IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received June 29, 2018, accepted July 30, 2018, date of publication August 21, 2018, date of current version September 7, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2866323

Detailed Examination of a Packet Collision Model for Bluetooth Low Energy Advertising Mode

**MOHAMMAD GHAMARI[1], EMMA VILLENEUVE[2], CINNA SOLTANPUR[3],
JAVAD KHANGOSSTAR[4], BALAZS JANKO[5], R. SIMON SHERRATT[5], (Fellow, IEEE),
AND WILLIAM HARWIN[5], (Senior Member, IEEE)**
[1]Department of Energy and Mineral Engineering, Pennsylvania State University, State College, PA 16801, USA
[2]CEA-Leti, 38054 Grenoble, France
[3]Department of Electrical and Computer Engineering, The University of Oklahoma, Norman, OK 73019, USA
[4]O2 Research Group, Telefónica, Slough SL1 4DX, U.K.
[5]Department of Biomedical Engineering, University of Reading, Reading RG6 6AY, U.K.

Corresponding author: R. Simon Sherratt (sherratt@ieee.org)

This work was supported by SPHERE IRC through the U.K. Engineering and Physical Sciences Research Council (EPSRC) under Grant EP/K031910/1.

ABSTRACT The aim of this paper is to investigate the amount of energy that is required to successfully transmit information inside the Bluetooth low-energy (BLE) advertising packets. There are applications that require more than one BLE node to simultaneously transmit data. The BLE protocol utilizes a specific communication method termed the advertising mode to perform unidirectional broadcasts of data from the advertising devices. However, with an increased number of BLE devices advertising simultaneously, there will be inevitable packet collisions from the advertising devices. This results in a waste of energy, specifically in low-power applications where lower consumption is desirable to minimize the need for battery replacements. This paper examines a packet collision model for the BLE advertising mode with the results validated using experimental data. Our analysis shows that when the throughput of the BLE network starts to fall due to an increase in the number of packet collisions, the energy consumption of the BLE nodes increases exponentially with respect to the number of nodes.

INDEX TERMS Bluetooth low energy, packet collision analysis, Bluetooth low energy advertising mode.

I. INTRODUCTION

Bluetooth Low Energy (BLE) is a short-range wireless communication technology primarily designed for use in battery-operated applications where ultra-low power consumption is of premium importance [1], [2]. The BLE protocol has extended the functionality and applicability of previous Bluetooth protocols by incorporating some advanced technical features and new innovations [2]. All of the necessary upgrades have been added into BLE in order to enable the BLE protocol to specifically support power-sensitive sensor-based devices that are typically used in personal healthcare devices to industrial monitoring applications [3], [4]. Compared to previous Bluetooth protocols, BLE utilizes fewer channels for pairing BLE devices. Hence, synchronization can be achieved in the order of a few milliseconds compared to seconds spent by previous Bluetooth protocols [5]. This is significantly valuable, specifically for resource-limited and latency-critical devices such as those used in health-monitoring and industrial applications [6]. The BLE protocol is able to provide data transmission rates of up to 1 Mbps and to operate at 2.4 GHz frequency band [1]. In terms of energy consumption, the BLE protocol is usually compared with low-power wireless technologies such as IEEE 802.15.4, ZigBee and ANT [7], [8]. The energy consumption of the BLE protocol had been evaluated and analyzed previously [9], [10] and has been compared with ZigBee and IEEE 802.15.4 technologies [11]–[13]. Compared to ZigBee based on the aforementioned analysis, BLE protocol has proven itself to be very energy efficient in terms of the number of bytes transmitted per joule spent.

In many health, industrial, military, habitat and environmental monitoring applications, energy efficiency is extremely important as devices are often battery-operated and require long maintenance-free operation [14]–[16].

The BLE protocol has been considered as one of the available standardized low-power off-the-shelf wireless communication technologies that can be used in the aforementioned applications [7], [8].

This work is licensed under a Creative Commons Attribution 3.0 License. For more information, see http://creativecommons.org/licenses/by/3.0/

According to the BLE specification [1], the BLE protocol is able to operate in two different communication modes: *advertising mode* and *connected mode*. A total of forty Radio Frequency (RF) channels are allocated for the two aforementioned communication modes. Three RF channels are exclusively assigned to be used by the advertising mode and thirty-seven RF channels are allocated to be utilized by the connected mode. The BLE protocol utilizes the advertising mode to inform BLE host controllers of their presence and to enable the establishment of a reliable, two-way communication link between two BLE devices [17], [18]. Although, the advertising mode is mainly designed to be used for device discovery, it can also be utilized for broadcasting application information [9], [17].

There are situations in many of the aforementioned applications where a number of small-sized sensor nodes are required to simultaneously transmit important information to a host [19], [20]. In addition, in many of the aforementioned applications as well as in other low-power embedded systems [21], [22], the size of the packet payloads are small, but it is possible to place useful information into the advertising packets.

By using the above technique, if data is transmitted successfully between communicating devices, there may then be no need to establish a two-way communication link between the BLE devices. Therefore, in this way, limited battery power can be conserved more efficiently and data can be transmitted to the receiver with low delay. This is significantly valuable specifically for resource-limited and latency-critical applications such as those mentioned above.

However, with a number of BLE devices advertising simultaneously, there will be inevitable packet collisions between advertising devices. Packet collisions result in the inability to successfully receive packets and thus reduce the effective throughput of the network.

The specific contributions of this paper are as follows: First, we examine a packet collision model for the BLE advertising mode through simulation and experimental data. Second, we investigate the saturation throughput performance of BLE advertising packets and finally we show how much energy is required to successfully transmit information using BLE advertising packets.

II. RELATED WORK

This article considers, in detail, a packet collision model for the BLE non-connected communication mode. Specifically, it investigates the effects of packet collisions on the network throughput and also the energy consumption of the nodes. To the best of our knowledge, consideration of packet collisions for BLE advertising mode has not been evaluated.

A BLE device is able to operate in two different communication modes: non-connected (i.e. advertising) and connected communication modes [1], [17]. The non-connected communication mode is primarily used for device discovery and has been previously modelled by Liu *et al.* [17], [18]. In a typical point-to-point non-connected communication system, one device acts as an advertiser and the other device operates as a receiver scanning for transmissions. The advertising and scanning mechanisms are shown in Fig. 1 and Fig. 2 respectively.

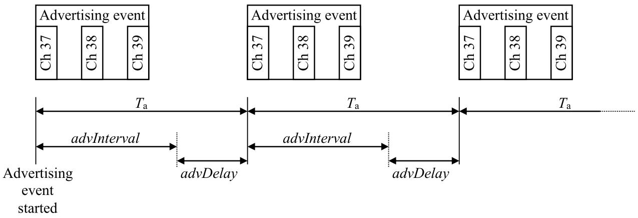

FIGURE 1. Bluetooth low energy advertising mechanism.

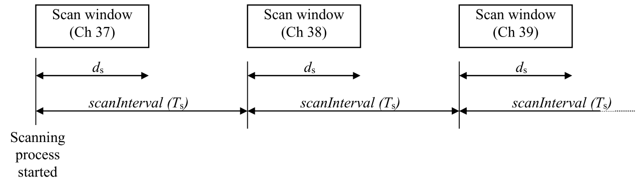

FIGURE 2. Bluetooth low energy scanning or initiating mechanism.

A BLE device periodically transmits a group of consecutive advertising packets. Advertisement packets are sent consecutively within the advertising channels (channel index = 37, 38, 39). An advertiser may send only its advertising information or may transmit payload information within the advertising packets. There are two primary types of advertisement packets defining the device as a connectable-device (which can be connected to) or a broadcasting device (which can be heard by the host controller but cannot be connected to, e.g. a beacon). Devices that send advertisements indicating a connectable device are required to listen for a possible response, *scan request*, from a receiver (host controller), for a limited duration of time after each advertisement duration. Advertising events occur repeatedly with an advertising interval (indicated as T_a in Fig. 1.) The advertising interval consists of a static interval *advInterval* and a pseudo-random interval *advDelay*. According to BLE specifications [1], *advInterval* must be in the range of 20 ms to 10.24 s and *advDelay* must be a random value with a range of 0 ms to 10 ms.

Independent from an advertiser, a host controller repeatedly turns on its receiver to listen for possible incoming packets from one or multiple advertisers for a limited duration of time, indicated as d_s in Fig. 2. This happens repeatedly at fixed time intervals of T_s (*scanInterval*). Due to the existence of a frequency hopping mechanism in the BLE protocol, the host controller must alternately hop to the next advertising channel to be able to listen for all transmitted advertising packets. According to the BLE specification [1], the host controller is required to scan all of the three dedicated advertising channels. In a typical bidirectional communication link, the host controller is required to respond back to the advertiser immediately after receiving an advertising packet. The advertiser usually expects a response on the same advertising channel 150 μs (termed *interframe-space*) after the end of the advertising packet. However, in a typical unidirectional communication link, the scanner is not required to respond back to the advertiser. This allows the reception of packets in a passive manner (broadcasting mode).

Although, broadcasting information without the need to establish a bidirectional communication link between the communicating devices seems to be more energy efficient, this type of communication is considered to be unreliable. If multiple advertisers simultaneously transmit their information over the same communication channel, there is a high probability that the transmitted packets collide. Packet collisions then result in a total loss of information that is contained in the collided packets. In addition, in latency-critical applications in which systems are required to react quickly to the events that are captured by sensors, when advertising interval (indicated as T_a in Fig. 1.) is purposely reduced to enable the advertising mechanism (as shown in Fig. 1) to comply with the requirements of such systems, then packet collisions occur with greater frequency. As a result of this increase in the number of packet collisions, the total amount of energy that each node is required to successfully transmit packets increases.

III. MEASUREMENT AND ENERGY MODEL

In order to better evaluate the BLE advertising mechanism, we present the results of a captured electrical current waveform that was recorded on an oscilloscope from the Nordic Semiconductor BLE System on Chip (SoC) (16 MHz ARM Cortex M0 CPU). Similar current measurements have been done before with a Texas Instruments CC2541 SoC [23].

A. CAPTURE OF WAVEFORM DURING AN ADVERTISING EVENT

In BLE protocol, when advertising, the BLE device must transmit its advertisement packet to the host controller. The rate is decided by the BLE device prior to transmission. In this section, as shown in Fig. 3, we measured the current consumption of the BLE tag in standby ("sleep mode"), prior to BLE TX advertisement ("get ready mode") and in advertising mode. In this way, the energy required for a given advertising rate was obtained.

B. ADVERTISING MODE ENERGY EXPENDITURE MODEL

Table 1 contains information that was extracted from Fig. 3 with measurement results from different BLE radio states. In Fig. 3, the advertisement rate was configured to 1 Hz and based on this advertisement rate, the average current consumption values of different states are recorded in Table 1.

According to Table 1, it is now possible to construct an energy consumption model for BLE advertising modes. We have used a model for comparison as previously discussed [10]. We initially introduced three energy variables that were used to construct an energy consumption model for the BLE advertising mode explained as follows.

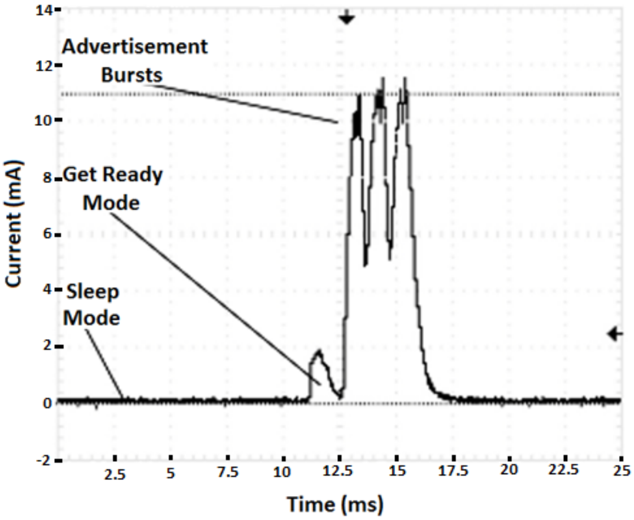

FIGURE 3. The measured SoC current, 2mA peak prior to BLE TX advertisement, three advertisement bursts at 11mA peak and 148uA static current in sleep mode (2 mA scale per vertical square and 2.5 ms scale per horizontal square).

TABLE 1. Time and current measurement of each state.

States	Time (ms)	Peak Current (µA)	Average Current (µA)
Sleep	994.9	148	148
Get Ready	1.5	1800	1000
TX	3.6	11000	8500

1. $E_{\text{Additional}}$: Additional energy consumption that occurs prior to BLE actual transmission in "get ready mode".
2. E_{TX}: Energy consumption that occurs due to transmission of three advertising bursts.
3. E_{Sleep}: Energy consumption that occurs when BLE device is not transmitting any packets and it is in "sleep mode".

Therefore, the consumed energy during an advertising interval (T_a) as shown in Fig. 1, is composed of the amount of energy that is used when the node's radio is in "TX State", in "Additional State" and in "Sleep State". This is shown in equ. (1) [10].

$$E_{T_a} = E_{\text{Additional}} + E_{\text{TX}} + E_{\text{Sleep}} \tag{1}$$

The energy that is consumed for a complete duration of an advertising interval (T_a) can also be explained in more detail as:

$$E_{T_a} = V\left(I_{\text{Additional}} \times \text{T}_{\text{Additional}}\right) + V\left(I_{\text{TX}} \times T_{\text{TX}}\right) + V\left(I_{\text{Sleep}} \times \left(T_a - T_{\text{Active}}\right)\right) \tag{2}$$

where V, I and T represent constant voltage, current and time respectively. $I_{\text{Additional}}$ and $T_{\text{Additional}}$ represent additional current and time prior to BLE actual transmission in "get ready mode". T_{Active} represents the time that the radio stays in an active state.

As previously explained in Section II, T_{a} consists of a static interval (*advInterval*) in the range of 20 ms to 10.24 s and a random part (*advDelay*) in a range of 0 ms to 10 ms. Based on this information, although T_{Active} in (2) is a constant value for all advertising intervals, T_{a} contains a random interval (0 to 10 ms) added to its static interval. It must be noted that, since we only present the current waveform in a single advertising event, the next time we try to record, a slightly different value is obtained. Therefore, (2) is valid for calculating the energy consumed for only one duration of an advertising event. In order to make this equation valid for a number of advertising intervals, we subtract T_{Active} with the static part (*advInterval*) of T_{a}. On a typical advertising mode scenario with i consecutive transmissions, the transmitter emits only one "get ready" pulse. Thus, the energy consumed for i number of advertising events can be calculated for $i = 1, 2, 3, \ldots, n$ as energy that is consumed for a complete duration of an advertising interval (T_{a}) can also be explained in more detail as:

$$E_i = iE_{\text{TX}} + iE_{\text{Sleep}} + E_{\text{Additional}} \tag{3}$$

IV. BLUETOOTH LOW ENERGY COLLISION ANALYSIS

In this section, we analyze the probability of packet collisions. In order to do the collision analysis, we initially make a number of assumptions as follows: 1) advertising nodes attempt to transmit according to a Poisson distribution; 2) *advDelay* is considered constant (as expectation of random delays); 3) advertising channel packet duration (d_{p}) for all three advertising channels (channel index = 37, 38, 39) is fixed; 4) the time duration that an advertiser requires to change its channel (d_{g}) is constant; 5) for simulation, we did not consider any distortions from the channel; 6) any number of packets that collide in one time interval is considered one collision.

Figure 4 shows the transmission time for two BLE advertisers. The advertising packets occur on a regular periodic basis. The advertising packets are sent repeatedly in a time window of the advertising interval (T_{a}) where the size of the advertising event (d_{AE}) is fixed. In a typical piconet network, BLE advertisers transmit their packets at any points in time. Thus, in our analysis we have used a realistic traffic model based on the Poisson distribution to comply with that requirement. In a BLE piconet, there can be situations when multiple BLE advertisers simultaneously transmit their information to the client. Therefore, packet collision is unavoidable. In our analysis, in order to check the existence of packet collisions, we compared the starting time of the created packets by each node with packets from other nodes. As an example, if the starting time of packet one from node A as shown in Fig. 4 is compared with the starting time of packet one from node B and determined that the time difference between the two transmission events is smaller than $d_{\text{p}} + d_{\text{g}}$, this means a packet collision has occurred and the collided packet is then discarded.

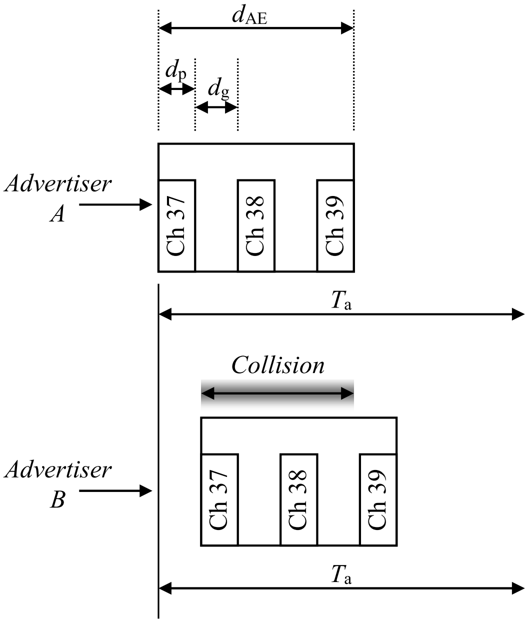

FIGURE 4. **Timing of two BLE packets from different advertisers.**

We assume that *advDelay* is smaller with respect to *advInterval* and can be replaced by its mean value. The arrival period for each node is *advInterval* + *advDelay*. Therefore, the arrival rate [24], the average number of packet transmission attempts, λ, is the inverse of advertising interval plus advertising delay, i.e., 1/(*advInterval* + *advDelay*). For N nodes, the average number of packet transmission is $N\lambda$. In N piconets, the packet collision probability was calculated by assuming a Poisson distribution for transmission events. The probability of a packet collision from i-th piconets can be approximated to [25]:

$$p_{\text{c}} = 1 - e^{-N\lambda 2d_{\text{p}}} \tag{4}$$

V. EXPERIMENTAL RESULTS

This section initially investigates the probability of packet collisions of the advertising packets in a BLE network. The results presented in this section can be useful for a vast number of applications such as those applications that previously have been discussed in detail [14]–[16]. We initially simulated the BLE advertising process as shown in Fig. 1 with the objective to determine the probability of packet collisions for a given *advInterval*. The packet collision probability as a function of the number of nodes, over the family of advertising rates is shown in Fig. 5.

In this simulation, an increasing number of nodes were run for 20,000 seconds to simultaneously advertise their packets. In our simulation, we used BLE standardized packet formats. The BLE link layer has been used for both advertising channel packets and data channel packets. Each BLE packet comprises of four fields: preamble, access address,

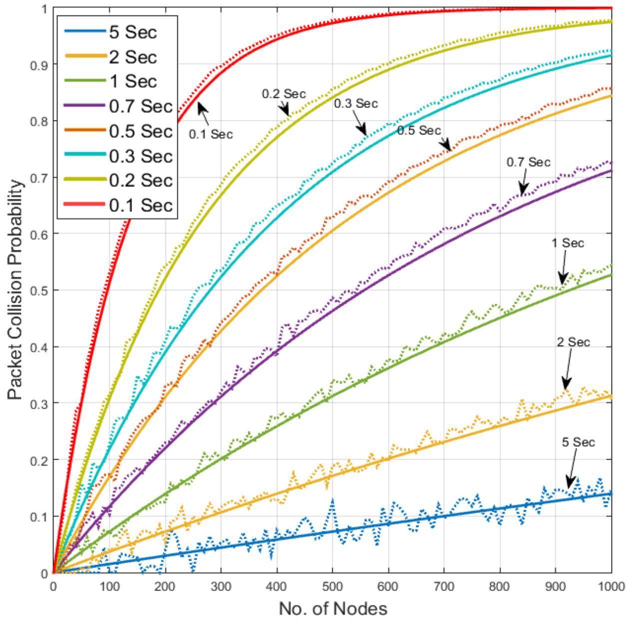

FIGURE 5. **Packet collisions in broadcasting mode with varied *advInterval*. Simulation data (dotted lines) are compared with theoretical values (solid lines) obtained from Eq. 4.**

Packet Data Unit (PDU), and Cyclic Redundancy Check (CRC). According to the BLE specification, the preamble is 1 byte, the access address is 4 bytes and the CRC is 3 bytes. The PDU range however, is varied. The PDU range can be from 2 bytes to a maximum of 39 bytes. In our simulation, we used a maximum of 39 bytes for the PDU field. Therefore, each packet in our simulation consists of 47 bytes in total.

To validate the simulation results, we compared the simulation results with an experimental data, and the results are presented in Fig. 6. The experimental data was collected from seven custom-designed wearable BLE-based sensor nodes as shown in Fig. 7a. The sensor nodes that we used were all equipped with a Nordic nRF51822 SoC mainly suited to be used for BLE and 2.4 GHz ultra-low power applications. The nRF51822 SoC is fabricated around a 32-bit ARM Cortex M0 microcontroller. In the experimental setup as shown in Fig. 7b, seven advertisers (only five shown for clarity) were arranged around a sniffer acting as a receiver. The advertisers are spaced a given distance apart from each other and in a common range of the receiver. Since in our collision analysis in Section IV, it was assumed that advertisers transmit their packets through a perfect channel condition, the transmitters in our experimental setup are placed close to the receiver and each packet was received when transmitted in isolation, maintaining perfect channel condition assumption. The receiver was programmed to capture and log all received packets on a particular channel (whether correctly received or corrupted). We then analyzed the probability of packet collisions for a given *advInterval* and compared the simulation and experimental results as shown in Fig. 6.

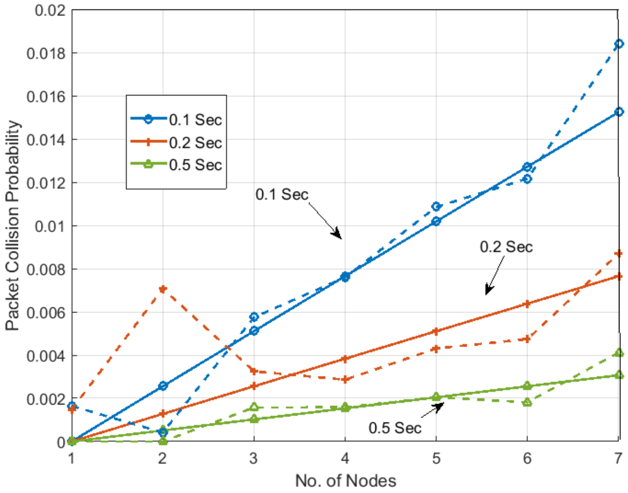

FIGURE 6. **Likelihood of packet collisions with varied *advInterval*. Dotted lines represent the experimental data whereas solid lines are theoretical values obtained from Eq. 4.**

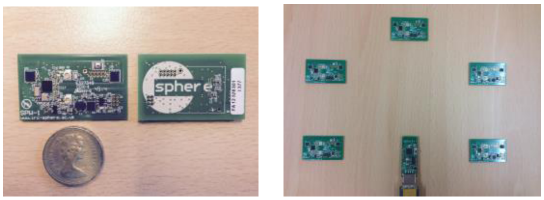
(a)
(b)

FIGURE 7. **a) Custom-designed sensor node, b) Experimental setup.**

In our simulations, we used the following parameter values from the BLE standard: The value of the uniformly distributed random value (*advDelay*) is between 0 ms to 10 ms according to the standard and we implemented a uniformly distributed delay averaged around 5 ms. We obtained results for different values of *advInterval* in the permitted range of 20 ms to 10.24 s.

The duration of one packet, d_p, was fixed to 0.376 ms and d_g was fixed to 0.02 ms.

The results in Fig. 5 and Fig. 6 show that the probability of packet collisions is highly dependent on the number of advertising nodes that are used in the network as well as the advertisement time intervals.

pAs an example in Fig. 5, for a given *advInterval* of 1 second, when 700 nodes were used in a network, only 40 percent of the advertisement packets collided; while for a different *advInterval* of 0.1 seconds, and when same number of nodes are used, nearly all of the advertisement packets have collided. Fig. 5 also has shown that the number of packet collisions in a large wireless sensor network grows exponentially with respect to an increased number of advertising nodes and decreased advertisement time intervals.

Figure 8 shows the network throughput as maximum rate of data transmitted by multiple nodes. For Fig. 8, we simulated both the BLE advertising process as shown in Fig. 1, and BLE scanning process as shown in Fig. 2. The simulation results

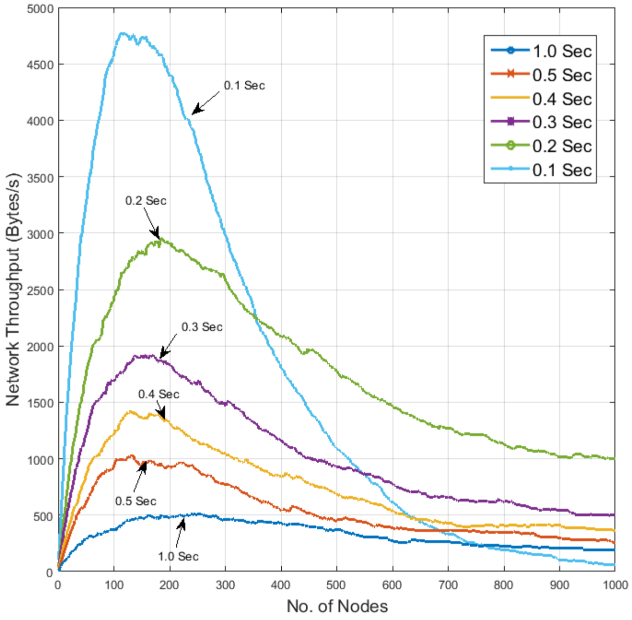

FIGURE 8. **BLE network throughput with varied *advInterval*.**

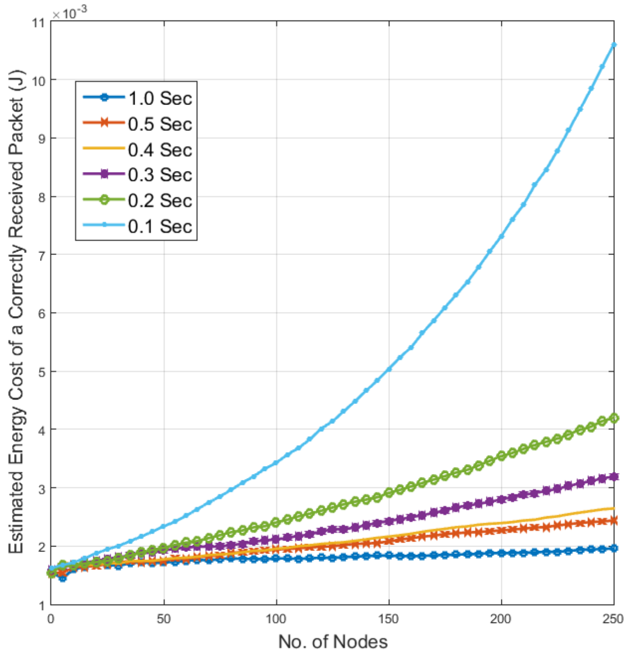

FIGURE 9. **Energy (J) cost of a correctly received packet with varied *advInterval*.**

are done for a given *advInterval* ranging from 0.1 to 1 second, where 1000 nodes were used in a network. The BLE advertising mode was used for this simulation. The BLE detector scans the medium with three different channels (37, 38, 39). While detector is scanning on a single channel, not all of three advertising packets can be detected. Therefore, the network throughput is affected by two main factors: Packets that are not detected by different scanning channels and packets that are lost due to packet collisions. In Fig. 8, the throughput of the BLE protocol rises smoothly with an increased traffic level up to a point. At this pivotal point collisions begin to occur with a greater frequency, which results in a gradual reduction in the network throughput.

With the advent of the Internet of Things (IoT), it is ever more important to discuss the limitations of the current low-power protocols that can be used in IoT applications such as BLE technology. One important limitation of such protocols would be when the network becomes congested with a high concentration of local sensors that are placed in a limited space. This problem can be solved by analyzing the throughput of the network. As can be seen in Fig. 8, nearly all of the network throughput peaks are between 100 to 200 BLE nodes. After reaching these throughput peaks, the network becomes congested and adding extra nodes significantly decreases the performance of the whole grid.

In Fig. 9, we used the information that was previously provided from Section III.A and III.B to calculate the required energy to transmit BLE advertising packets. The required energy for each correctly received packet was primarily influenced by the number of lost packets due to packet collisions and the number of lost packets due to not being detected by the receiver. Therefore, the average energy consumption of each correctly received packet was calculated by the total energy consumed for all transmitted packets per node divided by average received number of packets per node. Thus, as shown in Fig. 9, as we reduced the advertisement time intervals, then more packets collided. This resulted in a drop in the data completeness and quality. In Fig. 8, when the throughput of the BLE network started to fall due to an increase in the number of packet collisions, the energy consumption of the BLE nodes increased exponentially with respect to the number of nodes as shown in Fig. 9.

As an example, in Fig. 9, for a given *advInterval* of 1 second, when 150 number of nodes were used in the network, less than 2 Joules of energy was consumed for a correctly received packet; while for a different *advInterval* of 0.1 seconds, when same number of nodes were used in the network, 5 Joules of energy was consumed for a correctly received packet, clearly demonstrating an increase in required energy due to collisions.

VI. CONCLUSION

This article investigated the probability of collisions of advertising packets in a BLE network. Simulation and experimental results showed that decreasing the advertisement time intervals greatly increased the probability of packet collisions, which resulted in a reduction in data completeness and quality of the detected advertisements. In addition, increasing the number of packet collisions increases the amount of energy consumption of BLE nodes. Our analysis showed that the energy consumption of the BLE nodes increase exponentially with respect to the number of nodes. Although results are predictive, we have represented a rigorous way of analyzing the network which enable us to get quantitative values for the peak throughput and other parameters that congest the network at high volume concentration of BLE nodes. Our analysis is specifically important for applications such as large wireless sensor networks in which determining the optimum number of sensor nodes per cluster and also the point at which the throughput of the network is saturated are difficult. The results from this work enable designers to consider the performance of BLE devices where multiple devices are present or where a user expects their BLE devices operate in busy surroundings with a high population. In future work, we suggest to use receiver diversity where dedicated receivers simultaneously sweep over all channels. The effects of multiple receivers on packet collision, throughput and energy consumption of nodes are the subject of our current research. In this simulation, an increasing number of nodes were run for 20,000 seconds to simultaneously advertise their packets. In our simulation, we used BLE standardized packet formats. The BLE link layer has been used for both advertising channel packets and data channel packets. Each BLE packet comprises of four fields: preamble, access address, Packet Data Unit (PDU), and Cyclic Redundancy Check (CRC). According to the BLE specification, the preamble is 1 byte, the access address is 4 bytes and the CRC is 3 bytes. The PDU range however, is varied. The PDU range can be from 2 bytes to a maximum of 39 bytes. In our simulation, we used a maximum of 39 bytes for the PDU field. Therefore, each packet in our simulation consists of 47 bytes in total.

REFERENCES

[1] *Specification of the Bluetooth System V4.0*, Bluetooth Special Interest Group, Kirkland, WA, USA, 2010.

[2] C. Gomez, J. Oller, and J. Paradells, "Overview and evaluation of Bluetooth low energy: An emerging low-power wireless technology," *Sensors*, vol. 12, no. 9, pp. 11734–11753, 2012.

[3] A. H. Omre and S. Keeping, "Bluetooth low energy: Wireless connectivity for medical monitoring," *J. Diabetes Sci. Technol.*, vol. 4, no. 2, pp. 457–463, 2010.

[4] P. K. Yoon, S. Zihajehzadeh, B.-S. Kang, and E. J. Park, "Adaptive Kalman filter for indoor localization using Bluetooth low energy and inertial measurement unit," in *Proc. EMBC*, Aug. 2015, pp. 825–828.

[5] R. Negra, I. Jemili, and A. Belghith, "Wireless body area networks: Applications and technologies," *Procedia Comput. Sci.*, vol. 83, pp. 1274–1281, 2016.

[6] I. Al-Anbagi, M. Erol-Kantarci, and H. T. Mouftah, "A survey on cross-layer quality-of-service approaches in WSNs for delay and reliability-aware applications," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 1, pp. 525–552, 1st Quart., 2016.

[7] M. Ghamari, B. Janko, R. S. Sherratt, W. Harwin, R. Piechockic, and C. Soltanpur, "A survey on wireless body area networks for ehealthcare systems in residential environments," *Sensors*, vol. 16, no. 6, p. 831, 2016.

[8] M. Ghamari, H. Arora, R. S. Sherratt, and W. Harwin, "Comparison of low-power wireless communication technologies for wearable health-monitoring applications," in *Proc. CCCT*, Apr. 2015, pp. 1–6.

[9] P. Kindt, D. Yunge, R. Diemer and S. Chakraborty. (Mar. 2014). "Precise energy modeling for the bluetooth low energy protocol." [Online]. Available: https://arxiv.org/abs/1403.2919

[10] J. Liu, C. Chen, Y. Ma, and Y. Xu, "Energy analysis of device discovery for Bluetooth low energy," in *Proc. VTC Fall*, Sep. 2013, pp. 1–5.

[11] M. Siekkinen, M. Hiienkari, J. K. Nurminen, and J. Nieminen, "How low energy is bluetooth low energy? Comparative measurements with ZigBee/802.15.4," in *Proc. WCNCW*, Apr. 2012, pp. 232–237.

[12] A. Dementyev, S. Hodges, S. Taylor, and J. Smith, "Power consumption analysis of Bluetooth low energy, ZigBee and ANT sensor nodes in a cyclic sleep scenario," in *Proc. IWS*, Apr. 2013, pp. 1–4.

[13] K. Mikhaylov, N. Plevritakis, and J. Tervonen, "Performance analysis and comparison of Bluetooth low energy with IEEE 802.15.4 and Simpliciti," *J. Sens. Actuator Netw.*, vol. 2, no. 3, pp. 589–613, 2013.

[14] S. H. Lee, S. Lee, H. Song, and H. S. Lee, "Wireless sensor network design for tactical military applications: Remote large-scale environments," in *Proc. MILCOM*, Oct. 2009, pp. 1–7.

[15] S. N. Pakzad, "Development and deployment of large scale wireless sensor network on a long-span bridge," *Smart Struct. Syst.*, vol. 6, nos. 5–6, pp. 525–543, Jun. 2010.

[16] R. Szewczyk, A. Mainwaring, J. Polastre, J. Anderson, and D. Culler, "An analysis of a large scale habitat monitoring application," in *Proc. SenSys*, 2004, pp. 214–226.

[17] J. Liu, C. Chen, and Y. Ma, "Modeling neighbor discovery in Bluetooth low energy networks," *IEEE Commun. Lett.*, vol. 16, no. 9, pp. 1439–1441, Sep. 2012.

[18] J. Liu, C. Chen, Y. Ma, and Y. Xu, "Adaptive device discovery in Bluetooth low energy networks," in *Proc. VTC Spring*, Jun. 2013, pp. 1–5.

[19] R. K. Megalingam, D. M. Kaimal, and M. V. Ramesh, "Efficient patient monitoring for multiple patients using WSN," in *Proc. AMNCA*, vol. 2012, pp. 87–90.

[20] M. Aminian and H. R. Naji, "A hospital healthcare monitoring system using wireless sensor networks," *J. Health Med. Inf.*, vol. 4, p. 121, Feb. 2013.

[21] M. Ghamari, B. M. Heravi, U. Roedig, B. Honary, and C. A. Pickering, "Improving transmission reliability of low-power medium access control protocols using average diversity combining," *IET Wireless Sensor Syst.*, vol. 2, no. 4, pp. 377–384, Dec. 2012.

[22] M. Ghamari, B. M. Heravi, U. Roedig, and B. Honary, "Reliability comparison of transmit/receive diversity and error control coding in low-power medium access control protocols," *IET Netw.*, vol. 3, no. 4, pp. 284–292, 2014.

[23] S. Kamath and J. Lindh, "Measuring Bluetooth low energy power consumption," Texas Instruments, Dallas, TX, USA, Appl. Note AN092, 2010.

[24] T.-Y. Lin and Y.-C. Tseng, "Collision analysis for a multi-Bluetooth picocells environment," *IEEE Commun. Lett.*, vol. 7, no. 10, pp. 475–477, Oct. 2003.

[25] F. Gebali, *Analysis of Computer and Communication Networks*. New York, NY, USA: Springer, 2008.

MOHAMMAD GHAMARI received the B.Eng. degree in electronic and communications from the University of Leeds in 2006, the M.Sc. degree in communications and signal processing from Newcastle University in 2007, and the Ph.D. degree from Lancaster University in 2013, where he was involved in research at the School of Computing and Communications for four years.

His first professional work was with Reading University, where he was a Post-Doctoral Research Assistant for two years. He then moved to The University of Texas at El Paso, USA, as a Post-Doctoral Fellow and a Teaching Fellow, for two and half years. He is currently a Post-Doctoral Scholar with Pennsylvania State University. His current research interests are on wearable technologies and wireless environmental monitoring systems.

EMMA VILLENEUVE received the M.Eng. degree in physics from the School of Engineering PHELMA, Grenoble, in 2009, the M.Sc. degree in signal and image processing from the Grenoble Institute of Technology, France, in 2009, and the Ph.D. degree in hyperspectral signal processing from the University of Toulouse, France, in 2012.

From 2013 to 2015, she was a Research Assistant with the University of Reading, U.K. She then joined the NIHR CLAHRC South West Peninsula, University of Exeter, U.K., as an Associate Research Fellow. She is currently a Research Engineer with CEA Leti, Grenoble, France. Her research interests are in the areas of statistical signal processing, with a specific focus on healthcare applications.

CINNA SOLTANPUR received the M.Sc. degree in communication systems from Lancaster University, Lancaster, U.K., in 2011, and the Ph.D. degree in electrical and computer engineering from The University of Oklahoma, OK, USA, in 2016. His research interests are in information theory, signal processing, storage devices, and smart grids.

JAVAD KHANGOSSTAR received the B.Eng. in electronics and embedded computer engineering from the University of Leeds, U.K., in 2006. He was with Pace plc, U.K., and Alcatel-Lucent, Belgium, for four years on home networking technology solutions. He is currently pursuing the part-time Ph.D. degree with the Institute of Integrated Information Systems, University of Leeds. He has been with Telefónica since 2014, where he is currently a Senior Analytical and Performance Designer with the O2 Research Group. He is also with the Telefónica Research Group to deliver customer experience/satisfaction metrics using machine learning techniques based on network-related KPIs and customer surveys.

BALAZS JANKO received the M.Eng. degree from the University of Reading in 2009 and completed his Ph.D. thesis on a dual-drive robotic joint actuator design in 2014. He is currently a Research Assistant with the University of Reading. His current research interests are low-power wearable electronics, robotics, and haptics.

R. SIMON SHERRATT (M'97–SM'02–F'12) received the B.Eng. degree in electronic systems and control engineering from Sheffield City Polytechnic, U.K., in 1992, the M.Sc. degree in data telecommunications in 1994, and the Ph.D. degree in video signal processing from the University of Salford, U.K., in 1996.

In 1996, he was appointed as a Lecturer in electronic engineering with the University of Reading, where he is currently a Professor of biosensors. His research topics are signal processing and communications in consumer devices focusing on wearable devices and healthcare.

Dr. Sherratt received the first place IEEE Chester Sall Memorial Award in 2006, second place in 2016, and third place in 2017 and 2018. He is a reviewer of the IEEE Sensors Journal and currently an Emeritus Editor-in-Chief of the IEEE Transactions on Consumer Electronics.

WILLIAM HARWIN (SM'12) is currently a Professor of interactive systems with the University of Reading. His research interests include technology and healthcare, human–robot interactions, and haptic interfaces. More recent research interests include healthcare sensors in a residential environment and the emerging field of cognitive robotics.

• • •