The Many Communication Modes of Bluetooth® LE

Introduction

Background

Bluetooth technology first arrived in the world way back in the year 2000. The newer, more energy-efficient variant, Bluetooth Low Energy (LE), was released about ten years later and has become very well established, featuring as it does in an enormous number of products.

Bluetooth LE is well known as the wireless communication technology that lets your phone connect to your activity tracker and synchronize data repeatedly throughout the day, all without any noticeable impact on the battery level of either device. Efficient communication that involves frugal use of energy was one of the primary goals that were pursued in designing Bluetooth LE, and it's fair to say that it delivers well on that goal.

As end users of such products, we're accustomed to the *connect*, *exchange data*, *disconnect* sequence that Bluetooth LE uses, and we talk casually about our devices connecting (or occasionally, not connecting when we're having problems!).

But did you know that a *connection* is a specific technical state and that connection-oriented communication is just one of several communication modes that Bluetooth LE can use?

In this article, we'll introduce each of the communication modes and look more closely at each of them in subsequent articles.

Terminology

The Bluetooth Core Specification defines the various communication modes in rigorous technical language, but you won't find the term *communication mode* used. Instead, the formal term used in most cases is *logical transport*. But in some instances, there are significant variants of a logical transport, and each is best treated as a topic in its own right. For example, one of the newest features of Bluetooth LE, Channel Sounding, operates in a very distinct way but is not considered a logical transport within the overall Bluetooth LE architecture. Therefore, in this series of articles we'll be using the informal but useful term communication mode to refer to the different ways that Bluetooth LE can behave and be used by products and applications.

Seven Communication Modes

So, what are the different communication modes of Bluetooth LE? Here's the list that we'll be using in this series:

1. **LE-ACL** - Asynchronous Connection-Oriented Logical Transport
2. **ADVB$_L$** - Advertising Broadcast (legacy advertising)
3. **ADVB$_E$** - Advertising Broadcast (extended advertising)
4. **PADVB** - Periodic Advertising
5. **PAwR** - Periodic Advertising with Responses
6. **ISO** - Isochronous Communication
7. **CS** - Channel Sounding

Technically, Legacy Advertising and Extended Advertising are both variants of the same logical transport, *Advertising Broadcast (ADVB)*. However, there are significant differences between the two variations, so we'll treat them as distinct communication modes and dedicate a separate article to each.

Comparing Communication Modes (Properties)

In general, what is it that makes one Bluetooth communication mode different to another?

There are several properties that can be used to compare the Bluetooth LE communication modes. Each mode was originally designed with particular classes of applications in mind, and the properties each mode has stem from the requirements of the intended applications.

Below are some of the key properties to consider when comparing Bluetooth LE communication modes.

Topology

The topology of a communication system describes the relationship structure of the transmitting and receiving devices and has one of the following three values: one-to-one (1:1), one-to-many (1:m), or many-to-many (m:m).

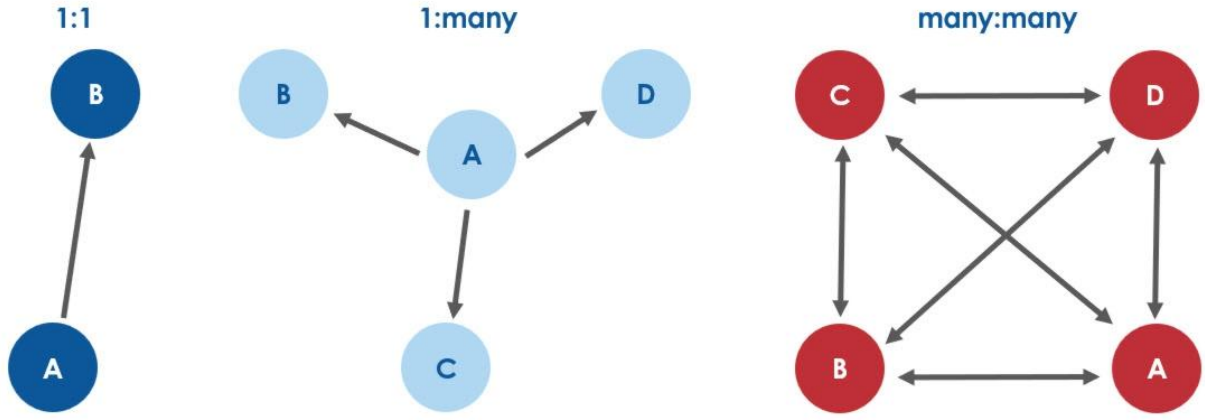

Figure 1 Communication Topologies (Simplified)

Transmitters vs Receivers

A device in a communication system can be a transmitter only, a receiver only or it can play both roles. As such from the perspective of two devices using a given Bluetooth communication mode, transmissions of packets from one device to another might be observed in only one direction or in both directions.

Application Data Transmission Direction

Application data is the payload which is transported using one of the Bluetooth LE communication modes. Some modes allow the inclusion of application data in transmissions going in one direction between devices only whilst others support application data being transmitted in both directions.

Connected or Connectionless?

Each Bluetooth communication mode is classified as either connection-oriented communication or connectionless communication. Connection-oriented means that devices first agree the values of certain parameters that will govern a range of details of the subsequent exchange of packets. In connectionless communication there is no prior agreement, and devices transmit and receive more or less independently of each other. There are pros and cons of each approach.

Data and Time

Bluetooth identifies three different relationships that data might have with time. These are defined in the portions of the specification relating to the various communication modes.

- ***Asynchronous*** communication - data is not time-bound, and its transmission schedule is based on other considerations only.
- ***Synchronous*** communication - data transmission uses regular time slots and a fixed packet size so that data rates are constant.
- ***Isochronous*** communication - similar to synchronous communication, but data rates do not need to be constant. Bluetooth isochronous communication includes further capabilities that can ensure that data received by different devices at different times is processed at the same time.

Receiver Concurrency

While topology defines the relationship between transmitting and receiving devices in geometric terms, receiver concurrency tells us how many devices can receive the same transmitted packet at precisely the same time. In a one-to-many topology for example, it might be the case that every one of the many receiving devices can receive data from the one transmitting device at exactly the same time, or it might be that the transmitting device will address a series of packets containing the same data to each receiving device one at a time in series.

Three possibilities are identified:

- One device at a time receives the transmitted data.
- A sub-set of devices receive the transmitted data at the same time.
- All devices receive the transmitted data at the same time.

Radio Channels

Bluetooth LE operates in the 2.4 GHz part of the radio spectrum. Each mode splits the spectrum into a number of channels, each with a given width and then uses a scheme or algorithm to determine how channels are selected for communication and when that selection must change. Most but not all communication modes involve forty channels, each 2 MHz wide. Which channels are used, for what purpose and how they are selected varies according to the mode.

The image below shows the Channels view in the Ellisys Bluetooth Analysis software. Here, you can see the 2MHz spacing of the Bluetooth LE channels, and spectral areas (purple bars) where the packetized communications are not present (or limited in number) by way of the adaptive frequency hopping (AFH) feature. In this case, those areas correspond to the three non-overlapping Wi-Fi channels (1, 6, and 11). Wi-Fi operates in the same 2.4G spectrum where Bluetooth operates. Note that the area being analyzed is about 26s in duration and begins about 79s after the start of the capture, long after the connection sequence, where advertising exchanges are prevalent (note there are no packets counted in the three advertising channels). Note also the placement of the three advertising channels relative to the bands where the three non-overlapping Wi-Fi channels operate.

Figure 2 Channels View in Ellisys Bluetooth Analysis Software

Scalability

Scalability is about maximizing certain aspects of performance and can take different forms. A primary concern might be the maximum number of devices that can concurrently receive transmitted data, or it might be that application data throughput rates are more important.

Choice of Bluetooth PHY

PHY is a term you'll find in the Bluetooth Core Specification. It's a shorthand for particular ways in which the Physical Layer of the stack can be configured and used (although strictly speaking, in one case it really relates to something that happens at the Link Layer, but for now we won't quibble).

One of the key concerns of the Physical Layer is to define how certain physical properties of radio signals are used to encode and convey information, although there's also a special case where transmissions contain no information at all, in which case they're called tones.

The Bluetooth Core Specification defines several PHY types with names **LE 1M, LE 2M, LE Coded** and **LE 2M 2BT**. Key differences include the rate at which symbols are transmitted and whether error correction is applied. Note that a symbol is the analog equivalent of a bit in the digital world.

- LE 1M and LE Coded both transmit at a rate of 1 mega-symbol per second.
- LE 2M and LE 2M 2BT both use a 2 mega-symbol per second transmission rate.
- LE Coded has a symbol rate of 1 mega-symbol per second but includes the application of a special error correction algorithm to packets which can increase range.
- LE 2M 2BT is specially designed for use with Channel Sounding.

Comparing Communication Modes (Examples)

As we approach the end of this introductory article on the many modes of Bluetooth communication, we'll now present a brief comparison of two of the most commonly used modes: Asynchronous Connection-Oriented Logical Transport (LE-ACL) and Advertising Broadcast (legacy advertising) (ADVBL).

LE-ACL - Asynchronous Connection-Oriented Logical Transport

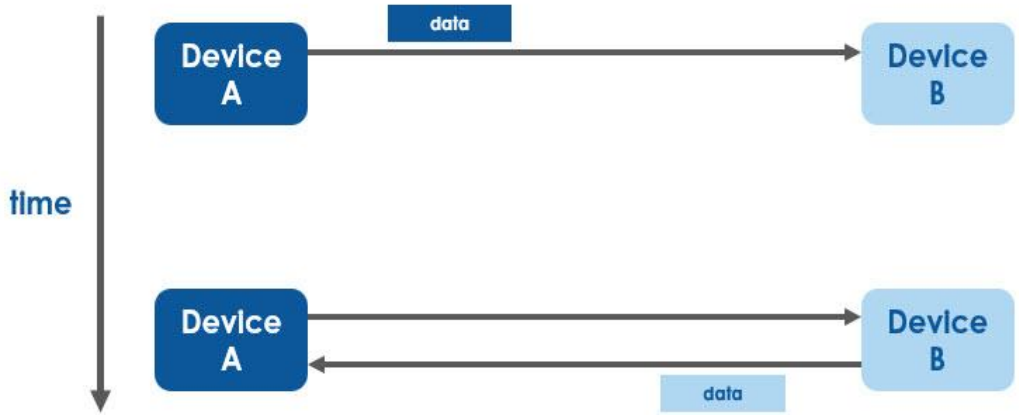

Figure 3 LE-ACL Communication.

Property	Comment
Topology	One-to-one (1:1).
Transmitters vs Receivers	Devices take turns to transmit and receive.
Application Data Direction	Application data can be transmitted in both directions.
Connected or Connectionless?	Connected.
Data and Time	Asynchronous.
Receiver Concurrency	Data packets are addressed to one receiver device at a time.
Radio Channels	Uses 37 of 40 x 2 MHz wide channels. Channel selection involves a process known as adaptive frequency hopping.
Scalability	Some devices can handle establishing more than one connection to other devices at a time. The Bluetooth Core Specification does not define a limit, but implementation issues generally limit this to a fairly low number. Application data throughput over an LE-ACL connection can be significantly improved using certain configuration parameters but will always be less than the underlying PHY symbol rate.
Choice of PHY	LE 1M, LE 2M, or LE Coded.

Table 1 LE-ACL Properties

ADVBL - Advertising Broadcast (legacy advertising)

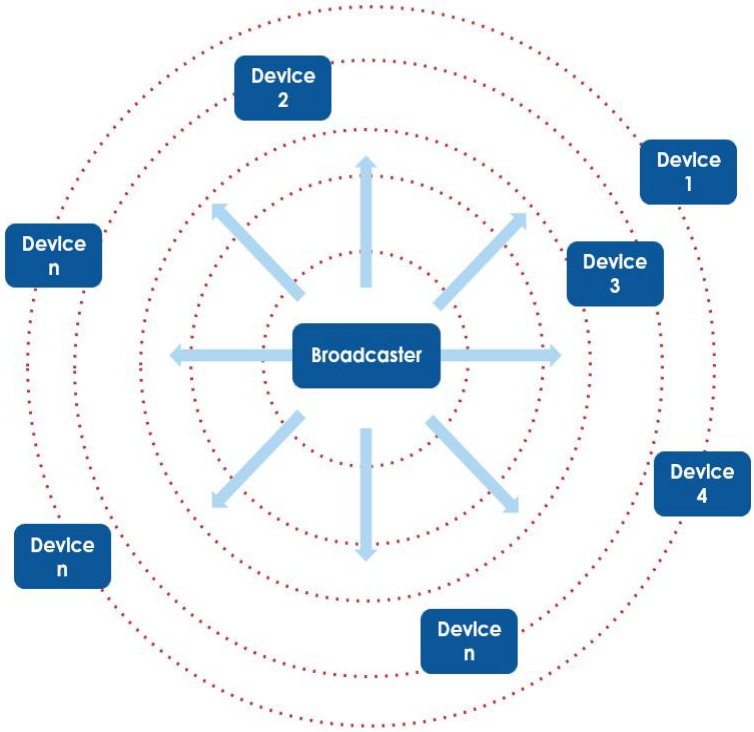

Figure 4 ADVBL Communication Example

Property	Comment
Topology	One-to-many (1:m).
Transmitters vs Receivers	Legacy advertising can work in a number of different ways. One device acts as the primary transmitter of advertising packets and depending on the details we'll cover in a later article in this series, is either known as the Broadcaster or as the Central device. Sometimes the Broadcaster/Central device transmits advertising packets only while other devices in range receive these packets but do not themselves ever transmit. Alternatively, the Broadcaster/Central device transmits packets but the other devices both receive these packets and can transmit their own packets as responses which the Broadcaster/Central can then receive.
Application Data Direction	Application data can only be transmitted by the Broadcaster/Central device to be received by the other devices. Those devices cannot send application layer data back in the other direction although they may be able to transmit types of packets that do not contain application data.
Connected or Connectionless?	Connectionless.
Data and Time	Asynchronous.
Receiver Concurrency	There is no limit to the number of devices that can receive packets containing application data that are transmitted by the Broadcaster/Central device in terms of the way that this Bluetooth communication mode works. Obviously, at some point it would become impossible to pack another device into the physical space that lies within the range of the transmitting device, so a limit would eventually be reached.
Radio Channels	Of the 40 x 2 MHz channels in the 2.4 GHz radio band, 3 are designated the primary advertising channels. Channels are referenced by an index number, and the primary advertising channels have index values 37, 38 and 39. An advertising device can use one, two or all three of these special channels.
Scalability	Per the Receiver Concurrency property, there is no limit to the number of devices to which data can be transmitted using legacy advertising. Application data throughput can be increased by exercising certain parameters but will always be somewhat limited due to the small size of ADVBL packets.
Choice of PHY	Legacy advertising can only use the LE 1M PHY with its symbol rate of 1 mega-symbol per second.

Table 2 $ADVB_L$ Properties

Capture, Analyze, Solve, Learn

Bluetooth is amazingly versatile, thanks in part to its collection of different communication modes. But the Bluetooth Core Specification v6.0 has over 3,800 pages and it's probably reasonable to say that some of it is a little complicated.

With an Ellisys Protocol Analyzer you get to see the transmission of packets over the air and through its clear presentation of the automatically decoded protocols from across the different layers of the stack, you quickly appreciate and understand how devices are communicating. For problem solving purposes, there's no substitute and the Ellisys system even checks compliance with the Bluetooth Core Specification in many respects.

An Ellisys protocol analyzer is a must-have tool for any Bluetooth engineer.

Next in the Series

In the next article in this series, we'll take a closer look at the LE-ACL communication mode.
View the PDF here: https://ellisys.com/technology/edu_bt01_lecomm_ch02_acl.pdf