Bluetooth Direction Finding

A Technical Overview

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Revision History

Version	Date	Author	Changes
1.0.0	20 March 2019	Martin Woolley Bluetooth SIG	Initial Version
1.0.1	9 December 2020	Martin Woolley Bluetooth SIG	Language Changes
1.0.2	22 February 2021	Martin Woolley Bluetooth SIG	Corrections to Text Labels in Figure 20

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1.0 Introduction

Bluetooth® technology has been used in the provision of various types of <mark>location-based services</mark> for many years. Those location services fall into two high-level categories known as *Proximity Solutions* and *Positioning Systems*.

Proximity solutions include point of interest (PoI) information solutions, such as those found in museums that provide the user with information about artefacts in the room. The category also includes *item finding solutions*, such as Bluetooth tags, that help with finding lost or misplaced items like keys, wallets, etc.

Positioning systems, on the other hand, leverage Bluetooth to determine the physical location of devices. Major use cases for positioning systems include real-time locating systems and indoor positioning systems. Real-time locating systems are used for asset tracking and people tracking while indoor positioning systems are used to enable wayfinding solutions that help people navigate through complicated indoor environments.

In the world of Bluetooth connected devices, the *Find Me* profile helps people find lost objects with special Bluetooth tags attached, and the *Proximity Profile* helps people keep important items nearby and find them if they move too far away. These are both examples of Bluetooth standards that apply to the item finding use case. But it's Bluetooth beacons that tend to steal the headlines.

The Bluetooth beacon is a phenomenally successful application of Bluetooth Low Energy (LE) technology. It's expected that hundreds of millions of beacons will be shipping per year within the next few years.

In 2013, Apple introduced *iBeacon*. The idea was simple but powerful. By exploiting Bluetooth LE's ability to broadcast data in a one-to-many communications topology, special devices, which became known as *Bluetooth beacons*, could be created. A beacon broadcasts a unique ID, and an application on a smartphone receiving that ID could look in a database to identify the transmitting beacon and then provide the user with information related to that beacon's location, all in the blink of an eye and without the user having to do anything.

Retail was one of the first sectors to see the potential of Bluetooth beacons, and it has become common to deploy beacons in shopping malls, large department stores, and prestigious shopping locations like London's Regents Street. Typically, a smartphone application from the retailer responds

to beacon transmissions containing IDs it recognizes by informing the user of special offers available in the nearby store or department where the beacon is installed. The retailer also has the added benefit of gaining information about customer traffic within the store.

These days, beacons are found in all sorts of situations, providing positioning and proximity services in airports, art galleries, train stations, stadiums, and more.

Whilst adoption of beacons was progressing in various sectors, there were developments on the technical front too.

Not long after iBeacon was announced, Android and other smartphone platforms joined Apple in supporting beacons so that users of all smartphones could benefit. Other beacon message formats were defined as well, notably Eddystone from Google. Currently, it's estimated that there are approximately 130 million Bluetooth beacons worldwide and increasing annual shipments are forecast for the future.

2.0 Current Beacon Technology

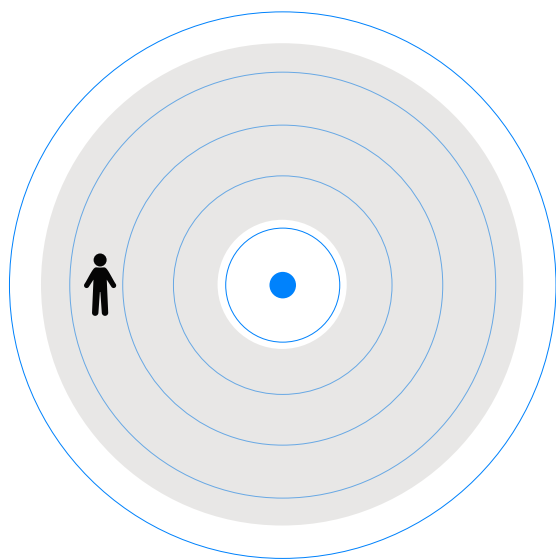Today's generation of beacon technology has been an enormous success, but it is not without its limitations.

2.1 Distance Estimation

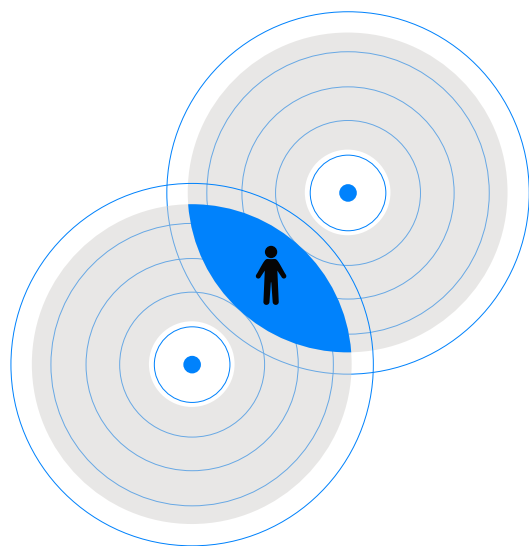It's common for an application to need to estimate the distance that the smartphone user is from a beacon whose broadcast transmission it has received. iBeacon and Eddystone both include a reference TX power value in their messages, and this informs the application of the signal strength that is expected at some fixed distance from the beacon, such as when one meter away. The basis for estimating distance from a single beacon then is to perform a calculation using the reference signal strength and the received signal strength (known as the RSSI). This approach works, but it's not accurate enough for many use cases and, even if the reference signal strength has been carefully calibrated when first installing the beacon, it can be affected by environmental conditions like the presence of people and humidity levels.

Figure 1 - Location estimation using today's beacons

2.2 Location Accuracy

Precisely locating a person in a building, for example, using today's beacon technology is not easy. Receiving a beacon message simply means that the user's smartphone is somewhere in range of the beacon. There's no way to determine the direction the beacon signal is coming from, and the person could be anywhere in a *more or less* circular zone around the beacon at a distance from the beacon which cannot be precisely determined, as shown in Figure 1.

More advanced solutions must therefore use multiple beacons and more complex algorithms, based on techniques like trilateration, to more accurately determine location. Even with this more complex approach, there are limits to the accuracy of position and direction information that can be derived.

Figure 2 - Using trilateration with today's beacons to improve positioning

3.0 The Need for Accurate Location and Direction Finding

There are many use cases that either require more accurate positioning data than today's beacons can offer, require the determination of the direction an object is in, or have both these requirements. iBeacon and the alternatives have served us well, but they cannot meet these higher-end requirements.

Example use cases that require greater accuracy and direction finding include high-accuracy indoor positioning, high-accuracy asset tracking, continuous direction finding, and directional discovery.

3.1 High-Accuracy Indoor Positioning

There's an obvious benefit in being able to more accurately determine the position of a person within a complex indoor environment, such as an airport. More dependable and user-friendly indoor navigation systems and more precisely targeted proximity solutions can be created.

3.2 High-Accuracy Asset Tracking

There are many scenarios that could be regarded as asset tracking scenarios, from keeping track of corporate assets in an office environment to monitoring the progress of product components as they pass through the various stages of a manufacturing process. Tracking use cases like these tend to need accurate positioning capabilities.

3.3 Continuous Direction Finding

There are devices on the market today that use Bluetooth LE to help you find lost objects. Keys are a commonly cited example. Smartphone applications use signal strength to estimate the distance from the lost object. But with no directional information available, using one of these devices to find something you've lost involves a degree of experimentation. This might include walking in various directions and observing the effect it has on the estimated distance from the lost object until you find the direction to walk in, which results in the distance steadily decreasing and, eventually, you finding your lost keys.

A direction finding capability where the direction to a lost object is continually updated would allow solutions to be created that guide the user directly towards the lost item, with no experimentation required.
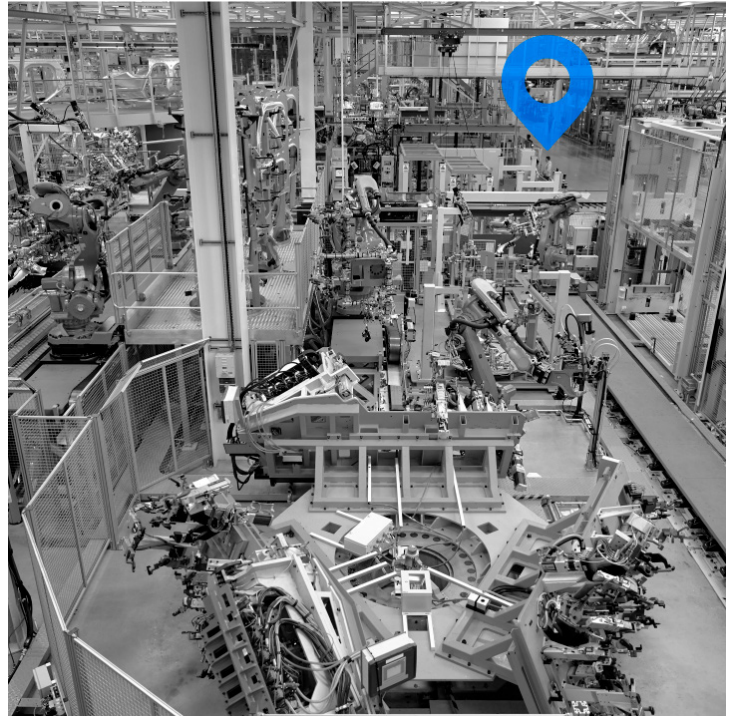
3.4 Directional Discovery

With directional discovery, if an art gallery has direction finding tags attached to its paintings, visitors can simply point their phone at a painting they're interested in, and the app on their phone filters out the signals from all the other paintings in the room, selecting the painting in the direction they're pointing and providing information about that painting.

Directional discovery goes a step further, allowing you to find an object in a given direction with a particular capability. Requests such as *find a printer over there* become easily dealt with if direction finding tags are in use.

4.0 About Bluetooth Direction Finding

The earliest radio direction finding work was conducted at the end of the nineteenth century by pioneers like Heinrich Hertz. Initial systems worked by comparing the strength of a signal when measured with an antenna pointing in various directions. The direction from which the strongest signal strength was measured was deemed to be the signal's direction of origin.

Work continued in the field throughout the twentieth century and new methods, especially those involving signal-phase comparisons, were introduced — delivering significantly better results.

Bluetooth Core Specification v5.1 introduces new capabilities that support high-accuracy direction finding. The controller specification has been enhanced so that specialized hardware that incorporates an antenna array can be used to support the calculation of the direction of a received radio signal. The Host Controller Interface (HCI) has also been modified so that data acquired by the controller can be made available to higher layers of the stack where direction calculations can take place.

4.1 Two Direction Finding Methods

Bluetooth direction finding offers two distinct architectures or methods, each of which exploits the same underlying basis. The first of the two methods is called Angle of Arrival (AoA) and the second is called Angle of Departure (AoD).

In each case, special *direction finding* signals are transmitted by one device and the signal is then used by another device to calculate the direction of the received signal.

Using AoA, the receiver contains a multi-antenna array as shown in Figure 3. Using AoD, it is the transmitting device that contains the antenna array, as shown in Figure 4.

4.2 Direction Finding Theory

Bluetooth direction finding exploits some of the fundamental properties of radio waves to acquire data that can be used in direction finding calculations. Applications use this data in calculations that involve
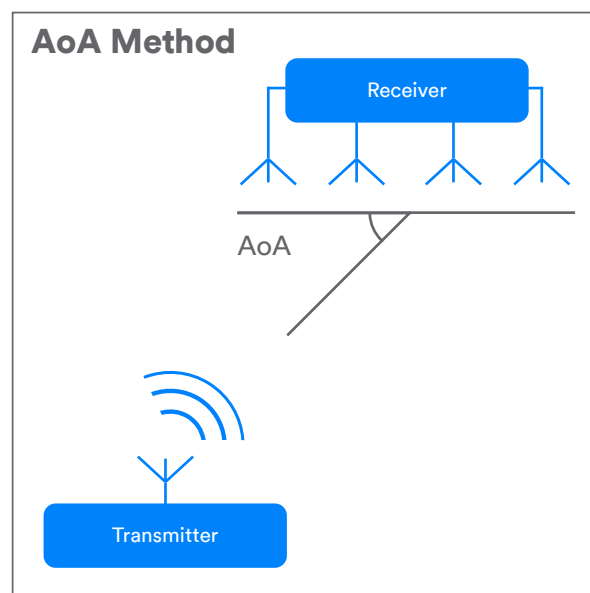

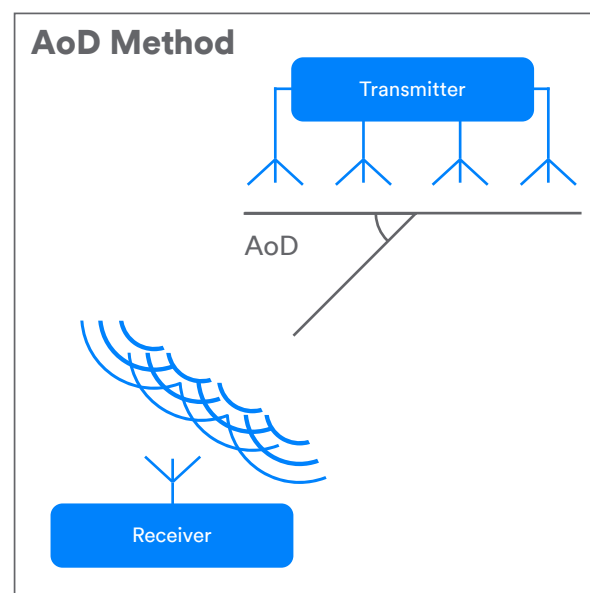*Figure 3 - The antenna array is in the receiver*

Figure 4 - The antenna array is in the transmitter

trigonometry and information about the design of the antenna array.

An explanation of the wave properties involved in Bluetooth direction finding follows.

Wave Cycle

Waves have a repeating pattern with peaks and troughs of maximum and minimum amplitude. Each repetition of the wave as it passes from an amplitude of zero to its peak down through zero amplitude to its trough and back up again to zero is called a *wave cycle*. The concept of wave cycle is illustrated in Figure 5.

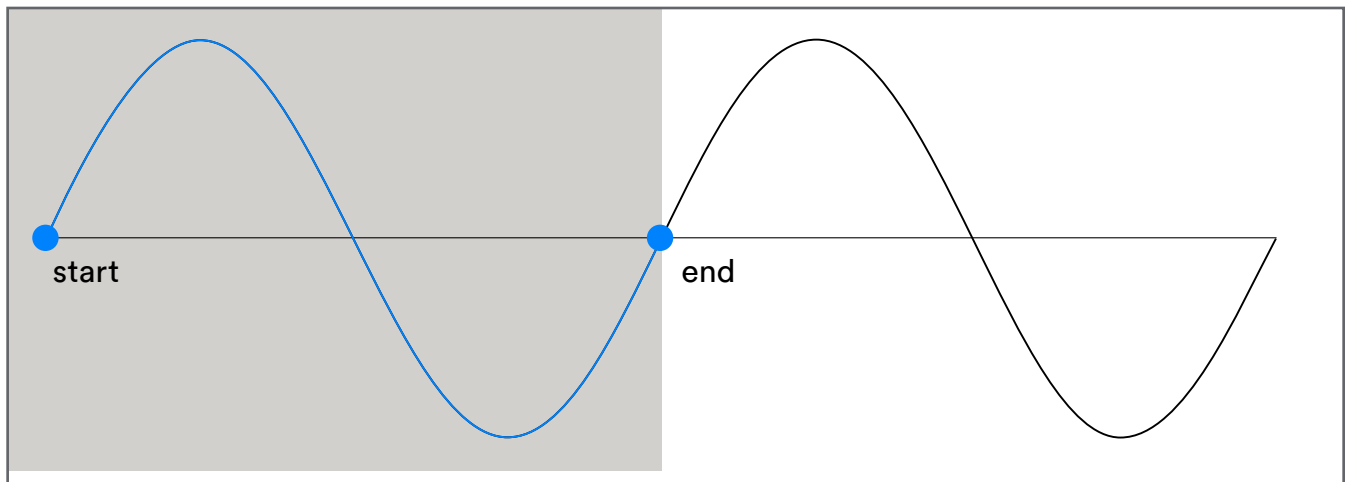

Figure 5 - Wave Cycle

Wavelength

Wavelength, shown in Figure 6, measures the distance between the start and end of a complete wave cycle. Depending on the frequency, Bluetooth has a wavelength of around 12.5cm.
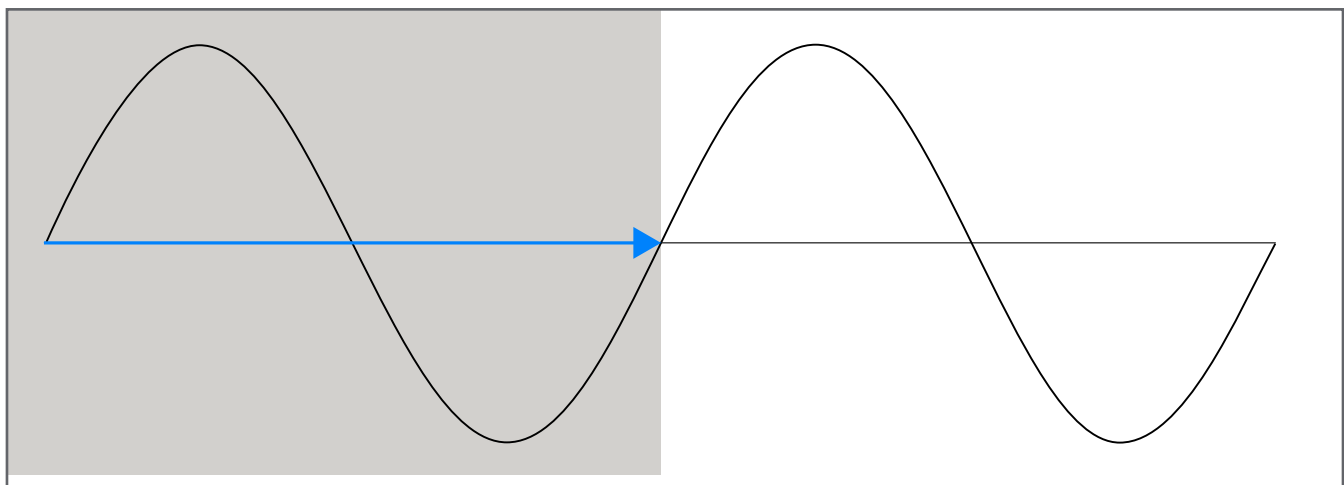

Figure 6 - Wavelength

Frequency

Bluetooth operates in the Industrial Scientific and Medical (ISM) band from 2.40GHz to 2.41GHz. Bluetooth Low Energy (LE) divides this band into 40 channels, each 2MHz wide. When in a connection, devices use 37 of the available channels with frequency changes driven by an adaptive frequency hopping algorithm. In connectionless scenarios, when using *extended advertising* introduced in Bluetooth Core Specification v5.0, all 40 radio channels are used. Consequently, communication using Bluetooth involves many different frequencies rather than just one fixed frequency. Wavelength, which is important in Bluetooth direction finding, will vary according to the frequency in use.
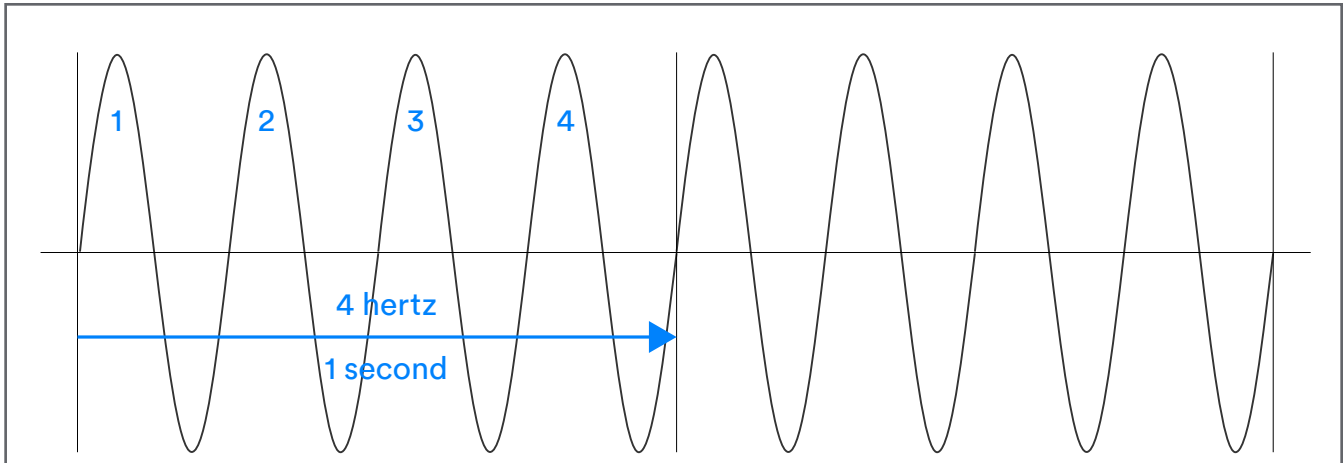

Figure 7 - Frequency

Phase

A specific point in a wave cycle, perhaps measured as the wave passes over an antenna, is known as its *phase*. Phase is measured as an angle from 0 at the start of the wave cycle to 360 degrees or 2π radians at the end of the wave cycle. Figure 8 illustrates the concept of phase.
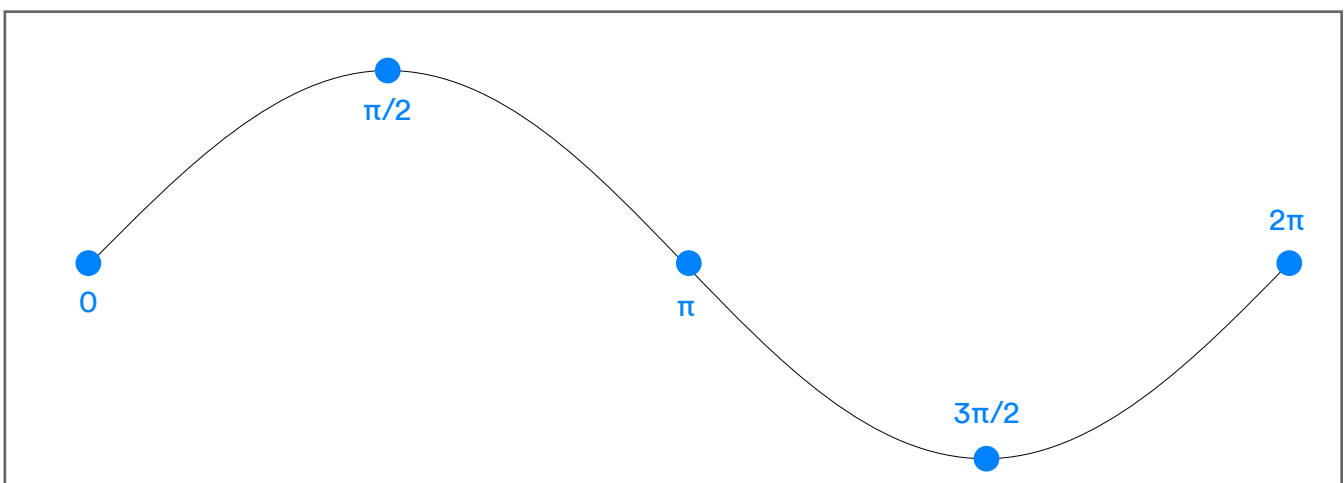

Figure 8 - Phase

Using Phase to Determine Signal Direction

When a transmitter emits a signal, in the absence of barriers or other factors that might impede it, it travels outwards from the transmitter at the speed of light in three dimensions. Its path traces an expanding sphere, and the wave front on the surface of that sphere has an amplitude that steadily reduces as the energy contained within the transmission is spread across a larger and larger surface area. As the sphere expands in size, it gets further from the transmitter.

To simplify this idea, it's easier to think in two dimensions rather than three, with the signal tracing a circular path like ripples that appear in a pool of water when a stone is thrown into it, spreading outwards away from the point at which the stone entered.

If we imagine an antenna placed in the signal's path, as the wave passes over it, the phase of that wave will vary continuously from 0 to 360 degrees. If we measure the phase at a given moment in time (*t*), the phase will have a value referred to as *p1*.

If we place another antenna in the signal's path, somewhere on the circumference of the circle which passes through the first antenna, then the second antenna must be at precisely the same distance from the transmitter as the first antenna. Given that each antenna has the same wave passing over it with the same frequency and, therefore, wave length, if we measure the phase of the radio wave passing over the second antenna at the same time, then the measured phase *(p2)* shall be equal to *p1.* See Figure 9.
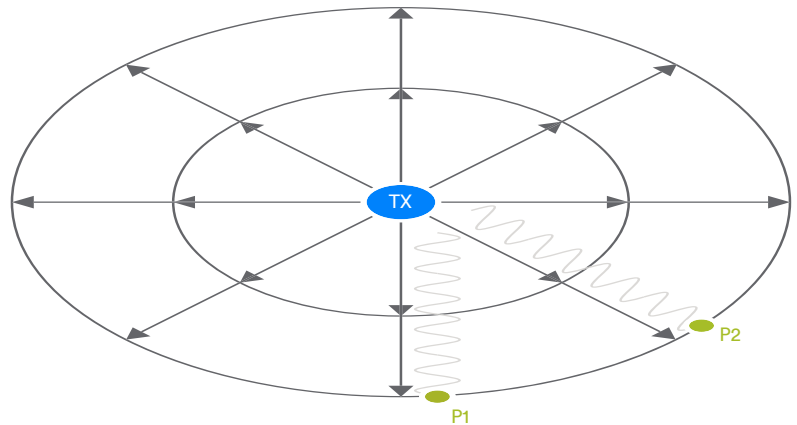
Figure 9 - Equal phase values at the same distance from the transmitter
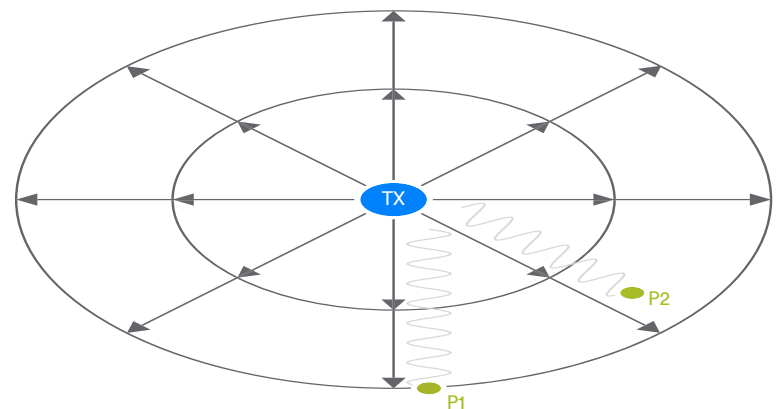
Figure 10 - Unequal phase values at different distances from the transmitter

If we now move the second antenna so that it is closer to the transmitter, taking care to ensure that the difference between the distance of antenna 1 to the transmitter and the distance of antenna 2 to the transmitter is not an exact multiple of the wave length, then if we measure p1 and p2 at time (t) we will obtain different phase values at each of the two antennae.

If we know the distance between the two antenna (in a straight line), the phase difference (p2 - p1), and the signal's wave length, then we can use basic trigonometry to calculate the angle of the signal as depicted in Figure 11a for the AoA method and Figure 11b for AoD.

$\boldsymbol{\theta}$ = arccos(($\boldsymbol{\psi\lambda}$)/($\boldsymbol{2\pi d}$))

$\boldsymbol{\psi}$ is the phase difference

$\boldsymbol{\lambda}$ is the wave length

$\boldsymbol{d}$ is the distance between adjacent antennae
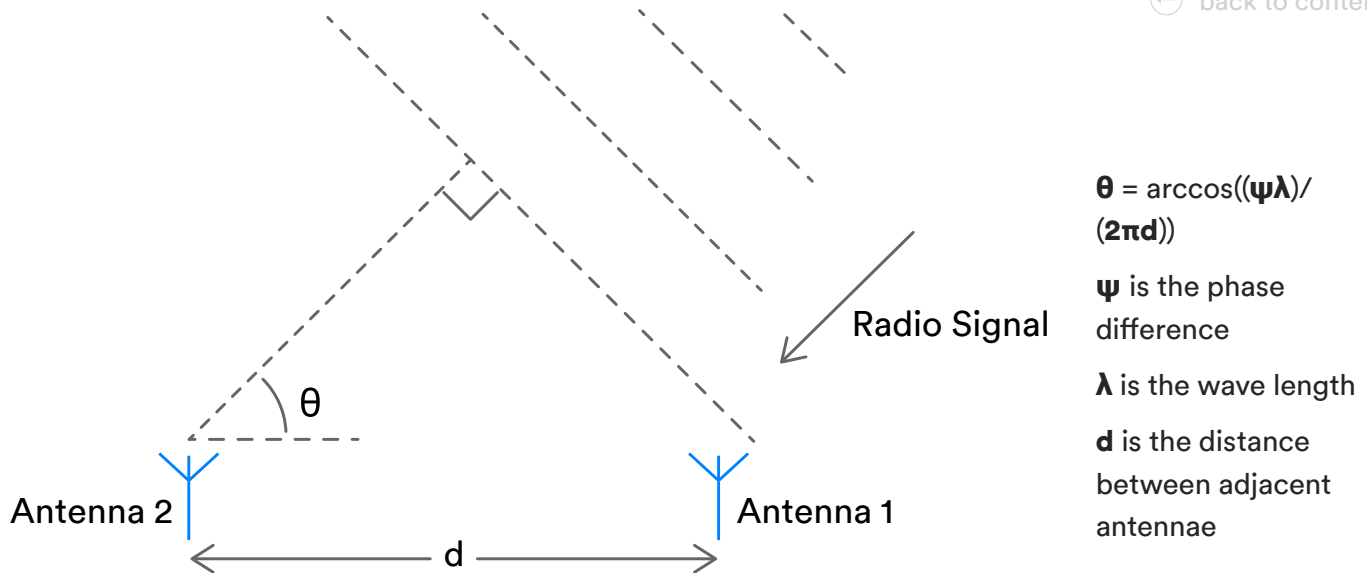
Figure 11a - Using phase difference to derive angle of arrival

$\boldsymbol{\theta}$ = arcsin(($\boldsymbol{\psi\lambda}$)/($\boldsymbol{2\pi d}$))

$\boldsymbol{\psi}$ is the phase difference

$\boldsymbol{\lambda}$ is the wavelength

$\boldsymbol{\theta}$ is the AoD
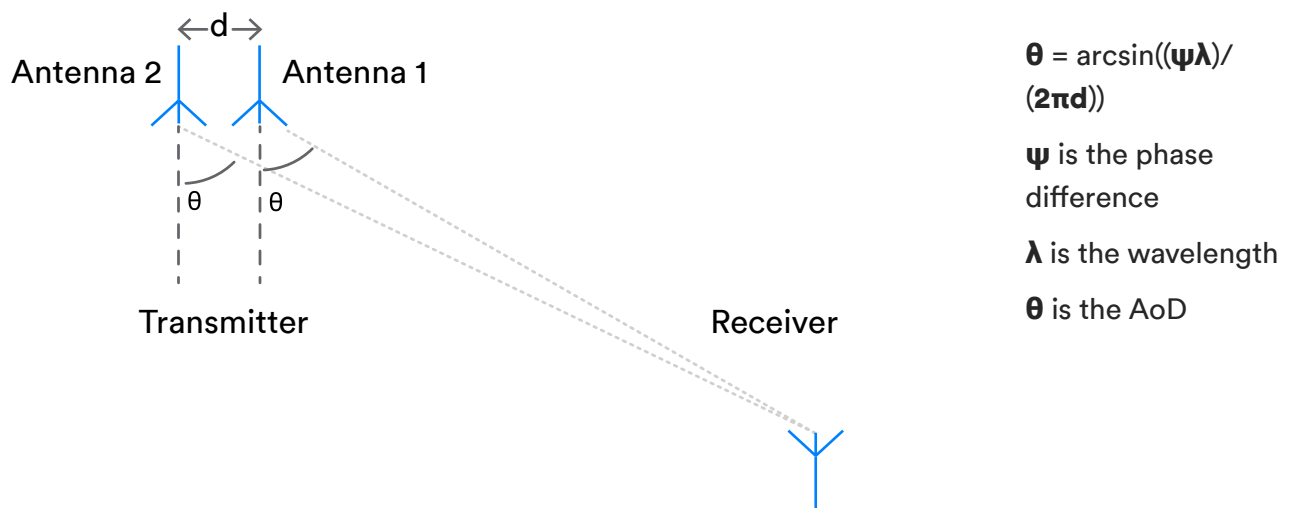
Figure 11b - Using phase difference to derive angle of departure

4.3 Sampling

Bluetooth direction finding makes use of specially formulated direction finding signals. A device receiving one of these signals proceeds by taking a number of phase and amplitude measurements at precise intervals in a process known as In-phase and Quadrature Sampling or IQ Sampling for short. A single IQ sample consists of the wave's amplitude and phase angle represented as a set of Cartesian coordinates. Applications can transform this Cartesian representation into corresponding polar coordinates that yield the phase angle and the amplitude value.
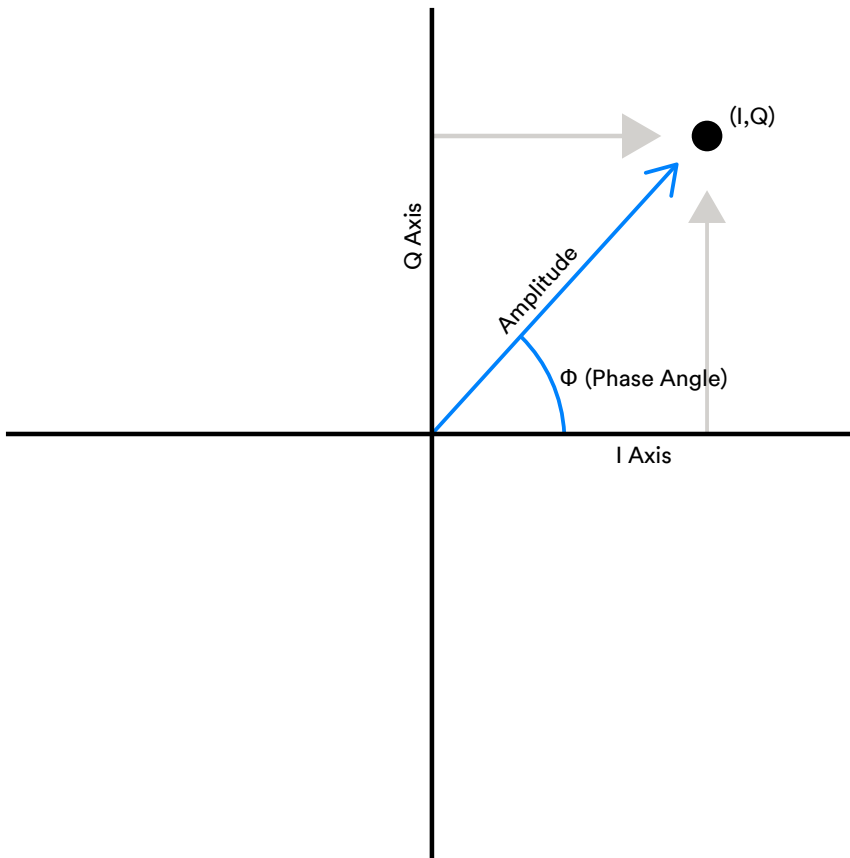
Figure 12 - Phase angle and amplitude as (I,Q) Cartesian co-ordinates

When performing IQ sampling in a device that has an antenna array, each of the samples captured must be attributed to a specific antenna in the array.

In the case of AoA, the receiver contains the antenna array and it will perform IQ sampling from each antenna in some suitable sequence.

In the case of AoD, it is the transmitter that contains the antenna array, but it is still the receiver that performs the IQ Sampling, taking measurements from its single antenna and using details of the design of the antenna array in the remote transmitter to attribute the measurements to particular antennae in the transmitter's array and in direction calculations. As such, for AoD to work, there needs to be a way of providing the receiver with details of the antenna array in the transmitter. Profiles that define how this is to be accomplished will be published by the Bluetooth Special Interest Group (SIG) in the future.

Figure 13 - Sampling from different antenna

4.4 Antenna Arrays

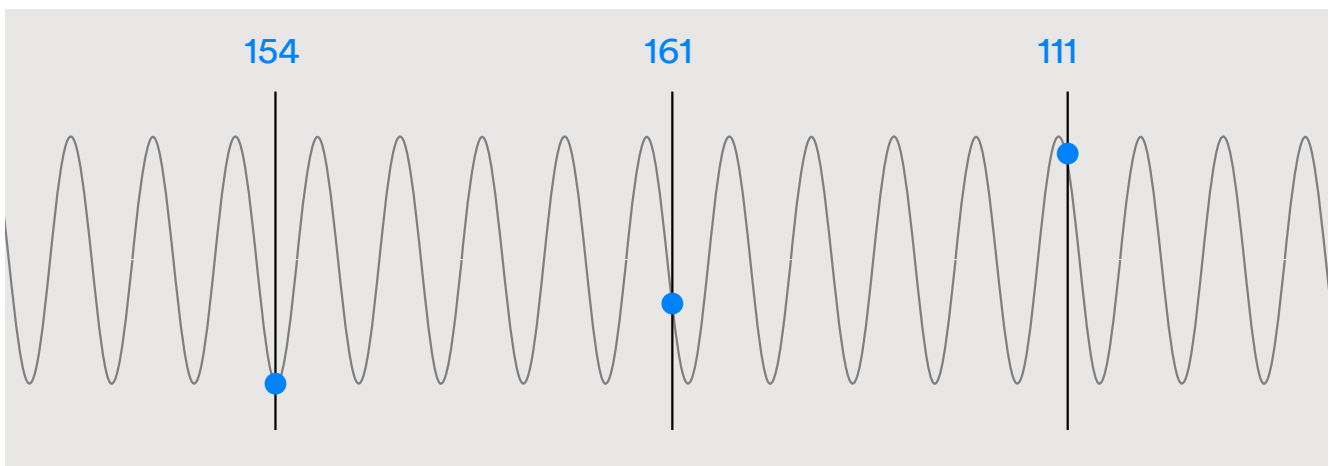Antenna arrays can have a variety of designs and numbers of antennae. A discussion about the pros and cons of different designs falls outside the scope of this paper, but an appreciation of the ways in which designs might vary should help form an understanding of the need for information defining the antenna array when calculating the direction of a signal from IQ sample data. Figure 14 shows a few example antenna array designs.
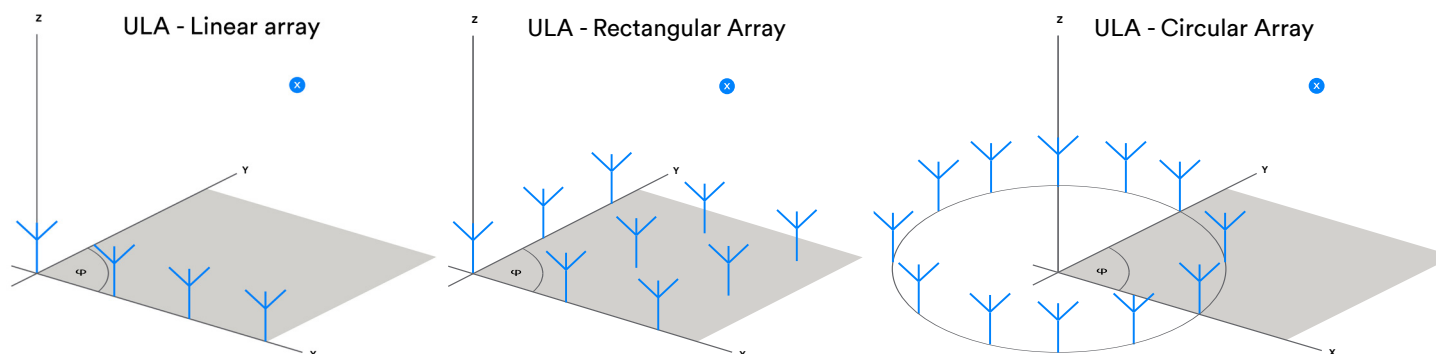
Figure 14 - Examples of antenna array designs

Simple, linear designs, such as the ULA, allow a single angle to be calculated from a signal. More complex antenna array designs can allow two or even three angles to be derived. It is common, for example, to need to calculate both the elevation and azimuth of the signal, relative to a reference plane. See Figure 15.

The intersection of the lines described by these angles can be used to pinpoint the location of the receiver device with a high degree of accuracy, measured in centimeters.

4.5 Bluetooth Direction Finding Signals

What is a direction finding signal?
New Bluetooth direction finding signals are an essential part of how Bluetooth direction finding works.

Direction finding signals provide a source of constant signal material that IQ sampling can be applied to. New Link Layer PDUs have been defined for direction finding between two connected devices, and a way to use existing advertising PDUs for direction finding purposes has been defined for connectionless direction finding. In each case, PDUs have additional data known as the Constant Tone Extension (CTE) added to their end. See Figure 16.

Figure 15 - Azimuth and Elevation Angles

The Constant Tone Extension

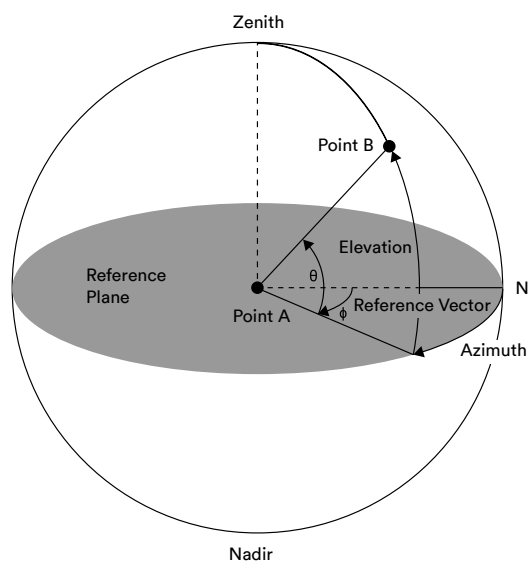The CTE consists solely of a series of symbols, each of which represents binary 1. The number of symbols contained within the CTE may be configured by higher layers of the stack so that a suitable amount of data and time is available for IQ sampling to be performed by the receiver, whose sampling capabilities may vary.
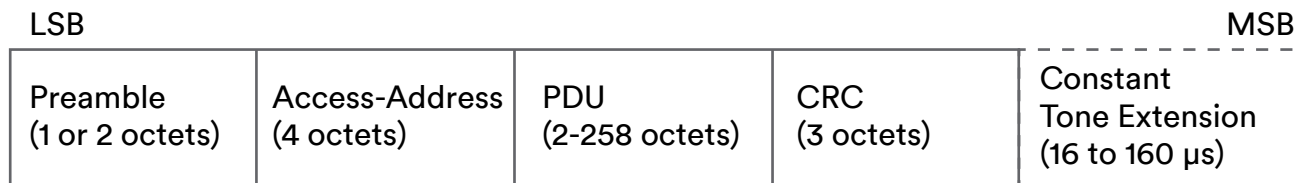
LSB   MSB

Preamble (1 or 2 octets)	Access-Address (4 octets)	PDU (2-258 octets)	CRC (3 octets)	Constant Tone Extension (16 to 160 µs)

Figure 16 - Bluetooth direction finding signal with CTE

Frequency Deviation

Within a selected radio channel, Bluetooth uses two frequencies: one to represent digital zeros and the other to represent digital ones. These two frequencies are arrived at by adding or subtracting a value known as the frequency deviation to or from the channel's center frequency.

Changing the frequency also changes the wavelength, and wavelength is a critical factor in the calculation of a direction from IQ samples. It is for this reason that the CTE consists solely of digital ones since it means that the entire CTE is transmitted at one frequency and, therefore, has a constant wavelength.

Cyclic Redundancy Check

All Bluetooth LE packets include a field known as the Cyclic Redundancy Check (CRC). The CRC is a value used for error detection. The transmitting device calculates a CRC value from the remainder of the packet to be transmitted, adds it to the end of the packet, and sends it. The receiving device performs the same calculation and compares the calculated CRC with the CRC on the end of the received packet. If they are found to be different, a communication error has occurred and changed one or more of the transmitted bits. The packet is then ignored by the receiver and may be retransmitted by the transmitter.

The CTE in direction finding packets is not included in the CRC calculation.

Message Integrity Check

If a connection is encrypted and authenticated, the link layer PDU includes a Message Integrity Check (MIC) field. The MIC is used to authenticate the sender of the PDU.

The CTE in direction finding packets is not included in the MIC calculation.

Whitening

Radio communications systems based on Frequency Shift Keying, including Bluetooth, often use a process known as whitening to scramble bits so as to avoid lengthy sequences of zeroes or ones in the transmitted bit stream. This is because there is a risk that such sequences will cause the receiver to lose its frequency lock and act as though the center frequency has moved up or down. Bluetooth LE uses whitening to scramble the PDU and CRC fields of all link layer packets.

The CTE in direction finding packets is not subject to the whitening process.

5.0 Using Bluetooth Direction Finding

5.1 Connectionless vs Connection-Oriented Direction Finding

The Bluetooth Core Specification v5.1 direction finding enhancements to the Bluetooth LE controller allow AoA and AoD to each be used in either connection-oriented or connectionless communication. However, it is expected that for typical use cases, AoD will be used with connectionless communication and AoA will be used over connections. This will be reflected in profiles that the Bluetooth SIG will release in the future.

Table 1 shows the four possible permutations of AoA/AoD and connectionless/connection-oriented communication. All are valid and, in all cases, support in the Bluetooth LE controller is optional.

	AoA	AoD
Connectionless	Controller support is optional	Controller support is optional *AoD will tend to use connectionless communication*
Connection-Oriented	Controller support is optional *AoA will tend to use connection-oriented communication*	Controller support is optional

Table 1 - AoA and AoD communication options

Connectionless direction finding makes use of Bluetooth periodic advertising and the CTE is appended to otherwise standard ADV_EXT_IND PDUs.

Connection-oriented direction finding conveys the CTE using new LL_CTE_RSP packets that are sent over the connection in response to LL_CTE_REQ PDUs.

In both cases, there are a variety of set-up and configuration steps that must be completed before IQ sampling is initiated and CTE-bearing packets are produced. The host will use host controller interface (HCI) commands to complete these steps.

5.2 The Host Controller Interface

The HCI provides the interface via which the host can configure the controller for direction finding CTE generation and receipt. The details vary according to whether connectionless or connection-oriented communication is to be used.
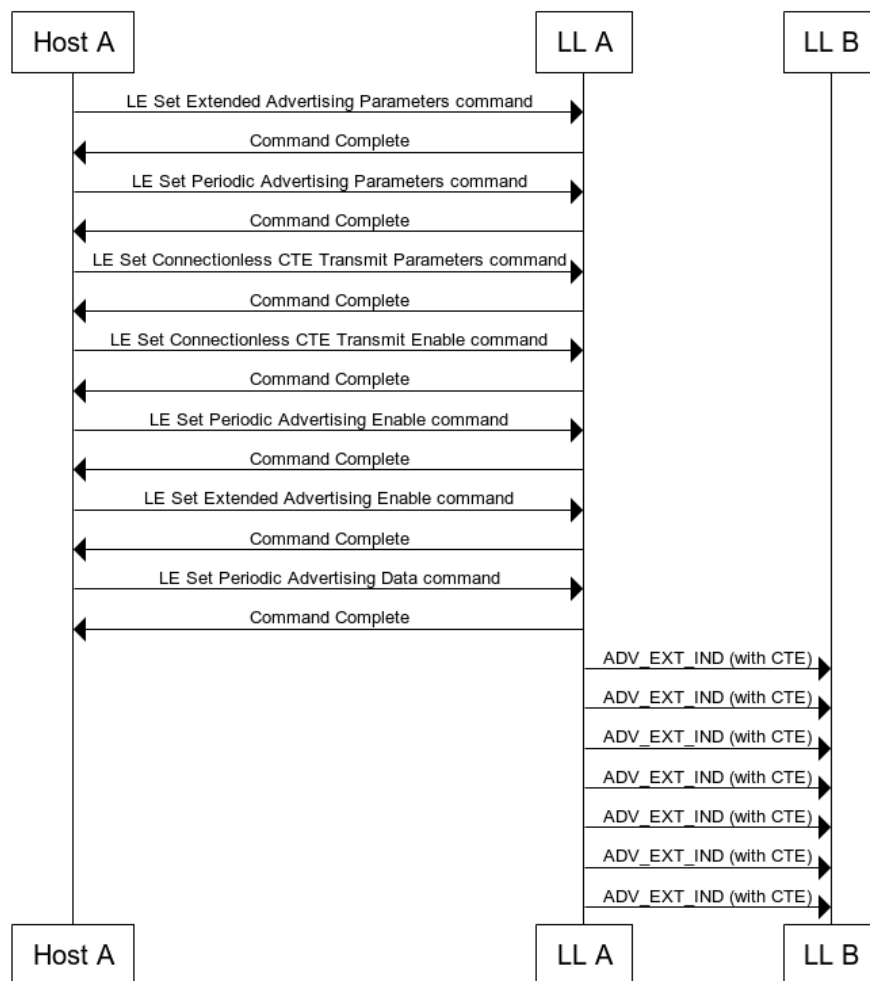
Figure 17 - HCI commands and connectionless CTE transmission by the advertiser

HCI and Connectionless Scenarios

In connectionless scenarios, the host in an advertising device must perform several controller initialization steps for periodic extended advertising packets with CTE to be produced. In summary, these are:

1. Configure extended advertising
2. Configure periodic advertising
3. Configure CTE transmission
4. Enable CTE advertising
5. Enable periodic advertising
6. Enable extended advertising
7. Set the advertising data

The corresponding HCI commands and their results are shown in Figure 17.

Connectionless AoA/AoD - Scanning
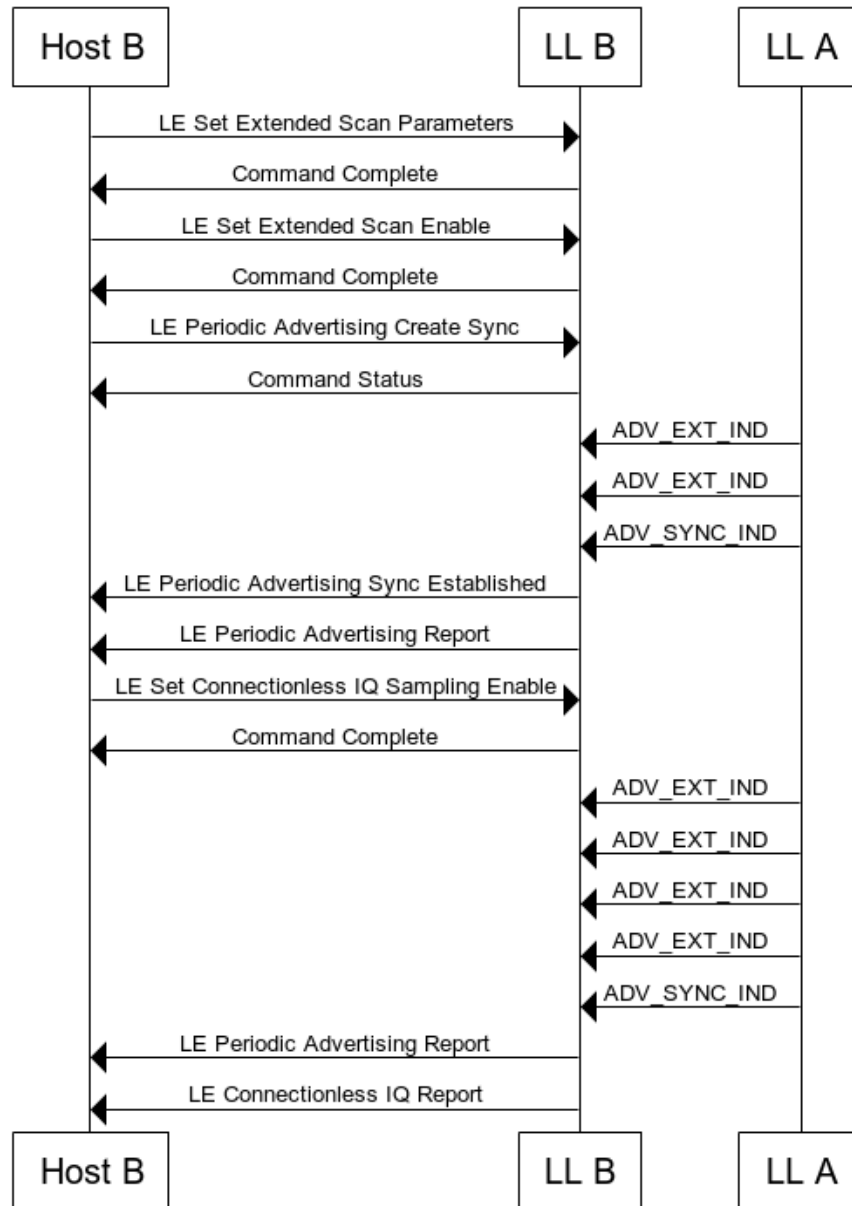
Figure 18 - HCI commands and connectionless CTE receipt by the scanner

Scanning devices wishing to receive and sample the CTE data transmitted by the advertiser must complete four controller configuration steps and then receive and process IQ sample data in the host. The four steps are:

1. Configure extended scanning
2. Start extended scanning
3. Synchronize with received periodic advertising sync packets
4. Enable connectionless IQ sampling

The corresponding HCI commands and their results are shown in Figure 18.

Connection-Oriented AoA/AoD
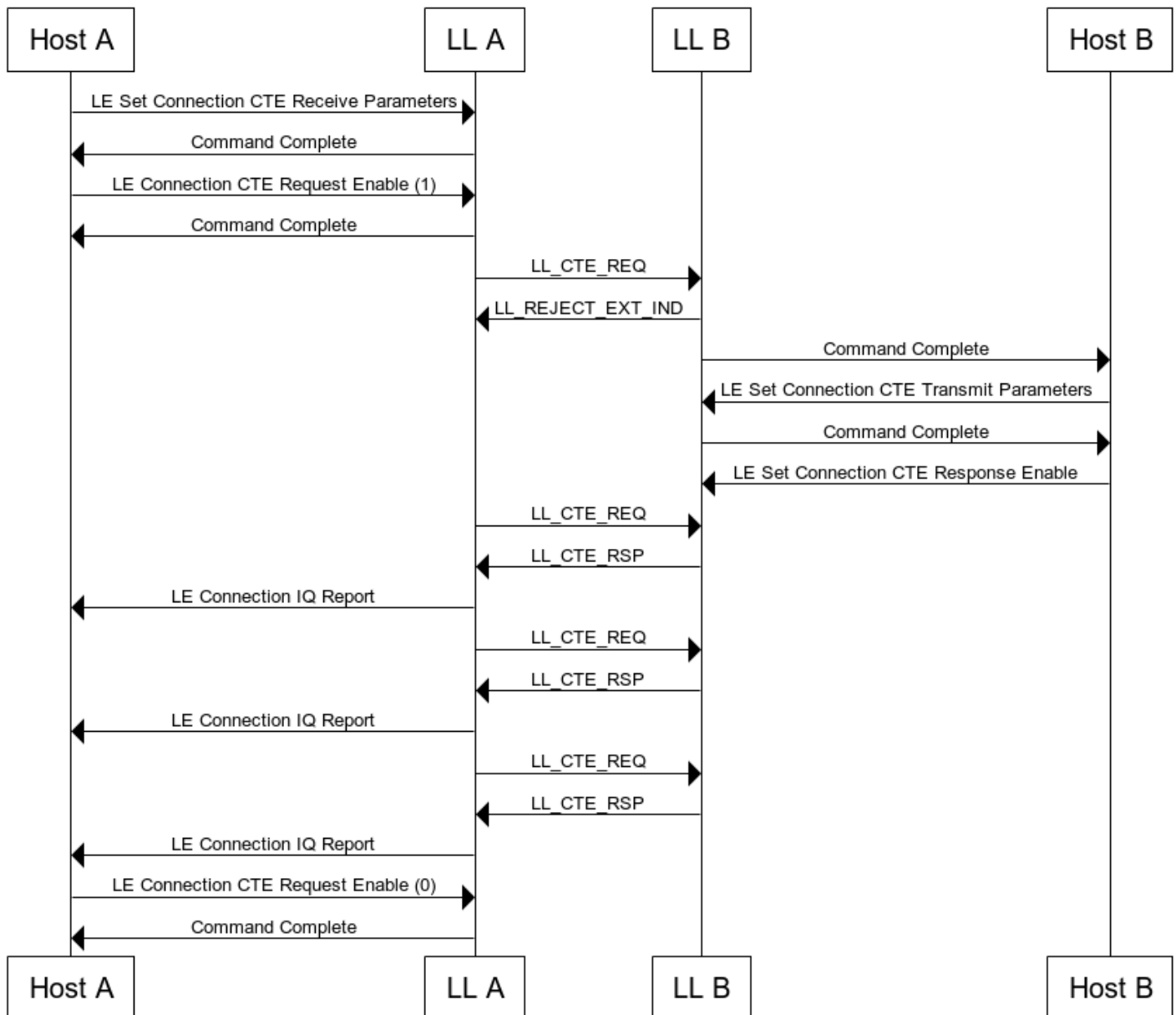
Figure 19 - HCI commands and connection-oriented CTE communication

HCI and Connection-Oriented Scenarios

In connection-oriented scenarios, either the Central or the Peripheral device may ask the other device to send a LL_CTE_RSP PDU containing a Constant Tone Extension. Requests are made by sending a LL_CTE_REQ PDU which contains a number of parameters that configure the CTE creation.

If the remote device does not support CTE, then it will indicate this by replying with LL_UNKNOWN_ RSP PDU and the local device will not send a LL_CTE_REQ PDU again using the current connection. The requesting host device will proceed by:

1. Configuring CTE receive parameters in the controller

2. Enabling CTE requests in the controller

3. Receiving and processing IQ reports

4. Disabling CTE request transmission when no longer required

The responding host will proceed by:

1. Configuring CTE transmit parameters in the controller

2. Enabling CTE responses in the controller

3. Receiving and responding to LL_CTE_REQ PDUs from the other device

Note that CTE requests are configured and enabled once by the requesting host, and CTE responses are configured and enabled once by the responding host. After which, LL_CTE_REQ and LL_CTE_RSP PDUs are exchanged until requests are disabled. If a LL_CTE_REQ is received before CTE responses have been enabled, it is rejected with a LL_REJECT_EXT_IND PDU.

Obtaining Antenna Array Information

The HCI also has a new command, *LE Read Antenna Information,* that allows the host to obtain information about the antennae supported by its controller. The procedure for obtaining information about the antenna array in a remote device will be defined in future profiles.

Parameters

The new HCI commands provide the host with the ability to configure various aspects of both CTE content and the procedures for creating CTEs and performing IQ sampling.

Parameters concerned with CTE content include the following:

CTE_Length	Length of the CTE measured in units of 8µs.
CTE_Type	CTE type may be AoA, AoD with 1µs slots, or AoD with 2µs slots. AoA CTE transmission does not require antenna switching whereas AoD CTE transmission does.
CTE_Count	Applies to connectionless scenarios and specifies how many packets that include a CTE are to be transmitted each periodic advertising event.

Parameters concerned with antenna switching and CTE sampling include the following:

Length_of_ Switching_ Pattern	Specifies the number of antennae in the set to be sampled from.
Antenna_IDs[]	Each antenna in the device's array can be referenced by a unique ID. The Antenna_IDs[] array lists the antennae to be switched through in the order they appear in the array. This is known as the *switching pattern*.
Slot_Durations	Specifies the duration of sample and switching slots as either 1µs or 2µs.
I_Sample[i], Q_ Sample[i]	Pairs of I and Q samples values in two arrays. Applications can transform the I and Q Cartesian format of these coordinates into amplitude and phase values.

The Bluetooth Core Specification v5.1 should be consulted for full details of the available parameters and the HCI commands they are used with.

Device Roles and Responsibilities

When a device is using an antenna array, antenna switching must be used according to a pattern specified in HCI configuration commands following strict timing rules. When performing IQ sampling, similarly strict timing rules apply but with some variation possible according to configuration. How these rules are applied and which device is subject to which rules depends on whether AoA or AoD is being used and whether the device is transmitting or receiving.

Antenna switching applies to devices that contain an antenna array. This is the transmitting device when utilizing the AoD method or the receiving device when performing AoA. Conversely, a transmitting device that does not contain an antenna array will transmit the Constant Tone Extension continuously without any antenna switching.

IQ sampling is always performed by the receiving device, irrespective of the number of antennae it contains.

Table 2 provides a simple summary of the roles and responsibilities of devices with respect to both antenna switching and IQ sampling.

	AoA		AoD	
	Switching	Sampling	Switching	Sampling
Transmitter			X	
Receiver	X	X		X

Table 2 - Switching and sampling roles and responsibilities

Timing

Timing rules governing both switching and sampling when handling CTEs are defined in Bluetooth Core Specification v5.1. Conceptually, the time for CTE processing is divided into an initial 4µs guard period, an 8µs reference period, and then a sequence of either switch slots, sample slots, or pairs of switch and sample slots. Sampling takes place during sampling slots and antenna switching during switch slots.

In the case of AoD, antenna switching is required when transmitting a CTE but not when receiving. When using AoA and receiving a CTE, antenna switching takes place according to the configuration provided by the host via HCI commands. When transmitting, no antenna switching is required.
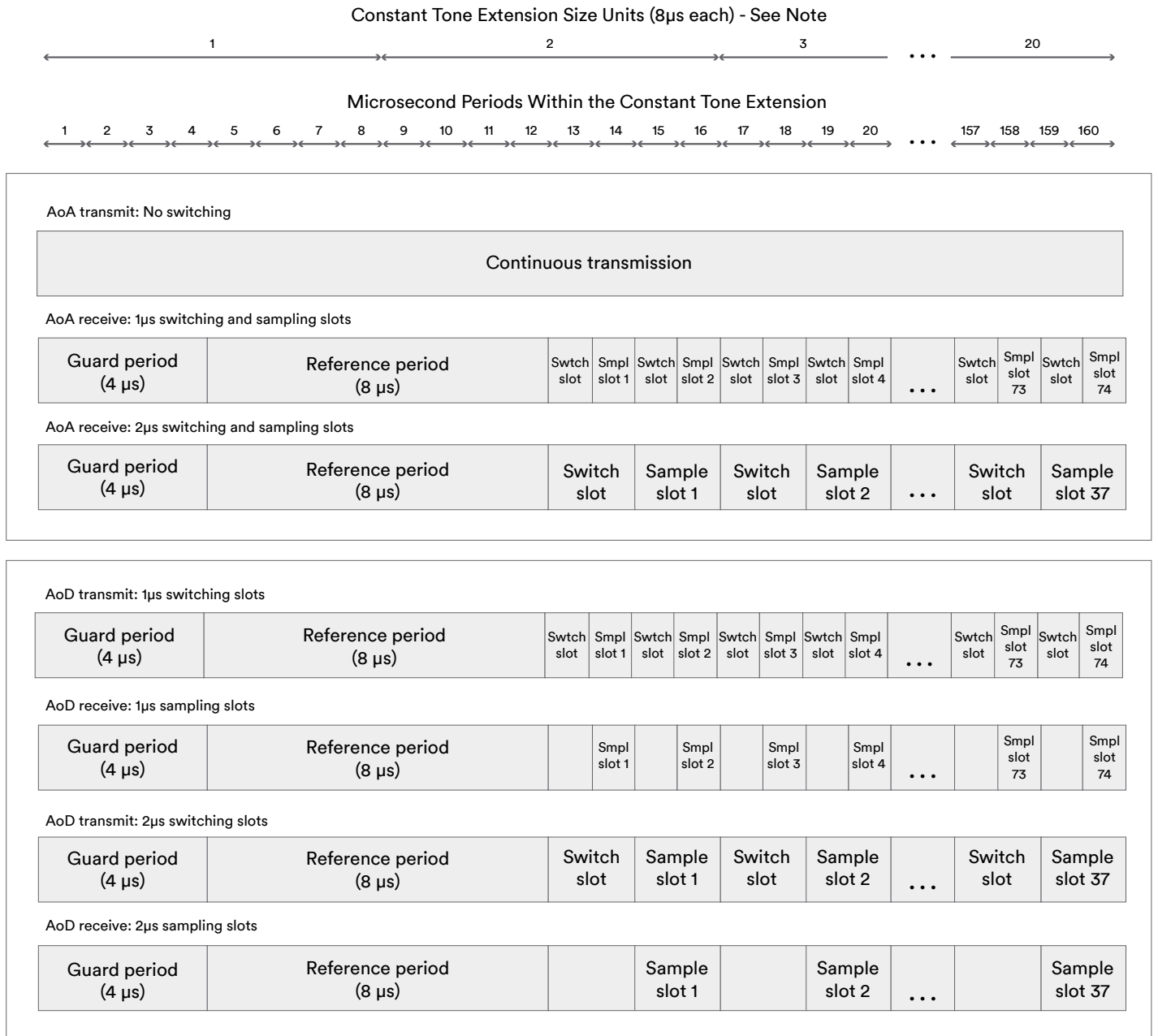

Figure 20 - CTE timing rules

Guard periods, used in many communications systems, are a technique designed to ensure there's a gap between adjacent transmissions so that they do not interfere with each other.

During the reference period, 8 x IQ samples are acquired from the first antenna at 1µs intervals. No antenna switching occurs during the reference period. The host may be able to use the 8 reference samples to estimate the frequency of the signal and, from this, the wavelength. This allows more accurate angle calculations to be performed.

Sample and switch slots may either be 1µs or 2µs long. Support for 2µs slots is mandatory while support for 1µs is optional. HCI configuration indicates which slot length is to be used by the controller.

Figure 20, reproduced from Bluetooth Core Specification v5.1, depicts the way in which timing rules apply to CTEs according to the transmit vs receive device role and AoA vs AoD method in use. Figure 21 summarizes the same data to show the options available.

guard period	reference period	switch slot 1	sample slot 1	switch slot 2	sample slot 2	switch slot 3	sample slot 3	switch slot n	sample slot n
4µs	8µs	1µs or 2µs	1µs or 2µs	1µs or 2µs	1µs or 2µs	1µs or 2µs	1µs or 2µs	1µs or 2µs	1µs or 2µs

Figure 21 - CTE timing options

5.3 Choices of PHY

The Bluetooth Core Specification v5.0 introduced three distinct physical layers (PHYs) to the stack.

LE 1M is the default PHY and provides a symbol rate of 1 megasymbol per second. Support for LE 1M is mandatory in all devices that support Bluetooth LE.

LE 2M provides a symbol rate of 2 megasymbols per second. Support for LE 2M is optional for devices supporting the LE controller.

LE Coded is designed for longer range communication and has the potential to quadruple the range that can be achieved whilst reducing the data rate. Support for LE Coded is optional for devices supporting the LE controller.

Bluetooth direction finding can use either of the LE 1M or LE 2M PHYs but not the LE Coded PHY.

5.4 Direction Finding Applications and Solutions

Application Responsibilities

Enhancements made to the LE controller in Bluetooth Core Specification v5.1 allow the raw material of direction finding to be produced through the link layer's Constant Tone Extension and the IQ sampling capability. Beyond this, to create direction finding applications, the applications themselves need to take responsibility for several issues, most of which will be covered by profile specifications to be released by the Bluetooth SIG in the future. The details will vary, depending on the use case an application is based upon, but common application considerations will include:

1. Determining beacon location

Indoor positioning will require applications to determine the precise location of beacons they encounter so that the location of the tracked device (typically a smartphone) relative to that beacon's known location can be calculated.

In some cases, the position of a beacon may need to be determined in three dimensions so that both its (x,y) coordinates in a horizontal plane are known and its elevation above or below some reference height. Either a global co-ordinate system may be used or some other local co-ordinate system.

It is only when the application knows the direction the received signal is coming from, the approximate distance to that beacon and the beacon's location, that the application can calculate the position of its host device.

The GATT indoor positioning service can provide this information.

2. Determining the point of interest (PoI)

In point of interest proximity applications, it will be necessary to determine what point or points of interest are nearby to the calculated location.

3. Phone orientation

In applications involving smartphones, it may be necessary for the application to take into account the orientation in 3D space of the phone when calculating signal direction.

4. Determining details of the antenna array

To correctly acquire and process IQ sample data, applications need to have a description of the antenna array in the local device (AoA) or remote device (AoD). Profiles will describe how applications can obtain antenna array descriptions from remote devices and it should be expected that APIs will emerge for both this case and for obtaining details of an antenna array in a local device.

5. Configuring CTE parameters

There are various parameters governing CTE production, such as the number of packets that include the CTE to transmit per periodic advertising event, the length of the CTE, the length of the antenna switching pattern, etc. Such parameters can be set via new HCI commands, and it is expected that platforms will add APIs to make it possible for applications to do so.

6. Configuring and enabling IQ Sampling

If sampling is to be performed, it must be configured and initiated. A series of parameters are defined, including sample slot duration (either 1μs or 2μs), the length of the switching pattern and the IDs of the antennae to be included in the sampling pattern.

7. Algorithms and the calculation of angles from IQ sample data

There is scope for taking anything from a mathematically simple approach to the derivation of angles from IQ samples to a more sophisticated multi-dimensional approach, calculating multiple angles and using their intersection to accurately determine locations. The Bluetooth SIG will not designate one algorithm as the standard direction finding algorithm, and so the choice of

algorithm is left to the application layer to address. It is believed that this is an area in which manufacturers and developers can compete. It should be noted that where appropriate, profiles that cover the other application issues listed in this section will be released, ensuring interoperability is safeguarded.

Requirements

Applications and solutions that provide or make use of location information will have accuracy and reliability requirements that may vary substantially from case to case. Bluetooth direction finding offers the potential to create solutions that can determine the location of a tracked object to within centimeters of its actual location. Not all solutions will require this level of accuracy, but when that is the case, there are a number of factors that solutions architects must consider when designing systems with these more demanding accuracy requirements.

There are two fundamentally different ways in which a location can be computed from radio signals.

Location Method 1 - Angle plus Estimated Distance

Using this method, the location of a device can be estimated by calculating the angle of a received direction finding signal from a single transmitter and estimating the distance from the transmitter by performing a path loss calculation on the Received Signal Strength Indicator (RSSI).

Estimating distance using the RSSI offers relatively crude distance estimation and, consequently, location calculations based upon it will not produce the most accurate results possible. It may be though that they are fit for purpose for many applications, and this approach offers the benefit of requiring the simplest components, such as the use of uniform linear antenna arrays.

Figure 22 illustrates this approach, and the gray area represents the region the user might be located within (not to scale). The angle is precisely calculated, but there is a more significant degree of uncertainty regarding distance from the transmitter.
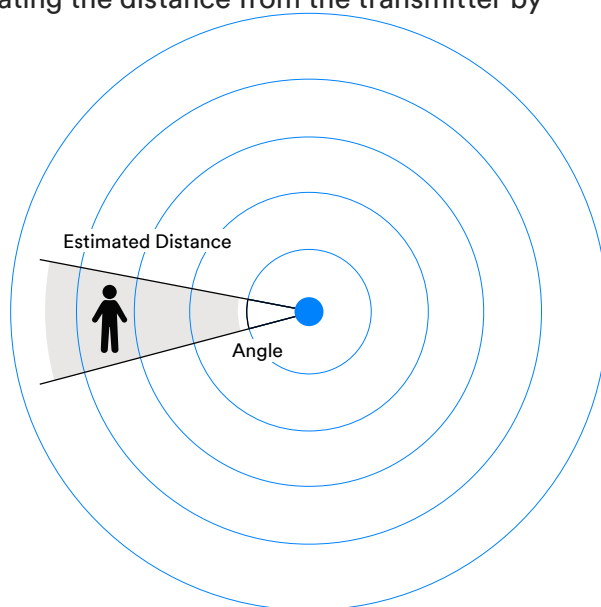

Figure 22 - Location determination using signal angle and RSSI distance estimation

The accuracy of location determination can be improved when using the angle plus distance estimation method by deploying multiple beacons to cover a given physical space and using trilateration to determine the region where the location areas calculated with reference to each beacon intersect.

Location Method 2 - Intersection of Multiple Angles

Using this method, either two angles are calculated from a direction finding signal from a single beacon or three angles are calculated from signals from two beacons. The intersection of the lines traced from the receiver back to the transmitter(s) along the measured angles provides the location of the receiver device, potentially in three dimensions.

This approach can yield the most accurate results possible but requires a more sophisticated antenna array to be used.

Accuracy and Reliability

The concept of accuracy provides a measure of how close to the actual location of an object we can expect our calculated locations to be. Allied to this is the concept of reliability, which provides a measure of the percentage of calculated locations that will fall within a given accuracy range. Figure 24 illustrates this idea.

Factors that will affect accuracy and reliability include physical environmental factors, such as the height of ceilings and the proximity of walls, each of which can give rise to multipath propagation of signals. Such issues can, to an extent, be mitigated by increasing the density of direction finding beacons.
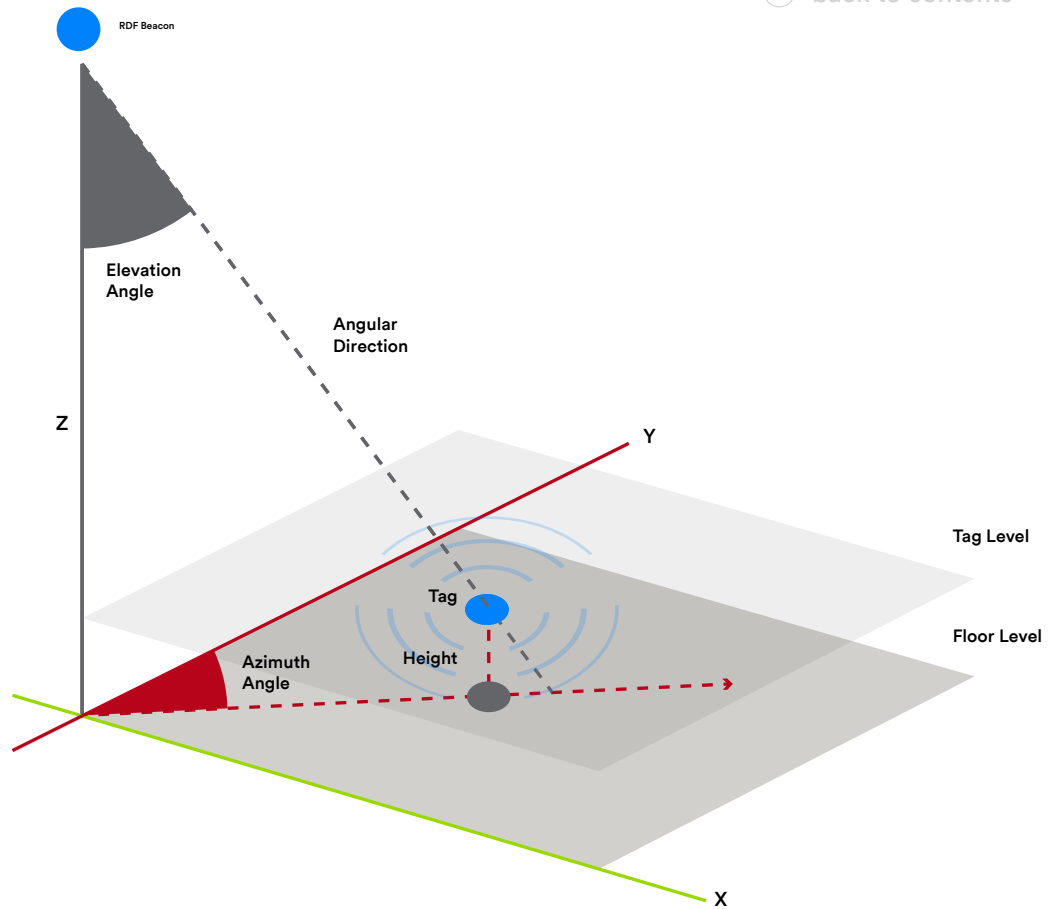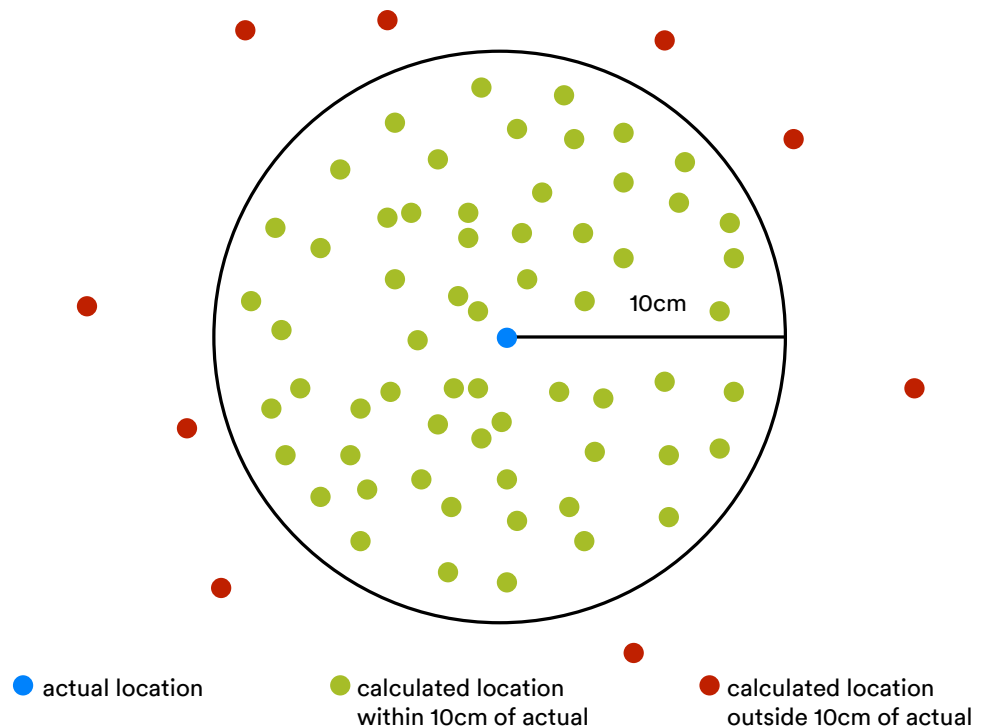
Figure 23 - Two angles calculated from one locator

10cm accuracy with 86% reliability

Figure 24 - The accuracy and reliability concepts

6.0 Conclusion

With Bluetooth direction finding, proximity and positioning systems operating at sub-meter accuracy levels can now be created for use cases, such as indoor positioning, way finding, asset tracking and object finding, and directional discovery.

Bluetooth direction finding leverages proven engineering techniques for determining signal direction and standardizes the interfaces, interactions, and important internal operations involved. Accurate direction finding is now interoperable across manufacturers and will be widely adopted to create a new generation of advanced Bluetooth location services.