networks of devices by employing a strong flooding mechanism (). However, their research results suggest messages sometimes took numerous hops (TTL values between 2 and 4), even when nodes were near to the gateway, resulting in a decrease in acknowledgement receipt from 91% to 63% as node distance grew. The managed-flooding strategy used by BT Mesh, which routes messages across numerous pathways, can cause delays and data collisions, especially in bigger networks. Wi-Fi, on the other hand, provides higher data rates that are suited for high-bandwidth applications such as video streaming, although it is susceptible to interference and congestion in densely populated areas. Zigbee is efficient for low-power, low-bandwidth jobs with minimal latency, but it has limited range and transmission rates.

Security in IoT

Securing IoT devices is critical for preventing data breaches and maintaining confidentiality in a variety of industries, including healthcare and business. Due to restricted device resources, lightweight cryptography algorithms are required. Mobility, wireless vulnerabilities, and scalability are three major security problems. A three-layer IoT design solves issues with: the application layer (verification, secure APIs), the network layer (traffic monitoring, anomaly detection), and the edge layer (authentication, encryption), each adapted to its own functions (HaddadPajouh *et al.*, 2021, p.6-11). Although BLE plays an important role in the Internet of Things (IoT), its limited processing power and memory provide serious security challenges. Its mobility and use of wireless signals make it susceptible to interception and unauthorised access. The lack of standardised security protocols compounds the problem, potentially exposing vulnerabilities. Therefore, robust and scalable security solutions are required. Effective IoT security must address the application, network, and edge levels in order to secure data confidentiality and system integrity across all connected devices.

BLE Performance and Results

As vehicles improve with more complex technologies, such as advanced driver assistance systems and wireless connectivity, the issue of successfully integrating these systems increases. Traditional wired networks in automobiles, while dependable, add complexity and cost to production and maintenance. A recent study by Biegelmeyer *et al*. (2024) investigates the possibilities of In-Vehicle Wireless Sensor Networks (IVWSNs) in public transportation, focusing on buses, which confront unique obstacles due to their size and number of sensors. This study focused on solving the limits of present wired systems by investigating Bluetooth 5 capabilities in a mesh network design, resulting in a more efficient and adaptable solution for large-scale vehicle networks. Another study by Lin *et al.* (2013), has shown BLE to be more robust than ZigBee in the presence of WiFi and Bluetooth interference, though BLE still has significant packet loss issues. The introduction of Bluetooth 5 has brought improvements in speed, range, and network capacity. Mourad *et al.* (2017) investigated how WiFi and Bluetooth interact in cars, particularly with info-tainment systems. They discovered that automobile WiFi networks are highly influenced by surrounding networks, but their research did not investigate how different types of vehicles or other devices affect this interference.

The experiment results (Biegelmeyer *et al.*, 2024) suggest Bluetooth 5 with mesh topology performed well in the bus environment, with packet loss rates equivalent to or better than other systems and, in some cases, similar to wired communications methods. The findings show that Bluetooth 5, in a mesh structure, is robust and well-suited for car networks, particularly for applications that require quick and reliable communication. Overall, the experiments demonstrated that Bluetooth 5's real-world performance nearly matches its theoretical potential.

Conclusion

BLE is expected to play an important part in the future of the IoT due to its low power consumption and versatility. BLE's improved range, speed, and efficiency make it perfect for a wide range of applications, from wearables to smart home devices. While BLE faces obstacles such as security and limited range, further advances are expected to solve these concerns. Compared to LoRaWAN, which excels at long-range, low-power communication for large-scale deployments, and Wi-Fi, which provides better data speeds but consumes more power, BLE provides a balanced solution for short-range, energy-efficient applications making it a critical technology in the IoT ecosystem.

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