Evaluation of Bluetooth Low Energy Performance for Local Positioning Systems in Wireless Communications

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ABSTRACT

In the coming years, billions of devices are anticipated to be equipped with Bluetooth Low Energy (BLE), a developing low-power wireless technology designed for short-range control and monitoring applications. Wearables, domestics, e-health systems, and other applications of small, tiny, and embedded sensors are only a few examples of the many uses of this ubiquitous technology in daily life. Wireless communication is important in this situation, and BLE is becoming more and more well-liked among the options. Broad diffusion, low energy consumption, and high performance are combined in BLE. This paper begins with a detailed explanation of the protocol, emphasizing its key features and implementation specifics. The state of the art regarding BLE performance and characteristics is reviewed in the second section. To determine the present boundaries of BLE technology, we specifically examine throughput, the maximum number of connectable sensors, battery consumption, latency, and the maximum attainable range. We assess how the quantity of ads affects the throughput and effective data reception rate. We demonstrate that BLE can still assure adequate data reception rates and meet the needs of a wide range of IoT applications despite the advertisement collision rate in our experiment fluctuating between 0.22 and 0.33 due to the multiple transmissions of adverts.

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1. INTRODUCTION

The Bluetooth Special Interest Group (SIG) has been working on a new wireless technology called Bluetooth Low Energy (BLE) for short-range communication. BLE has been developed as a low-power option for monitoring and control applications, in contrast to earlier Bluetooth flavors. The feature that sets the Bluetooth 4.0 specification apart is called BLE. When BLE first appeared, other low-power wireless solutions—like Z-Wave, 6LoWPAN, and ZigBee—were gradually gaining traction in application domains that needed multihop networking. BLE, however, is a single-hop solution that may be used for a variety of use cases in industries like electronic goods, medical care, smart power, and security. The ubiquitous usage of Bluetooth technology (found in computers, mobile phones, cars, and other devices) may encourage the development of BLE since it shares features with traditional Bluetooth. Forecasts that have been published [1] indicate that billions of devices are anticipated to adopt BLE in the near future. Indeed, the significance of BLE for the Internet of Things has already been acknowledged by the IETF 6LoWPAN Working Group (WG). The 6LoWPAN WG is working on a specification as of the time this article was written for IPv6 packet transfer over BLE.

While the BLE standard provides a clear definition of the communication mechanism, there are still many areas of the system's energy efficiency that require research [2]. Among these elements is the performance attained while the parameter settings are changing in the operating state.

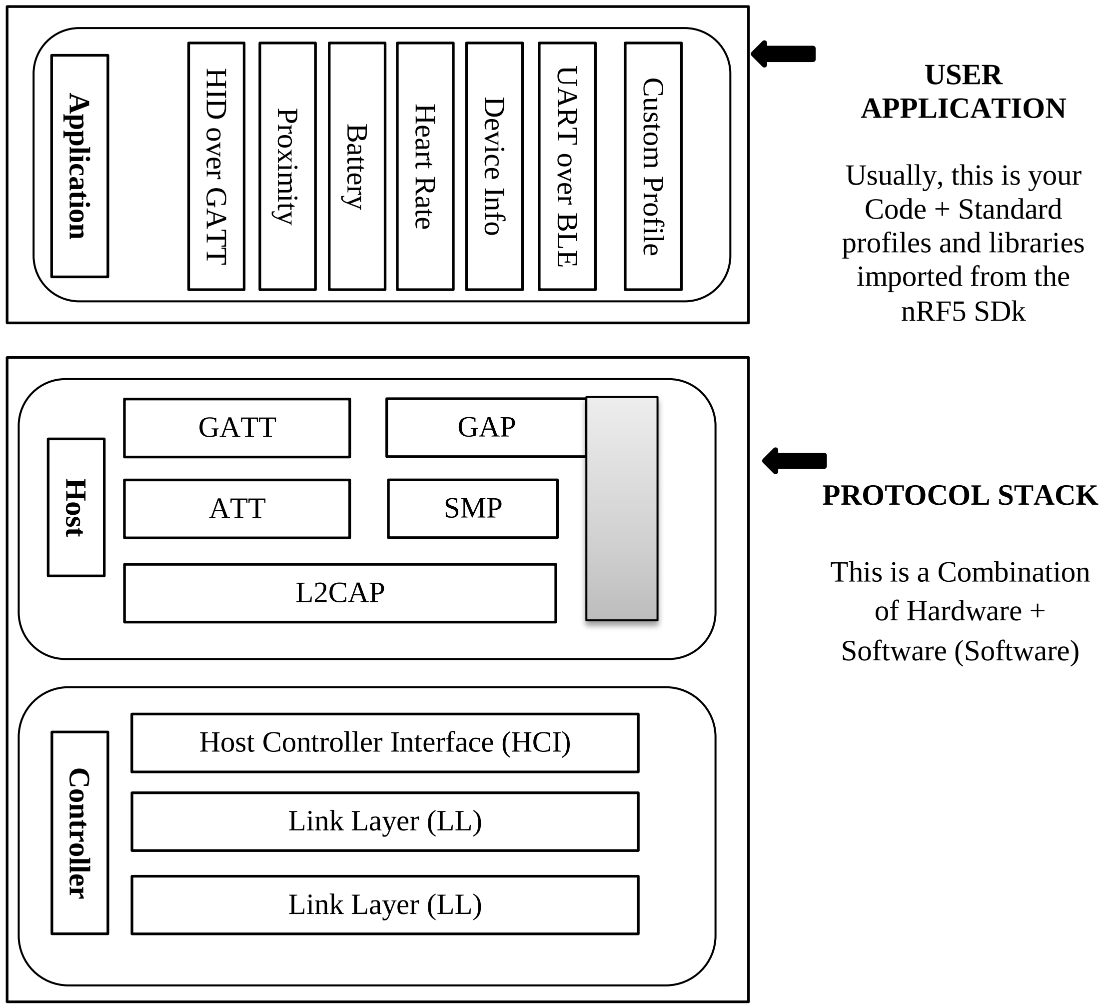

Figure 1. Block diagram of Bluetooth Low Energy

The examined instances greatly profit from BLE features in Figure 1, including its low power consumption, which enables its integration into compact devices with low-charge and tiny batteries that have a few-year lifespan. BLE is a strong contender to be a game-changing technology in the current wireless communications market for all of these reasons. Despite these encouraging uses, the BLE currently lacks a thorough and organised evaluation of its actual performance in various experimental scenarios, which might assist designers in creating devices that are best suited for certain uses. The goal of this review is to create a helpful overview of BLE by outlining its primary features and standards and suggesting a path towards a methodical performance characterisation. This will open the door for additional research.

Furthermore, the Bluetooth SIG issued the Bluetooth 5 specs towards the end of 2016. Numerous research have previously attempted to determine the properties of this new Bluetooth technology, which promises increases in performance such as range, data rate, and advertising channel functioning [3]. As has already been done with BLE, our study can potentially aid future research efforts to analyse this new technology in a methodical manner.

The structure of this work is as follows:

- First, we outline the primary frames and features of the BLE protocol stack, delving further into the operation of communication, packet structure, and potential network typologies.
- Subsequently, we conduct a thorough analysis of the literature pertaining to the application of BLE, offering a shared theoretical framework for a detailed discussion of the key findings identified in these investigations as well as establishing best practices for the BLE configuration under various usage scenarios.
- We conclude by summarising research on the primary features, applications, and limitations of BLE. Our goal is to establish a framework for understanding what has already been established in the literature, identify unresolved concerns, and recommend future research directions for this technology.

The primary characteristics of BLE are discussed in this paper, along with its possible uses and the effects of important parameters on its operation. This is how the remainder of the paper is structured: A summary of the BLE protocol stack and its key features are given in Section 2. The application layer BLE throughput is covered in Section 3 along with an analysis of BLE's energy consumption, latency, and network size. Section 4 looks at potential applications and market uptake for BLE and compares it to other wireless low-power technologies. Section 5 provides the important remarks that wrap up the paper.

2. RELATED WORKS

Numerous academic fields, including social science, architecture, and health, could be impacted by accurate human proximity detection [4]. The phenomena being observed often determine whether or not proximity detection is appropriate. For example, when considering the spread of a particular virus, only brief events involving a small distance between participants are relevant in some circumstances, while in other cases, only longer interactions that would allow people to engage in meaningful conversation are relevant. This paper examines a particular scenario that considers social interactions that occur in an office setting. In a situation like this, coincidental encounters—such as a user glancing out of an office doorway—might be significant and a sign of productivity.

The IEEE 802.15.4 standard was first introduced in its original edition in 2003. Many research papers covering various facets of the IEEE 802.15.4 protocol were published in the years that followed. A study on IEEE 802.15.4 performance may be found in [5]. The time needed to transfer the frame header, data, acknowledgement (if applicable), and wait period between frames defines the upper bound of the throughput in the IEEE 802.15.4 nonbeacon-enabled network for the single-hop scenario, according to the authors. Their investigation indicates that 140.9 kbit/s is the highest effective throughput for unacknowledged single-hop data transmission.

We measured delivery ratio and round-trip duration for both static interference and different dynamic traffic conditions during our studies [6]. Additionally, we list and address a number of flaws that prevent the present BLE version from being appropriate for all applications. We come to the conclusion that BLE can be utilised to transmit data between moving cars. Because of this, BLE is a compelling option for certain deployments; but, in light of the results, it is not a perfect substitute for on-board communication ports like DSRC/802.11p. We created a proof-of-concept mobile application to demonstrate how BLE may be used to transport data over several hops using readily available cellphones, greatly expanding the application's potential.

Neighbour discovery protocol (NDP) was one of the primary changes made to traditional Bluetooth in order to create an ultra-low-power BLE system. Since NDP allows a BLE device to establish a connection or exchange data with its neighbours, it is a prerequisite for all communications in BLE networks [7]. For this reason, having a quick and energy-efficient NDP is quite desirable. For this reason, BLE only uses three unique channels, referred to as advertising channels, for neighbour detection, as opposed to traditional Bluetooth, which may use all available channels. It should be noted that fewer advertising channels promote quick discovery, which increases the likelihood that the devices' transmitter and receiver circuitry will go to sleep.

BLE uses a frequency-hopping method in both its marketing and data channels to reduce congestion during communication because most technologies these days use the ISM band for communication, which has made it increasingly crowded and congested [8]. While the BLE is intended to function in the 2.4 GHz ISM band using 40 channels, each with a width of 2 MHz, the classical Bluetooth has 79 channels, each of which has a width of 1 MHz for operation. Three of these 40 channels—numbers 37, 38, and 39—are utilised for broadcasting, such as device detection and other activities, while the other 37 channels are in charge of data transfer. The design of a compact state-machine facilitates the device discovery process and aids in power saving functionality.

Even while these earlier works offer energy results from both theoretical and experimental viewpoints, they are by no means comprehensive. One clear shortcoming of their approach is that it only takes into account the connected state [9], failing to take into account another important element that influences energy consumption: the energy cost of device detection. Given that BLE networks frequently experience intermittent device detection, it's critical to comprehend this crucial parameter and how much it could affect battery life. However, due to a fundamental alteration in the design of the discovery mechanism, Bluetooth Low Energy (BLE) devices cannot be studied using traditional methods. Therefore, creating a fresh, precise energy model is essential for BLE device discovery.

Another method for enabling the home energy management (HEM) system to interact with and monitor household appliances is through the use of PLC. In recent years, a number of literary works have been released. For example, the proposed smart home control network uses the WN for data sensing and the PLC as the network backbone [10]. Empirical studies and simulations demonstrate that the proposed smart home control network offers significant energy savings and a good packet failure rate. Additionally, a working prototype of the network with smart lighting control is put into place. We provide an additional home energy management system that takes energy generation into account. To keep track of the solar panels' state, PLC modems are put in each of them.

3. METHODS AND MATERIALS

3.1 Overview of Bluetooth Low Energy

The Controller and the Host are the two main parts of the Bluetooth protocol stack. Controllers are often built as System-on-a-Chip (SoC) with integrated radios, handling the physical layer and link layer of the BLE stack. The host has application-level capability and is powered by an application processor. An overview of each layer is provided below in brief:

- The Attribute Protocol (ATT) describes the exchange of data between two devices that function as servers and clients.
- The framework that employs the ATT for discovery services and the sharing of characteristics between devices is known as the Generic ATT (GATT).
- The device role, modes, and process for device discovery and services are defined by the Generic Access Profile (GAP).
- The primary purpose of the Logical Link Control and Adaptation Layer Protocol (L2CAP) is to multiplex the data of three upper layer protocols: Link layer control signalling, SMP, and ATT.

3.2 Link Layer States and Channel Information

Two distinct technologies are defined by the Bluetooth specification version 4.0: the new BLE (sensors) and the traditional Bluetooth (high-quality audio or hands-free situations). Commercial products only support BLE or traditional Bluetooth since the two technologies are incompatible with one another. Devices that support both protocols and operate in dual mode are known as Bluetooth smarty ready.

The 2.4-GHz unlicensed frequency [11], or 2402–2480 MHz, is where Bluetooth low energy operates wirelessly. It defines 40 channels, each of which is 2 MHz wide. Special channels 37 (2402 MHz), 38 (2426 MHz), and 39 (2480 MHz) are used for discovery services. Data can be transmitted over the remaining 37 channels without restriction.

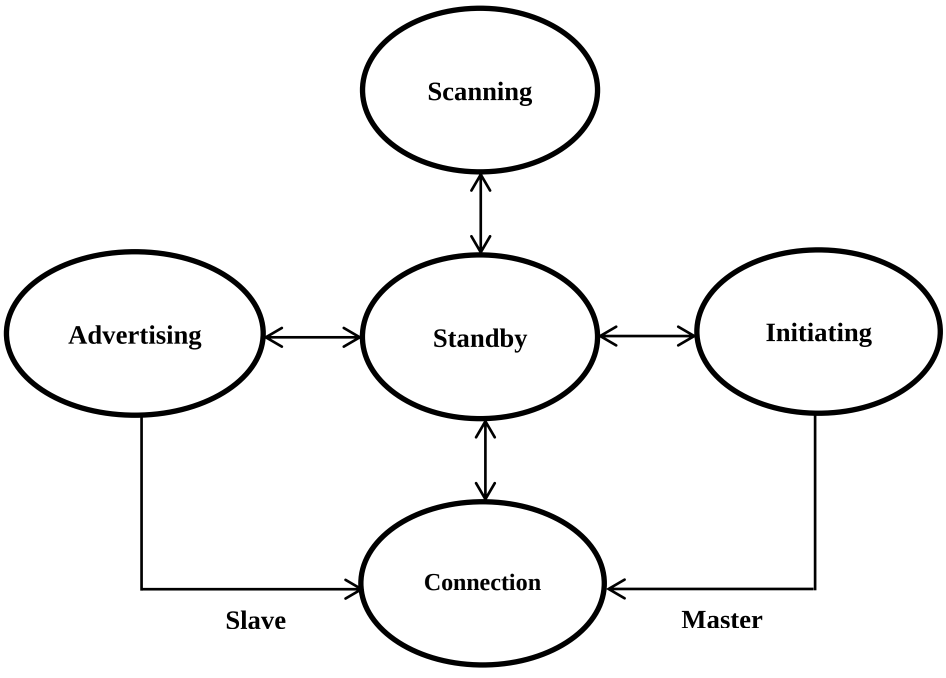

Figure 2. Diagram showing the relationships between the states as defined in BLE. When a device is in the scanning mode, the state advertising permits the transmission of packets that are discoverable by any device.

Bluetooth low energy technology is distinguished by five states in the link layer: standby, scanning, advertising, initiating and connection in Figure 2 [12]. Moreover, BLE enables fundamental functions like packet receipt and basic information requests even in the absence of a link. This feature addresses the requirement for intermittent sensor data transmission. The two most intriguing states in indoor positioning scenarios are advertising and scanning, which are covered in greater detail in the sections that follow. These states are important in the device search process.

3.3 The Condition of Advertisement

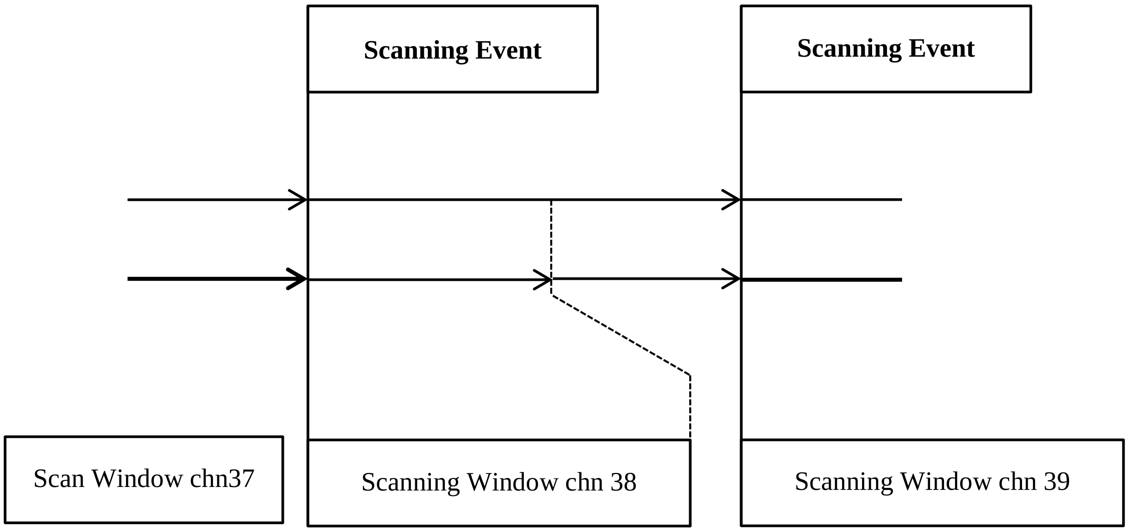

Figure 3. Diagram illustrating the key elements and activities taking on in the state of advertising

One way to lessen these issues is to add various signal post-processing techniques to the data acquisition process in addition to eliminating multipath effects or using filtering techniques to lessen the issue of cross-correlation, which requires removing the strongest signals in favour of the weaker ones (See Figure 3).

Practically speaking, the majority of systems make use of an observable known as the received signal strength indicator (RSSI) to measure signal intensity. The many methods used to extract information once this value has been measured in a particular device can be divided into two groups: range-based and range-free. In order to reproduce RSSI values in real-time later, range-based algorithms require an initial training phase when such values are previously measured at various places. Additionally, it is common practice to use a method known as fingerprinting, which also necessitates the usage of particular devices (as access points). The foundation of the system is the utilisation of each access point's RSSI to map the whole infrastructure.

These methods are frequently used in conjunction with other sensor types—like accelerometers—and the use of signal filters—like Kalman filters—to boost the signal-to-noise ratio and, in turn, improve tracking by predicting an object's motion. Additional post-processing methods include artificial neural networks.

4. IMPLEMENTATION AND EXPERIMENTAL RESULTS

Only tags A and B were transmitted in scenario 1 [13]. There was a range of 11 to 37 advertisement messages received per single sequence number from tag A, with an average of 26 advertisements.

For 78,996 s, or around 19 hours and 10 minutes, this scenario was executed (Table 1). The goal was to find out how many advertisement messages the hub correctly receives, processes, and stores, as well as what the predicted percentage of missing messages is because the RPi isn't working well.

Table 1. Scenarios for evaluation and their specifications

Scenario	Tags Transmitting	Tags Recorded	Duration	Sequence Numbers Sent
1	2	2	19 h 10 min	6900
2	210	2	21 h 15 min	7652
3	210	52	3 h 10 min	1175

The probability density function for the quantity of advertisement messages for each sequence number is displayed in Figure 4[14]. This PDF is next. Distribution normal with s = 3.9 and m = 25.2.

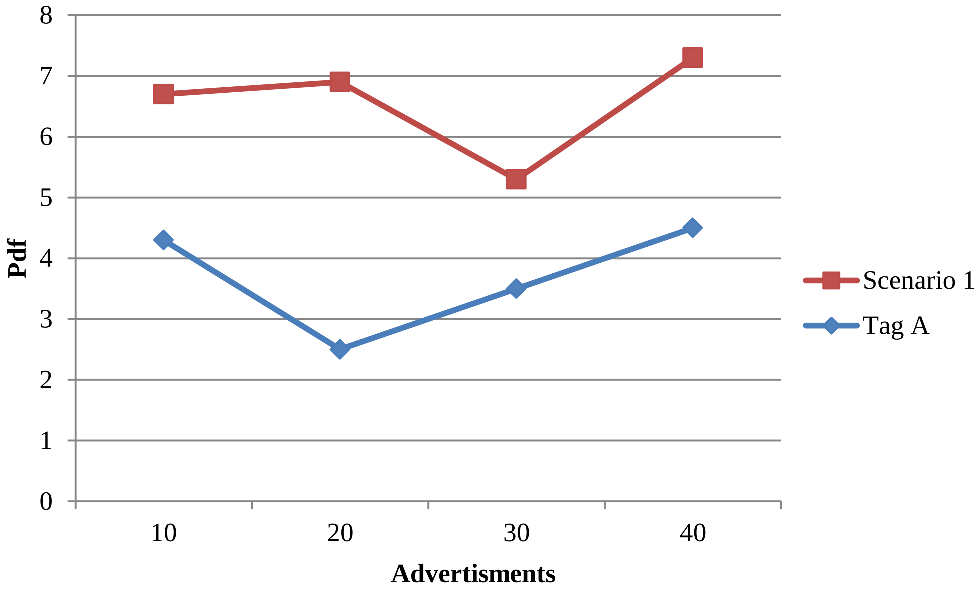

Figure 4. Probability density functions approximating the normal distribution for the number of advertising per sequence number for tag A

As seen in Figure 4. and Table 2, only 36 out of the 39 anticipated ads were correctly received. In the worst scenario, ten advertising messages containing the same sequence number were received. Approximately half of the 39 predicted messages—17 or more—had over 99% of the sequence numbers correctly received. Tag B successfully transmitted up to 14 advertisements per sequence number in the same scenario, which is equal to the predicted quantity. However, for some sequence numbers, there was only one advertisement (Figure 4.2) [15]. Nevertheless, the hub was able to correctly receive every sequence number in the experiment, and 99% of the numbers were received at least four times.

Table 2. Data for Tags A and B in the Various Circumstances

Metrics	**Tag A Scenario**			**Tag B Scenario**		
	1	**2**	**3**	**1**	**2**	**3**
A_{min}	12	5	4	3	2	2
A_{avg}	27	19	12	10	8	6
A_{max}	38	31	25	16	15	12
$A_{99\%}$	19	11	6	6	4	2
$S_{missing}$	2	2	2	2	7	12
μ	**27.1**	**18.2**	**11.4**	**9.6**	**7.7**	**5**
σ	**4.10**	**4.6**	**4**	**2.10**	**3.2**	**2.8**
DRR_{10s}	100%	100%	100%	100%	99.9%	99.1%
PDR	66%	45%	28%	62%	49%	31%

Notably, PDR for tags A and B is equal to 64% and 60%, respectively, even if DRR10s (i.e., the data reception rate when TDI = 10 s) is 100% for both tags in this case. Since there were only two tags transmitting, we can conclude that there were very few collisions and that the RPi's poor performance served as the cause of the 40% PDR loss.

Scenario 2's packet reception ratio decreased, but it was still very high DRR10s and satisfied the application's needs. For tag A, all sequence numbers (DRR10s = 100%) were received correctly; however, some were only present in 3 out of 39 transmitted marketing messages. There were sequence numbers missing for tag B (DRR10s = 99.9%), and there was a 25% decrease in the average number of advertisement packets per sequence number. In comparison to Scenario 1, the packet receipt rate for tags A and B decreased by roughly 22%.

In Scenario 3, the quantity of advertising received per sequence number decreased even further. The average number of advertisements per sequence number decreased from 25 to 10, even though all sequence numbers were received from tag A. Some sequence numbers were obtained in just two messages. Ten sequence numbers for tag B were not obtained. Only a small percentage of those that were received received them nine or ten times. When compared to the first eight and nine times, the majority of the sequence numbers were really effectively conveyed in three or four commercials, which is a huge decrease. Both tags A and B were able to match the requirements of the anticipated monitoring application with DRR10s being above 99%, despite having the worst PDR.

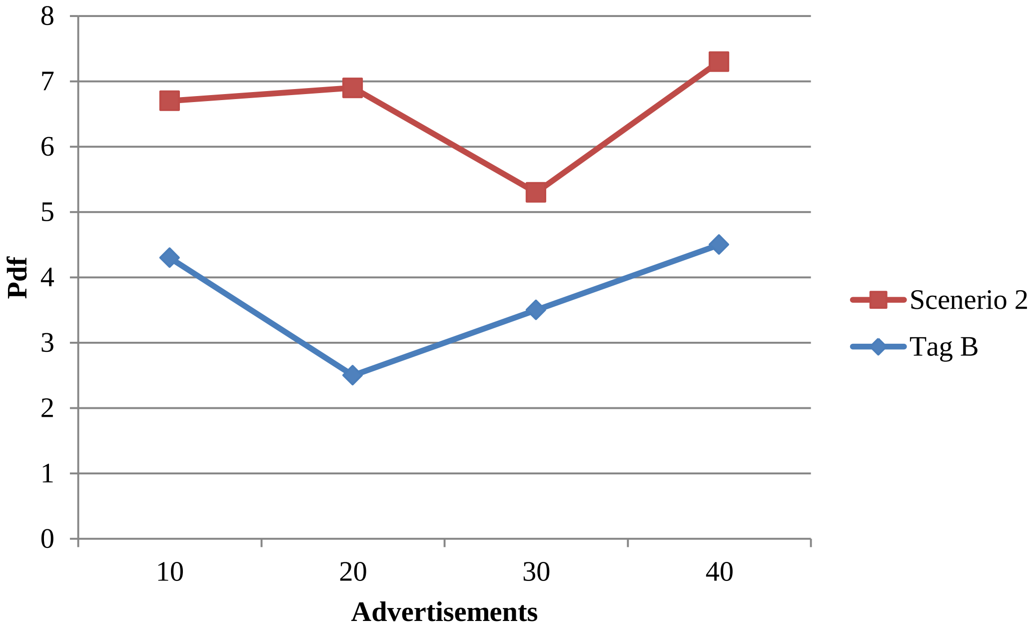

Figure 5. The probability density function for tag B's Number of Advertising Per Sequence Number and its Normal Distribution Approximation

Figure 5 contrasts Tag A's PDF with Scenarios 1 and 2. As shown, as the number of transmitting devices and hub workload increase, the number of advertising per sequence number decreases. A normal distribution approximation yields reliable results. Tag B exhibits a decline that is comparable.

Table 2 displays PDR and DRR for all circumstances and both tags A and B, along with statistics on ads by sequence number (min, average, max, 99%, and missing sequence numbers).

Even in the initial scenario, when there was no interference from other BLE tags, the efficiency of advertisement transmission (PDR) is moderate (just above 60%). PDR falls below 50% as interference increases (Scenario 2). The hub's poor performance in processing ads from 52 different tags is most likely the cause of the additional reduction (Scenario 3). The low PDR in Scenario 1 and the notable decline in Scenario 3 when compared to Scenario 2 demonstrate how crucial the hub's efficiency is to overall performance. The primary cause of the decrease in performance between Scenarios 1 and 2 is interference and collisions brought on by all of the BLE tags broadcasting simultaneously with tags A and B. We can determine the likelihood of a collision in the communication channel while 210 tags are advertising based on the decline in PDR values. It comes out that the likelihood of a collision is roughly 0.22 for tag B and 0.33 for tag A.

These numbers closely resemble the theoretical and simulation results that were displayed, where it was estimated that, for 200 tags and advertisement intervals of 200, 300, 700, and 1000 ms, the likelihood of collision was roughly 0.51, 0.4, 0.22, and 0.15, respectively.

5. CONCLUSION

The experimental evaluation of BLE advertisement communication when several advertisers are deployed in a limited region was reported in this research. These kinds of situations are typical of many different Internet of Things applications.

In light of the experimental findings, we contend that, in comparison to sub-GHz radio technologies, the BLE connectionless mode is more appropriate for Internet of Things applications, particularly those that need higher throughput, run indoors, or operate in small or medium-sized areas. An appealing alternative to conventional radio technologies is BLE technology, which has a long projected lifetime, no constraints on duty-cycling, low energy consumption, and good coexistence when used in large quantities. The breadth of potential BLE applications to IoT systems is further expanded by additional capabilities of BLE technology, including advertisement extensions, optional scan request/response communication, the ability to communicate in connected mode, and the capacity to predict the angle-of-arrival.

The results of the research demonstrate that BLE communication based on advertisements scales effectively and has practical uses in Internet of Things scenarios. Future research might measure the energy used by the tag (depending on its characteristics and the quantity of tags communicating at once) and conduct a more thorough analysis of how external advertisements affect the system's functionality.

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