Performance Analysis of BLE 5.1 New Feature Angle of Arrival for Relative Positioning

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ABSTRACT:

The official release of Bluetooth Core Specification, version 5.1 in 2019, provides a new feature for direction determination. It introduces a fine-grained angle measurement capability including Angle of Arriva (AoA) and Angle of Departure, which is deemed essential to the development of Internet of Things applications for localization or relative positioning within the area where Global Navigation Satellite System signals cannot be received. In this paper, we set up a series of experiments to empirically evaluate the direction of the Bluetooth Low Energy transmitter based on the AoA mechanism using the commercialised equipment. The experimental evaluation is performed, for the first time to date, under four different testing environments and other various conditions to inspect the fidelity of angle measurement against the high accuracy given in the specifications. In details, an ideal environment (i.e., anechoic chamber with no multi-path effect), an underground mine, an open area and a typical office area are all tested comprehensively. The experimental results reveal that the ideal environment has the best performance with the minimum error and conforms with the provided datasheet. The worst case occurs on the data collected from the office area. We also find a regular pattern always showing up repeatedly on the error plots based on the measurement results and scrutinize the truthfulness of this rule by adding more innumerable tests conducted in the office. Our results show that the performance of accuracy does depend on the data channel selection due to the multi-path effect.

1. INTRODUCTION

The development of indoor positioning and navigation system has been facilitated at a growing speed. This is a promising research topic that has piqued interest of a large amount of industry companies, the research community and technical developers. Indoor and outdoor positioning systems play an important role in the location based services. However, there hasn’t been a positioning system as common as Global Navigation Satellite System (GNSS) that can be applicable when devices are out of range of the satellite signal reception.

Numerous indoor localization systems using different technologies have been proposed to date. Most of them demonstrate remarkable performance in terms of the positioning accuracy. Over the past few years, Wi-Fi (Kumar et al., 2014; Vasisht et al., 2016), Bluetooth (Conte et al., 2014; Dahlgren, Mahmood, 2014), ultra wideband (Kempke et al., 2015; Kempke et al., 2016; Li et al., 2020a), Light Detection and Ranging (LiDAR) (Sánchez et al., 2015) etc. have been applied with Internet of Things (IoT) devices. However, none of them has been as widespread as Bluetooth devices considering the practical utilization. Due to the advantage of low power consumption and standardized localization methodology, it is estimated that there will be more than 400 million Bluetooth devices to be produced for indoor localization and outdoor positioning every year (Bluetooth SIG, 2019a).

In 2019, a new Bluetooth Core Specification (i.e., version 5.1) was established by the Bluetooth Special Interest Group (Bluetooth SIG) to provide a solution to enable numerous smart user devices to perform positioning precisely. Within the landscape of IoT, it introduced a set of new features that are primarily capable of ubiquitous localization with high accuracy. Specifically, two signal processing approaches, Angle-of-Arrival (AoA) and Angle-of-Departure (AoD), have been used in the standard to allow angular estimation. In the case of the AoA function, the Bluetooth transmitter can send direction finding-enabled packets to make the device location available using a single antenna. While the receiver with multiple antennas will be able to calculate the angular position based on the phase delay of the received signal. The difference between AoA and AoD is that AoD requires the transmitter to have several antennas and the receiver to be equipped with one single antenna, and the angular location of the receiver in relation to the transmitter to be determined on the receiver side. If these positioning techniques are integrated with direct distance measurements within 2-dimensional domain, the service of precise positioning can be provided exactly and comprehensively (Li et al., 2020b).

As reported in (Bluetooth SIG, 2019b; Woolley, 2019), the Bluetooth 5.1 AoA function can provide localization service to an accuracy within a few centimetres, which inspired researchers to investigate truthfulness of this statement. To augment these findings, in this paper, we assessed the fidelity of angular determination provided by Bluetooth 5.1 AoA, using an extensive empirical analysis. The empirical experiments were built on a series of experiments, with a single focus: pure performance of accuracy when a typical Bluetooth device implements direction finding using the AoA mechanism specified by Bluetooth 5.1 standard. To this end, the Bluetooth devices and corresponding software, firmware used for further development provided by the Texas Instruments (Texas Instruments, 2021a; Texas Instruments, 2021b). Our study provides a first glimpse into the accuracy performance of AoA, an angular detection method, particularly in terms of the accuracy at specific angles, and highlight the limitations that may affect angular estimation, and the extensions that might be implemented in the future.

The remainder of this paper is structured as follows. Section 2 presents an overview of Bluetooth related technology that can be used for localization and positioning. Section 3 provides an overview of the AoA and AoD mechanism specified by Bluetooth 5.1 specification. Section 4 introduces the experimental setup used for the performance evaluation,

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implementation details and the testing conditions. Section 5 presents the experiment results and inferences that can be drawn. It also gives further analysis and extensions. Finally, section 6 concludes the paper.

2. RELATED WORK

Signal angular detection indicates exactly the matter of a wireless device's relative position determination. The problem of Angle-of-Arrival calculation with respect to a transmitted signal has been extensively researched and partially tackled. In order to measure the phase delay between the duplicated time-varying signals received by adjacent antennas, lying in an unavoidable antenna array. Multiple signal classification (MUSIC) (Schmidt, 1986), which yields great angular resolution, is the most frequent method for determining the AoA based on measured phase delay. Determination of the angular position of a transmitter in commodity wireless systems, is generally relied on measuring the signal intensity of received packets (RSSI). The accuracy of location frameworks based on iBeacon technology has been examined in (Li et al., 2016) and (Lin et al., 2015) using Bluetooth Low Energy (BLE) technique. The first instance reduced the average localisation error to 4 m, which is only possible when 36 beacons are deployed. The second case can obtain localization errors up to 5 m if limited within two subareas that are next to each other, where the testing area is composed of 12 subareas. The experimental results in (Ji et al., 2015) presents a detailed discussion of the relationship between the number of BLE beacons and accuracy performance of localization service. Then, the work of De Blasio et al. was carried out in a 168 m^2 testbed, where encompassed 12 devices using BLE 5.0 standard. The accuracy is reported to be less than 2.5 m (De Blasio et al., 2018). Existing positioning systems based on different technologies have a major flow that Bluetooth channel assignment has to be specified precisely, and this is extremely difficult to obtain. Furthermore, different BLE channels may have distinct properties and can exhibit different characteristics, and it contributes to an appropriate range of positioning accuracy when relying on RSSI (Powar et al., 2017). To resolve these issues, MUSIC has been used to figure out where BLE transmitters are based on the AoA measurement conducted by a set of nodes (Monfared et al., 2018).

The new direction-finding feature proposed in the new BLE standard is a significant decision and it reshapes the problem of indoor localization. In details, MUSIC mechanism requires multiple coherent Radio Frequency (RF) channels for signal transmission. However, there is only a single channel to be included and incorporate with an antenna array with multiple antennas enabled and an RF switch to make a decision that which element is selected among all the available options (Bluetooth SIG, 2019b). With the known assumption that the transmitted sequence has to be used to carry out AoA experiments, the simulations conducted in (Zhu, Bocus, 2018) presented the assessment of accuracy performance in this case. Nevertheless, no thorough experimental results and related results analysis are yet to appear since physical implementations of this work are still not practically feasible in reality. To the best of our knowledge, this work is the first to provide a comprehensive empirical analysis to evaluate the accuracy performance of BLE 5.1 new nature, AoA in several different testing conditions.

3. WORKING PRINCIPLE

Bluetooth is a wireless communication standard, particularly designed for wireless personal area networks (WPANs) that require low power consumption and low data rates at low cost in most cases. Ever since 2010, the Bluetooth SIG has merged Bluetooth and BLE together into the Bluetooth Core specification, version 4.0. In the physical layer (PHY), Bluetooth and BLE both operate in the same frequency band, which is the 2.4 GHz industrial, scientific, and medical (ISM) band. The medium access method of Bluetooth and BLE adopts a hybrid time-frequency division multiplexing scheme. The allocated 80 MHz bandwidth is divided into 40 orthogonal RF channels with central frequencies equally spaced by 2 MHz.

Normally, there are two different types of BLE channels and they are advertising channels and data channels. The number of advertising channels is 3 and they occupy the channels 37, 38 and 39; they are used for new user device discovery, connection configuration and signal broadcasting. Data channels take all of the remaining channels, 37 channels to exchange data. After the connection is established between the transmitter and the receiver, the adaptive frequency technique (AFH) scheme is used to reduce the negative impact of signal interference via a sequence of random selection of transmission channels. The channel access policy can be dynamically modified according to the actual condition of signal transmission, the poorer connection between devices in the proximity, the lower possibility to access this channel. Moreover, there is a separation of a fixed time interval after each run of communication between adjacent nodes.

With respect to signal transmission, BLE utilises Gaussian Frequency Shift Keying (GFSK) binary modulation with two possible transmission rates: 1 Mbps and 2 Mbps. In general, there are four different transmission modes that can be included for BLE connection, two uncoded modes have two distinct symbol rates, 1 Mbps and 2 Mbps respectively, whereas the uncoded modes uses the transmission rate of 125 kbps and 500 kbps. However, only uncoded transmission mode in the physical layer suits for BLE new direction finding mechanism, AoA. Hence, only the mandatory PHY mode, which is LE 1M (i.e., a typical configuration for BLE uncoded radio physical layers) with the data rate of 1 Mbps, is considered in the rest of this paper.

3.1 Angle of arrival mechanism specified by Bluetooth 5.1

The Bluetooth user device makes the location available to the receiver side by sending direction-finding enabled packets from the transmitter node at low power consumption. Conspicuously, the transmitter device employs a single antenna only while the receiver device uses multiple antennas, which can be grouped as an antenna array, along with an RF switch to switch from one antenna to another at random. Both phase (I) and quadrature (Q) samples of the received signal are captured by the receiving device in order to calculate the phase difference between the replicas of the same radio signal with different time delay that can be detected. Naturally, the angular position can be finally determined based on the calculation results of phase delay. The AoA mechanism specified in the Bluetooth 5.1 standard can be depicted in Figure 1.

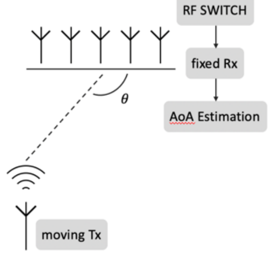


Figure 1. Bluetooth 5.1 AoA mechanism.

In details, the phase difference φ of the transmitted signal to be calculate on the received device between two adjacent antennas can be obtained using the formula of:

$$\varphi = \frac{2\pi d cos\theta}{\lambda}, \tag{1}$$

where λ = signal wavelength
d = distance between the antennas
θ = angle of arrival

The value of θ can be expressed in an alternative way using the following equation:

$$\theta = cos^{-1}(\frac{\varphi\lambda}{2\pi d}). \tag{2}$$

3.2 Packet format and antenna switching time

An additional field, which can be called Constant Tone Extension (CTE), allows the angular determination capability of BLE devices, and the format of uncoded packets using the transmission mode of LE 1M in PHY has been presented in the Table 1. Actually, CTE is a sequence of consecutive 1-second without whitening, and it is used to represent the binary number 1. These unwhitened 1-valued bits provides a sector of unchanged signal after the transmission from one side to another due to the lack of phase shifts caused by signal modulation. The length of CTE duration can be varied with time, and normally it takes around 16-160 µs. The number of symbols included within the CTE is confined by the application layer and this enables an adequate collection of data packets and IQ sample sets to be received. The CTE consists of several different subperiods, at first, a reference periods of 8 µs, and then a guarding period with no operation performed (4 µs), lastly timeslots used for data sampling and antenna switching with two possible durations: 1 µs and 2 µs. In particular, only 2 µs slots suits for all direction finding enabled BLE devices, on the other hand, slots of 1 µs cannot support thoroughly as slots of 2 µs does.

Preamble	Access Address	PDU	CRC	CTE
8 bits	32 bits	16-2056 bits	24 bits	16-160 µs

Table 1. Packet format for AoA used in PHY uncoded mode.

The BLE device collects 8 IQ samples every time, during the reference period, if sampled at 1 MS/s, using one antenna only at the receiver side. Each sample slot captures one IQ sample and this is not affected by the length of sample slots to be used. The switching pattern can be manually configured and the simplest possible pattern makes use of two antennas and lasts the shortest period of duration (16 µs).

4. EXPERIMENTAL SETUP

To scrutinize the fidelity of direction finding capability proposed by the Bluetooth 5.1 specification, we selected the Bluetooth devices from Texas Instruments, including a transmitter board with only one single antenna and a receiving board with multiple antennas embedded. Also, TI provides a list of technical documents and implementation tools that are of correspondence. Therefore, we purchased and implemented the SimpleLink™ CC1352R device (Texas Instruments, 2021a) to incorporate with a launch board and work as a transmitter, the SimpleLink™ Angle of Arrival BoosterPack (Texas Instruments, 2021b) to be the receiver device with two groups of antenna array. These working prototypes is seen in Figure 2 and Figure 3.

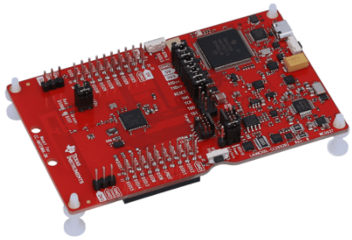


Figure 2. SimpleLink™ multi-standard CC26x2R wireless MCU LaunchPad™.

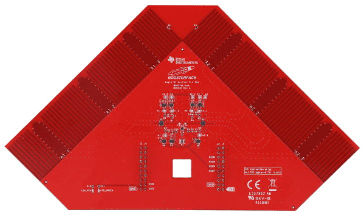


Figure 3. SimpleLink™ Angle of Arrival BoosterPack.

Our experimental setup consists of multiple Bluetooth devices including one signal launch pad used to send out data packets and one AoA BoosterPack used for signal reception and angular determination, and a PC used as a node manager to be connected to the receiver device so that all useful data information can be collected instantly. The laptop also fully supplies power to the receiver and supports all related software to be running in real-time using an Intel i7 CPU clocked at 1.3-3.9 GHz with 32GB of RAM. This computer works with the Windows 10 operating system. The transmitter device is powered by a fully charged power bank which was placed at least 1 m away from the receiver node. The complete experiment layout of all nodes during measurements is shown in Figure 4.

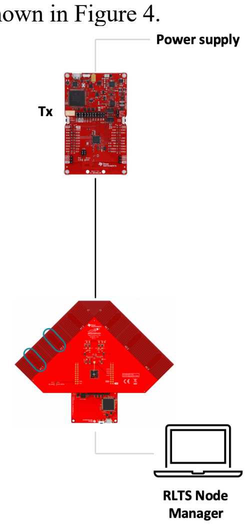


Figure 4. Experimental setup.

Next, in terms of implementation details of BLE AoA mechanism, we selected to use on particular side of antenna array which includes 3 antennas that are separated with an identical distance, and this distance is a known value recorded by the receiver. However, only one antenna can be triggered and step into active status at any given time, received signals from 2 adjacent antennas will be considered as a group to attain the phase difference. 3 antennas will switch from one to another according to a sequence of pseudo random numbers which is known by both transmitter and receiver. Based on the usage of

CTE, the phase difference between adjacent antennas, and AoA can be both estimated and calculated using Equation 1 and Equation 2 respectively.

5. EXPERIMENTAL RESULT & RESULT ANALYSIS

As described in the Bluetooth 5.1 specification (Bluetooth SIG, 2019b), this technical breakthrough makes it possible to achieve the positioning accuracy up to sub-meter or even centimetre level using Bluetooth / Bluetooth low energy 5.1 new features (i.e., AOA and AOD). Therefore, we set up a series of experiments to empirically evaluate the performance, particularly in terms of the measurement accuracy of BLE 5.1 AOA function under different testing conditions and explore the inherent characteristics underlying the results of different groups of analogy experiments. Specifically, the tests were performed in four different typical scenarios including an ideal environment (i.e., anechoic chamber with no multi-path effect), different positions within an underground mine (i.e., a metal mine in NSW), an open area and an office area, as presented in Figure 5. For each testing environment, both intermediate and final results were collected repeatedly. The intermediate result, also called ‘raw data’, can be referred to the phase difference that is computed using different signals received by adjacent antennas. The final result implies the ultimate outcome of this AoA measurement, which means it is the value of AoA. To collect data more comprehensively and make result analysis more reliable, the measurements were carried out at a set of different angles (i.e., 45°, 90°, 135°). According to the requirement of experiment equipment, the placement of BLE receiver at different measurement angles is presented in Figure 6.

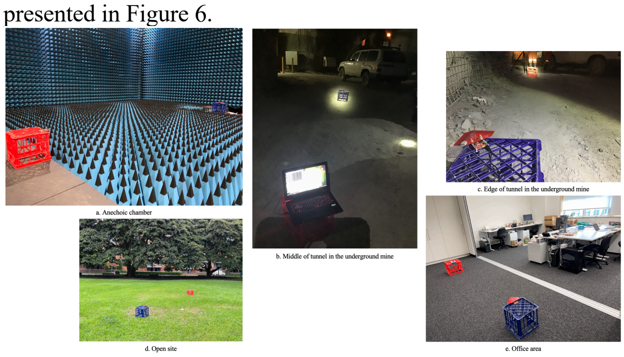


Figure 5. Experimental site for different testing scenarios, (from left to right, up to bottom) (a) Anechoic chamber; (b) Middle of tunnel in the underground mine; (c) Edge of tunnel in the underground mine; (d) Open site; (e) Office area.

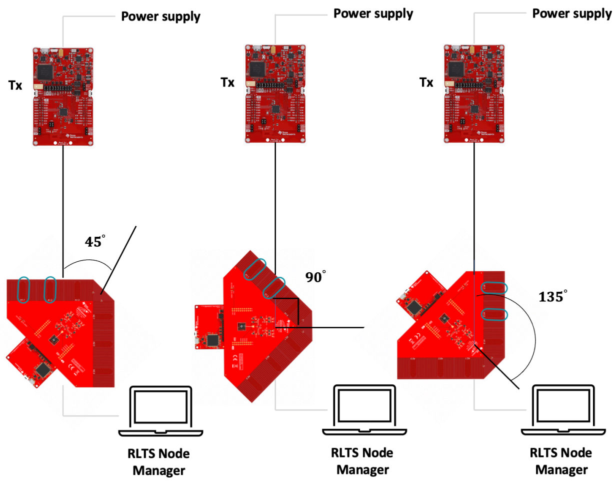


Figure 6. Device placement at the angle of 45°, 90°, 135°.

The following error plots are obtained directly from the collected AoA results. Blue and red lines both represent the difference between measured result and expected result, however, each of them present the performance of one dataset. Blue lines are related to Dataset 1 and red lines represent Dataset 2. In order to make results more representative and reliable, for each testing condition (i.e., specified test site, distance, angle), the same data collection process was executed multiple times to isolate the accidental measurement error. The black dotted line which is the third line in each plot is the average value calculated from blue and red lines.

5.1 Ideal environment

The plots in Figure 7 are all obtained from the tests in an ideal measurement environment, an anechoic chamber within UTS tech lab. The distance between the transmitter and receiver is 5 m. The results were collected at three different angles (i.e., 45°, 90°, 135°).

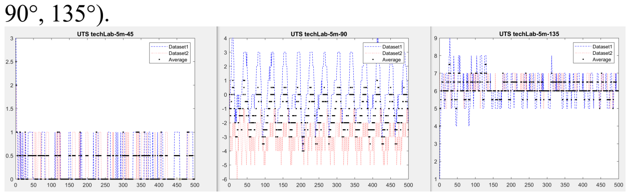


Figure 7. Results of the tests in the ideal environment.

The ideal environment implies that all radio frequency signals are fully absorbed by walls made from special materials, therefore no multi-path effect may occur. Based on these plots, we note that the accuracy of angular positioning in the ideal environment is quite close to the statement provided in (Bluetooth SIG, 2019b; Woolley, 2019) that the precision of BLE AoA based localization system is up to a few centimetres. However, the performance of angle 135 is the worst of all, and the fluctuation of average error measured at angle 45 remains more stable than the case of angle 90.

5.2 Underground mine

The plots in Figure 8 and 9 are all obtained from the tests in an underground mine (a metal mine in Australia). The distance between the transmitter and the receiver is 5 m. The results were collected at three different angles (i.e., 45°, 90°, 135°) and different position of tunnel (i.e., middle of tunnel and edge of tunnel).

5.2.1 Middle of tunnel: Figure 8 demonstrates that the AoA measurement accuracy is affected by various obstacles in underground mines, and the fluctuation of average error measured at angle 135 is much larger than the others.

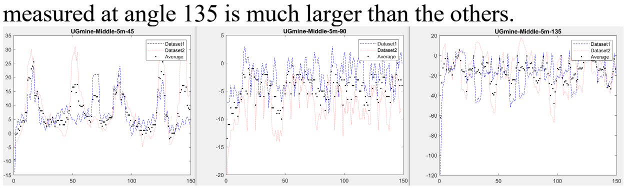


Figure 8. Results of the tests at the middle of tunnel in underground mines.

5.2.2 Edge of tunnel: Figure 9 reveals that obvious obstructions (i.e., for instance, walls, etc.) that leads to signal reflection and multi-path effect, affects the localization accuracy effectively. Since the devices are deployed at the edge of tunnel, the overall performance degrades compared with the middle of tunnel. Nevertheless, the fluctuation of average error measured at angle 135 is still worse than other directions.

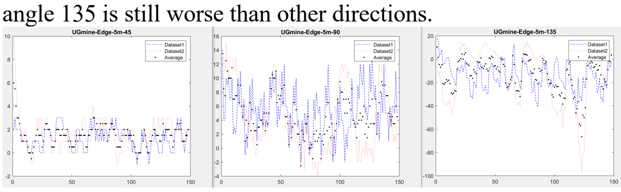


Figure 9. Results of the tests at the edge of tunnel in underground mines.

5.3 Open site

The following plots are all obtained from the tests in the open space, a lawn in campus. The distance between the transmitter and the receiver is 5 m. The results were collected at three different angles (i.e., 45°, 90°, 135°).

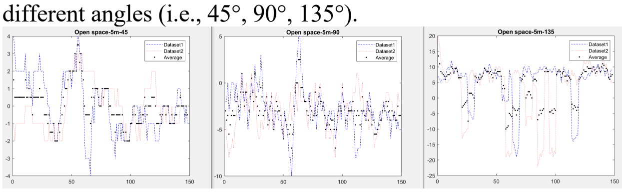


Figure 10. Results of the tests in the open site.

The open site that we conduct our experiments is almost free of any obstructions that can cause severe signal reflection, the achieved performance is very close to the ideal environment except the stability of result values. As indicated in Figure 10, the fluctuations of average error are all larger than that of Figure 7, but better than the case of underground mines. In addition, the fluctuation of average error measured at angle 135 is still the worst case compared with the ideal case and underground mines.

5.4 Office area

The following plots are all obtained from the tests in the office area. The distance between the transmitter and the receiver is 5 m. The results were collected at three different angles (i.e., 45°, 90°, 135°).

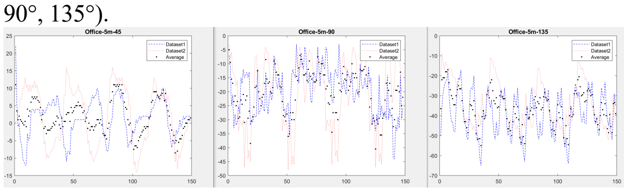


Figure 11. Results of the tests in the office area.

Overall, the performance of the office area is the worst compared with other testing environments. Nevertheless, the fluctuation of average error measured at angle 135 is similar with the case of angle 90 and angle 45 outperforms the rest, which is quite different from other testing environments.

Additionally, we also note that there is always a particular pattern repeatedly occurring on each result plot obtained from the office area. Therefore, a series of tests followed up to verify the consistency of this interesting phenomenon. We decided to perform the measurements at more different angles including 45°, 90°, 135°, 0° and -45°. During the experiment, the distance between the transmitter and the receiver also gets more diverse (i.e., 5 m, 2 m, 1 m). A detailed device placement of the BLE transmitter and receiver at the angle of 0 and minus 45 can be found in Figure 12.

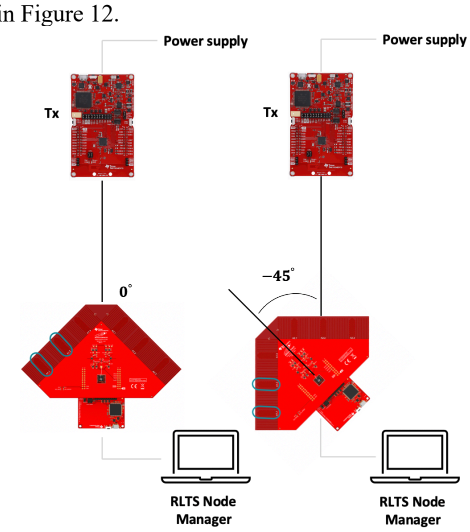
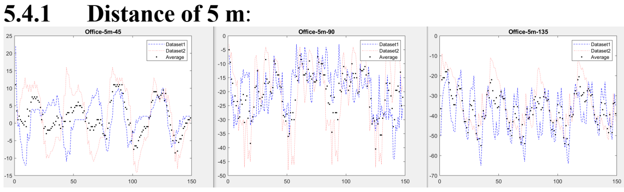


Figure 12. Placement of BLE devices at the angle of 0°, -45°.

5.4.1 Distance of 5 m:



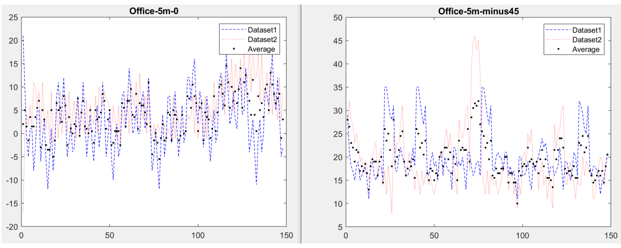


Figure 13. A further average error plot including more angles at the distance of 5 m.

5.4.2 Distance of 2 m:

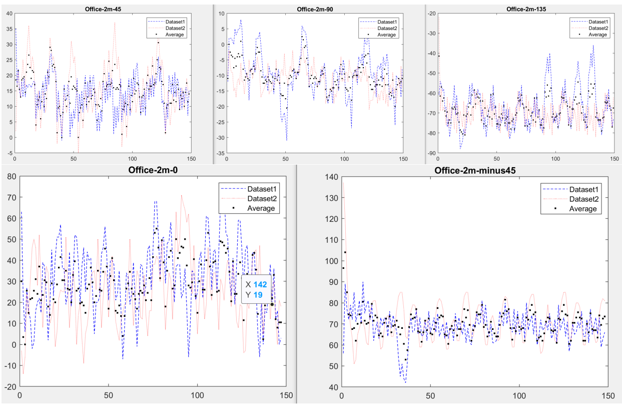


Figure 14. A further average error plot including more angles at the distance of 2 m.

5.4.3 Distance of 1 m:

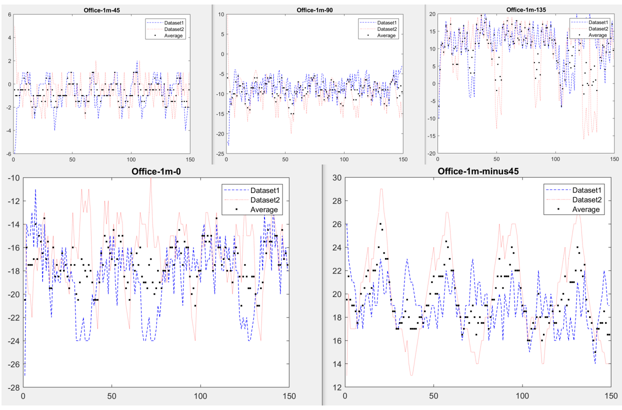


Figure 15. A further average error plot including more angles at the distance of 1 m.

Figures 13-15 reveal that each error plot includes a unique pattern indeed, and each pattern is showing up regularly, no matter how we changed the value of distance and angle during the measurements. Given that, we inferred this regular pattern is related to the signal reflection caused by the office environment that includes many obstructions. In fact, the deterministic reason for this phenomenon is the variety law of transmission channel random selection based on our further investigation on the raw data. To be specific, the same BLE data channel has a consistent transmission characteristic that affects the propagation path of RF signal. In that case, every time the same sequence of BLE channels is selected, the corresponding results of accuracy has the same variation trend, and this leads to the occurrence of the 'regular pattern'.

5.5 Root Mean Square Error (RMSE)

Lastly, we exploited the characteristic of Root Mean Square Error (RMSE) for each testing conditions, as shown in Figure 16. Each RMSE result was computed based on the average values achieved from all available datasets for each case. This result plot reported that the direction finding capability at the angle of -45 and 135 are more difficult to remain stable, compared with the rest. The discontinuities occurred at angles 0 and 90 demonstrate that the direction finding capability of BLE 5.1 AoA mechanism degrades significantly when the angle between the propagation direction of the transmitted signal and the axis the antenna array gets larger, particularly when it's larger than 135 degrees. This can be considered as a threshold to decide whether the accuracy performance of BLE 5.1 AoA function is satisfactory or not.

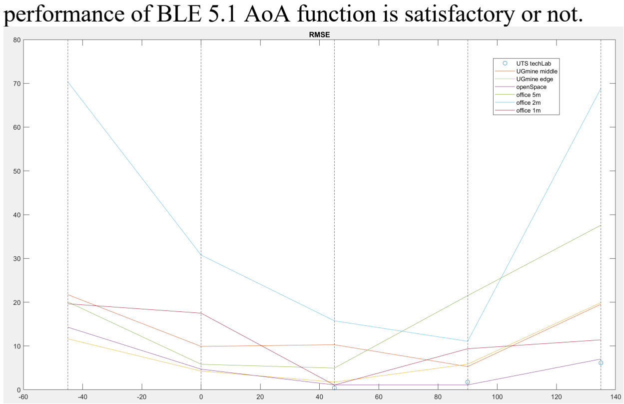


Figure 16. The result of RMSE for all testing environments and conditions.

6. CONCLUSION

In this paper, the accuracy of direction finding capability specified by BLE 5.1 standard was empirically evaluated. We can provide the following insights.

1) As expected, the angular detection result is highly sensitive to the testing environment and to achieve the AoA based positioning accuracy within a few centimetres remains difficult. Alternatively, the number of large metal or concrete obstructions that may cause signal reflection leading to multi-path effect, the strength of interference sources and the placement of experiment equipment that are decided by various testing environments, imposes strict constraints on the precision of AoA estimation in different ways.

2) The error plots gained from the office environment with a few desks, walls, and Wi-Fi access points, always surprisingly show a particular regular pattern on the average error plots. This phenomenon we believe is due to the random variation law of data channel selection leading to different levels of multi-path effects caused by the propagation and reflection of RF signals within the office area.

3) The RMSE of AoA estimation in different cases indicates that the accuracy of angular positioning varies significantly with different measurement angles. Within the range of 0 to 90 degrees, the performance still can be maintained relatively stable, however, the results degrade significantly if the measurement angle gets out of this range (e.g., -45, 135).

Overall, BLE 5.1 new nature AoA can be used effectively in the open environment. While in other environments with obstacles, only transmitted signal in line of sight condition can be guaranteed.

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