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On the System-level Performance Evaluation of Bluetooth 5 in IoT: Open Office Case Study

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***Abstract*—The Internet of Things (IoT) has recently revolutionized the concept of connectivity from humans to surrounding objects through the Internet infrastructure. To Enable the wide range of IoT use cases, several communication technologies are introduced. Among the others, short range radio technology is an essential part of IoT for enabling the local area networks. Bluetooth Low Energy (BLE) version 5 is recently developed by Bluetooth Special Interest Group (SIG) which claims to be better suit for IoT use cases. However, the complexity of BLE 5 protocol and the lack of system-level simulator hinder the detailed analytical study of this new technology. To this end, we develop comprehensive system-level tool for simulating BLE 5. Some of the most important features of BLE 5 are developed and results are investigated in this paper. We investigate the BLE 5 with new physical (PHY) layer from networking perspective by analyzing end-to-end delay, battery life time, packet error rate and throughput in open office environment. To this end, we investigate the scalability of the network for different PHYs. The results show that, in this case study, the coded PHYs have weaker performance when network becomes congested.**

***Index Terms*—Bluetooth Low Energy, performance, system-level simulation, IoT**

I. Introduction

The latest improvement in the embedded and connected technologies has tremendously increased the volume of the pervasive objects around us. The number of connected devices is expected to reach up to 25 billion by 2020 [1]. These connected devices with a wide range of potential applications interact with each other via the Internet in order to realize their goals determined by their use cases and services. Such applications incorporate intelligent transportation, smart cities, asset tracking, industrial automation, agriculture, medical monitoring, etc, thus forming so-called Internet of Things (IoT) [2]. IoT refers to the ways enabling automated applications that provide connectivity among devices without human intervention. To enable full automation of IoT, several challenges should be addressed. One of the important challenges in IoT is to provide data communications for different applications while satisfying their diverse quality of service (QoS) requirements such as reliability, energy efficiency, security, and privacy [3]. In this regard, Bluetooth Low Energy (BLE) is considered as a promising technology for IoT use cases.

The BLE was standardized in 2010 as part of the Bluetooth Core Specification with version 4.0 under the Bluetooth Special Interest Group (SIG) [4]. Ever since, several versions have been standardized and improved the performance of the BLE technology. SIG released the version 5.0 of the protocol in Dec. 2016 and version 5.1 in Jan. 2019 preparing for the upcoming wave of the IoT devices and applications. Bluetooth 5 comes with the longer range, higher data throughput, increased broadcasting capacity and improved coexistence with improved channel selection algorithm which satisfies the requirements of the most of IoT use cases [5]. Bluetooth 5 supports larger coverage, higher data throughput and broadcasting capacity, and improved coexistence with advanced channel selection algorithm to satisfy the requirements of IoT applications [5].

The BLE has attracted many interests from both academia and industry in the recent years and many studies have been conducted in this regard. In [6], [7], and [8] different applications including occupancy, positioning and health-care are discussed by using BLE devices. More works were studied in healthcare application in [9], [10], [11], and [12]. Discovery performance of the BLE was studied in [13] while the performance of the protocol was discussed in [14] and [15]. The simulation of network-level performance is done in [16]. The probability of successful data channel selection in BLE and its related simulation were carried out in [17] and [18]. The author in [19] discussed about the suitability of the BLE and its challenges for the IoT applications. All of the above-mentioned studied has been carried out for the BLE version 4.x. Finally, [20] investigated the applicability of the Bluetooth 5 for the IoT. However, this work is limited to the study of BLE 5 scalability for IoT applications.

Nevertheless, the networking aspect of BLE 5 is lacking and to the best of authors' knowledge, no system-level simulator developed for BLE 5. To this end, the main contribution of this paper is developing a full-fledged system-level simulator for BLE 5. Furthermore, by using this tool, we simulate an open office environment as a case study and analyze the new PHYs of BLE 5.

The remainder of this paper is outlined as follows. Section II provides overview of bluetooth 5. Section III presents the system model. Simulation results are presented in Section IV, followed by the conclusion given in Section V.

II. Overview of Bluetooth 5

BLE is a robust, low cost short-range radio technology which originally designed for replacing cable between electronic devices. This technology is designed for low cost

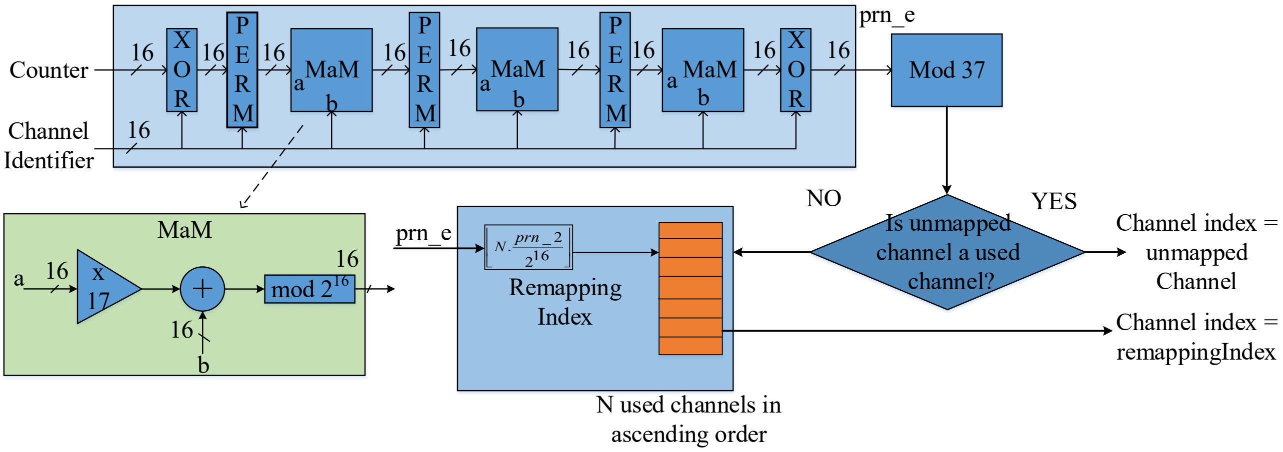

Fig. 1. Channel Selection Algorithm #2 in Bluetooth Low Energy 5

and low energy consumption products which is suitable for application with low duty cycle and low data rate. Therefore, IoT use cases with loose QoS requirements on data rate and duty cycle can benefit from this technology.

BLE 5 comes with new features compared to previous versions that improves its functionality for IoT applications. Some of the new features of BLE 5 are covered in this section.

A. *New features*

1) New PHYs: One of the most important features of BLE 5 is its new PHYs compared to previous versions. BLE 4.x only supports *1 Mbps* rate, while BLE 5 supports *1 Mbps PHY* and *2 Mbps PHY*. Since BLE employs shaped, binary frequency modulation, symbol rates are 1 M symbol per second (Msym/s) and 2 Msym/s, respectively. The mandatory symbol rate for BLE 5 is 1 Msym/s, which refers to *LE 1M PHY*. The BLE 5 transmits and receives packets with double speed through utilizing *2 Mbps PHY*. The benefit of faster PHY is that the data is exchanged in much shorter time which this eventually leads to the less power consumption. In addition, faster transmission and reception means less channel access time which will reduce the interference and congestion.

Another improvement of BLE 5 is the optional new coded PHY supported in *1 Mbps PHY* which refers to *LE Coded PHY*. Two coding schemes are used including $S = 2$ in which 2 symbols correspond to 1 bit of information and $S = 8$ in which 8 symbols equal to one bit of information. The *LE coded PHY* with S=2 and S=8 achieve up to 500 kbps and 125 kbps data rate, respectively. BLE 5 can reach up to four times increase in the coverage compared to BLE 4.x and guaranty robust and reliable communication system by using the coded PHY.

2) Channel Selection Algorithm # 2: The Channel Selection Algorithm #2 (CSA#2) is a new feature of BLE 5 to determine the next hopping frequency channel. The CSA#2 is an improvement over the CSA#1 used in the BLE 4.x.The CSA#2 enhances the interference tolerance in frequency domain by using the state of the art algorithm and keeping the minimum number of the utilized frequency channels up to 15 channels.

The CSA#2 is employed to select channels for the connection and periodic advertisement packets. In the beginning of each connection event or periodic advertisement, the algorithm generates a channel index which should be used during that event. The CSA#2 employs the following inputs: *channelIdentifier* and *counter*. The *channelIdentifietr* is a 16 bit input obtained from the *Access Address* given by:

$$channelIdentifier = (AccessAddress_{31-16} \ XOR \ AccessAddress_{15-0}) \quad (1)$$

and *counter* is initialized from zero in the beginning of connection event or periodic advertisement and incremented by one in the beginning of each event.

The CSA#2 is composed of two parts: 1) *unmappedChannel* and 2) *remappingIndex* event. The *unmappedChannel* event itself consists of two stages. In the first stage, a 16 bit unsigned pseudo-random number, namely, *prn_e* is generated and in the second stage, the *unmappedChannel* index is calculated as *prn_e* module 37. If the *unmappedChannel* is the index of the used channel index then it is chosen as a channel index for the event. Otherwise, the CSA#2 calculates the channel index by:

$$remappingIndex = \left\lfloor \left(\frac{N \star prn\_e}{2^{16}} \right) \right\rfloor \quad (2)$$

and then uses *remappingIndex* to calculate channel index by using it as an index into the remapping table which is created from N used channel in ascending order. Fig. 1 presents the overall process of channel selection algorithm #2.

3) Extended Advertising: BLE 5 comes with major updates on the advertising capability which makes it even more suitable for IoT use cases. Some of these updates of the advertising feature are explained in the following.

BLE 4.x versions are limited with the number of advertisement channels up to 3 and the amount of transmitting payload up to 31 bytes in the advertisement mode. While BLE 5 changes the advertising functionality by using the 3 advertisement channels as primary advertisement channels for backward compatibility and interoperability and in addition, using the 37 data channels as secondary advertisement channel. In other words, BLE 5 can use secondary advertisement

TABLE I
SIMULATION PARAMETERS

Parameter	Value	Description
MaxTXPower	5 mW	Maximum Transmission Power
Sleep Current	0.00015 mA	Current draw for CC2640R2F in sleeping mode
RX Current	6.1 mA	Current draw for CC2640R2F in receiving mode
TX Current	9 mA	Current draw for CC2640R2F in transmitting mode
Traffic	$Periodic$	Periodic sensor traffic model
N	30	Distance power loss coefficient
$L_f(n)$	14 dB	Floor penetration loss factor
n	1	Number of floors
Battery Capacity	1000 mAh	CR2477 coin cell battery
Voltage	3 V	Voltage of the battery

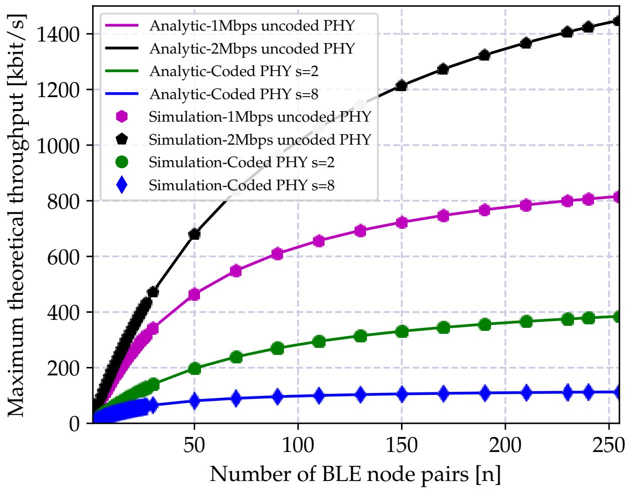

Fig. 2. Maximum achievable throughput calculated via equation and system-level simulation.

channels to broadcast even more data and offload the primary channels. Furthermore, BLE 5 enhances the advertising functionality by increasing the amount of transmitting payload up to 8 times (255 bytes).

III. System Model

We simulate BLE 5 with a system-level simulator using OMNeT++ engine. OMNeT++ is a popular discrete-event simulator written in C++. Our simulator has rather complex details of MAC and PHY layer of the BLE 5 yet a simple application layer. Some of the new features of BLE 5 including channel selection algorithm #2, coded physical channels and 2 Msym/s PHY are implemented in the simulator. It is to be noted that there is only one active link supported at a time for each simulated node.

The playground of the simulation is an open office with the size of $10\times10\times4$ m and devices are randomly distributed on it. The payload size is fixed to 255 bytes for all of the experiments and traffic is periodically generated by inter-arrival time of 0.03125 second which approximately generates 64 kbit/s of traffic. In this work, the master nodes only generate the traffic and slave nodes receive the packets and send the ACKs in reply. We use the energy related parameters of the simulation from the CC2640R2F BLE 5 chip. Detailed parameters for all physical channels can be found from the data-sheet of the chip. Table I provides the details of the parameters utilized in the simulation.

In the simulation, we use the ITU indoor propagation model for open office environment [21]. The ITU indoor path loss model is formally given as:

$$L = 20\ log_{10}f + N\ log_{10}d + L_f(n) - 28 \tag{3}$$

where f is the transmission frequency in MHz, d is the distance in meter, N is the distance power loss coefficient, n is the number of floors between the transmitter and receiver and finally, $L_f(n)$ refers to the floor penetration loss factor in dB.

A. Validation of Simulator

In order to validate our system-level simulator, we compare the maximum theoretical LL throughput of P2P BLE against analytical one given in [15]. In addition, We further extend the analytical throughput for BLE 5 as follows:

$$Th(n,m)=\frac{(n*8)}{\frac{H}{R}+\frac{(n+m)S*8}{R}+2\tau+2max(T_{IFS},T_{TX_{prep}}+T_{RX_{proc}})} \tag{4}$$

where n stands for the payload of packet sent from master to slave in bytes, m is the payload of the reply packet in bytes, R indicates the bitrate, S accounts for code rate, H represents the header size in bit, $T_{TX_{prep}}$ and $T_{RX_{proc}}$ refer to the required time for processing the packet before transmission and after reception, respectively, T_{IFS} indicates the inter-frame space, and finally τ refers to radio signal propagation delay. Obviously, maximum BLE LL throughput is achieved if $n = 255$ and $T_{TX_{prep}} = T_{RX_{proc}} = \tau = m = 0$. Fig. 2 depicts the maximum theoretical throughput of BLE using the analytical formula and simulation. As it can be seen, Fig. 2 confirms the validity of our BLE system-level simulator.

IV. Results of BLE 5 System-Level Simulation

This section presents the performance evaluation of all four physical channels of BLE 5 in terms of different metrics such as throughput, end-to-end delay and battery life time. To increase the accuracy of the results, every single simulation scenario are repeated 100 times with different random seeds and the average of results are calculated by using Monte Carlo method.

First of all, we investigate the P2P throughput in four different scenarios owing two uncoded and two coded PHYs. To this end, we simulate a network consisting of the master and slave pairs while varying from 1 to 100 pairs. Note that the *connInterval* parameter utilized for all simulation scenarios is 3200.

Fig. 3 demonstrates that all of the channels excluding *codedS8* can deliver the intended traffic for one pair of nodes which is 64 kbps. The reason that *codedS8* has lower throughput is its longer packets which takes longer channel

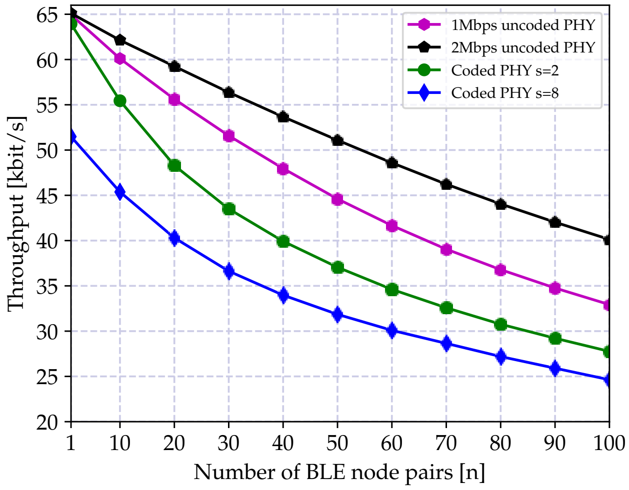

Fig. 3. Comparison of average throughput of slave in multi-node BLE 5 network for different physical channels.

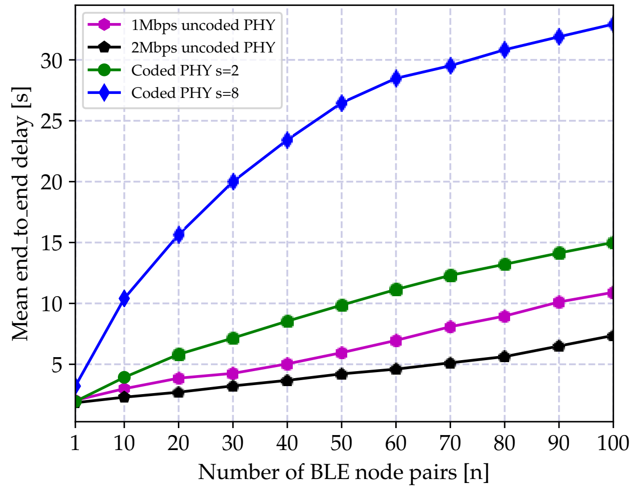

Fig. 5. Average end-to-end delay for different physical channels in multi-node BLE 5 network.

access. As the number of pairs grows, the throughput drops for all of the PHYs. As expected, the *uncoded2Mbps* has the highest throughput in the most congested scenario. This can be explained by the fact that the packets are sent in shorter time and therefore they experience less collision with other neighboring nodes. The second best throughput for this scenario is *uncoded1Mbps*; *codedS2* stays right after that. This figure reveals that the appropriate PHY needs to be chosen for some IoT use cases which require to work in congested network and fulfill certain requirements on the bitrate.

Second, on the same simulation setup, we study the packet error rate (PER) of BLE 5 network with respect to the varying number of pairs. The highest acceptable PER is 1% to provide a reliable communication link for IoT use cases. As it can be observed from Fig. 4, all the PHYs satisfy the PER requirement even with the large number of nodes in the network. The PER rapidly increases as the number of nodes grows in the

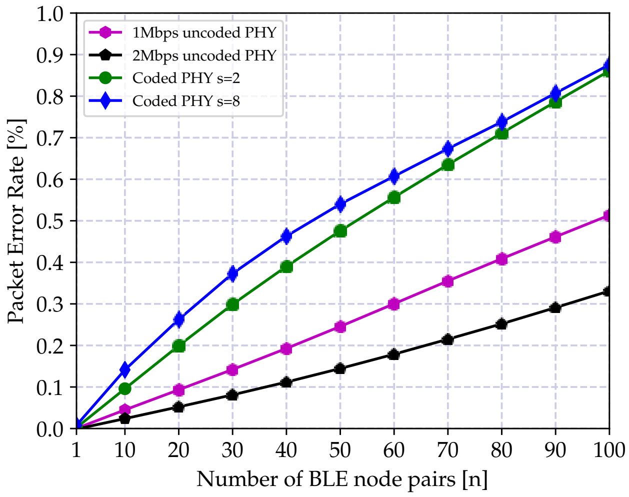

Fig. 4. Average packet error rate of slave in multi-node BLE 5 network.

network. Due to the same reason mentioned for throughput, the PER of the *codedS8* is the worst and *uncoded2Mbps* is the best among the PHYs. This can be explained due to the reason that signal to noise and interference ratio (SNIR) is high in this scenario and the coded packets are long that experience large amount of collisions.

In the third experiment, we consider average end-to-end delay experienced by the received packets. The end-to-end delay is the time difference when the packet is generated by the application layer until received by the peer application layer. In this setup, we don't consider the delay induced by the application and network layer. Fig. 5 shows the mean end-to-end delay for the nodes with varying number from 1 to 100 pairs of BLE devices. As it is expected the *uncoded2Mbps* has the lowest delay compared to other channels and *codedS8* has the highest one. The delay is increased with increasing number of nodes in the network due to the increase in the number of collision and thus re-transmission of the packet which, in turn, imposes delay on the received packets. One point that should be considered here is the effect of *connInterval* on the delay. We use the maximum numbered allowed for *connInterval*, which is 3200, and that equals to 4 seconds. This means that if some packets generated in the following connection event and they cannot be transmitted thus, they need to wait for the next connection event. In addition, the generated packets during the sleeping time will also wait for the next connection event. The longer *connInterval* imposes the longer delay. This figure is important in case of choosing the appropriate PHY and *connInterval* for the delay-sensitive applications in IoT use cases.

Finally, in this paper, we consider the battery life time as it is of vital importance for the IoT devices. We take into account a battery of 1000 mAh capacity and depicted result is shown in Fig. 6. The battery life time, of course, depends on the traffic and the activity level of the devices. On the other hand, as it can be observed from the figure, due to collision in congested scenarios, the battery life time declines as the number of pairs

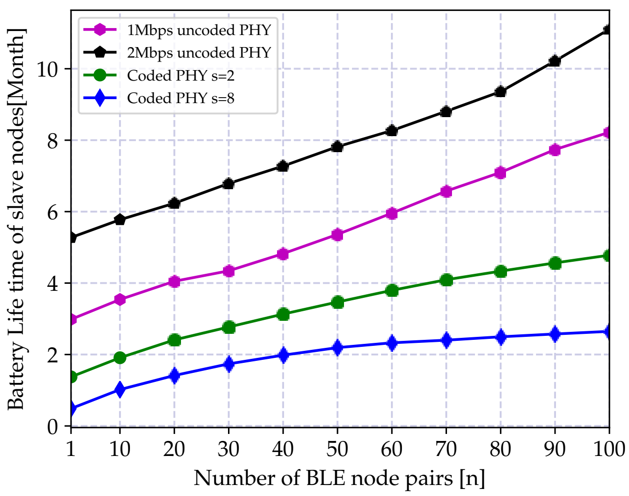

Fig. 6. Average battery life time of slave for different physical channels in multi-node BLE network.

grow in the network. Needless to add that, coded PHYs deplete the battery faster as they use longer packet to transmit.

V. Conclusion

BLE 5 has recently developed by Bluetooth Special Interest Group as an IoT enabler technology for local area network. BLE 5 comes with new features that makes it promising to use for IoT applications. New PHY channels are the most important features of this short-range communication technology. In this regard, we have developed a comprehensive system-level simulator that simulates the most important features of BLE 5. We prove the validity of the simulator by comparing the matching results of simulation and analytical formula of maximum theoretical throughput. We analyze BLE 5 from networking aspect by considering throughout, end-to-end delay, battery life time and packet error rate. This paper focuses on the scalability study of new PHYs in BLE 5 in specific case. The study analyzes and compares all PHYs in BLE 5 with the above mentioned metrics. The results show that in small office environment with strong SNIR the uncoded PHYs outperform the coded PHYs. In addition, the results reveal that appropriate PHY must be chosen according to the requirements of the specific IoT use cases. Furthermore, paper shows that coded PHYs have longer packet error rate in congested network as the packet lengths are larger and eventually, experience more collisions.

References

[1] M. ONeill *et al.*, "Insecurity by design: Todays iot device security problem," *Engineering*, vol. 2, no. 1, pp. 48–49, 2016.

[2] A. Zanella, N. Bui, A. Castellani, L. Vangelista, and M. Zorzi, "Internet of things for smart cities," *IEEE Internet of Things journal*, vol. 1, no. 1, pp. 22–32, 2014.

[3] J. Lin, W. Yu, N. Zhang, X. Yang, H. Zhang, and W. Zhao, "A survey on internet of things: Architecture, enabling technologies, security and privacy, and applications," *IEEE Internet of Things Journal*, vol. 4, no. 5, pp. 1125–1142, Oct 2017.

[4] Bluetooth Core Specification, The Bluetooth Special Interest Group, https://www.bluetooth.com/ specifications/bluetooth-core-specification.

[5] P. P. Ray and S. Agarwal, "Bluetooth 5 and internet of things: Potential and architecture," in *Signal Processing, Communication, Power and Embedded System (SCOPES), 2016 International Conference on*. IEEE, 2016, pp. 1461–1465.

[6] P. Barsocchi, A. Crivello, M. Girolami, F. Mavilia, and F. Palumbo, "Occupancy detection by multi-power bluetooth low energy beaconing," in *Indoor Positioning and Indoor Navigation (IPIN), 2017 International Conference on*. IEEE, 2017, pp. 1–6.

[7] S. Ndzukula, T. Ramotsoela, B. Silva, and G. Hancke, "A bluetooth low energy based system for personnel tracking," in *Industrial Electronics Society, IECON 2017-43rd Annual Conference of the IEEE*. IEEE, 2017, pp. 8435–8440.

[8] W. Bronzi, R. Frank, G. Castignani, and T. Engel, "Bluetooth low energy for inter-vehicular communications," in *Vehicular Networking Conference (VNC), 2014 IEEE*. IEEE, 2014, pp. 215–221.

[9] B. Yu, L. Xu, and Y. Li, "Bluetooth low energy (ble) based mobile electrocardiogram monitoring system," in *Information and Automation (ICIA), 2012 International Conference on*. IEEE, 2012, pp. 763–767.

[10] Y.-j. Park and H.-s. Cho, "Transmission of ecg data with the patch-type ecg sensor system using bluetooth low energy," in *ICT Convergence (ICTC), 2013 International Conference on*. IEEE, 2013, pp. 289–294.

[11] A. J. Jara, D. Fern'ndez, P. López, M. A. Zamora, B. Ubeda, and A. G. Skarmeta, "Evaluation of bluetooth low energy capabilities for continuous data transmission from a wearable electrocardiogram," in *Innovative Mobile and Internet Services in Ubiquitous Computing (IMIS), 2012 Sixth International Conference on*. IEEE, 2012, pp. 912–917.

[12] K. Komai, M. Fujimoto, Y. Arakawa, H. Suwa, Y. Kashimoto, and K. Yasumoto, "Elderly person monitoring in day care center using bluetooth low energy," in *Medical Information and Communication Technology (ISMICT), 2016 10th International Symposium on*. IEEE, 2016, pp. 1–5.

[13] K. Cho, W. Park, M. Hong, G. Park, W. Cho, J. Seo, and K. Han, "Analysis of latency performance of bluetooth low energy (ble) networks," *Sensors*, vol. 15, no. 1, pp. 59–78, 2014.

[14] 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. 11 734–11 753, 2012.

[15] K. Mikhaylov, N. Plevritakis, and J. Tervonen, "Performance analysis and comparison of bluetooth low energy with ieee 802.15. 4 and simpliciti," *Journal of Sensor and Actuator Networks*, vol. 2, no. 3, pp. 589–613, 2013.

[16] K. Mikhaylov, "Simulation of network-level performance for bluetooth low energy," in *Personal, Indoor, and Mobile Radio Communication (PIMRC), 2014 IEEE 25th Annual International Symposium on*. IEEE, 2014, pp. 1259–1263.

[17] M. O. Al Kalaa and H. H. Refai, "Selection probability of data channels in bluetooth low energy," in *Wireless Communications and Mobile Computing Conference (IWCMC), 2015 International*. IEEE, 2015, pp. 148–152.

[18] M. O. A. Kalaa and H. H. Refai, "Bluetooth standard v4.1: Simulating the bluetooth low energy data channel selection algorithm," in *2014 IEEE Globecom Workshops (GC Wkshps)*, Dec 2014, pp. 729–733.

[19] S. Raza, P. Misra, Z. He, and T. Voigt, "Bluetooth smart: An enabling technology for the internet of things," in *Wireless and Mobile Computing, Networking and Communications (WiMob), 2015 IEEE 11th International Conference on*. IEEE, 2015, pp. 155–162.

[20] S. Böcker, C. Arendt, and C. Wietfeld, "On the suitability of bluetooth 5 for the internet of things: Performance and scalability analysis," in *Personal, Indoor, and Mobile Radio Communications (PIMRC), 2017 IEEE 28th Annual International Symposium on*. IEEE, 2017, pp. 1–7.

[21] Recommendation ITU-R P.1238-9, "Propagation data and prediction methods for the planning of indoor radiocommunication systems and radio local area networks in the frequency range 900 mhz to 100 ghz," *P Series Radiowave Propagation*, 2017.