Direction Finding Capability in Bluetooth 5.1 Standard

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Abstract. Bluetooth technology is a standard prescribed for short-range wireless communication that uses low-power radio frequency at a low cost. It is interoperable with all devices as it consumes a very small amount of energy. The Bluetooth Core Specification provided by Bluetooth Special Interest Group (SIG) will be adding direction finding feature in the Low Energy (LE) standard. This feature will enable a tracker to find the target by estimating the relative angle between the tracker and target. It uses either Angle of Arrival (AoA) or Angle of Departure (AoD) method with multiple antennas switching for direction estimation. To support this feature, the packet structure in LE physical layer is modified. The frames of the LE uncoded packets like the Protocol Datagram Unit (PDU) Header is modified and an additional frame known as Constant Tone Extension (CTE) is added to the LE packet structure. To implement the above ideas, we need to generate a portion of the LE packets in the National Instruments (NI) Bluetooth measurement toolkit. NI Bluetooth measurement toolkit is used for testing and measurement of Bluetooth RF signals. The results show that the CTE, which is needed for direction finding capability, is successfully incorporated in the BLE.5.1 packet structure.

Keywords: Angle of Arrival · Angle of Departure · Bluetooth · Constant tone extension · Low Energy · PDU header

1 Introduction to Bluetooth Standard

Direction finding is the measurement or the technique of calculating the direction from which a signal has been transmitted [1]. The basic need of a direction finding system is a directional antenna. Using this antenna system we can find the direction of an incoming signal using phase-based methods, Received signal strength indicator (RSSI) method, triangulation techniques etc. [2]. However more and more accurate methods are still being developed [3–5]. Presently a standardized framework for direction finding has been introduced within Bluetooth. This is based on AoA/AoD estimation i.e. phase-based estimation techniques. Historically direction finding techniques have been developed for as long as electromagnetic waves have been known. There have been many applications of direction finding such as in indoor positioning, asset

N. Kumar and R. Venkatesha Prasad (Eds.): UBICNET 2019, LNICST 276, pp. 53–65, 2019.
https://doi.org/10.1007/978-3-030-20615-4_4

tracking, security services, military intelligence and in intelligent communication systems like Space division multiple access which needs to acquire the direction of waves. For example, asset tracking is an application that is possible due to the direction finding capability in Bluetooth. The object can be tracked by attaching a simple Bluetooth radio tag to it. The tag is continuously transmitting signals and location observers are receiving direction finding enabled Bluetooth signals. As the tag moves, a terminal connected to various location observers computes its location. The asset can also be a user's mobile phone [6].

Another application is indoor positioning. Let us say we have a mobile phone, which has direction finding capability. With the help of an indoor positioning application running on the mobile phone and based on the measured properties of the received direction finding enabled Bluetooth signals coming from another device such as a positioning beacon, one can identify the direction of the beacon. This indoor positioning solution can be very useful in places like hospitals and can provide cm level accuracy and hence improves the navigation experience. Lastly, another application known as service discovery is also possible. This can be used in places where a large number of objects are on display such as a museum. Different objects are equipped with Bluetooth tags that continuously transmit direction finding signals to a mobile phone. Based on the collected signal, the mobile phone enables the user to get more information about the object, which will be collected from the Internet.

These are just some of the applications that are possible with direction finding ability. There are many more yet to be discovered and utilized. Some more applications involve finding a parked car in a crowded parking lot, item finding applications like finding a lost item or searching for a product in a shopping mall and various other IoT applications.

With the growth in usage of the Internet, wireless technology and IoT, Bluetooth evolved as one of the industry standards for Low Rate Wireless Personal Area Networks (IEEE 802.15-LR-WPANs) specially used for short-range wireless communication. As we all know Bluetooth exchanges the information or data between fixed or wireless devices over the unlicensed ISM frequency band of the range 2.4–2.485 GHz. Bluetooth is mainly managed by the SIG. The SIG first emerged with five members: Ericsson Technology licensing, Intel, Nokia, Toshiba, and IBM, prescribed to transfer the data over short distances of range 10–100 m. Moreover many versions have been released like v1.1, v1.2, v2.0, v2.1, v3.0, v4.0 and more recently v5.0 with speeds ranging from 723.1 kbps to 25 Mbps. Bluetooth 5.1 is a recent standard that uses LE packets for transmission. An added feature called direction finding capability shows the location of the Bluetooth device, which is a new feature that is being implemented in the Bluetooth standard [5, 7–10]. For instance, when you want to transfer instructions or signals from one device to many, direction finding capability will be helpful especially if there are a large number of devices and therefore it is an important feature which should be introduced. Two mechanisms for finding the direction in Bluetooth 5 standard has been proposed by the Bluetooth SIG, one using AoA and the other using AoD [6].

In [7] the author has proposed a direction finding method based on sonification, which can be used for search and rescue operations. It proposes the use of a person's cellphone as a localization beacon. Different direction of arrival techniques has been used to determine the location. This was performed on a GSM network but Bluetooth was not used. The authors were able to achieve a method for tracking the signal strength of the user's cellphone. However, the authors state the need for accurate distance estimation techniques due to the urgency related to search and rescue operations. Lymberopoulos *et al.* [8] developed indoor position finding techniques mainly through the use of Wi-Fi. Both infrastructure-less and infrastructure-based (positioning beacons) methods were used. The results showed that indoor positioning was not satisfactorily solved. According to the authors, there did not seem to be a technology that could replicate the results of an outdoor GPS in terms of accuracy and smaller enclosures. From [9] and [10] the authors have used location fingerprinting methods to find the direction of a device using Bluetooth LE and comparisons have been made to its improvement over the use of Wi-Fi. However, the direction estimation is done based on RSSI and on the location of positioning beacons and not on the angle method, which again seems to lead to problems related to accuracy. In [11] the researcher found the location using RSSI signals and trilateration. With this method, a location accuracy of 2 m is achieved. Direction finding using AoA/AoD with legacy Bluetooth devices was carried out in [12]. From the results, it is seen that backward compatibility is possible and doesn't require any extra hardware. [13] details direction finding using angle estimation and compares its advantages over other methods like Time of arrival (ToA) methods. However, no simulation was carried out at the time. In [14], the author has simulated direction finding using AoD, which has yielded promising results. However, no hardware implementation was carried out to verify the results in real time. Based on reviewing the previous literature related to direction finding we can say that there is still a lot of improvements to be done with respect to better estimation using direction finding techniques. We will now have a look at our work, which is based on angle estimation techniques and how it improves upon the previous direction finding techniques especially in terms of accuracy.

In this work, we propose direction finding using Bluetooth 5.1, with angle estimation techniques which can provide accuracies even for indoor applications such as museums, shopping malls etc. For this, we need to make changes in the LE packet to accurately determine the phase difference at the antennas to find the direction. In order to do this, LE data packets have been given as input to an FSK modulator VI (Virtual Instrument file), where the modulated signal varies according to the frequency of the message signal. That means if 1 is given as input to the VI, +250 kHz is added to the RF carrier and if 0 is given, −250 kHz will be added. Later the FSK modulator output is fed to a waveform multiplier where it gets multiplied with an envelope signal and finally a Bluetooth LE waveform is generated. Moreover, the Bluetooth SIG have also given the core specification requirements and the requirements for AoA and AoD estimation [15]. Hence in this work, the implementation of direction finding on hardware and the results associated with it are also discussed.

Section 2 contains the terminologies and methodologies used for direction finding such as the measurement of AoA and AoD. Section 3 details the design and implementation of the overall packet structure including the modifications done to the Bluetooth LE packet structure. Section 4 shows the relevant results obtained after implementing direction finding in Bluetooth and a discussion on this. Section 5 gives a conclusion and some ideas regarding future work that can be done for the better utilization of direction finding.

2 Terminologies and Methodology Used for Direction Finding

In this section, we first discuss the basics of AoA, AoD, roles of the target and tracker, the LE packet format and the CTE.

2.1 General Requirements for Target and Tracker Device

A device assigned with a target role is not required to estimate the direction, but it is required to show its direction to the tracker device based on a trusted relationship. However, direction detection is based on antennas switching in a multi-antenna array. In such a solution the target device is required to support either a single antenna or a multi-antenna array or both. A tracker device should be able to request the target to send directional signals. Therefore, the target and tracker needs to support either a single or multiple transmit antennas depending on whether AoA or AoD is used.

Angle of Arrival

An LE device can make its direction available to a peer device by transmitting direction finding enabled packets using a single antenna. The peer device, consisting of an RF switch and antenna array, switches antennas while receiving part of those packets and captures in-phase (I) and quadrature (Q) samples. The I and Q samples can be used to calculate the phase difference in the radio signal received by different elements of the antenna array which in turn can be used to estimate the AoA.

Consider a receiver device with an antenna array consisting of antennas, separated by a distance ‘d’ as shown in Figs. 1 and 2.

The transmitter device uses a single antenna to transmit a signal. This can be seen in Fig. 3 where a perpendicular line is drawn from an incoming signal wave front extending to the antenna on the left at the point of intersection to the closest antenna i.e. the antenna on the right. The adjacent side of that right triangle represents the path difference relative to the angle of incidence of that wave front between both antennas. The phase difference, ψ, in the signal arriving at the two antennas is then calculated using Eq. 1.

$$\psi = (2\pi d \cos\theta)/\lambda \tag{1}$$

Where λ is the signal wavelength and θ is the AoA, and it can be derived from Eq. 1.

$$\theta = \cos^{-1}(\psi\lambda/2\pi d) \tag{2}$$

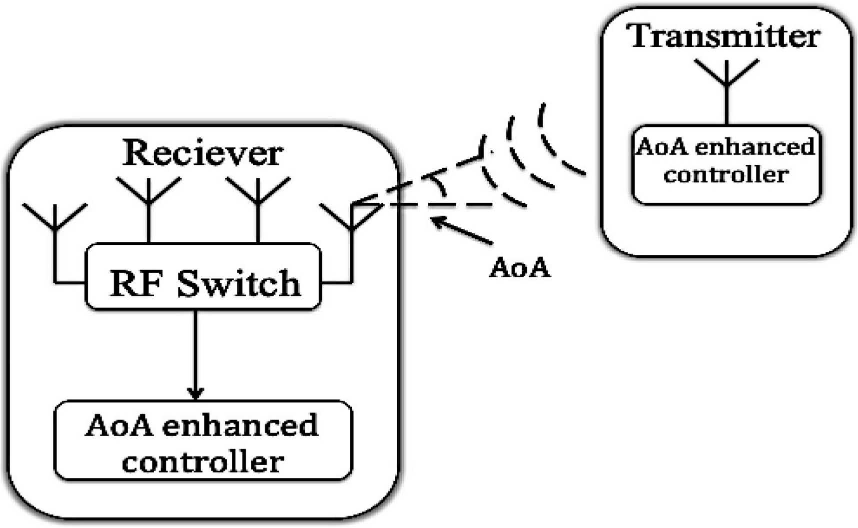

Fig. 1. AoA usage in direction finding [6].

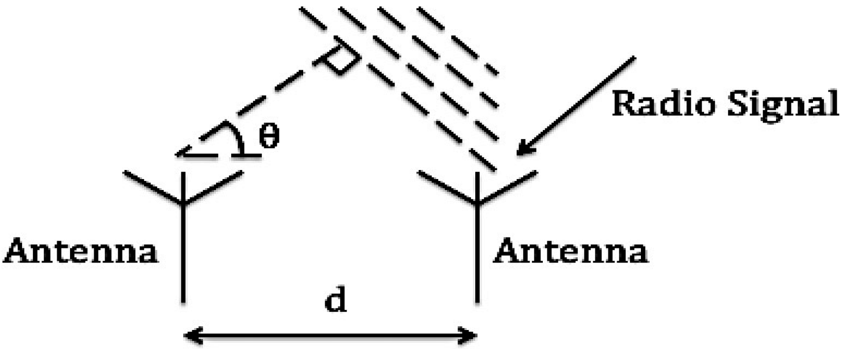

Fig. 2. Measuring the AoA [6].

2.2 Angle of Departure

A device consisting of an RF switch and antenna array can make its AoD detectable by transmitting direction finding enabled packets and switching the antennas during transmission.

The peer device receives those packets using a single antenna and captures I and Q samples. Determination of the direction is based on the different propagation delays of the LE radio signal between the transmitting elements of the antenna array and a receiving single antenna. The propagation delays are detectable with I and Q measurements. Any receiving LE radio with a single antenna that supports the AoD feature can capture I and Q samples and with the aid of profile-level information specifying the antenna layout of the transmitter, we can calculate the angle of incidence of the incoming radio signal.

The difference between AoA and AoD is that in AoA there is a single antenna on the transmitter side and multiple antennas at the receiver. In AoD method, there are multiple antennas on the transmitter side and a single antenna at the receiver. The difference in phase is calculated due to the multiple antennas at either the transmitter or receiver side switching between each other. This is used for the calculation of direction as being discussed. While making modifications on LabVIEW to test the packet we need to add specific controls to select whether we use AoD/AoA method.

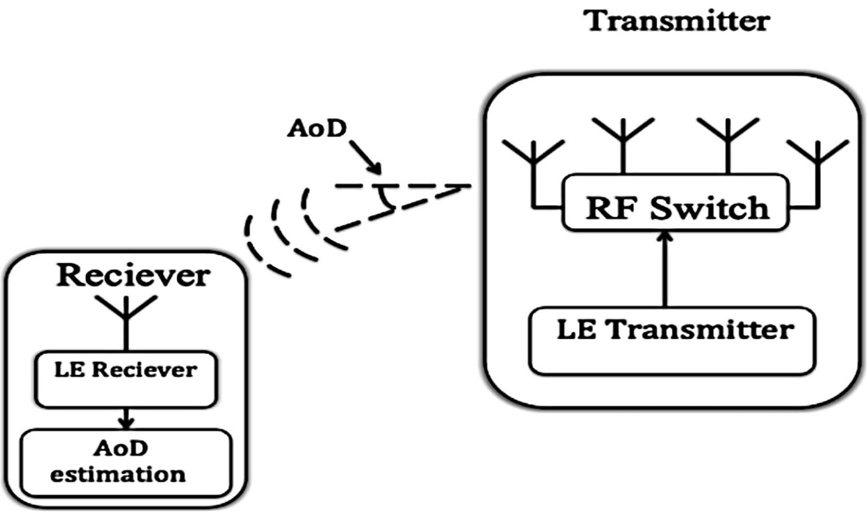

Fig. 3. AoD usage in direction finding [6].

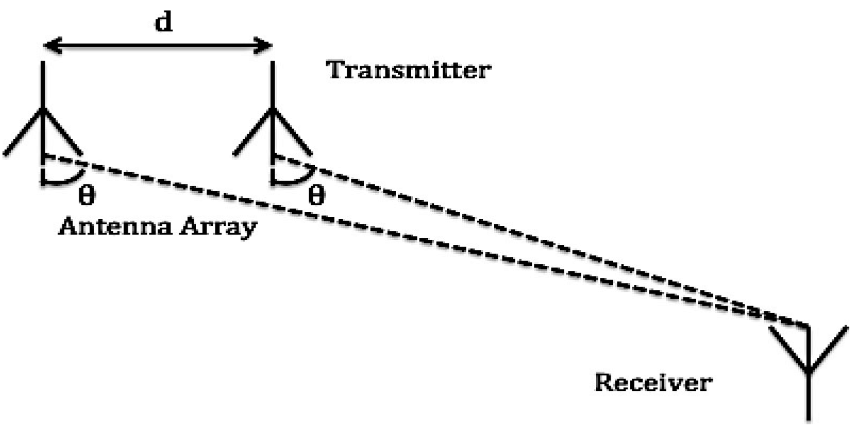

Fig. 4. Measuring the AoD [6].

Consider a transmitter device with an antenna array consisting of antennas, separated by a distance 'd' as shown in Figs. 3 and 4. The receiver device uses a single antenna to receive the signals. The phase difference, ψ, between the signal coming from the antenna on the left and the signal coming from the antenna on the right arriving at the receiver is then calculated using Eq. 3.

$$\psi = (2\pi d\, sin\theta)/\lambda \tag{3}$$

Where λ is the signal wavelength and θ is the AoD, and θ is calculated using Eq. 4.

$$\theta = \sin^{-1}(\psi\lambda/2\pi d) \tag{4}$$

3 Proposed Packet Design

The design and implementation of direction finding capability are carried out in LabVIEW using Bluetooth Generation Toolkit v18.0, which generates the test packets. Hence to do this, we considered the LE test packet, modified at some specific places to include the direction finding capability.

Figure 5 shows the packet format of the LE uncoded test packet. It consists of a Preamble of 1 byte, Sync Word or access address of 4 bytes, PDU header and PDU length each of 1 byte (together referred to as the PDU Header), a PDU payload which varies from 37–256 bytes, the Cyclic Redundancy Check (CRC) of 3 bytes and then followed by the CTE of varying length between 2–40 bytes. It is an addition to the packet format for making direction finding possible.

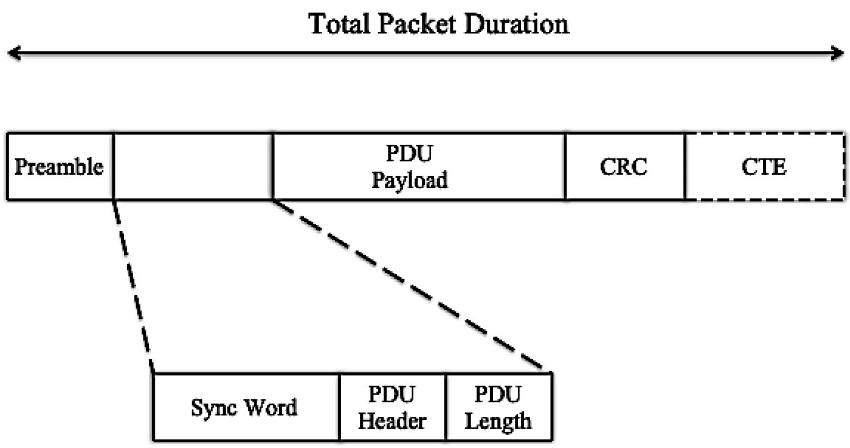

Fig. 5. LE uncoded test packet format

Generally, the PDU Header is of 2 bytes, but for the purpose of our work, we have added an extra 1 byte thus making the total length of the PDU Header 3 bytes. The 1 byte added to the PDU Header is known as CTEInfo consisting of a 5-bit CTETime to specify the length of the CTE, a 1-bit Reserved for Future Use frame (RFU) and a 2-bit CTEType frame. The CTETime field is varied from 2 to 20, which are in units of 8 µs (0.5 µs or 1 µs is the symbol duration). Therefore CTEType is 5 bits long as representation up to at least the number 20 is required. CTEType is used to specify which method of direction finding is used such as AoA or AoD. This one-byte CTEInfo is justified, as the angle estimation method of direction finding is more accurate compared to previous methods and leads to a better calculation of the direction from which the received signal came from [13].

We have modified the payload header to check whether CTE is present or not. To do this, an extra bit called Constant tone extension Present (CP) is included in the RFU as shown in Fig. 7. If the CP bit is marked as 0 then CTE and CTEInfo are absent indicating direction finding is not present. Whereas 1 indicates direction finding is enabled. Figure 6 shows the PDU header and length format without the inclusion of direction finding capability. Also as shown the CTEInfo field is missing.

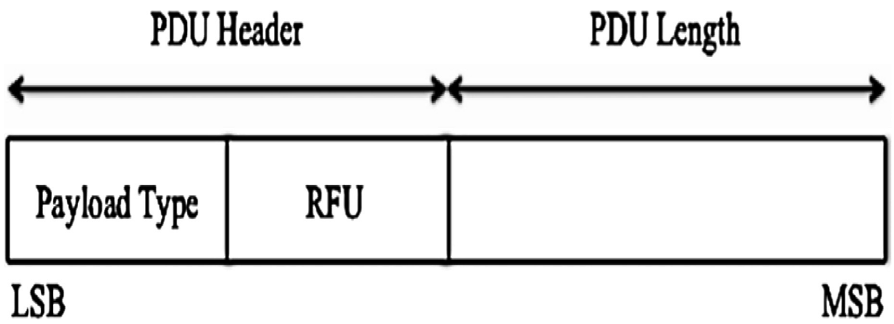

Fig. 6. LE Header format without direction finding

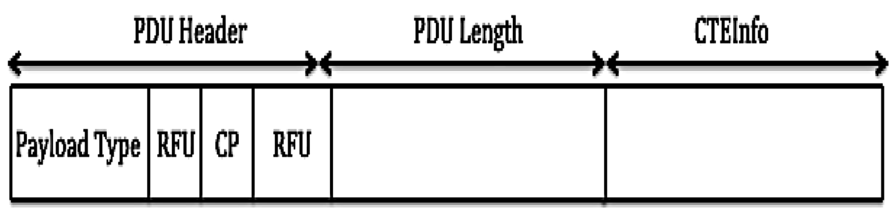

Fig. 7. LE Header format with direction finding

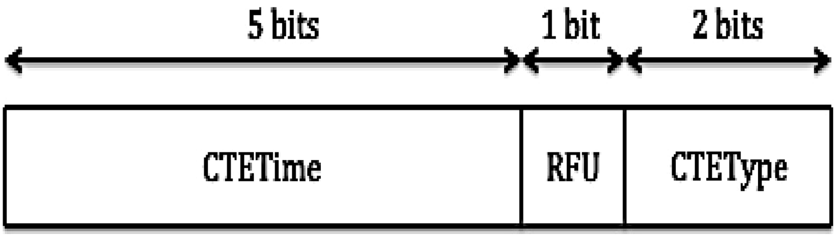

Fig. 8. CTEInfo frame

CP bit as shown in Fig. 7 specifies whether the CTEInfo is present or absent. The CTE is a series of continuous '1's or '0's. Initially, the simulations were carried out in LabVIEW software. The relevant fields i.e. 'VI's' in the LE uncoded packet format were modified and simulated in Bluetooth Generation Toolkit to add this direction finding capability. The CTEInfo frame, which as explained previously, is the additional 1 byte added to the PDU Header to incorporate direction finding and is shown in Fig. 8.

Though the addition of the extra byte produces an overhead the resulting improvement in accuracy more than compensates for this. In RSSI method the accuracy has been shown to be lacking especially in an indoor environment. Another method ToA is present which calculates the time of travel between the transmitting and receiving signal to acquire the distance. However, this method requires a very high clock accuracy to get a good estimation of the distance. Moreover, there is a standardized framework for AoD/AoA methods in Bluetooth [13].

4 Results and Discussion

In this section, we will be discussing how implementation and testing have been carried on NI hardware and the results associated with it. The resulting waveforms will be analyzed and discussed.

Figure 9 shows the front panel of the property controls for the Bluetooth LE packet. Here the payload length, payload sequence type, whitening settings, power ramp settings such as settling time and ramp time etc. can be set. As you can see we have included a special control panel for enabling the CTE. This is responsible for direction finding. Here we can also choose whether we want to use AoA or AoD method and we can also specify the length of the CTE through CTETime. These settings are tweaked accordingly to get the desired length and frame structure. Now to show that direction finding has been implemented we have to show that the CTE frame has been successfully transmitted while testing on hardware. The next sub-section will discuss the results acquired and the change in the packet power spectrum and frequency trace. This difference will be shown with respect to before adding CTE and after adding CTE respectively.

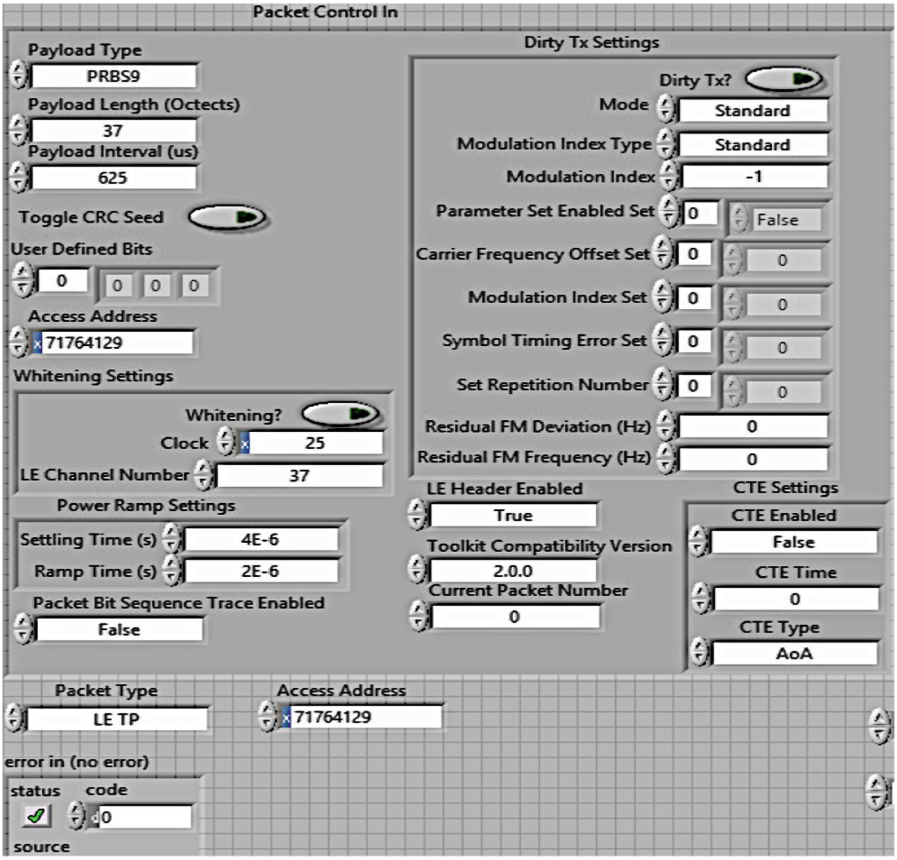

Fig. 9. Specifications of the LE packet.

4.1 Hardware Testing Results for Direction Finding Capability

The hardware testing was done on the NI PXIe hardware. Figures 10a and 10b show the power spectrum traces for LE packet without and with direction finding capability respectively. The x-axis is in frequency (Hz) and the y-axis is in power (dBm). The center RF frequency is 2.408 GHz. When a 1 is transmitted +250 kHz is added and when a 0 is transmitted −250 kHz is added to the center frequency as shown in Fig. 10a. A power spike in the +250 kHz part of the spectrum can be seen in Fig. 10b due to the extra CTE which is a continuous series of 1's. Due to this power spike, we can say that the CTE is present in the frame structure.

The frequency deviation trace for a single LE packet without and with direction finding capability is shown in Figs. 11a and 11b respectively. The x-axis is in time (sec) and the y-axis is in frequency (hertz). In Fig. 11b due to the presence of the CTE frame at the end of the LE packet which contains a continuous series of 1's, the frequency deviation trace shows +250 kHz continuously at the end.

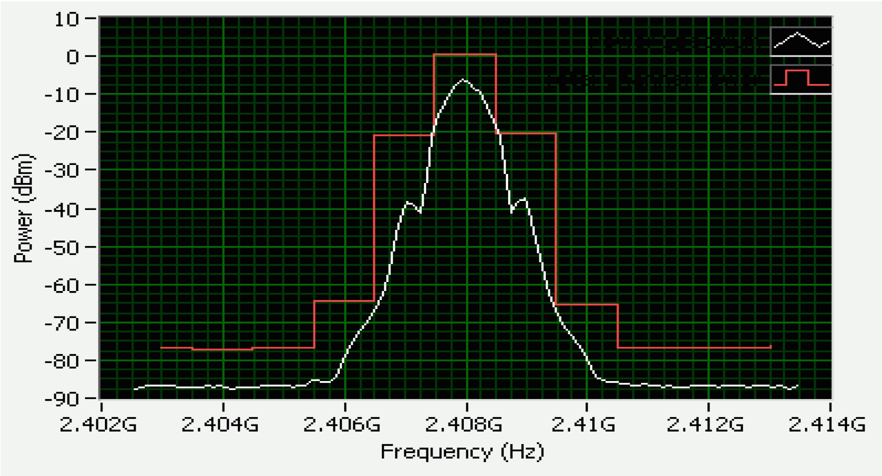

Fig. 10a. Power spectrum traces without direction finding + LE in-band emission channel powers (red line) as per the test specifications. (Color figure online)

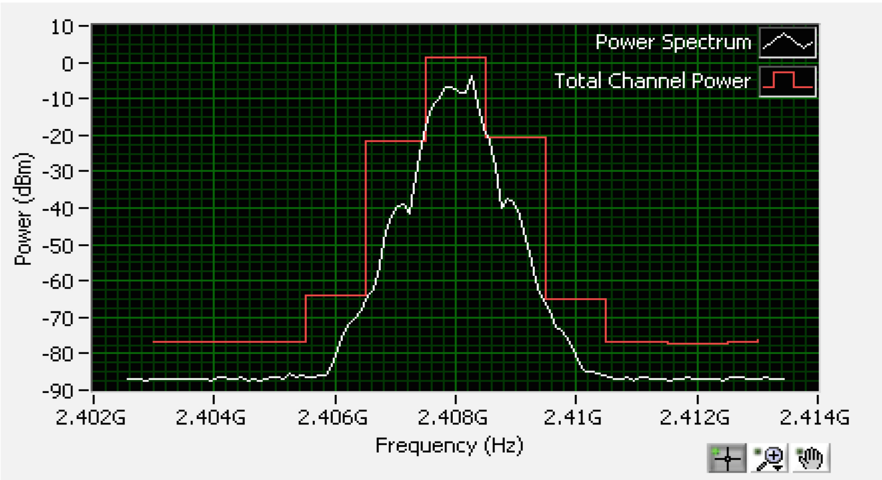

Fig. 10b. Power spectrum traces with direction finding + LE in-band emission channel powers (red line) as per the test specifications. (Color figure online)

From these tests and the resulting analysis, we can say that the CTE has clearly been integrated into the packet frame structure. The long series of ‘1’s of the CTE at the end of the packet makes sure there is no phase change during that time the CTE is received. This ensures that the phase difference between different signals can be calculated without any interference from the packet itself. When there is a change from

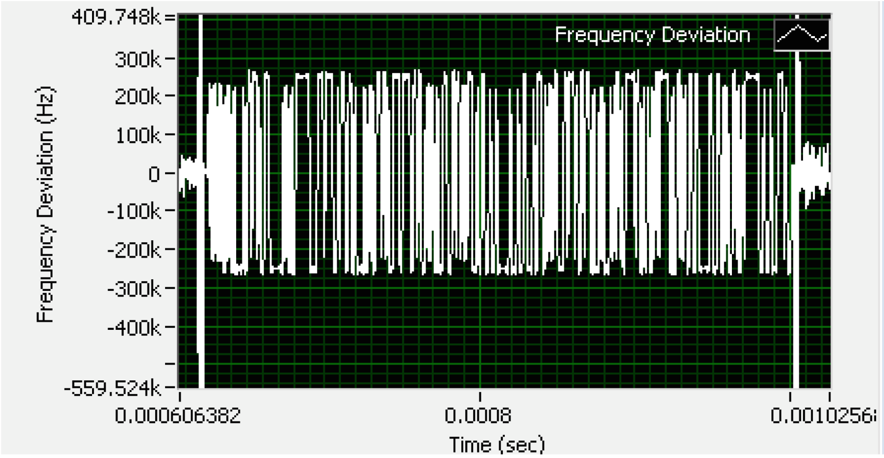

Fig. 11a. Frequency deviation trace without direction finding capability.

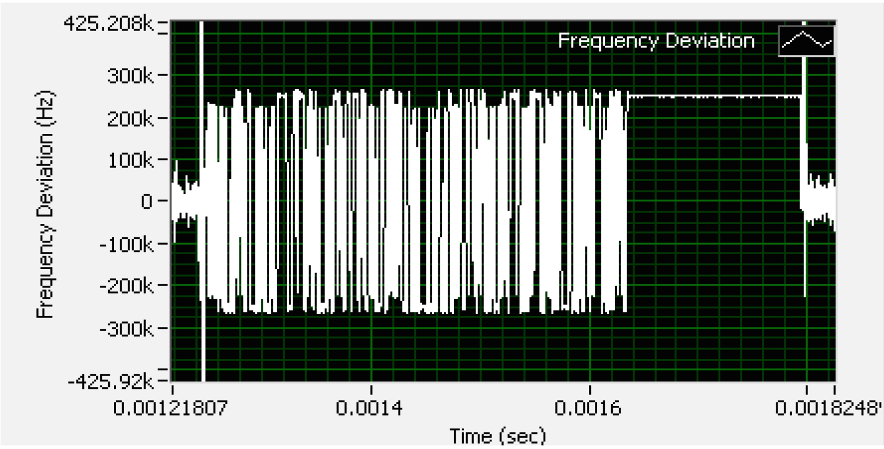

Fig. 11b. Frequency deviation trace with direction finding capability.

0 to 1 or vice versa in the packet frame there is a phase change. This does not happen when the CTE is being received as it only contains a series of '1's and hence doesn't interfere with the calculation of phase difference during antenna switching. Due to this the accuracy of obtaining the direction is greatly increased.

5 Conclusion and Future Work

In this paper, we implement direction finding capability in Bluetooth v.5.1. To implement this, we have modified the LE packet and the packet interval to accurately determine the phase difference in the antennas to find the direction using CTE.

The result for both the simulation and hardware shows that the direction finding is successfully implemented. The phase of the signal can be determined to perceive the direction of the Bluetooth device. Further in future work, the creation of emulated multiple antennas at the receiver side can be done for hardware testing. Also, modifications in the Bluetooth analysis toolkit for receiving the LE packets with CTE should be looked into.

Acknowledgment. This work was carried out at National Instruments R&D, Bengaluru, India, as a part of an internship course. The authors acknowledge the company for providing the resources during the course of the internship, without which the execution of the project would not have been possible. The authors would also like to thank the manager Abraham George for his constant support.

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