A Comprehensive Experimental Evaluation of Radio Irregularity in BLE Networks

Ali Nikoukar
Communication and Networked Systems
Faculty of Computer Science
Otto-von-Guericke University
Magdeburg, Germany
ali.nikoukar@ovgu.de

Seyedehyalda Akbarzadeh
Magdeburg, Germany
yalda.akbarzadeh@gmail.com

Mansour Abboud
Communication and Networked Systems
Faculty of Computer Science
Otto-von-Guericke University
Magdeburg, Germany
mans.abboud@gmail.com

Mesut Güneş
Communication and Networked Systems
Faculty of Computer Science
Otto-von-Guericke University
Magdeburg, Germany
mesut.guenes@ovgu.de

Behnam Dezfouli
Internet of Things Research Lab
Department of Computer Science & Engineering
Santa Clara University
Santa Clara, USA
bdezfouli@scu.edu

***Abstract*—Bluetooth Low Energy (BLE) is low-power and widely available. It is one of the dominant wireless technologies used in various Internet of Things applications. Many indoor localization applications use BLE beacons, however, these beacons lack precise distance estimation due to multipath fading, interference, and radio irregularity. Unfortunately, the impact of radio irregularity is often either assumed or neglected in many research studies, which question the applicability of these solutions in real-world scenarios. In this paper, we evaluate the impact of radio irregularity on BLE broadcasting beacons. We conducted extensive hardware experiments in two indoor environments, in all BLE advertisement channels of different BLE hardware, and at different distances and transmit powers. These experiments generate values of degree of irregularity which serve as an input parameter for the radio irregularity model. Our results and reported data sets are of vital importance for developing BLE based studies and simulation tools, particularly for indoor localization applications.**

***Index Terms*—Bluetooth Low Energy, Radio irregularity, Indoor Positioning Systems, Internet of Things**

I. INTRODUCTION

Bluetooth Low Energy (BLE) is a dominant technology in IoT applications due to its low-power characteristics as well as its availability in most smartphones, tablets, laptops, and smart gadgets. The global Bluetooth beacon market is expected to witness a significant compound annual growth rate (CAGR) of 95.3% from 2017 to 2025 and to reach $58.7 Billion market value in 2025 [1].

BLE beacons are mostly used for connection initiation and *Received Signal Strength* (RSS) based *Indoor Positioning System* (IPS). In IPS systems, for example, the RSS of beacon packets received from multiple sources are used to perform triangulation. This necessitates the importance of understanding and modeling wireless channel.

As BLE advertisement channels are used to transmit beacons packets, several studies conducted experiments on modeling the impact of path loss, multipath fading, and interference on these channels [2], [3]. In [4], we performed various experiments considering BLE advertisement channels in different environments. In this paper, we extend our experiments by addressing the irregularity of BLE radio and the impact of hardware heterogeneity.

Commonly, in wireless channel modeling, non-isotropic nature of signal propagation is neglected and it is assumed that RSS values are similar in all directions. This unrealistic assumption in analytical models, simulation tools, and node deployments deteriorates the performance quality for applications such as IPS. In reality, we can observe that signal quality on a circle around the transmitter is not similar. Although the *Radio Irregularity Model* (RIM) has been developed to address this gap, lack of a realistic experimental dataset leads to inaccuracy in research and development.

The contributions of this paper are as follows:

1) Empirical analysis of radio irregularity on BLE's advertisement channels by conducting extensive hardware experiments.
2) Presenting an open-source experiment dataset available for the research community to be used for verification and validation, e.g., in simulation tools or analytical models. The results of our experiments are available as an open-source dataset.[1]
3) Evaluation of the impact of hardware heterogeneity, transmit powers, distances, and indoor environments on RIM.

[1]The full dataset is available at: https://github.com/ComSys-OVGU/BLE-Radio-irregularity-Experiment

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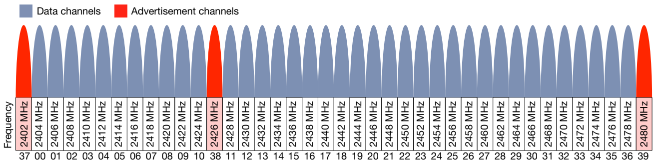

Fig. 1. *Bluetooth Low Energy* (BLE) channel assignment.

The remainder of this paper is organized as follows. Related work is presented in Section II. A brief overview of BLE is given in Section III. Research methodology, including the experimental setup, and experimental parameters are discussed in Section IV. Section V analyzes and presents the obtained results. Finally, we conclude the paper in Section VI.

II. Related Work

The *Radio Irregularity Model* (RIM) [5] was proposed to characterize the anisotropic effect of wireless radio propagation. RIM is characterized by *Degree of Irregularity* (DoI), which identifies signal propagation variation in different directions. The main goal of RIM was to analyze the transmission range, connected range, and link asymmetry due to radio irregularity for multi-hop networks [6], [7].

Recently, by increasing advancement in indoor localization systems and demand for higher accuracy, RIM is used by researchers [8] to improve the range estimation. For example, in [9] authors studied the impact of radio irregularly in BLE based indoor localization. The study aims to increase localization precision by considering the irregular effect of radio in each direction. The limited sample size and unclear experimental environment increase the uncertainty in the result accuracy of their experiment. Jiang *et al.* [10] performed limited experimental study on collaborative localization in wireless sensor networks by exploring the impact of radio irregularity in using omnidirectional antennas. In addition to their limited experiment size, most of the *Internet of Things* (IoT) devices are using PCB printed antennas. Similarly, in [11] authors studied the effect of node rotation on wireless propagation for IPS. Unfortunately, their experimental study suffers from limited samples and does not consider the importance of precise hardware setup. Authors in [12] developed a OMNeT++ based simulation tool for RIM. However, the simulation tool lacks input parameters, such as DoI values from real-world experiments.

This overview shows the importance of a comprehensive empirical evaluation of radio irregularity for BLE's advertisement channels.

III. Bluetooth Low Energy

The main focus of the BLE standard is to minimize the energy consumption for battery-powered wireless devices. The standard introduces a new PHY and MAC layer compared to Bluetooth classic, which was mainly designed for file sharing and audio streaming. BLE has connection-less and connection-oriented modes designed for different applications. In the BLE's PHY (see Figure 1) two types of channels are introduced for communication: advertisement channels and data channels. While advertisement channels are mainly used for connection-less mode, data channels are designed for connection-oriented information exchange.

Therefore, in this study, we explicitly focus on analyzing radio irregularity on these channels. BLE provides 40 channels (3 advertisement and 37 data channels) operating in a globally unlicensed 2.4 GHz frequency band shared by other wireless technologies such as IEEE 802.11b/g/n. Advertisement channels are intentionally placed in the specific center frequencies to reduce interference with most frequently used IEEE 802.11b/g/n channels, i.e., channels 1, 6, and 11. Therefore, most IPS applications rely on beacon packets. Both data and advertisement channels are sharing the same PHY characteristics, and each BLE channel is 2 MHz wide and employs *Gaussian Frequency Shift Keying* (GFSK) modulation. The transmit power in BLE PHY is configurable with the approximate range of -20 dBm to +20 dBm.

BLE based distance estimation for indoor positioning applications relies on RF signals sent through advertisement channels. As point-to-point range estimation is the basis of positioning algorithms such as triangulation, recently, there has been increasing interest in identifying the challenges (e.g., multipath fading and interference) [13]. However, radio irregularity as one of the main factors impacting the signal variation in different directions is less considered.

IV. Methodology

In this section, we first explain RIM to model radio irregularity. Then we discuss in detail the conducted experiments.

A. Radio Irregularity Model (RIM)

Analytical modeling of path loss is the key to represent wireless signal propagation and channel characterization studies in simulation tools [14]. In this direction, many models were proposed to estimate the path loss or RSS, e.g., the free-space propagation model, the two-ray model, and the *Log-Normal Shadowing Model* (LNSM) [6]. Equation (1) presents path loss and signal variation due to multipath

$$PL(d) = PL(d_0) + 10\eta \log_{10}\left(\frac{d}{d_0}\right) + N(0, \sigma_{ch}) \quad (1)$$

where $PL(d)$ denotes the path loss at distance d, d_0 is path loss at reference distance, η is path loss exponent, and $N(0, \sigma_{ch})$ is a zero-mean Gaussian random variable with standard deviation σ_{ch}. However, these models are isotropic, which means they assume constant path loss in all directions. Authors in [5] proposed RIM that includes the non-isotropic wireless propagation by adding the DoI value in LNSM as given in Equation (2).

$$PL(d, \theta) = \left(PL(d_0) + 10\eta \log_{10}\left(\frac{d}{d_0}\right)\right) \times K_\theta + N(0, \sigma_{ch}) \quad (2)$$

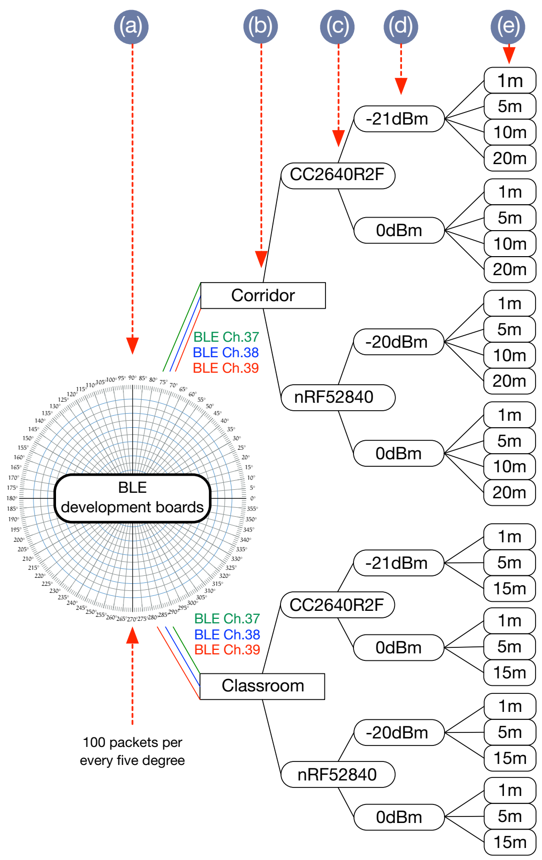

Fig. 2. Visualization of all the conducted experiments on BLE advertisement channels: (a) Rotating of the transmitters in each for 360° and transmission of 100 packets in every 5°, (b) experiment environments, (c) development boards, (d) transmit powers and, (e) distances in meter.

where $PL(d, \theta)$ represents the adjusted DoI for path loss at direction θ, and K_θ is the path loss coefficient to represent path loss variation in different directions. K_θ is computed as follows.

$$K_\theta = \begin{cases} 1, & i = 0 \\ K_{\theta}\;{}_{1} \pm Rand \times DOI, & 0 < i < 360 \land i \in N \end{cases} \quad (3)$$
$$where\ |K_0 - K_{359}| \leq DoI$$

Using Equation (3), we generate 360 values of K_θ at different directions. The authors in [5] show that Weibull distribution [15] has the maximum likelihood of matching with the random variation of RSS in different directions.

B. Hardware Setup

Communication setup. To evaluate hardware heterogeneity in our experiments, in the transmitter side, we used two pioneer BLE 5 development boards: nRF52840DK, and CC2640R2F LaunchPad. In the receiver side, we used two nRF52840DK boards, one as a receiver and alongside with it, an additional nRF52840DK collects the noise floor to ensure that IEEE 802.11 interference does not impact RSS. Figure 2 illustrates our experimentation methodology. In each environment, for different hardware, distances, transmit powers, and

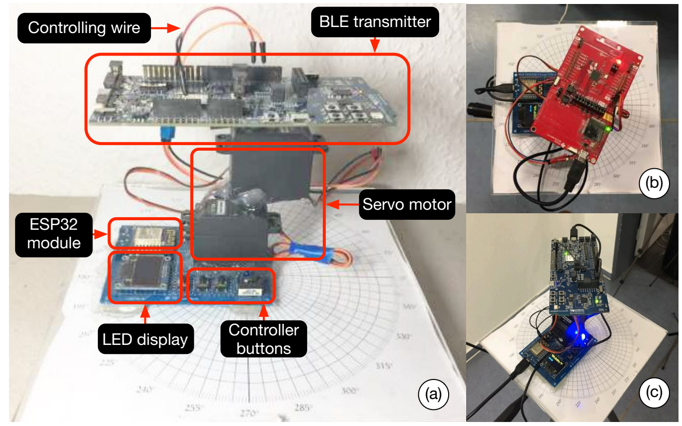

Fig. 3. Experiment setup for transmitter: (a) automatic rotation setup, (b) CC2640R2F [16] board on the setup, (c) nRF52840DK [17] board on the same setup.

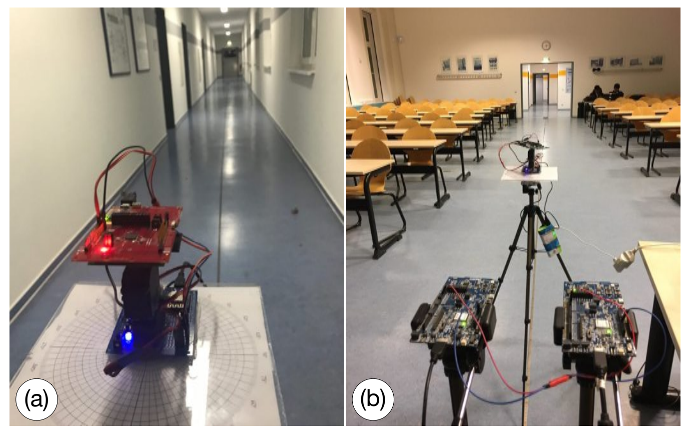

Fig. 4. Experimental environments: (a) corridor located in a university building; (b) classroom at the same university building.

advertisement channels, we fully rotate the transmitter at 5-degree steps (72 steps in total). To avoid the error caused by multipath fading, we transmit a packet every 9μs for a total of 100 packets in each direction and average the *Received Signal Strength Indication* (RSSI) values. Besides, we record the corresponding *Packet Error Rate* (PER) for each direction. **Rotation setup.** We designed a custom hardware setup to avoid the errors caused by manual node rotation. Besides, the setup allows having immediate and precise movement of the node after transmitting 100 packets in each direction. In the setup, a servo motor controlled by ESP32 module is responsible for the node rotation and triggering the transmitter (see Figure 3(a)). Figure 3(b) and Figure 3(b) are the nRF52840DK, and CC2640R2F LaunchPad, respectively, placed on the top of the rotation setup for BLE packet transmission.

C. Environments

Figure 4 shows the experiment environments. As can be seen in this figure, we performed our experiment in two different indoor environments i.e., corridor and classroom. Both environments are located in a university building with

TABLE I
SUMMARIZED RESULTS OF CORRIDOR ENVIRONMENT

Device	TX [dBm]	Distance [m]	Ch	DoI	$\bar{x}_{RSSI}$	PER[%]
CC2640R2F	0	1	37	0.104	-37.57	0.00
			38	0.066	-35.38	0.01
			39	0.110	-36.56	0.02
		5	37	0.098	-55.57	0.02
			38	0.083	-53.33	0.72
			39	0.143	-57.06	1.66
		10	37	0.154	-58.22	0.01
			38	0.115	-58.22	0.12
			39	0.103	-55.46	0.00
		20	37	0.086	-58.93	0.04
			38	0.191	-61.34	0.06
			39	0.093	-60.35	0.01
	-21	1	37	0.171	-58.28	0.00
			38	0.107	-57.14	0.06
			39	0.195	-63.69	0.01
		5	37	0.088	-72.10	0.73
			38	0.125	-73.60	2.56
			39	0.108	-71.32	0.05
		10	37	0.116	-73.01	0.45
			38	0.127	-73.16	0.06
			39	0.181	-78.22	1.76
		20	37	0.171	-81.78	6.48
			38	0.175	-81.76	4.27
			39	0.242	-78.45	24.7
nRF52840DK	0	1	37	0.165	-39.26	0.01
			38	0.116	-35.68	0.01
			39	0.125	-38.03	0.04
		5	37	0.166	-57.30	0.20
			38	0.220	-57.36	0.04
			39	0.141	-50.72	0.01
		10	37	0.142	-55.18	0.06
			38	0.131	-53.55	1.15
			39	0.155	-60.42	0.12
		20	37	0.119	-63.16	0.09
			38	0.130	-59.91	0.00
			39	0.116	-57.03	0.09
	-20	1	37	0.070	-60.58	0.11
			38	0.068	-57.13	1.22
			39	0.090	-57.36	0.00
		5	37	0.155	-77.64	4.55
			38	0.177	-75.71	0.06
			39	0.169	-71.29	0.00
		10	37	0.151	-76.20	3.34
			38	0.172	-74.43	0.23
			39	0.146	-71.29	0.91
		20	37	0.225	-81.53	11.23
			38	0.207	-78.92	4.59
			39	0.152	-76.94	1.73

$\bar{x}_{RSSI}$: average of 72 RSSI values collected for every 5 degrees
PER: packet loss percentage out of the total transmitted 7200 packets

line-of-sight transmission. In the corridor environment, we conducted the experiment in four different distances. However, due to the limited size of the classroom, the number of distances is reduced to three.

TABLE II
SUMMARIZED RESULTS OF CLASSROOM ENVIRONMENT

Device	TX [dBm]	Distance [m]	Ch	DoI	$\bar{x}_{RSSI}$	PER[%]
CC2640R2F	0	1	37	0.093	-36.68	0.58
			38	0.076	-34.61	0.66
			39	0.101	-35.22	1.15
		5	37	0.082	-48.23	0.55
			38	0.080	-45.69	0.75
			39	0.120	-49.07	0.70
		15	37	0.124	-56.98	0.33
			38	0.150	-58.18	0.83
			39	0.077	-58.22	0.69
	-21	1	37	0.113	-57.19	0.83
			38	0.121	-57.56	1.04
			39	0.113	-60.46	0.84
		5	37	0.170	-71.85	2.33
			38	0.098	-73.21	5.15
			39	0.085	-73.34	0.31
		15	37	0.175	-78.32	7.36
			38	0.247	-81.62	23.44
			39	0.111	-79.71	4.50
nRF52840DK	0	1	37	0.125	-40.98	1.18
			38	0.114	-39.59	3.11
			39	0.096	-37.50	2.43
		5	37	0.118	-53.39	0.73
			38	0.101	-50.60	2.22
			39	0.115	-48.92	2.04
		15	37	0.123	-64.61	1.45
			38	0.177	-62.60	1.55
			39	0.105	-55.56	1.69
	-20	1	37	0.083	-61.44	1.70
			38	0.120	-59.67	2.06
			39	0.120	-57.66	1.00
		5	37	0.149	-74.23	0.58
			38	0.124	-71.84	5.11
			39	0.081	-69.75	2.37
		15	37	0.185	-84.27	18.29
			38	0.198	-82.98	13.34
			39	0.102	-76.14	4.10

$\bar{x}_{RSSI}$: average of 72 RSSI values collected for every 5 degrees
PER: packet loss percentage out of the total transmitted 7200 packets

V. RESULTS AND DISCUSSION

In this section, we study the non-isotropic nature of BLE radio using PER and RSSI metrics. The extensive experimental results present a realistic radio propagation in indoor environments. The measurement parameters are explicitly selected to analyze the effect of irregular radio propagation on range estimation in indoor environments. To demonstrate path loss variation in advertisement channels of BLE in all directions, we visualized the results as polar plots shown in Figure 5. It is important to mention that, due to the page limitation, only a few scenarios are visualized in the paper and the rest of results are summarized in Table I and Table II. Each plot demonstrates the BLE channels 37, 38, and 39 for the corridor and classroom environment. Alongside with every polar plot for RSSI there is a corresponding polar plot for its PER. In the experiment, we configured the transmit power to 0 dBm

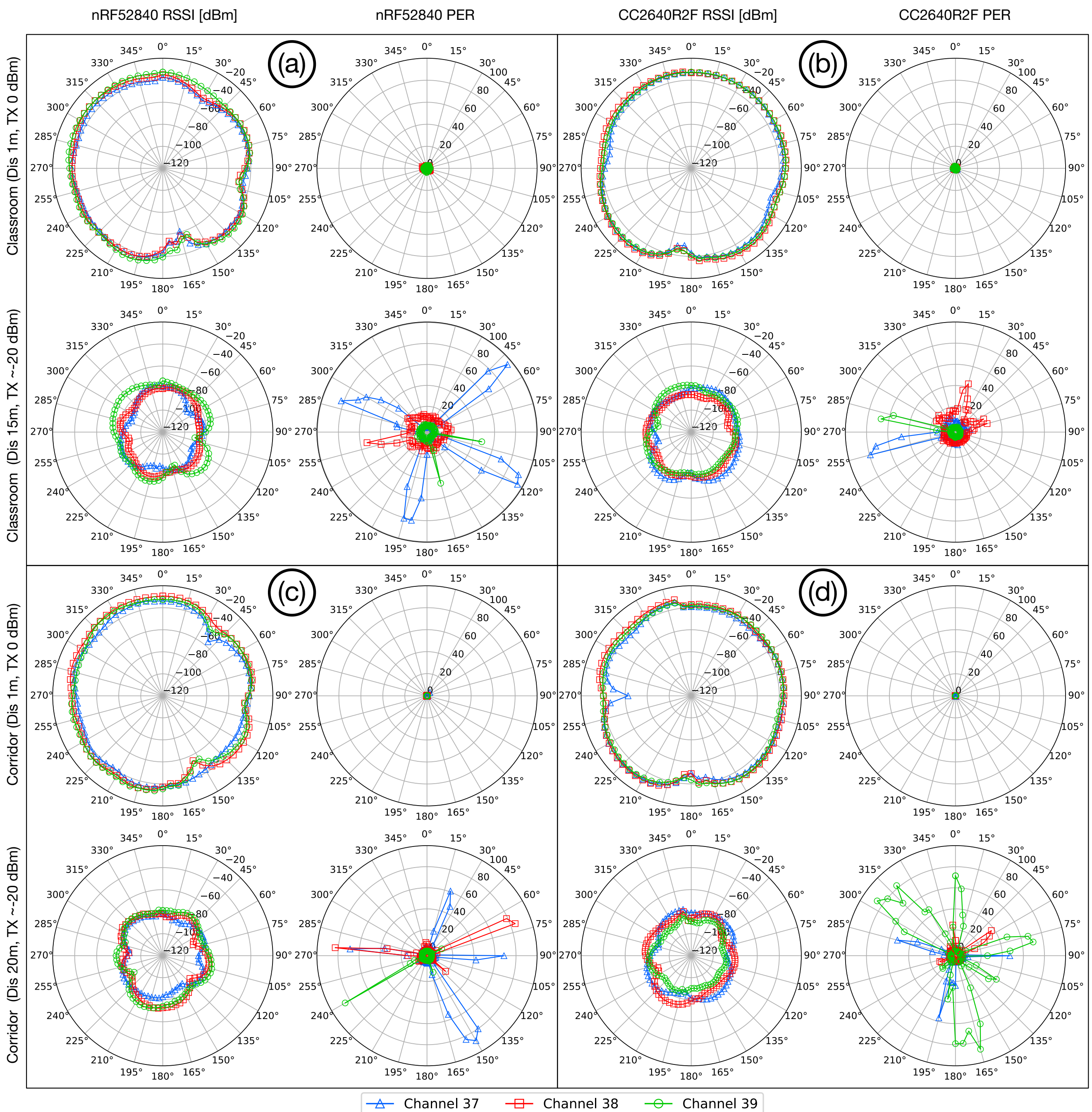

Fig. 5. Radiation pattern result for the conducted experiment in corridor and classroom environments. (a) is classroom environment with nRF52840 SoC, (b) is the same classroom with CC2640R2f SoC, (c) is the corridor environment with nRF52840, (d) is the same corridor with CC2640R2f

and −20 dBm for every scenario. Please note that, due to the hardware configuration limitation, the minimum transmit power for nRF52840 is −20 dBm, where the similar transmit power with CC2640R2F is −21 dBm.

The detailed results for corridor and classroom are presented in Table I and Table II, respectively. The ideal radiation is assumed to be a perfect circle, and the main goal of the study is identifying the parameters causing irregularity. DoI is the metric to measure the spherical radio radiation pattern, and the higher number of the DoI value indicates the higher irregularity. These values can be used by numerical studies and used as input parameters for simulations.

As depicted in Figure 5, radio irregularity exists in all cases. For the longer distance, in particular, radio irregularity affects PER considerably. For example, at 20 m away from the sender, PER varies between less than 10% to more than

90%. Moreover, although all the three advertisement channels have similar radio configuration, environment, and hardware, yet they behave differently from each other. For example, in Table II, in the classroom environment using nRF52840DK and distance 15 meters, we can see the average RSS value and PER in channel 39 is significantly lower than the other two channels.

These results show the importance of considering radio anisotropy when designing low-power wireless systems. For IPS, radio anisotropy could considerably affect the distance perceived from a beacon source. Although the results presented in this paper enables the researchers to build a realistic-simulation environment, accurate operation of IPS systems in any given environment requires precise mapping of radio irregularity or employing correction mechanisms. For example, employing rotating antennas or multiple sender and transmitters would enable the receiver to achieve a better estimation of distance.

VI. Conclusions

Various mathematical and trace-based models have been proposed to enhance the simulation performance of BLE networks. However, the impact of radio irregularity is usually neglected. This simplification, for example, affects the accuracy of range estimation, which is crucial for applications such as IPS.

In this paper, we studied the irregular propagation characteristics of BLE advertisement channels in different scenarios. Our results show the high impact of radio irregularity regardless of the board and environment. Also, the provides dataset can be used to augment the accuracy of path loss models.

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