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Phase-based Angle estimation approach in Indoor Localization system using Bluetooth Low Energy

Gaurav Kumar [1] , Dr. Vrinda Gupta [2] , Rahul Tank [3]

[1] School of VLSI and Embedded System Design, National Institute of Technology Kurukshetra

[2] ECE Department, National Institute of Technology Kurukshetra

[3] NXP Semiconductor India Private Limited

[1] gauravkumarnitkkr@gmail.com, [2] vrindag16@gmail.com, [3] rahul.tank@nxp.com

Abstract: **As the demand for a highly accurate indoor positioning system (IPS) increases, the selection of technology and methodology becomes a critical aspect by making it an active area for the researchers. Several techniques are already in the competition to provide an accurate, power-efficient, and low-cost system such as Wireless Fidelity (Wi-Fi). In this paper, we present a phase-based angle measurement approach for calculating the angle using Bluetooth Low Energy (BLE). Bluetooth Low Energy, or colloquially BLE also known as "Bluetooth SMART," promises an improved accuracy and low power requirement for its operation. The proposed BLE direction-finding approach introduces a phase-based method to measure the angle, i.e., Angle of Arrival (AOA). Herein, the estimation locator listened for the Constant Tone Extension (CTE) packet and measured the In- Quadrature (IQ) samples based on which the angle calculation has been performed. The experimental results show a mean error of 1.9^0 in the indoor environment.**

Keywords:* *Indoor positioning system (IPS), Bluetooth low energy (BLE), Angle of arrival (AOA).

I. INTRODUCTION

In this era of growing technology, the demand for navigation and proximity system has been increasing rapidly. Bundles of efforts have been made to get a more reliable, precise, and ever-present positioning system. For the wireless positioning system, various technologies are available in the market. We all are aware of the global positioning system (GPS), which is the most widely used satellite-based positioning system that provides precise location-based services. But unfortunately, it is more useful for the outdoor environment. It doesn't perform effectively in indoor environments, buildings, street canyons, etc. Due to the multi-path radio signal propagation, the signal becomes very weak, and the line of sight (LOS) between transmitters (Tx) i.e., satellite and Receiver (Rx), is inferior. Thus, GPS becomes less effective for indoor positioning [1].

As a solution to this limitation, various other positioning systems are available for indoors [2], i.e., Infrared based, and Radiofrequency (RF) based. Herein focus on RF-based methods for AoA estimation, which further include technologies like Bluetooth, BLE, RFID, Wi-Fi, etc. In bluetooth over the past decades, lots of improvement has been made and new features were introduced [3], which makes it a perfect candidate to be used in short range wireless connectivity positioning system.

For the angle of arrival or direction of arrival, estimation beacons play an essential role [4-5]. However, in place of BLE beacon, Wi-Fi can also be used. But in comparison to BLE beacons, it requires an external power source for its operation and high setup cost. Besides that, the advantage of using BLE beacon is based on the fact that it follows standard BLE protocol, which is again used by smartphones worldwide. The other benefits, such as low power consumption [6], can run batteries for a few years.

For AoA estimation, a lot of literature is available. The researchers have used various algorithms, viz. measuring the time delays of signal arrival at the antenna array elements [7], switching of antenna beams [8] using omnidirectional monopole rotatable, as well as static antenna arrays [9], or using RSSI. Many other AoA estimation approaches have been developed or studied [10-12].

In this paper, we present a phase-based angle of arrival estimation using BLE (v5.1). In an earlier version of Bluetooth, we relied solely on the RSSI method to determine the proximity between the two BLE devices. This AoA estimation approach comprises a moving Tx device (BLE beacon), continuously transmitting the signal, whether it's advertising packets or Constant Tone Extension (CTE) packets during a connection using a single antenna. On the other hand, the Rx or locator, which is usually fixed and equipped with an array of multiple antennae, listens to the CTE packets and takes IQ-samples from the received signal while sequentially switching the antenna and forwards the IQ data to the controller for angle estimation. The angle estimation concept is that receive signals will have a different phase when arriving at each of the Rx's antenna based on the difference between the phases of the receive signals at each of the antenna. Since the distance between the antennas is fixed and known to the Receiver, it can estimate the moving device's direction.

The remaining part of this paper is organized as follows. Section II presents the related work. The methodology of the proposed work is discussed in section III. Section IV shows the experiment procedure at the hardware and firmware levels with the results. Section V contains the conclusion of this method, and the future scope of this proposed method is presented in section VI.

II. BACKGROUND AND RELATED WORK

Several work has been done on AoA estimation, based on different methods:

A. Received Signal Strength Indicator (RSSI)

This localization technique method is based on the received signal strength and is a widely used method for indoor localization [13] - [14]. As the peer device moves closer to the Rx, the strength of the signal transmitted by the peer device at the Rx's antenna increases. Similarly, the signal's strength starts decreasing as the transmitter (peer device) moves away from Rx. The strength of the signal received is measured in decibel milliwatts (dBm). A more negative dBm indicates a weaker signal. The fluctuation of the RSSI in BLE is one of the significant big challenges. In [15] - [16], shifting of BLE device by less than 10 cm results in a drop of approximately ten dBm in the RSSI. Several methods have been proposed to reduce RSSI fluctuation in reference [17] - [18].

In reference [19], a method for estimation of the angle of arrival is obtained using omnidirectional monopole rotatable and static antenna arrays placed on a circular plate. The advantage of choosing rotatable and static antennas is to get proper resolution and eliminate the movable part, respectively. The idea behind the algorithm used for this method is to calculate the arrival angle where RSSI is minimum. For this, the transceiver receives the packets sent by Tx, and based on the voltage level of the incoming signal, it calculates the RSSI. So after collecting all the RSSI information from all the transceivers placed on the circular plate, and based on the minimum RSSI obtained, the corresponding angle of arrival is measured with an extra addition of $\pm 180^0$. This method gives better results with the rotatable antenna compared with static antenna, i.e., the relative error of 4% for outdoor & 14% for indoor. In addition to it with Gaussian approximation and static antennas, the results improve by 1%, i.e., 3% for indoor and 18% for outdoors. This approach's limitation is the relative error for the indoor environment, which is around 15%, which is still high.

B. Time of Arrival/Flight (ToA /ToF) and Time Difference of Arrival (TDoA)

The time of arrival/time of flight approach is based on the arrival time of a transmitted signal from target to the multiple (at least three) receiving beacons. When the target device sends a timestamp signal, obtained by the beacons, the distance between the target and the beacons is evaluated using the transmission time delay and speed of the message. In this method, the target/mobile device and beacons should be highly synchronized with a time source. This requirement is its disadvantage.

The time difference of arrival approach is based on the relative time measurement instead of absolute time measurement. Calculation of the target's relative location or angle using the time difference between the signal transmitted by target and received at several beacons e.g., three beacons (receivers), gives two TDOAs and the intersection point is the estimated target location. In this method, only receiving devices needs to be time-synchronized, which is again a disadvantage. It has another drawback, i.e. multi-path effect.

C. Switched beam system (SBS)

The author of reference [20] has proposed a less complicated hardware system for the angle of arrival estimation, which is based on the switching of the antenna beam. In this method, the omnidirectional signal is collected first which is taken as reference. Then scanning of the angular section is done by switching the main beam. Then the received/obtained signals from switched beams with the omnidirectional signal are cross correlated, which is taken as reference. After that the angle of arrival is calculated where the cross-correlation coefficient is maximum. This approach improves the complexity with O (MN), where M is no of receivers used, and N is the number of signals required to collect the reference signal compared with MUSIC complexity [21], i.e., O ($M^2N + M^2P$), where P is the number of the angle of arrivals. This approach has a limitation of the number of devices to be detected, and that depends on the number of switched beams.

III. METHODOLOGY OF PROPOSED WORK

The direction-finding feature of Bluetooth leverages two methods of direction finding based on whether the antenna array is present on the transmitter (Tx) side or receiver (Rx) side, i.e., AoA, and other one is Angle of departure (AoD). In this paper, implementation of AoA method is presented.

A. The angle of Arrival (AoA) method

In AoA method, the Tx transmits the direction-finding enabled packets to peer using a single antenna. At Receiver, which consists of an antenna array and Radio Frequency switch, switches antennae while receiving those packets, and it captures the IQ samples. Calculation of the direction is based on the difference in the phase of the received radio signal using different elements of the antenna array. The IQ samples, thus captured in turn, can be used to estimate the AoA, illustrates more in fig.1.

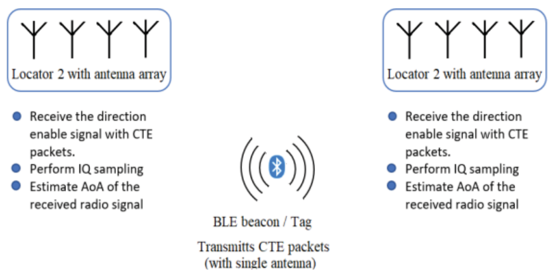

Fig. 1: The overall structure of AoA method.

B. Signal Direction Estimation Using Phase Method

When Tx transmits radio signals, which travels at the speed of light in all the three dimensions in the presence of hurdles or other attenuation factors, it spreads while moving ahead, and the energy within the transmission starts reducing further because of attenuation factors.

To understand the concept of phased method for angle estimation, we consider a two-dimensional approach. Let's consider a Tx antenna that is placed at the center, as shown in Fig. 2. It spreads signal in two dimensions, so the signal traces a circular path. If we put the Rx antenna in the signal's way, the signal wave crosses across, and the phase of the wave varies. Here let p1 is the phase of the wave measured at any time't' when it crosses the first antenna, which is located at a fixed distance (position A) from the Tx. If we introduce second antenna, placed at some other point(position B) on the same circumference where first antenna is placed, given same distance from the Tx also having same wave come across, the phase p1' of the wave crossing the second antenna if measured at the same time 't', will result same as p1 i.e. p1 = p1' .

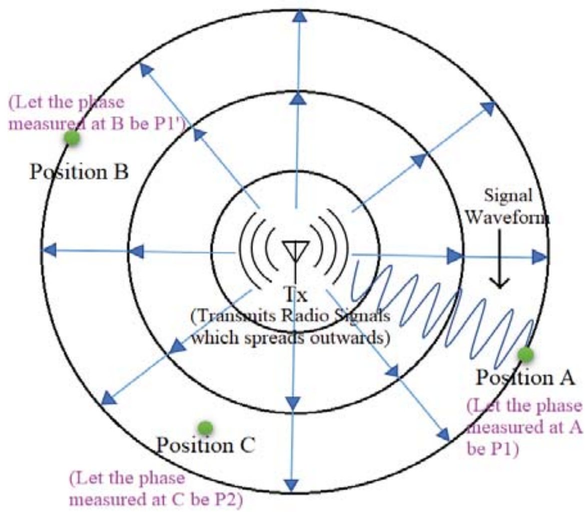

Fig. 2: Equal and unequal phase values at different distance from transmitter.

Now if we move one of the antennae closer to Tx(at position C), make sure the distance gap between the first antenna w.r.t Tx and distance between second antenna w.r.t Tx must not have equal multiple of signal's wavelength. For this case, the phase measured at both the antenna p1 and p2 at time't' will be different.

So knowing distance between the antenna, the difference in the phases, i.e. (p2-p1), and the frequency or wavelength of the signal, and then using the trigonometric concept, we can calculate the angle of radio signal as illustrated in Fig. 3.

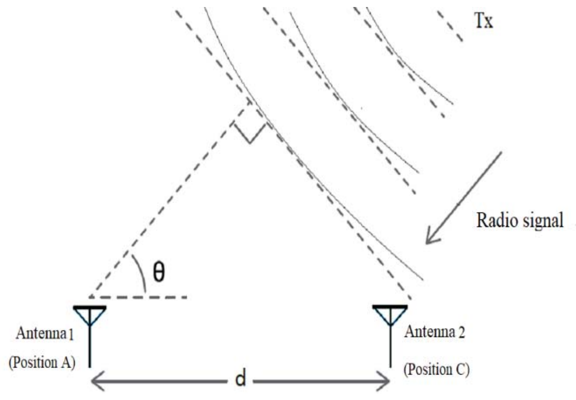

Fig. 3: The AoA of radio signal can calculated using the phase difference (p2-p1) , wavelength λ and the distance 'd' between the two antenna.

The phase difference let's say Ψ = (p2-p1),

So the angle 'θ' is calculated as:

$$\theta = \arccos\left((\Psi \lambda) / (2\pi d)\right) \text{ --- } (1)$$

Where, λ is the wavelength of the signal, and d is the distance between the two antenna places at position 1 and 2.

C. IQ sampling

The BLE device calculates its angular position relative to other BLE device by transmitting direction finding enabled packets to peer device using single antenna. The remote or peer device on receiving those signals, will proceed by taking the amplitude and phase measurement at fixed intervals in the process known as IQ sampling. One IQ samples consists of signal's amplitude and phase angle in Cartesian coordinates which further converted into polar form, shown in fig. 4.

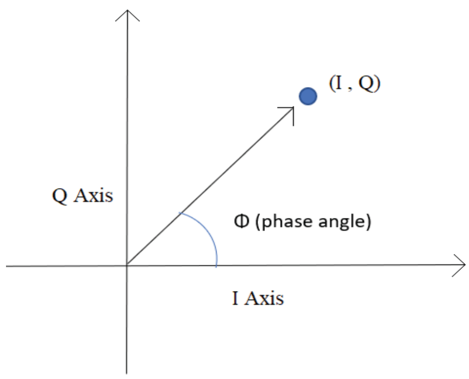

Fig. 4: Phase angle and amplitude as (I, Q)

While performing the IQ sampling in a system having antenna array, each samples taken must be ascribe to a distinct antenna. For AoA, performing IQ sampling on each antenna must be done in a proper sequence.

Whenever Host requested, the Rx shall perform IQ sampling when a valid packet that contains CTE is received. It may also perform IQ sampling when receiving a packet having valid CTE but an invalid Cyclic Redundancy Check (CRC). While receiving a packet having an AoA CTE, antenna switching is needed at the Rx side, and the rate is decided as per the switching pattern configured by the Host. Rx shall take IQ samples at each microsecond during the reference period and at each sample slot. Thus, we have eight reference IQ samples and 2 to 74 IQ samples with 1 µs slot or 1 to 37 IQ samples with 2 µs slot. These IQ samples are then reported to the Host by the controller. To get accurate data useful for angle calculation, the IQ samples should be taken at the exact point in each IQ sampling window shown in Fig. 5.

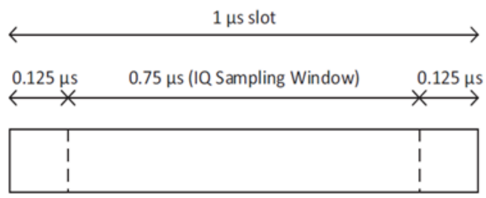

Fig.5: IQ sampling window for 1 µs slot.

D. Constant Tone Extension (CTE)

It is an important part of how the direction finding feature of Bluetooth works. it delivers a constant source of signal on which IQ sampling can applied. A new Link Layer (LL) PDU have been defined for this feature which is extended version of existing advertising PDU with an additional data information related to direction finding called CTE.

Preamble	Access Address	Protocol Data Unit (PDU)	CRC	Constant Tone Extension (CTE)

Fig. 6: Bluetooth direction finding signal with CTE

The CTE contains modulated series of symbols, represents 1 (binary). These symbols may be configured by upper stack layers to ensure proper time and data is available at the Receiver to perform IQ sampling. It is not whitened. Also, it doesn't affect the CRC, a value used for error detection. Its length is variable (at least 16 µs), and it goes up to 160 µs. The structure of AoA CTE is given in fig. 7:

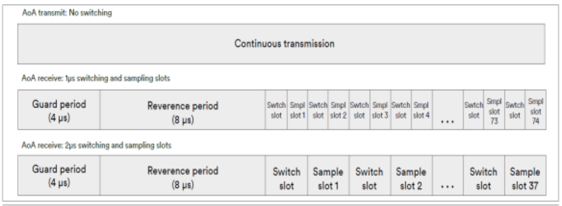

Fig. 7: CTE timing structure for AoA
(Image source: Bluetooth SIG)

An RF switch controls the switching of antennae. It happens during switch slots. The first 4 µs period of CTE is known as the guard period. The next 8 µs period is known as the reference period. The IQ Samples are captured in between reference and period known as sample slot. After the guard and reference period, CTE consists of a sequence of the alternating switch and sample slots of either 1 µs or 2 µs period as specified by the Host.

E. Antenna Array

Antenna Arrays play an essential role while receiving CTE packets for the AoA method. Various antenna arrays design are available [22-23], i.e., uniform linear array (ULA), a uniform linear rectangular array (URA), and uniform linear circular array (UCA).

For our experimental setup, we use ULA. It is a commonly used antenna array capable of calculating a single angle from a radio signal. To derive two or more angle, a more complex design of antenna array is needed.

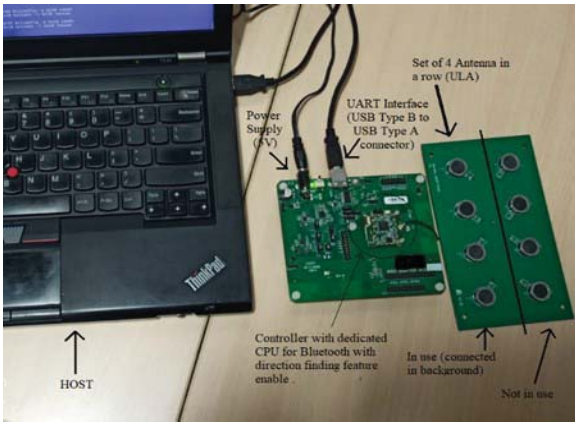

Fig. 8: Locator setup having antenna array (ULA) connected with controller which is controlled by host.

F. Architectural Flow Of Proposed Method

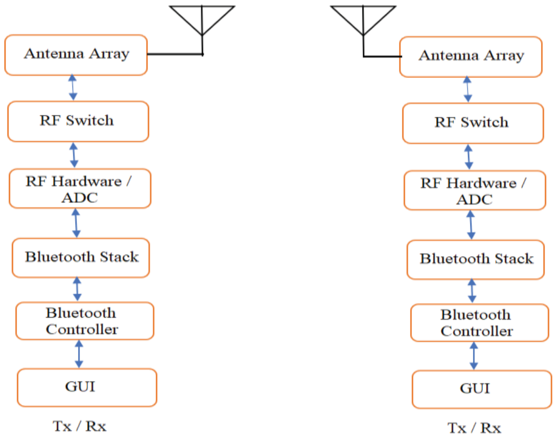

Fig. 9: Architectural flow

The architectural diagram shown in fig. 9 consists of the following:

1. The application software with Graphical User Interface (GUI) to show the measured angle in degree.

2. Bluetooth stack that contains supported profiles and set of all the commands/events to interact with the corresponding Bluetooth controller.

3. BLE controller running a firmware that supports the over-the-air (OTA) protocol for communicating with peer/remote device. The controller also has an antenna array and switching mechanism as per the configuration it is needed to generate the IQ samples.

4. RF Switch, which is used for switching the antenna whenever needed.

G. Changes required at different levels

The BLE technology consists of two entities, i.e., Host and Controller. The host side uses Bluetooth Stack and deploys various profiles to facilitate different services for applications. The Host can determine the position based on the IQ samples, RSSI, and profile level information. The profile level information contains details of the antenna array layout. The controller side takes care of the "wireless" part.

At hardware-level, the wireless SoC employed needs to have the capability to generate the IQ samples based on received CTE enabled packets. For the AoA approach, the Hardware (HW) must have antenna array and RF switch at the receiver end, and it must support sequential switching of the antenna based on the preconfigured antenna map.

At firmware-level, It should support to handle Bluetooth Core Specification 5.1 [24], defined HCI

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command and events for the protocol adherence. Also, proper firmware buffer management should collect and forward the IQ samples to host in the specified format.

The host side needs to implement the algorithm to derive the angle based on the IQ samples received and display it on a coordinate plane. The support for the commands about the AoA feature was added as a plugin in the existing framework. This allows the configuration of sequence, duration, enabling of the antenna switch from the Host. The GUI was implemented (Fig. 11) to compute and display the angle derived from the IQ samples received from the controller and the antenna layout information.

H. CTE Request and IQ Report Generate Procedure

The Bluetooth protocol provides two ways to implement this AoA feature, namely: Connectionless AoA and Connection-oriented AoA. Here the connection-oriented approach is implemented. In this, a peer-to-peer connection is established, and the message exchange happens on this dedicated connection. The communication over the link is bi-directional.

The sequence of the commands and events for connection-oriented AoA are shown in the fig. 10. Once the BLE connection is established in between Device A and B, the Master or slave may request the peer device to transmit CTE.

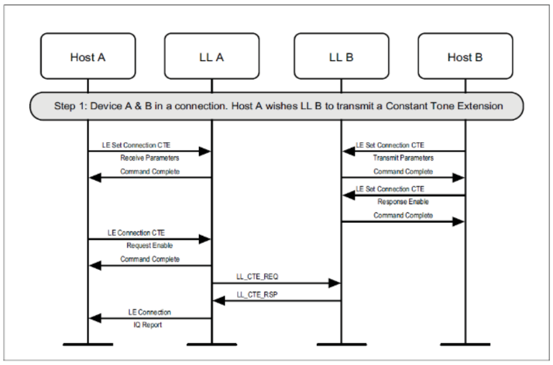

Fig. 10: Connection-Oriented CTE communication with HCI commands (image source: Bluetooth SIG)

Note: The protocol and technology being used are the standards adopted by Bluetooth Special Interest Group [24].

IV. VERIFICATION AND RESULTS

A wireless SoC board with four antenna array is used. The AoA feature was implemented in FW running on an RTOS. For the HCI interface, we used HCI TooLbox v2.0.0.77 runs on a windows machine.

A. Procedure

Step 1. Establish LE Connection between the devices: Set Advertise parameters from a remote device and Enable Advertising. HCI Events are:

LE Set Advertising Parameters
Adv_Interval_Min: 0x0800
Adv_Interval_Max: 0x0800
Adv_Type: ADV_IND –
Connectable undirected (default)
Own_Address_Type: Public Device Address
Direct_Address_Type: Public Device Address
Remote BD_ADDR: 0x0050432444B9
Adv_Channel_Map: 0x07
Adv_Filter_Policy: Scan Request: Any
Connect Request:Any

LE Set Advertise Enable: Enable

Step 2. Send Create Connection request from the controller to peer/remote device. In response, a complete connection event is received on both the sides i.e., Locator and Tag/Remote.

At Tag/Remote side: HCI Events
LE Connection Complete Event
Status: Connection successfully completed
Connection Handle: 0x0080
Role: Slave
Peer Address Type: Public Device Address
Peer Address: 0x0050432444B9
Connection Interval: 0x0010
Connection Latency: 0x0000
Supervision Timeout: 0x0800
Master Clock Accuracy: 250 ppm

And at Locator side: HCI Event
LE Connection Complete Event
Status: Connection successfully completed
Connection Handle: 0x0080
Role: Master
Peer Address Type: Public Device Address
Peer Address: 0x112233445566
Connection Interval: 0x0010
Connection Latency: 0x0000
Supervision Timeout: 0x0800
Master Clock Accuracy: 250 ppm

Once the connection happens, the requesting Host further follows the steps, as shown in fig. 10.

Step 3. Configure CTE receive parameters and Enable CTE Request in the controller.

LE Set Connection CTE Receive Parameters
Connection Handle: 0x0080

Slot Durations: Switch and sampling slot 1us
Length of Switching Pattern: 0x04
Antenna IDs: 0x03010200

LE Connection CTE Request Enable
Connection Handle: 0x0080
Enable: Enable Constant Tone Extension Request for the connection
CTE Request Interval: 0x0001
Requested CTE Length: 0x0E
Requested CTE Type: 0x00

Step 4. Receiving and processing IQ reports.

LE Connection IQ Report
Connection Handle: 0x0080
RX PHY: 1 Ms/s
Data Channel Index: 0x0F; RSSI: -21
CTE Type : AoA Constant Tone Extension
Slot Duration: 1 us sample slots
Packet Status: CRC was correct
I Sample: 0x3A
Q Sample: 0xE9

3E-7E-16-80-00-00-0F-DC-00-01-00-3A-E9-1C-E3-E9-16-E4-1A-17-E7-1A-E6-E7-18-E6-18-19-E7-E5-16-1B-EB-E1-11-1E-ED-E0-10-1F-F1-DF-0D-20-F3-DE-09-21-F6-DD-08-22-F8-DD-05-22-FB-DC-02-23-FE-DC-00-23-01-DC-FA-23-06-DD-F6-21-08-DD-F5-21-0A-DE-F2-21-0E-DF-F0-1F-0F-DF-ED-1E-12-E2-EC-1D-14-E3-E9-1B-17-E5-E7-19-1A-E7-E3-15-1C-EB-E2-13-1D-EC-E1-12-1E-EE-E0-10-20-F0-DE-0C-21-F4-DD-0B-22-F6-E2-16

At Responding Host:

Step 5. Configure CTE Transmit parameters and Enabling CTE response in the controller. Receiving and responding to CTE_REQ PDU from the other device.

For User Interface to see the calculated angle using HCI Tool Box, shown in fig. 11. First configure the antenna setup(Step #1), then turn on the Tag i.e., enable ready, connect and start (Step #2), next start scan for remote/tag, once found select the address (Step #3) and turn on the locator for estimating the AoA (Step #4)

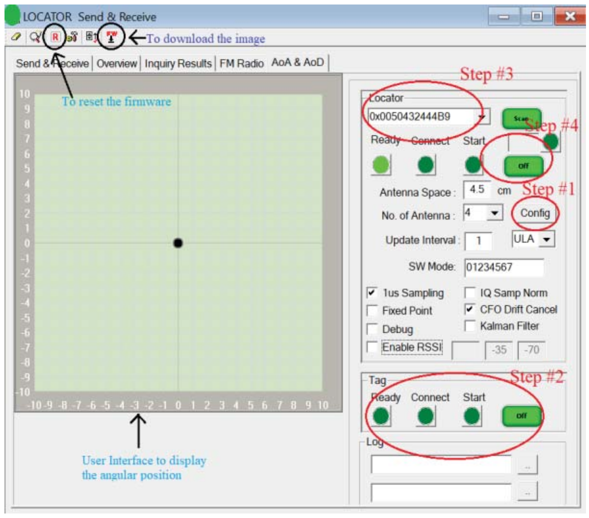

Fig. 11: AoA user interface of HCITool box.

The angles obtained are plotted below:

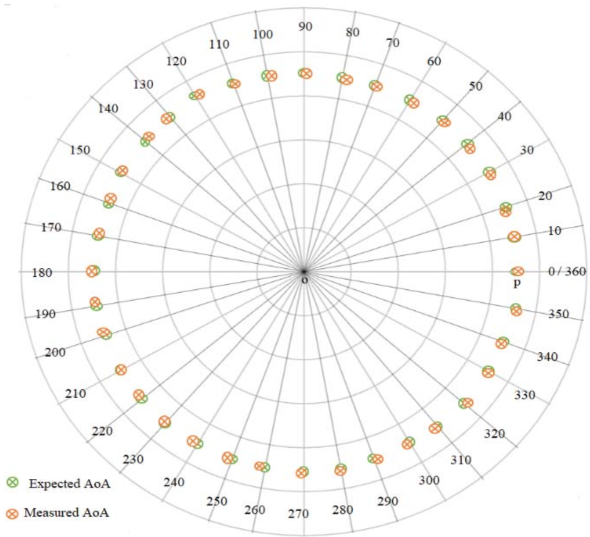

Fig. 12: The estimated AoA is plotted from the observation taken from the GUI of HCI Tool box .where ‘p’ is fixed distance between locator and remote/tag. (Angle is measured in degrees)

From the above results following observations are made:

1. The accuracy is higher towards 0 and 180 degrees. However, the accuracy is bit away from ideal angles near +/- 120 degrees.

2. Maximum of 3^0 deviation is observed.

3. Mean error is calculated as 1.9^0.

4. The divergence in the angle (errors) depends on the setup environment and the BLE beacons vendors.

V. CONCLUSION

The introduction of new features, i.e., AoA in BLE, has made it more reliable for indoor positioning systems, tracking assets/people, and wayfinding. For this, multiple antenna or antenna array is needed at locator end to capture the advertising packets containing data and control protocol data unit (PDU). Also, RF switches are needed for switching the antennae in the array. The algorithm for angle estimation and antenna array configuration should be chosen carefully for this system. Compare with others such as RSSI based using omnidirectional monopole rotatable and static antenna arrays, ToA/ToD, switched beam system, etc. This approach provides more accurate results with a mean error of 1.9^0 when performed in indoor environment and maintaining the distance between locator and remote/tag same throughout the experiment.

VI. FUTURE SCOPE

The Bluetooth direction finding feature (i.e. an angle estimation) combined with the RSSI (for distance measurement), will make BLE a very accurate IPS with sub-meter accuracy with an advantage of low power consumption. It makes it more famous across different manufacturers and will be widely adopted for building the next generation of advanced location-based services using Bluetooth.

Using the concept of multiple angle intersection, two or three angles are calculated from a single or two beacons. The intersections of the line drawn from the Rx to the Tx(s) along the calculated angles give the Receiver's location, likely in a three-dimensional coordinate system, which could result in the most accurate possible results with cost of the sophisticated antenna array configuration.

Although the application of this technology is novel and has a wide array of use cases, it has certain limitations. Using this technology in indoor environments has its problems. The multi-path propagation of the radio waves causes issues as to whether the transmitter's actual location might be incorrectly interpreted. Thus, each path would have different angle-of-arrival and time of flight.

There are different approaches to mitigate this, available for generic wireless technologies. Research is in progress, usually limited to the chip vendors to apply this to Bluetooth correctly.

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