Introduction to System-on-Chip and its Applications

Individual Project Report

Bluetooth BR/EDR (basic rate/enhanced data rate)

and Bluetooth LE (Bluetooth low energy)

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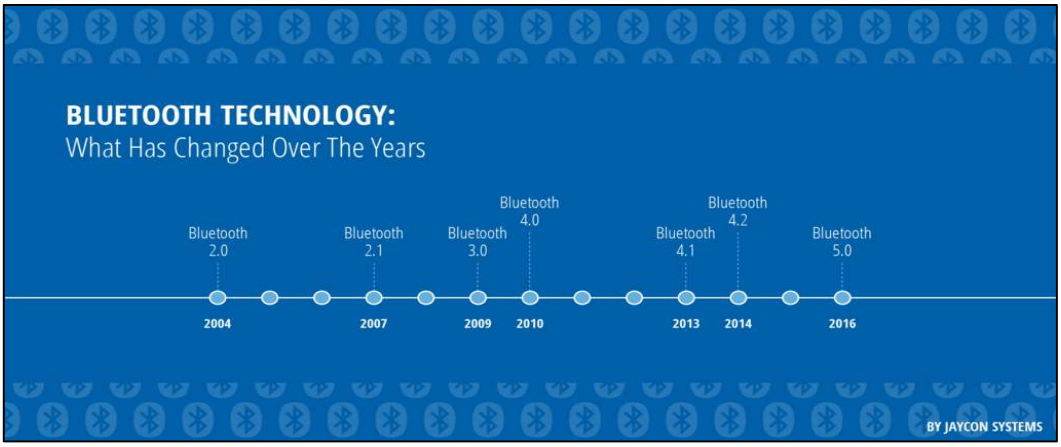
Technology Analysis

1. System Applications

Bluetooth is a wireless technology which transmits the information within short distance. It supports the connectivity and collaboration between different products and industries. Nowadays, most of the electrical devices have Bluetooth, which shows that Bluetooth is now an important technique in our life. There are lots of applications in different field such as audio streaming, data transfer, device network and so on.

2. System Background and Evolution



Background

In 1996, Intel, Ericsson, and Nokia met to plan the standardization of the short-range radio technology in order to support connectivity and collaboration between different products and industries. Bluetooth is a temporary code name at first, which was suggested by Jim Kardach from Intel. He was quoted as saying, “King Harald Bluetooth…was famous for uniting Scandinavia just as we intended to unite the PC and cellular industries with a short-range wireless link.” When it came time to select a

serious name, there are three options for naming this technology: RadioWire or Personal Area Networking (PAN) or Bluetooth. At last, Bluetooth is still the most suitable name among those choices. Its logo is a bind rune merging the Harald's initials from Younger Futhark runes (Hagall) (ᚼ) and (Bjarkan) (ᛒ). In 1998, Ericsson founded Bluetooth Special Interest Group (SIG) in collaboration with Nokia, Intel, IBM, Toshiba, to bring the technology to the consumer market.

Evolution

Bluetooth 1.0 ------ 1999:

First version of Bluetooth. It is far slower than what we have now. The data speeds are at 1 Mbps and the range only reaches as far as 10 meters. It uses Gaussian Frequency Shift Keying (GFSK), which is a modulation scheme that the modulated carrier shifts between two frequencies representing 1s and 0s.

Bluetooth 2.0 (EDR) ------ 2004:

The most important feature of this version is the implementation of Enhanced Data Rate (EDR) technology. In Bluetooth 2.0, GFSK is taken out in favor of two newer schemes: $\pi/4$-DQPSK and 8DPSK. These two modulation schemes make the data speeds increase to 2 Mbps and 3 Mbps, respectively. Besides, power consumption is cut in half compared to the Bluetooth 1.0.

Bluetooth 2.1 ------ 2007:

Secure Simple Pairing (SSP) plays a vital role in this version. This function allows the system to have a simpler pairing process and more secure by a shared secret Link key between two Bluetooth devices. Sniff-subrating is also an important feature of this version. Sniff-Subrating mode reduces the power consumed by a pair of connected Bluetooth devices, which reduces the duty active cycle of devices and increases the battery life.

Bluetooth 3.0 (HS) ------ 2009:

In this version, it improves the data speeds with the addition of 802.11 Wi-Fi radio. This High-Speed version can reach data speeds of up to 24 Mbps for data transfer. It still uses Bluetooth radio for discovery, connection, and configuration. Therefore, though the use of Wi-Fi radio will enhance the power consumption, it remains off most of the time until data transfer is required.

Bluetooth 4.0 ------ 2010:

This version is the significant milestone of Bluetooth technology. In Bluetooth 4.0, also called Bluetooth Smart, it has a new category of technique: Bluetooth Low Energy (BLE). Bluetooth Low Energy can frequently transmit data to devices while conserving battery. With this low power consumption property, there are many coin-cell battery-operated IoT application such as heart rate monitors and thermometers. Moreover, this version also introduces the Generic Attribute Profile (GATT), which provides the profile of the devices, and Security Manager (SM) services with AES encryption.

Bluetooth 4.1 ------ 2013:

This version has more improvement on the software. It focuses a lot on the IoT devices. With this new protocol, it can connect devices through the clouds indirectly which will otherwise be out of range. Besides, Bluetooth 4.1 allows the devices to be a host and peripheral at the same time. Therefore, the peripherals can talk to each other directly without an intermediary host.

Bluetooth 4.2 ------ 2014:

In Bluetooth 4.2, Bluetooth SIG announces that the devices can use Internet Protocol Version 6 (IPv6) to transmit the data over the internet directly. This version also improves the speed and privacy. It increases the capacity of the data packets, which results in 2.5 times faster than the previous version. As for the privacy, others are harder to track your device without the permission.

Bluetooth 5.0 ------ 2016:

Bluetooth 5.0 further optimizes the IoT application, audio quality, speed, power, range and data capacity. It has two times speed, four times range, and eight times message capacity compared to the previous version. It also provides four different data rates to support various transmission ranges: 125kbps, 500kbps, 1Mbps, 2Mbps. The flexibility in data speeds allows low power devices to send more complicated data to the end user. Besides, in the new specification of this version, the user can connect the devices at up to 200 meters away when you are outdoor.

Bluetooth 5.1 ------ 2019:

Bluetooth 5.1 provides the direction sensing by Angle of Arrival (AoA) method and Angle of Departure (AoD) method. Due to caching enhancement of Generic Attribute Profile (GAP), the devices can save the connection information in the cache. Therefore, the devices don't need to check for the connection continuously, which saves more power and also provides a faster connection capability.

Bluetooth 5.2 ------ 2020:

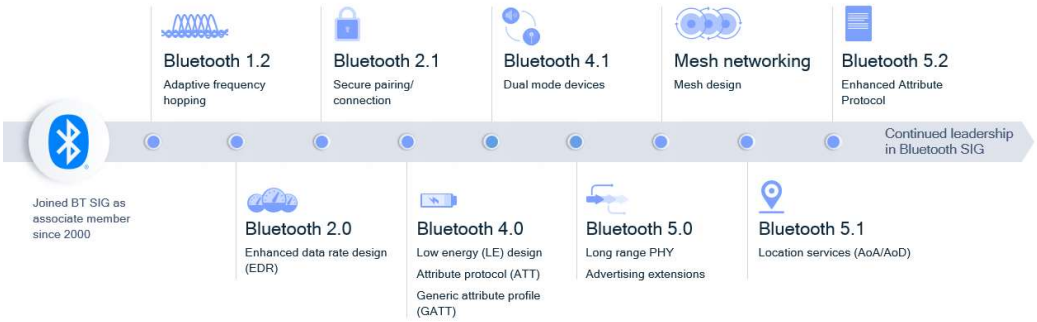
In Bluetooth 5.2, new features such as Enhanced Attribute Protocol (EATT), LE Isochronous Channels, and so on are added. The most significant feature of this version is LE Audio. LE Audio enables one-to-many and many-to-one broadcasts. It uses the latest LC3 codec, which is a new high quality, low-power audio codec compared to the standard SBC codec used in Bluetooth Classic. Apart from the application of earbuds, it would also add support for hearing aids.

Bluetooth 5.3 ------ 2021:

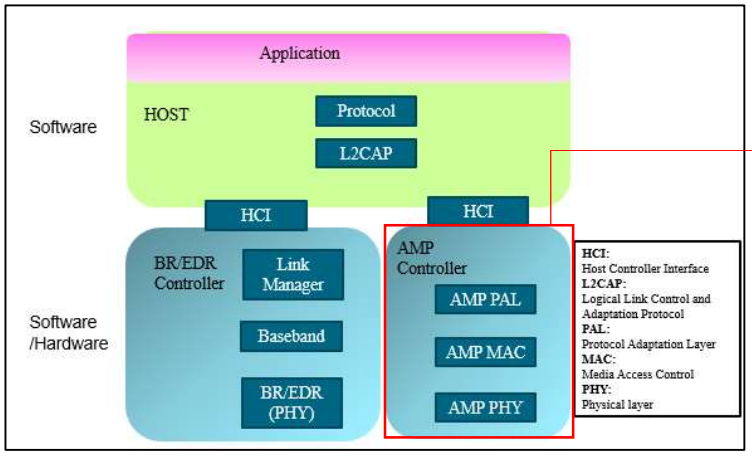
Bluetooth 5.3 has enhancements on connection subrating, channel classification enhancement, encryption key size control enhancements and, periodic advertisement interval. It has low-duty cycle connections with power-saving characteristics. Besides, it also increases reliability and throughput by reducing interference occurring at the peripheral. This version will be more beneficial to IoT applications such as access control, portable medical devices, and so on.

3. System Functions, Block Diagrams, and Technology

From the Bluetooth evolution, it can be classified to Classic Bluetooth and Bluetooth low energy.

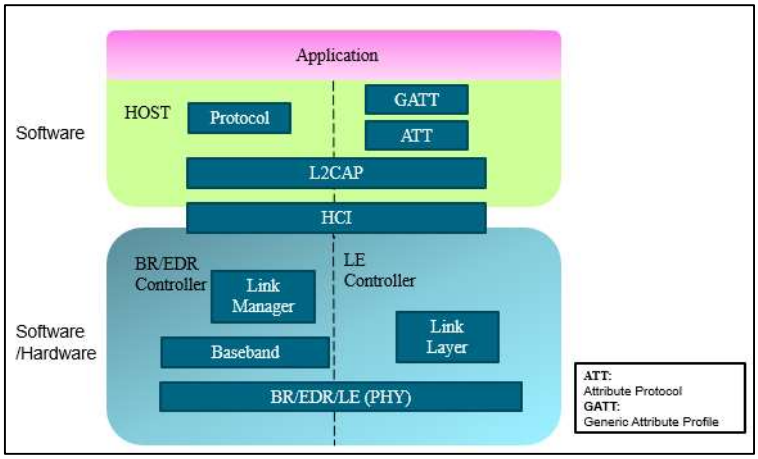


Classic Bluetooth (BR/EDR + HS (High Speed))



Using WiFi architecture concept. When Bluetooth needs to transfer the data faster, it will switch to this specification.

Bluetooth Low Energy (BLE (Dual Mode))



(5 states of LE: Standby, Advertising, Scanning, Initiating, Connected)

	Bluetooth Basic Rate/Enhanced Data Rate (BR/EDR)	Bluetooth Low Energy (LE)
Frequency Band	2.4GHz ISM Band (2.402 – 2.480 GHz Utilized)	2.4GHz ISM Band (2.402 – 2.480 GHz Utilized)
Channels	79 channels with 1 MHz spacing	40 channels with 2 MHz spacing (3 advertising channels/37 data channels)
Channel Usage	Frequency-Hopping Spread Spectrum (FHSS)	Frequency-Hopping Spread Spectrum (FHSS)
Modulation	GFSK, π/4 DQPSK, 8DPSK	GFSK
Data Rate	EDR PHY (8DPSK): 3 Mb/s EDR PHY (π/4 DQPSK): 2 Mb/s BR PHY (GFSK): 1 Mb/s	LE 2M PHY: 2 Mb/s LE 1M PHY: 1 Mb/s LE Coded PHY (S=2): 500 Kb/s LE Coded PHY (S=8): 125 Kb/s
Tx Power*	≤ 100 mW (+20 dBm)	≤ 100 mW (+20 dBm)
Rx Sensitivity	≤-70 dBm	LE 2M PHY: ≤-70 dBm LE 1M PHY: ≤-70 dBm LE Coded PHY (S=2): ≤-75 dBm LE Coded PHY (S=8): ≤-82 dBm
Data Transports	Asynchronous Connection-oriented Synchronous Connection-oriented	Asynchronous Connection-oriented Isochronous Connection-oriented Asynchronous Connectionless Synchronous Connectionless Isochronous Connectionless
Communication Topologies	Point-to-Point (including piconet)	Point-to-Point (including piconet) Broadcast Mesh
Positioning Features	None	Presence: Advertising Direction: Direction Finding (AoA/AoD) Distance: RSSI, HADM (Coming)

Frequency-Hopping Spread Spectrum (FHSS)

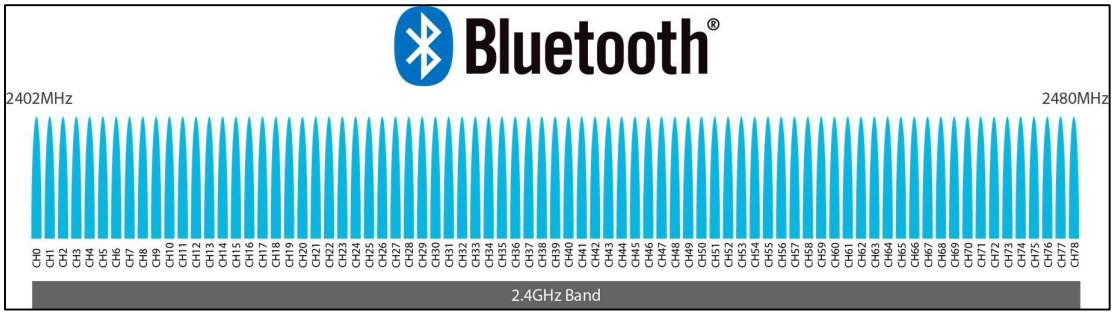
Frequency-Hopping Spread Spectrum transmission is a technique that the carrier frequency keeps switching to avoid running into the frequency jam during radio transmission. It uses an algorithm to calculate a pseudo-random sequence that is known to the transmitter and receiver. By doing so, it can hop between the available narrowband frequencies and reduce the interference during the transmission.

The benefits of using frequency-hopping technique are as following:

- Reduce narrowband interference
- Avoid interception due to the unknown frequency-hopping pattern
- Allow multiple transmitter and receiver pairs to transmit the data in the same space on the same channel simultaneously.

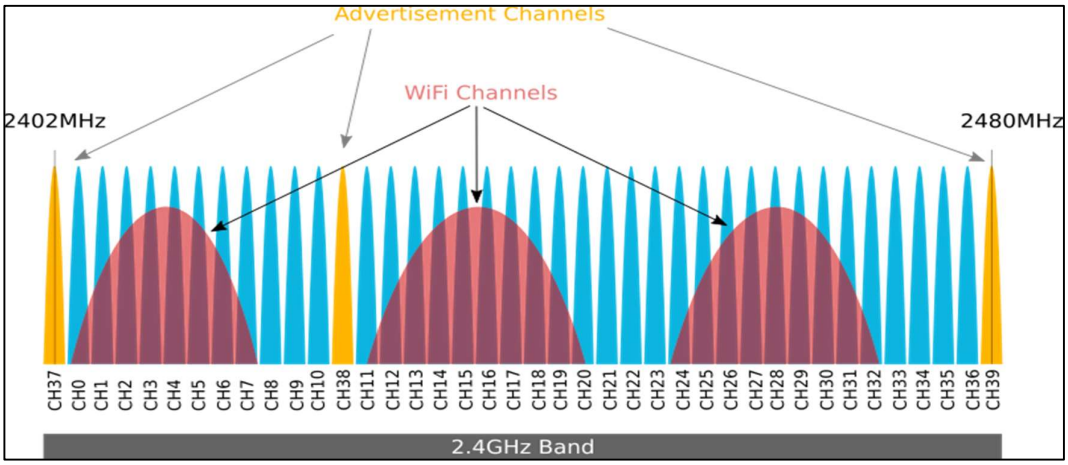
Classic Bluetooth (BR/EDR)

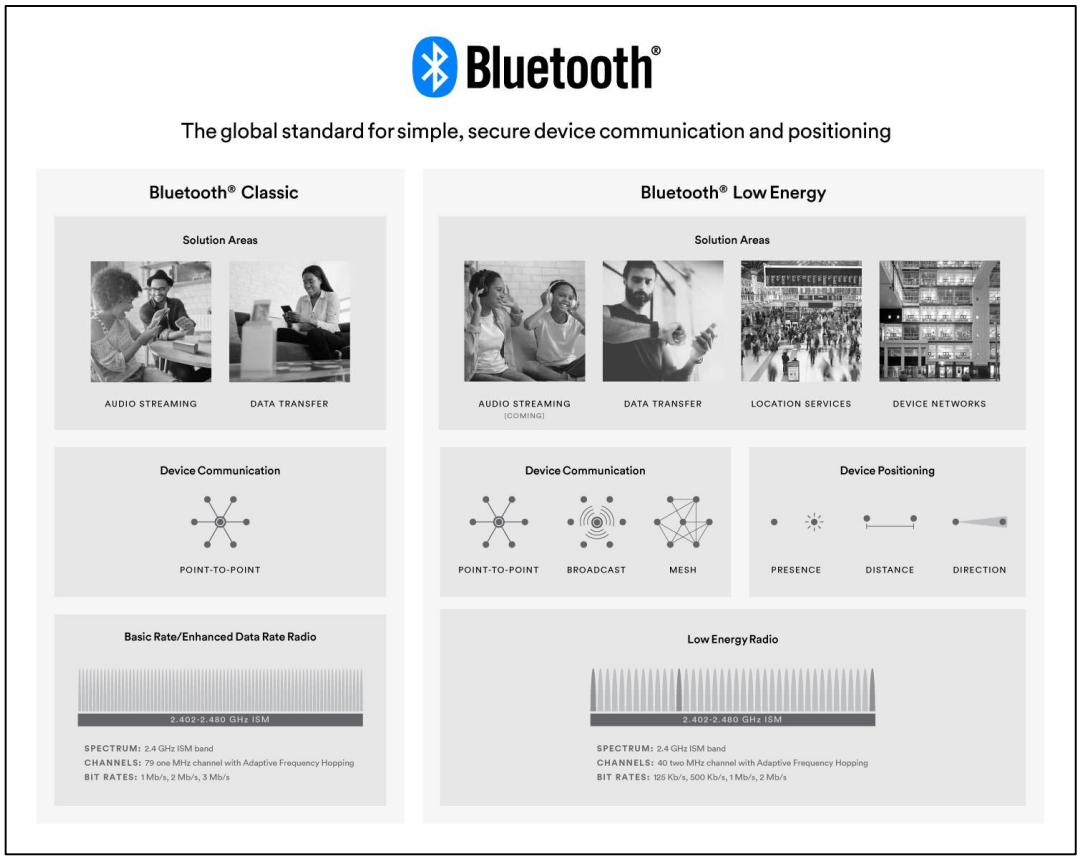
In Classic Bluetooth, the 2.4GHz Industrial Scientific Medical Band (ISM) Band is divided into 79 channels. The streaming data will hop between those channels with the Frequency-Hopping Spread Spectrum transmission technique.



Bluetooth Low Energy (BLE)

In Bluetooth Low Energy, the 2.4GHz ISMB and is divided into 40 channels. Channel 37, 38, 39 are advertising channels used to transmit and receive broadcast advertisement among devices.

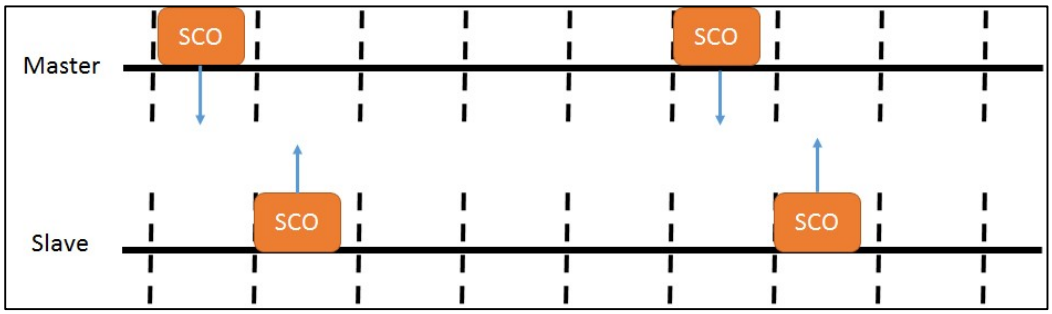




Data Transports

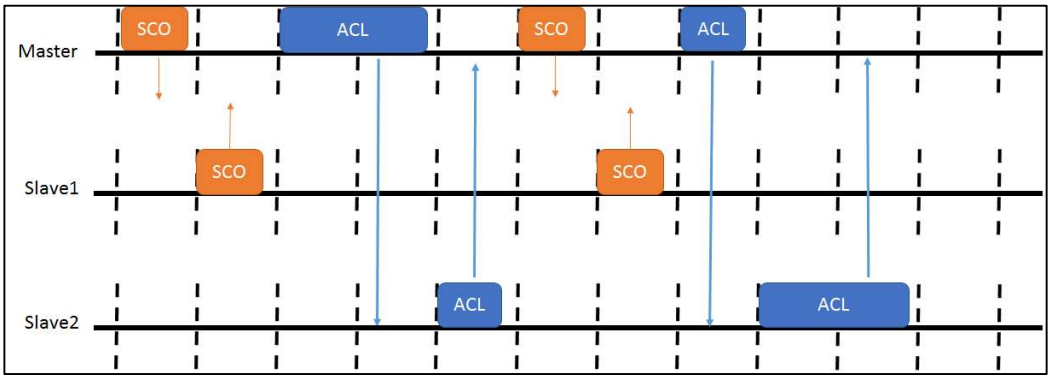
For Classic Bluetooth, the data transports technology it uses are Synchronous Connection-oriented (SCO) and Asynchronous Connection-oriented (ACL). For Bluetooth Low Energy, apart from the above data transports technology, the most different specification of data transports technology Isochronous Connection-oriented and Isochronous Connectionless (Isochronous Channels, ISOC) are added.

Synchronous Connection Oriented (SCO)



Synchronous Connection Oriented (SCO) is a point-to-point link between the master and slave device. It is a symmetric link that is established before communication starts to reserve fixed time slots for each transmission direction. A master device can support three SCO links to connect with the same or different slaves and a slave device can have up to 3 of the SCO links with master devices. However, when it comes to lost frame issue, SCO frames can't be retransmitted because the transmission is time critical. Therefore, there is a enhanced SCO(eSCO) links to improve this situation with limited packets retransmission.

Asynchronous Connection-Oriented (ACL)



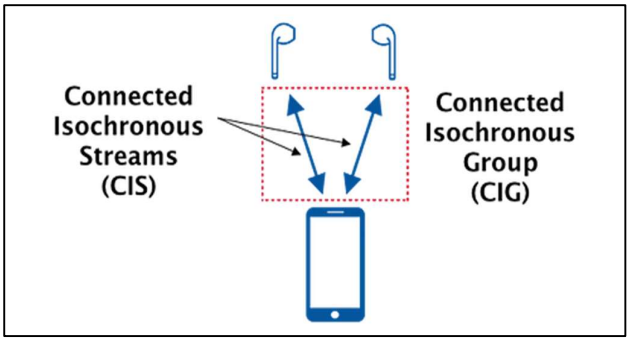
Asynchronous Connection-Oriented (ACL) is a packet-oriented link that can transmit the data at the irregular intervals. It is also a point-to-multipoint link that a master device can connect with up to seven slave devices to form a piconet. Therefore, it can support broadcast messages. Different form SCO link, ACL link can retransmit the lost frame due to the packets are delivered on best-effort basis. In this technology, maintaining data integrity is more important than the time latency.

Isochronous Channels (ISOC)

Isochronous Channels (ISOC) is a bi-directional link. Streams that are part of the same group share timing reference data that synchronized every device.

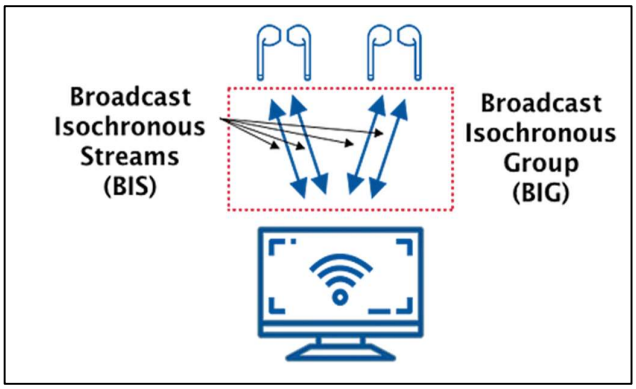
1. Connection-oriented

Each stream is referred to as Connected Isochronous Streams (CIS). When those CIS streams need to be synchronized, they are configured to be part of the Connected Isochronous Group.



2. Connectionless (Broadcast)

Similar concept as CIS and CIG, in connectionless, we have Broadcast Isochronous Streams (BIS) belongs to a Broadcast Isochronous Group (BIG). Those synchronized streams are streaming the data from a single source to multiple sinks.

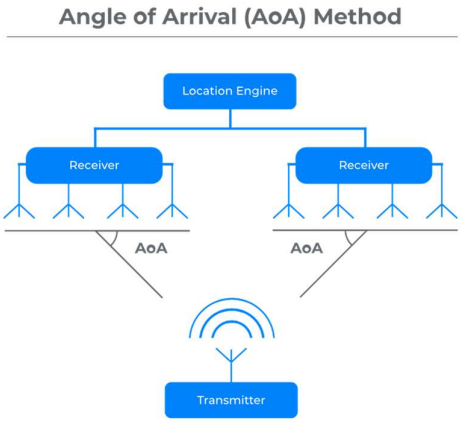


Positioning Features

The significant difference between Classic Bluetooth and Bluetooth Low Energy is positioning feature. In Bluetooth Low Energy, there are two methods to detect objects' positions: Angle of Arrival (AoA) and Angle of Departure (AoD).

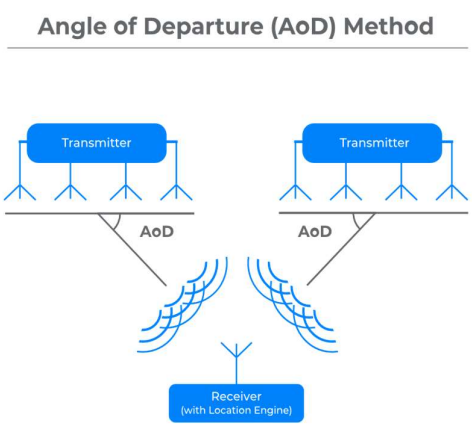
Angle of Arrival (AoA)

In Angle of Arrival (AoA), a transmitter uses a single antenna to transmit a signal and a receiver has multiple antennas that are arranged in an array. The receiver collects the transmitted signal which crosses the array and calculate the signal direction.



"Enabling buildings to determine the location of people and things within"

Angle of Departure (AoD)

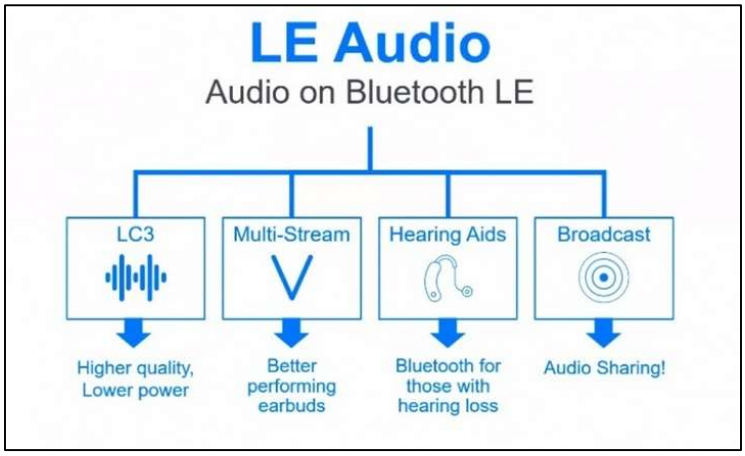


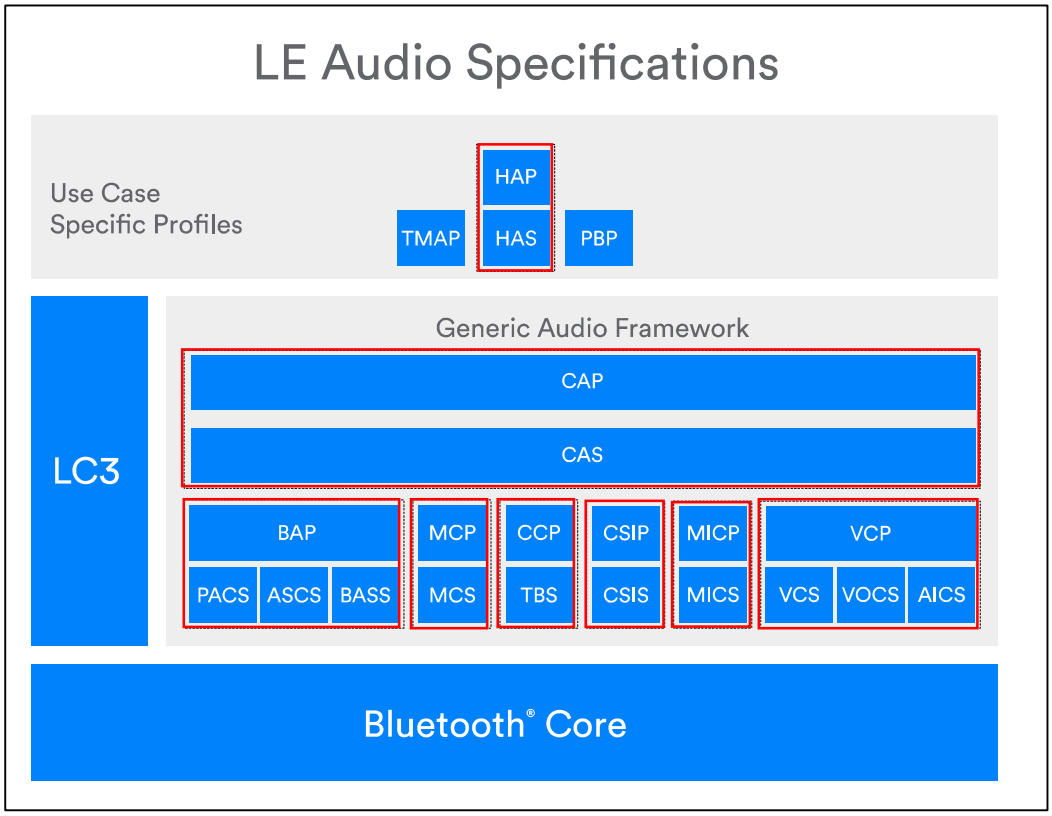
In Angle of Departure (AoD), a transmitter uses multiple antennas that are arranged in an array to transmit a signal and a receiver uses a single antenna to collects the transmitted signal which crosses the array and calculate the signal direction.

"Enabling people and things to determine their location within a building"

LE Audio

LE Audio, which operates on the Bluetooth Low Energy radio, is a next generation of Bluetooth audio. It enhances the performance of Bluetooth audio and introduces the new Bluetooth use case, Auracast Broadcast Audio. Besides, LE Audio also adds support for hearing aids, which will benefit the growing number of people with hearing loss. The technique can not only support the use case of Classic Audio, but also introduces exciting new features with better performance of new products and use cases.





HAP, HAS: Hearing Access Profile and Service

TMAP: Telephony and Media Audio Profile

PBP: Public Broadcast Profile

LC3: Low Complexity Communications Codec

CAP, CAS: Common Audio

BAP, PACS, ASCS, BASS: Stream Management

MCP, MCS: Media Control,

CCP, TBS: Call Control

CSIP, CSIS: Coordinated Devices

MICP, MICS: Microphone Control

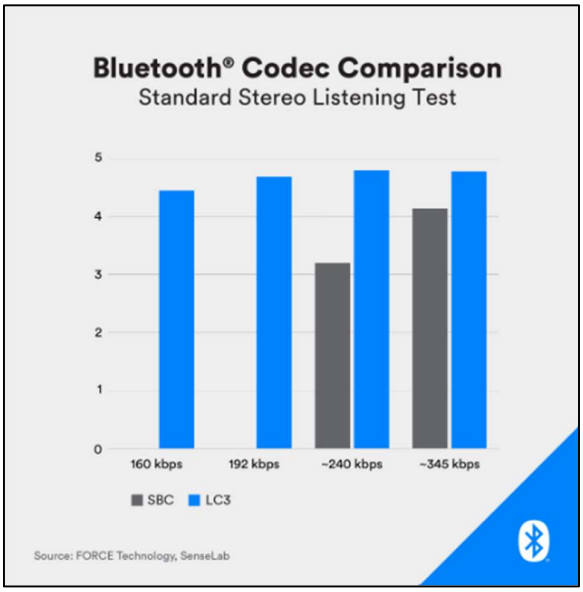
VCP, VCS, VOCS, AICS: Volume Control

Auracast Broadcast Audio

Auracast Broadcast Audio enables an audio source to broadcast one or more audio streams to an unlimited number of audio sinks. With this significant progress, we can use broadcast audio to share our audio experiences with our friends, unmute what was once silent and hear our best wherever we go.

Low Complexity Communications Codec (LC3)

Low Complexity Communications Codec (LC3) is a new high-quality, low-power audio codec. It supports multiple, synchronized audio data streams and provides high quality audio even at lower data rates compared to the standard SBC codec used in Classic Bluetooth.



"Extensive listening tests have shown that LC3 will provide improvements in audio quality over the SBC codec included with Classic Audio, even at a 50% lower bit rate. Developers will be able to leverage this power savings to create products that can provide longer battery life or, in cases where current battery life is enough, reduce the form factor by using a smaller battery."

------ Manfred Lutzky, Head of Audio for Communications at Fraunhofer IIS

Industrial Analysis

The following products are the newest SoC support Bluetooth 5.3 from each company.

1. Qualcomm QCC5171

	SPECIFICATIONS
Product	QCC5171
CPU	**Architecture:** 32-bit **Clock Speed:** Up to 80 MHz **Features:** Programmable CPU
DSP	**Name:** 1x Qualcomm® Kalimba™ **Clock Speed:** 2x 240 MHz **Data RAM:** 1408 kB **Program RAM:** 384 kB **Features:** Programmable DSP
Bluetooth	**Specification Version:** Bluetooth® 5.3 Qualified **Connection Technology:** Bluetooth® Low Energy, Bluetooth® Classic **Topologies:** Qualcomm TrueWireless™ Mirroring technology **Classic Data Rate:** 3 Mbps, 2 Mbps, 1 Mbps **Low Energy Data Rate:** 1 Mbps, 2 Mbps
Interfaces	UART, I²S, I²C, 1x USB

2. Nordic nRF5340

	SPECIFICATIONS
Product	nRF5340
CPU	128/64 MHz Arm Cortex-M33
Memory	1 MB Flash + 512 KB RAM
Cache	8 KB 2-way set associative cache
Performance	514/257 CoreMark
Efficiency	66/73 CoreMark/mA
Wireless protocol support	Bluetooth Low Energy/Bluetooth mesh/ NFC/Thread/Zigbee/802.15.4/ANT/2.4 GHz proprietary
On-air data rate	Bluetooth LE: 2 Mbps/1 Mbps/125 kbps 802.15.4: 250 kbps
Bluetooth Low Energy	Bluetooth 5.3 LE Audio Direction Finding 2 Mbps, Advertising Extensions and Long Range
Interfaces	Full-speed USB 96 MHz encrypted QSPI 32 MHz high-speed SPI

3. Airoha AB1585

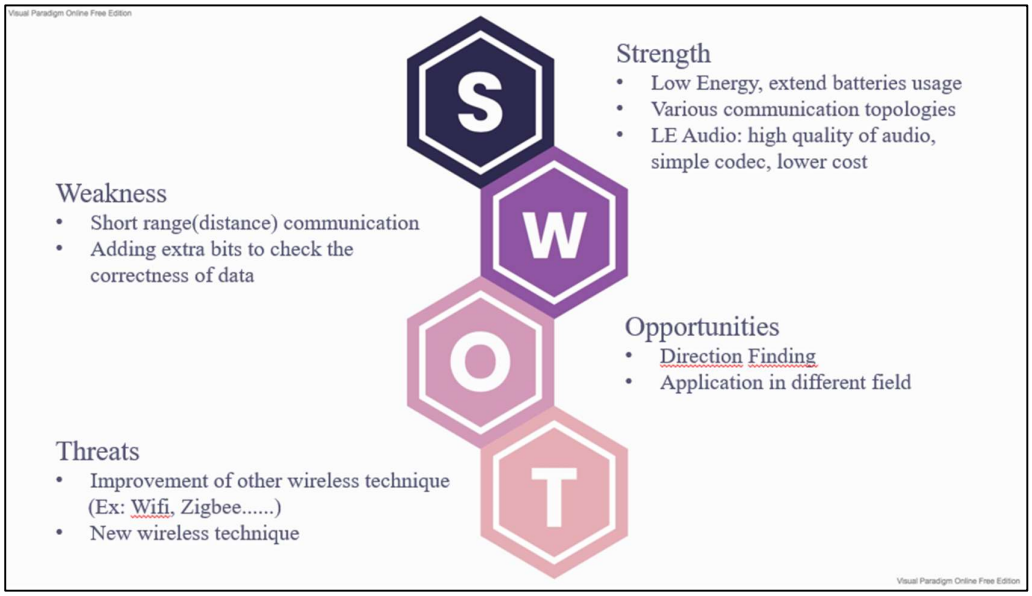
Airoha AB1585 will be launched in the first half of 2023

	SPECIFICATIONS
Product	AB1585
Host Processor (CPU)	ARM® Cortex®-M33F
DSP Processor	on Cadence® HiFi5®Audio Engine DSP coprocessor
Bluetooth	Bluetooth 5.3 BR, EDR, Bluetooth Low Energy, LE audio, Dual-mode
Flash	Embedded Flash 8MB/16MB
Power Management	Highly integration PMU Li-ion battery charger for internal charging

Among these three products:

- Qualcomm QCC5171 has the best audio quality
- Nordic nRF5340 has the application in IoT and high temperature endurance
- Airoha AB1585 will have the best environment for AI computation due to HiFi5 DSP coprocessor embedded on it

SWOT Analysis for Bluetooth Low Energy



Strength:

Due to low power consumption, the BLE products can extend the batteries usage. Besides, the various communication topologies (Point-to-Point (including piconet), Broadcast and Mesh) can easily meet the design requirements of customers. The most significant milestone, LE Audio, will give us an exciting whole new audio experience.

Weakness:

Though the distance between devices is getting larger, the design purpose of Bluetooth technology is still in short range. Therefore, if we want to operate the function on longer distances, we will have to use other wireless technology. Besides, due to the change of specification, we have to add extra bits to check the correctness of data. This will reduce the bits number that the actual data can use during transmission.

Opportunity:

In BLE specification, direction finding is one of the key functions that Classic Bluetooth didn't has. Therefore, we can make good use of the various communication topologies in different fields and innovate new products.

Threats:

It is possible that the BLE function might be replaced if other wireless technologies, such as WiFi, Zigbee, improve faster or better than Bluetooth. Moreover, there might be a new wireless technology that replace Bluetooth completely.

Conclusion

Bluetooth are now widely used in most of our electrical devices such as phones, personal computers, wearable devices and so on. As time goes by, Bluetooth Low Energy is the main specification that we are now focusing and improving. No doubt LE Audio will open the new era of the Bluetooth audio application. The life with better audio transmission system, closer audio sharing experience and more advanced hearing aids that bring benefit to society is just around the corner.

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