Evaluating Bluetooth Low Energy in Realistic Wireless Environments

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***Abstract*—The 2.4 GHz ISM band is crowded with a wide variety of wireless devices operating under various access protocols, Bluetooth Low Energy (BLE) among them. Low power requirements, low cost, and ease of integration have promoted BLE's rapidly growing popularity. BLE applications range from providing wireless interface for monitoring household equipment status to reporting critical information from medical devices that might have less tolerance for transmission errors to function properly. In this paper, we identify risks in a real world wireless environment that adversely affect BLE system functionality. We also propose a methodology utilizing spectrum surveys to quantify probability of transmission failure relative to the system's interference detection threshold. Spectrum surveys were conducted in a basketball sport facility, a university student union and a hospital intensive care unit (ICU). Results demonstrate how a BLE system selects data transmission channels in the presence of interference. Moreover, findings of this study confirm that a BLE system is able to maintain a low probability of failed transmission while operating in the presence of high interference unless the environment noise floor is close to the employed interference detection threshold.**

I. Introduction

A broad range of wireless devices operate in the unlicensed 2.4 GHz Industrial, Scientific and Medical (ISM) band. Devices utilizing this band employ a variety of technologies, including the IEEE 802.11 family of standards, Classic Bluetooth, Bluetooth Low Energy (BLE), and ZigBee, among others. Because the band remains unlicensed, it has become a popular choice for an increasing number of wireless devices. Applications span a wide spectrum of functions: from Internet-enabled devices (e.g., smartphones and laptops) running 802.11 to medical devices exploiting BLE to deliver highly sensitive patient data to care givers.

BLE is a short range wireless communication protocol that follows specifications published and maintained by the Bluetooth Special Interest Group [1]. BLE is designed as power-friendly using coin cell battery technology. Health sensors that communicate biological readings and status to a smartphone serve as exemplary applications for BLE. Healthcare applications built on BLE have been well presented in literature such as monitoring systems of Electrocardiogram (ECG) [2]–[4], glucose [5], and blood pressure [6] in addition to commercially available products found in [7], [8]. Low power consumption and simple hardware implementation make BLE a key enabler technology for The Internet of Things [9]. Although BLE employs a frequency hopping mechanism over 2 MHz channels for combating interference and fading, it is not considered as Frequency Hopping Spread Spectrum (FHSS) technology like Classic Bluetooth [10]. Instead, the technology falls under spread-spectrum radio regulations that permit a radio to transmit on fewer frequencies than those permitted by frequency hopping radio regulations. Consequently, BLE uses 40 channels in the ISM band: three are labeled *advertising channels* and the remaining 37 are labeled *data channels*. The former are used to initiate a connection; the latter exchange data following connection establishment. Advertising channels center frequencies are selected to minimize probable interference with 802.11 channels 1,6 and 11. Based on the critical nature of health-oriented wireless applications designed with BLE (e.g., a medical implant that reports health related readings to a caregiver.) there is a need to quantify the probability of failed transmission when BLE devices are deployed in realistic wireless environments. In this study, we report our results from spectrum surveys of environments within which BLE devices are expected to operate. We use simulation to identify risks that might obstruct devices from fulfilling their communication function. Surveyed environments exhibited high spectrum occupancy due to a large number of WiFi users. High interference can lead to the following potential risks:

Failure to start a connection. At the moment of initiating a connection, it is possible that a BLE device will find fewer available data channels than those needed to fulfill a connection. Standard specifications mandate at least two available data channels. If the minimum is not met, connection would be blocked. Advertising channel blockage is neglected in this paper due to their vicarious positioning in the spectrum.

Transmission failure. Once a connection is established, both communicating BLE nodes will hop over a set of available data channels previously determined by the master node. Changes in spectrum interference status over time require a specific link layer procedure to deliver updates about recent unavailable data channels set to the slave node. Hence, it is possible

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that a given available data channel selected for transmission by a BLE device might actually become unavailable due to interference. In this case, transmission will fail.

In the investigation reported herein, the aforementioned risks are studied and evaluated for multiple interference sensitivity thresholds to examine the expected behavior of a BLE system in realistic wireless environments. This serves as a valuable tool for the system developer when evaluating concerns of wireless coexistence. The remainder of this paper is organized as follows: Section II provides a background on related work. Methodology used to evaluate risks to a BLE system in real world environments is described in Section III. Spectrum survey tools and surveyed environments are detailed in Section IV. Results are examined in Section V. Section VI concludes the paper.

II. Background

Spectrum surveys and wireless coexistence in the 2.4 GHz ISM band are well-reported topics in literature. The novelty of our study is the integration of spectrum survey results with BLE simulation toward evaluating the likelihood of device coexistence in the presence of interference in a given environment. Many researchers have studied 2.4 GHz ISM band occupancy by performing spectrum surveys and examining observed interference profiles. Energy detection is a common method for performing spectrum surveys by sensing signal energy at given frequency bands for given time spans. Authors of [11], [12] analyzed the 2.4 GHz ISM band with an omnidirectional antenna and spectrum analyzer. Power-frequency plots were constructed to study WLAN emission activity in each environment. Using distributed directional antennas, [13] characterized the influence of spatial dimension on duty cycle (DC). Data was collected using a 7-signal Sapphire measurement system. This work was extended in [14]. Researchers used two measurement devices to facilitate cooperative spectrum sensing. In a similar manner, controlled environment sensing was performed in [15], [16] using a vector signal analyzer (VSA) to collect complex baseband data. Unlike other studies, [17] conducted an energy-based spectrum survey in an uncontrolled environment utilizing distributed sensing nodes connected to a centralized controlling unit. In addition to the aforementioned studies that focused primarily on characterizing band occupancy, others have examined the effect of coexisting, collocated, wireless schemes. Studies [18]–[20] characterized interference between IEEE 802.11x and Bluetooth operating in the 2.4 GHz ISM band. Coexistence of 802.15.4 in the presence of 802.11g/n was assessed in [21]. Development test boards were used to generate both Zigbee and 802.11x signals. A National Instruments USRP was used for spectrum sensing. Similarly, Body Area Networks (BAN) performance in RF Smog scenarios, i.e., cross technology interference, has been detailed in [22].

Simulation and modeling of different wireless technology parameters under specific wireless environments have also been investigated. In [23], interference between IEEE 802.11 and Classic Bluetooth was studied. A simulation model for the RF channel and the PHY layer was developed in C, and a simulation model for the MAC layers was developed in OPNET. Applying a similar approach, authors of [24] simulated a model to study interference between Bluetooth and IEEE 802.11b. Bluetooth and Wi-Fi coexistence was studied in [25] using MATLAB® to model a full duplex Bluetooth communication link that operated along an interfering 802.11b packet generator and simulated interference. [26] implemented an air interface simulation to evaluate Bluetooth performance under various channel types, packet types, and signal-to-noise values.

Few studies have investigated BLE coexistence with other competing technologies. The study presented in [27] tested interference between BLE, WiFi, Classic Bluetooth, and X-Bee under two controlled environment scenarios. The study obtained Bit Error Rate (BER) and RSSI measurements for a single room and an anechoic chamber. Recently, in their investigation of BLEs suitability for vehicular applications, the authors of [28] conducted experiments to evaluate BLE performance in the presence of 802.11g interferers occupying channels 1, 6, and 11. Interestingly, authors observed that there exist a chance of selecting a data channel that has not yet been removed from the channel map which resulted in packet delivery delay due to retransmission of initially lost packet. This falls in line with our attempt to quantify the probability of failed transmission due to selecting a data channel that is under interference.

III. Methodology

BLE Data Channel Selection algorithm relies heavily on interference-free channel information provided by channel map (ChM) connection parameter: a bit sequence of 40 bits that assigns Used channels (i.e., those used by connection to exchange data) a bit value of 1. Unused channels (i.e., those avoided by the algorithm) are assigned a bit value of 0. A detailed analysis of the BLE Data Channel Selection algorithm can be found in [29] using simulation and analytically in [30]. Specifications [1] imply that it is possible for a device host to provide channel classification information to the controller's Link Layer. This information includes current channel conditions that could be obtained through passive band scanning. Hence, it is reasonable to assume that various BLE hosts could have differing interference sensitivity thresholds when using passive band scanning. Spectrum surveys of the 2.4 GHz ISM band enable the creation of various sets of observed BLE ChMs, corresponding to multiple interference sensitivity thresholds. We refer to each set of observed ChMs that correspond to a given interference sensitivity threshold as S_{th}. The sets represent possible ChMs obtained by a BLE device at the moment of connection initiation. S_{th} reflects the status of spectrum interference throughout the observation period. Following spectrum occupancy, certain ChM combinations will be more probable than others. Accordingly, we have established the following:

A. Probability of data channel selection

A BLE device fulfills a connection by hopping over available channels indicated in ChM. Probability of BLE data channel selection can be found by observing hopping patterns resulting from BLE data channel selection algorithm while considering all $ChM \in S_{th}$ as possible input. Let D_i be the event of selecting data channel i ($i \in [0, 36]$) by a BLE device, and $\mathcal{C}$ a 37-element vector containing selection counts of each data channel i by logging BLE data channel selection algorithm output.

$$Pr(D_i) = \frac{\mathcal{C}_i}{\sum_{j=0}^{36} \mathcal{C}_j} \quad (1)$$

Where $\mathcal{C}_i$ is the element of $\mathcal{C}$ corresponding to channel i. Grouping $Pr(D_i)$ values obtained from examining a given S_{th} for all i's forms the vector $\mathcal{V}_{th}$. The BLE data channel selection algorithm was implemented to construct $\mathcal{V}_{th}$ via a simulation code using MATLAB. The code iterates over all possible input parameters of the algorithm, as identified in [29], and uses ChMs from S_{th}.

B. Probability of data channel availability

Let $\mathcal{A}$ be a 37-element vector where every element i contains the count of all instances of data channel i availability (i.e., corresponding ChM bit is equal to 1) in S_{th}.

$$p_i = \frac{\mathcal{A}_i}{n} \quad (2)$$

Where p_i is the probability that data channel i is available in S_{th}, and n is the number of observations in S_{th}. Assembling p_i values in S_{th} for all i 's forms the vector $\mathcal{P}_{th}$.

C. Probability of failed transmission

Successful transmission depends on selecting a data channel i while interference on the corresponding frequency band is absent. We assume that selecting a data channel in the presence of interference on the corresponding frequency band will result in total loss of information (i.e., an unsuccessful transmission). Accordingly, the probability of successful transmission for a BLE device employing th as the interference sensitivity threshold in an environment represented by the set S_{th} (denoted $P_{S,th}$) is found by:

$$P_{S,th} = \mathcal{V}_{th} \times {\mathcal{P}_{th}}^T \quad (3)$$

where $\times$ refers to matrix multiplication. Finally, probability of failed transmission $P_{F,th}$ is found by:

$$P_{F,th} = 1 - P_{S,th} \quad (4)$$

D. ChM Rejection Ratio

BLE specifications requires that ChM has at least two bits set to 1 (i.e., at least two data channels are available for use). ChM Rejection Ratio illustrates the probability that a BLE system will fail to start a connection because at least two data channels are not available at the time of connection initiation.

$$RR_{th} = 100 \times \frac{NR_{th}}{n} \quad (5)$$

where RR_{th} is ChM rejection ratio for set S_{th}, NR_{th} is the count of ChMs having less than two available data channels in S_{th} and n is the number of observations in S_{th}.

IV. Data Collection

National Instrument (NI) VSA PXIe-5644R [31] was used to scan the 2.4 GHz ISM spectrum in frequency domain by running a custom software developed at the University of Oklahoma (OU). Power measurements were collected on 1992 frequency bins of 40 KHz bandwidth each during a time sweep of 4 mS. Start frequency was set to 2.40 GHz, and stop frequency was set to 2.48 GHz. Measured dBm power samples were logged in text files wherein each line represented one spectrum sweep. Environments where a BLE system is expected to operate include a wide range of possibilities. Based on criteria of busy locations with noticeable wireless activity that would generate high spectrum usage, we selected the following environments for spectrum surveys:

A. Sport Facility

A sport venue was surveyed during a heavily attended basketball game. NI PXIe-5644R was placed at lower seating levels in close proximity to a large number of media representatives who were operating a variety of equipment with wireless interfaces. Fig. 1a illustrates a spectrogram of wireless activity for survey duration of 2 hours and 24 minutes. High spectrum usage is present across the 2.4 GHz ISM band - noticeably where 802.11 channels 1, 6, and 11 operate.

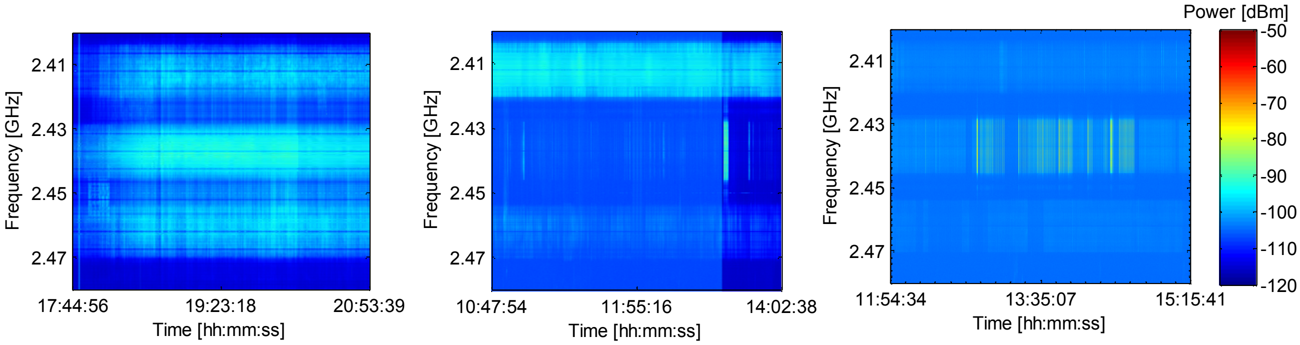
B. University Food Court

The OU Norman campus student union food court was surveyed during lunchtime. NI PXIe-5644R was placed in a corridor that separates food vendors from the dining hall where a large number of students and staff were having lunch and using smartphones and laptops. Fig. 1b illustrates a spectrogram of wireless activity throughout survey duration of 2 hours and 41 minutes. The primary occupied spectrum band corresponds to 802.11 channel 1, with lower levels of activity recorded for spectrum bands corresponding to 802.11 channels 6 and 11 coming from far deployed access points.

C. Hospital Intensive Care Unit (ICU)

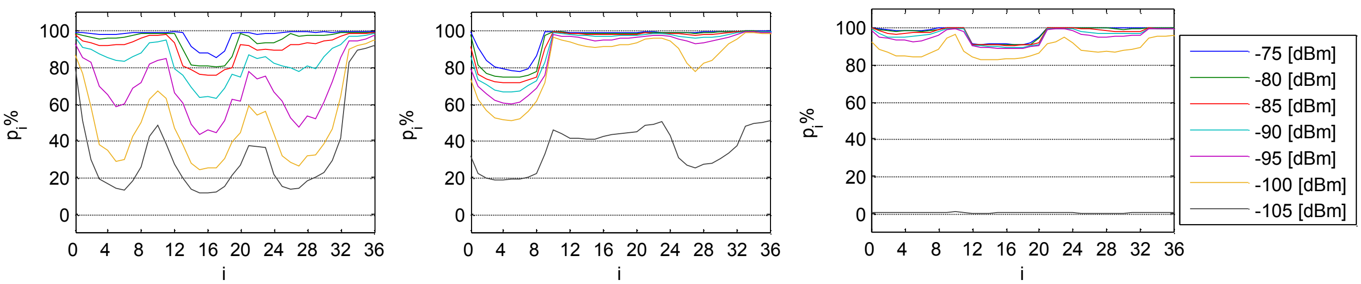
A hospital ICU facility was surveyed during regular weekday working hours for a duration of 3 hours and 21 minutes. NI PXIe-5644R was placed inside a patient room close to an 802.11 access point and a number of medical devices employing wireless interfaces. Fig. 1c shows that primary wireless activity occurred on the spectrum band corresponding to 802.11 channel 6 with lower activity on bands corresponding to channels 1 and 11. When compared with other surveyed environments, observed activity in this context was more sporadic.

Acquired power measurements were used to create S_{th} sets for th values in the range -75 dBm to -105 dBm at 5 dB increments. Elements of S_{th} are ChMs determined by



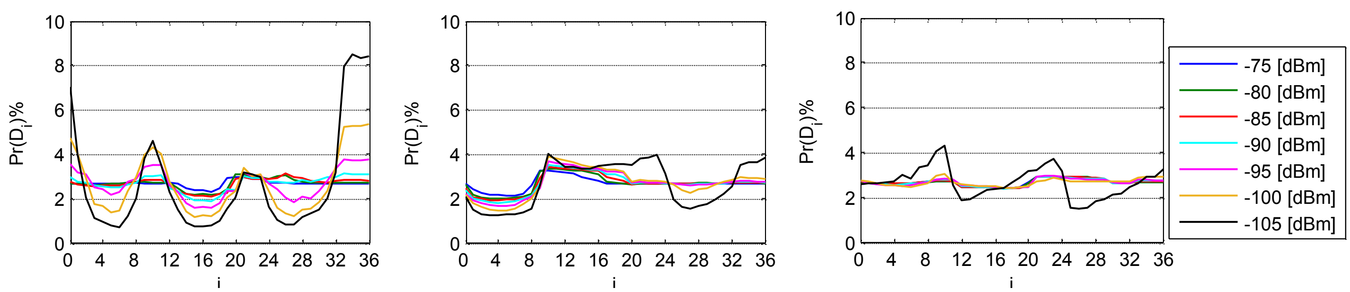
(a) Environment A: Sport Facility (b) Environment B: University Food Court (c) Environment C: Hospital ICU

Fig. 1. Spectrograms for survey duration



(a) Environment A: Sport Facility (b) Environment B: University Food Court (c) Environment C: Hospital ICU

Fig. 2. Probability of data channel availability



(a) Environment A: Sport Facility (b) Environment B: University Food Court (c) Environment C: Hospital ICU

Fig. 3. Probability of data channel selection

analyzing spectrum sweeps sequentially, and averaging power values in spectrum bands that correspond to each data channel then comparing with th. If data channel power average exceeds th, corresponding ChM bit is set to 0; otherwise, it is set to 1. Power values and thresholds are reported per measured frequency bin. Subsequently, a MATLAB® code iterates on S_{th} elements to calculate parameters defined in equations (1) (2) (4) and (5).

V. Results

Various activity patterns were observed in the three surveyed environments described above. These ranged from high activity across the entire 2.4 GHz ISM band in the basketball sport facility (Fig. 1a) to sporadic activity concentrated in a portion of the band in the hospital ICU (Fig 1c). Noise floor varied between environments as well. As the assumed interference detection threshold approaches the noise floor of an environment, the probability of data channel availability decreases until data channels become unavailable throughout the survey duration as it is illustrated in Fig. 2c for the case the hospital ICU. Figures 3a, 3b and 3c detail the probability of data channel selection for the surveyed environments. We notice that the BLE data channel selection algorithm successfully concentrates data transmission on channels less prone to interference and avoids those with high interference. When interference sensitivity threshold is high (e.g., -75 dBm), data channels will be selected with a near uniform probability. As the interference sensitivity threshold value decreases, a BLE system becomes more aware of spectrum interference status; therefore, channels less prone to interference are selected with a higher probability over those under heavy interference.

The higher the sensitivity to interference, the more difficult the connection becomes. Table I lists observed ChM rejection ratios in the surveyed environments. For thresholds higher than -95 dBm, all observed ChMs were suitable for initiating a BLE connection with a zero ChM rejection ratio primarily because environment noise floor is sufficiently far from affecting BLE operation. With the exception of an extremely high value for the near noise floor threshold of -105 dBm in the hospital ICU, low values of ChM rejection ratio in surveyed environments were reported for thresholds [-95,-100,-105] dBm.

Fig. 4 shows that for interference sensitivity thresholds higher than -100 dBm, probability of failed transmission was highest in the basketball sport facility. For significant occupancy of a wide portion of the spectrum, the number of channels suitable for BLE communication is reduced. Despite this, probability of failed transmission remained close to or below 10% in the student union food court and hospital ICU. Results from Table I and Fig. 4 confirm that a BLE system would be able to initiate a connection and exchange data with low probability of transmission failure given that the system operates in environments with various interference profiles. This is true whether the system had high interference on the entire 2.4 GHz ISM band (e.g., the sport facility) or sporadic interference on a portion of the spectrum (e.g., the hospital ICU) except for the extreme case scenario of environment noise floor close to the BLE system interference detection threshold.

Packet retransmission is not taken into consideration in this discussion, which can further enhance BLE's packet delivery performance on the cost of increased delay. Future work will address packet retransmission in addition to use cases where time constraints are essential to fulfill the device function successfully.

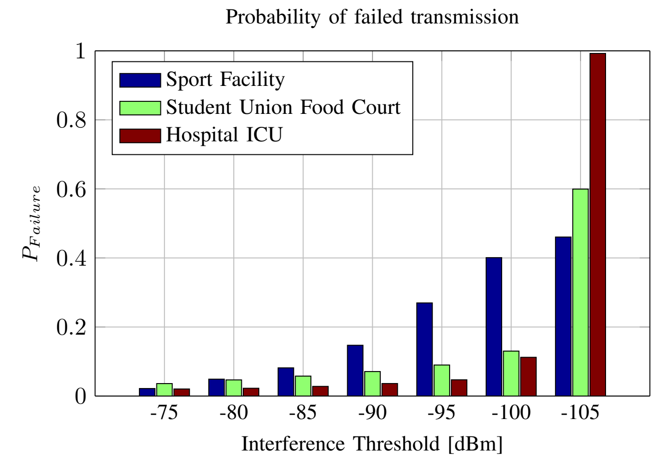


Fig. 4. Comparing the probability of failed transmission between the three surveyed environments. We notice the sharp increase in probability of failure for the ICU environment to the point of near total failure when the observed noise floor is close to the system's interference detection threshold.

TABLE I
ChM REJECTION RATIO%

Threshold $[dBm]$	Sport Facility	Student Union	ICU
-95	0.014	0	0
-100	0.051	0	0
-105	0.901	0.407	97.05

VI. Conclusion

The authors propose a method to characterize BLE system behavior based on spectrum surveys in real world wireless environments. This effort provides insight about the expected performance of BLE system when deployed in a given environment as an alternative to observed performance in controlled test beds. Spectrum surveys of three environments were conducted using an NI PXIe-5644R device. Results were used to identify probable BLE system failure to initiate a connection using ChM rejection ratio. In the event of successful connection, the probability of failed transmission was derived. Results illustrated BLE's high ability to initiate a connection and successfully exchange data in high interference environments.

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