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Streaming Audio with Bluetooth : A Deep Dive into A2DP and LE Audio

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ABSTRACT

The evolution of Bluetooth audio streaming has been significantly shaped by the adoption of various audio codecs, with A2DP (Advanced Audio Distribution Profile) and AVRCP (Audio/Video Remote Control Profile) serving as its foundation. These codecs each come with their own set of trade-offs, which include bitrate, latency, compatibility, and power usage. While Bluetooth technology has seen advancements in terms of versions and capabilities, current implementations still face limitations. These limitations have paved the way for the emergence of Bluetooth Low Energy Audio as a potential solution to address the challenges related to power consumption, particularly in specific use cases. This article provides a detailed comparison of existing audio codecs supported in A2DP, highlighting the limitations of classic Bluetooth audio and how LE Audio's enhancements address those challenges.

Keywords: Bluetooth Audio Streaming, Audio Codecs, Power Efficiency, Bluetooth Profiles, Wireless Connectivity, Low Complexity Codec

1. Introduction

1.1. Overview of Bluetooth

Bluetooth is a wireless technology standard used for exchanging data over short distances (using short-wavelength radio waves) between fixed and mobile devices, that is governed by Bluetooth Special Interests Group. It's commonly used to connect devices like smartphones, headphones, speakers, keyboards, mice, and more, without the need for cables. The Bluetooth Special Interest Group (SIG) [1-3] has specified the profiles for the usage models. Each profile defines a set of messages & procedures from the Bluetooth specification and each device must support at least one profile.

Key Features and Benefits:

- **Wireless Communication:** Eliminates the need for cables, providing convenience and flexibility.
- **Short-Range:** Designed for communication over short distances, typically up to 30 feet (10 meters) in case of Class-II [4], making it ideal for personal area networks.
- **Radio Waves:** Bluetooth uses 2.4 GHz radio wave spectrum that is available for unlicensed use in most parts of the world.
- **Low Power Consumption:** Bluetooth Low Energy (BLE) technology is designed for devices that require low power consumption, such as wearables and IoT devices.
- **Widely Available:** Bluetooth is a standard feature in most modern smartphones, tablets, laptops, and many other devices.
- **Versatile:** Supports various applications, including audio streaming, data transfer, device control, and location services.

The use of Bluetooth devices has experienced consistent growth over the years, resulting in widespread adoption. Analysts anticipate seeing long-term forecasts returning to strong growth post pandemic. By 2028, 7.5 billion Bluetooth enabled devices are forecasted to ship annually, representing an eight percent compound annual growth rate (CAGR) over the five years span from 2023 to 2028. [4]

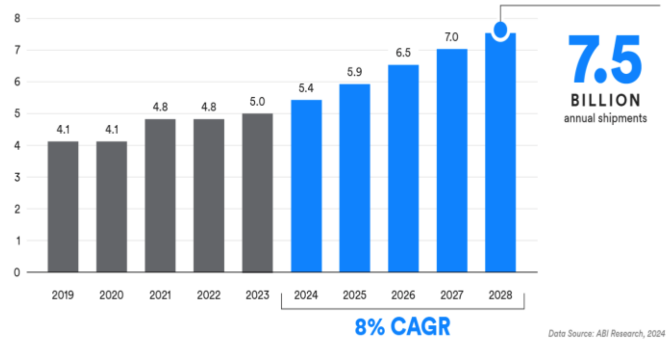

Fig 1: Industry adoption analysis

2. Bluetooth Versions

Bluetooth technology has undergone continuous evolution, marked by significant enhancements in power efficiency and data rates. Key milestones in this development are highlighted below.

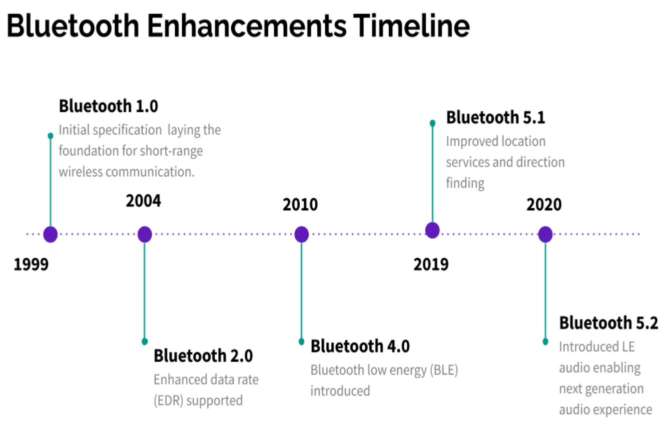

Fig 2: Key bluetooth enhancements over the years

Each new Bluetooth version has been engineered for lower power consumption while simultaneously enhancing data transfer rates. Bluetooth Low Energy (BLE) has been a key innovation in power efficiency, making Bluetooth a suitable technology for a wide range of devices, including those with limited battery capacity.

Following table summarises the high level comparison between Bluetooth Classic and Bluetooth LE

Categories	Bluetooth Classic	Bluetooth Low Energy
Frequency Band	2.4 GHz	2.4 GHz
Channels	79 one MHz Channel	40 two MHz Channel
Data Range	1-3 Mbps	1 Mbps
Latency (Time between packets)	~100 msec	~6 msec
Range	< 30 m	50 m (~150 m in open area)
Topology	Peer-to-peer (1:1)	Peer-to-peer(1:1) Star (many:1) Broadcast(1:many) Mesh(many:many)
Device pairing	Required	Not required
Voice capable	Yes	No
Nodes / Active Slaves	7	Unlimited
Security	64b/128b, user defined application layer	128 bits AES, user defined application layer
Target applications / use cases	Audio streaming, file transfers and headsets	Location beacons, smart home applications, media devices, industrial monitoring, fitness trackers

Table 1: Bluetooth classic vs Bluetooth LE comparison[11]

3. Bluetooth Profiles

Bluetooth profiles are essentially pre-defined sets of rules and specifications that standardize Bluetooth devices interacting with each other to fulfil the desired function in usage models. Bluetooth SIG has specified the profiles that devices have to implement for the use-case defining the interoperability.. They standardize the way devices connect and exchange data, ensuring interoperability between different manufacturers.

Here's a breakdown of some common Bluetooth profiles and what they're used for:

- **A2DP (Advanced Audio Distribution Profile):** Stream high-quality stereo audio wirelessly. It is used for connecting Bluetooth headphones, speakers, and car infotainment systems..

- **HFP (Hands-Free Profile):** Used for connecting Bluetooth headsets or car kits for hands-free calling. It handles the audio and control functions for phone calls.
- **HSP (Headset Profile):** A simpler version of HFP, primarily used for basic mono voice calls delivery to headsets.. Basic hearing aids implement this profile.
- **AVRCP (Audio/Video Remote Control Profile):** This profile allows you to control playback functions (play, pause, skip, adjust volume) of audio or video devices remotely. For example, using your Bluetooth headphones to control the music playing on your smartphone/tablet.
- **HID (Human Interface Device Profile):** Used for connecting wireless input devices like keyboards, mice, and game controllers.
- **PAN (Personal Area Networking Profile):** Allows devices to create a personal area network (PAN) using Bluetooth. This can be used for tethering or connecting other trusted devices in a small network for data transfer.
- **GATT (Generic Attribute Profile):** This is a key component of BLE devices. It defines how data is organized, exchanged and accessed between BLE devices. It provides a standardized framework for communication, device discovery and data interaction in a structured way.. GATT is essential for enabling functionality of BLE devices such as fitness trackers, IoT devices etc.,

In essence, Bluetooth profiles are agreed upon capabilities to ensure seamless and reliable communication for fulfilling the targeted use-case.. Without these standardized profiles, connecting different Bluetooth devices would be chaotic and unreliable.

4. Overview of A2DP and AVRCP

4.1. A2DP

A2DP stands for Advanced Audio Distribution Profile. It's a Bluetooth profile that enables high-quality audio streaming between devices.

Here's what it essentially does:

- **Wireless Stereo Audio Streaming**: A2DP allows wireless stereo audio streaming (like music, podcasts, or phone calls) from one device (like your phone, tablet, or computer) to another device (like headphones, speakers, or a car stereo) via a Bluetooth connection.
- **High-Quality Audio**: Compared to older Bluetooth voice profiles like HSP/HFP, A2DP supports higher quality audio streaming, offering a more enjoyable listening experience.
- **Unidirectional Streaming**: Audio is streamed in one direction i.e., from audio source device to a sink device.

A2DP source and receivers are paired by Bluetooth and perform codec negotiation before the streaming session starts. Once streaming establishes, the Source encodes the audio data using the negotiated Codec and compressed stream sent over to the Receiver. The receiving device decodes the audio data and plays it through the speakers/headphones.

The A2DP Standard is supported by virtually all modern computing platforms, including smart phones, desktop computers, laptops, tablets, smart TVs and media players.

This widespread compatibility enables the playback of audio data on suitable devices across various platforms. This technology is particularly prominent in the automotive sector, where devices are coupled with hands-free kits or car stereos via Bluetooth. When the connection is not being used for telephone calls, it's possible to play music stored on the connected device with very high audio quality via the A2DP profile.

4.2 AVRCP

The Advanced Audio Distribution Profile is frequently used in conjunction with the Audio/Video Remote Control Profile (AVRCP) profile which is designed to allow remote control of audio video playback on a connected device.

Here's what it allows:

- **Control playback:** Play, pause, next track, previous track, stop, rewind.
- **Volume Control**: Adjust volume controls, mute
- **Metadata Support:** Transmits the metadata about the media being played, such as track information (artist, song title, album) on the controlling device.

4.3 Supported Codecs

A2DP (Advanced Audio Distribution Profile) itself doesn't specify a single audio codec. Instead, it supports multiple codecs, each with different characteristics in terms of audio quality, compression efficiency, and latency.

Some common audio codecs used with A2DP:

- SBC (Subband Coding)
- AAC (Advanced Audio Coding)
- aptX family (aptX, aptX HD, aptX LL, aptX Adaptive)
- LDAC (Low Latency Audio Codec)
- LHDC (Low Latency High Definition Codec)

5. Codec Deep Dive - A Comprehensive Comparison

5.1 Codec Feature Comparison

When comparing audio codecs, it's important to consider factors such as audio quality, bitrate, latency, compatibility, and power consumption.

Here are some common audio codecs used with A2DP:

- **SBC (Subband Coding):** Its perceptual coding and provides efficient compression by dividing audio signals into frequency bands and encoding each band separately. Its computationally efficient coding and its key component in many other audio codecs.. It's a mandatory audio codec that should be supported by all Bluetooth devices, ensuring universal compatibility.
  - Bitrate: Up to 345 kbps (typically around 192-256 kbps) [5]
  - Audio Quality: Basic audio quality, suitable for casual listening.
  - Latency: High latency (around 100 to 200 msec)
  - Compatibility: Mandatory A2DP profile. So universal support.
  - Power Consumption: Less complex codec, so consumes low power.
- **AAC (Advanced Audio Coding):** It's a lossy digital audio compression developed by Apple, AAC is known for its efficient compression and generally better sound quality than SBC. This is common in music streaming services in Apple devices where balance of audio quality and efficiency is needed. Requires licensing fee.
  - Bitrate: Up to 256 kbps (Apple), ~320 kbps (rest)
  - Audio Quality: Better than SBC, Quality depends on implementation.
  - Latency: Moderate (~100 - 150 msec)
  - Compatibility: Widely supported in Apple Devices
  - Power Consumptions: Moderate
- **aptX family (aptX, aptX HD, aptX LL, aptX Adaptive):** Developed by Qualcomm, these codecs offer improved audio quality and lower latency compared to SBC. aptX HD supports high-resolution audio, while aptX LL is designed for low-latency applications like gaming. aptX Adaptive dynamically adjusts the bitrate based on the environment. This has a licensing fee [6]
  - Bitrate: Up to ~352 kbps
  - Audio Quality: Offers higher fidelity and clearer sound compared to SBC and AAC.
  - Latency: Lower Latency (~ 40 - 80 msec).
  - Compatibility: Common on Android devices. But not supported by Apple.
  - Power Consumptions: Good for general use in the Android ecosystem as quality is superior compared to SBC.

- **LDAC (Sony's Low Latency Audio Codec):** Developed by Sony, LDAC supports high-resolution audio and offers higher bitrates than many other codecs. Its variable bit rate is the defining feature, in theory it should consistently transfer up to 3x compared to SBC. LDAC was initially limited to Sony products but has been part of the Android Open Source Project(AOSP) since Android 8.0 "Oreo. [7]
  - Bitrate: Upto 990 kbps according to quality modes
  - Audio Quality: Near lossless, suitable for high-res audio streaming
  - Latency: Up to ~200 to 300 msec. Higher due to high bit-rate
  - Compatibility: Supported in Sony devices and some Android devices 8.0 onwards.
  - Power Consumptions: High due higher bit-rate processing.
- **LHDC (Low Latency High Definition Codec):** Developed by the HWA Alliance, LHDC focuses on high-resolution audio and low latency. This codec allows 3x data transmission afforded by SBC. It's supported by Android 10.0 and above aspart of AOSP
  - Bitrate: Up to 900 kbps
  - Audio Quality: Comparable to LDAC, with high-res audio support.
  - Latency: Low latency (around ~30 - 50 msec)
  - Compatibility: Limited support, mainly on some Android devices and specific headphones
  - Power Consumptions: Moderate to high depending on bit-rate.

Supported codecs comparison (bit rate, complexity, licensing, compatibility...etc)

Parameter	SBC	AAC	aptX	LDAC	LHDC
Bitrate	Up to 354 kbps	Up to 256 kbps	Up to 352 kbps	Up to 990 kbps	Up to 900 kbps
Audio Quality	Basic	Good (iOS optimized)	Better	Near-lossless	Near-lossless
Latency	High	Moderate	Low	High	Low
Compatibility	Universal	Apple, Android	Android	Sony, Android 8.0+	Limited
Power Consumption	Low	Moderate	Moderate	High	Moderate to High
Best Use Case	Default for most devices	Apple devices	General Android use, gaming	Audiophiles, high-res audio	Gaming, video, high-res audio
Adopted models	Universal support	Apple Devices, Sony, Bose	Android Devices, Senneheiser, Bose, Gaming headsets	Sony, Android 8.0+	Huawei, Xiamoi, Oppo (Asian Markets)
Licensing/Propriety	No	Yes	Yes	No	No

Table 2: Supported codecs comparison

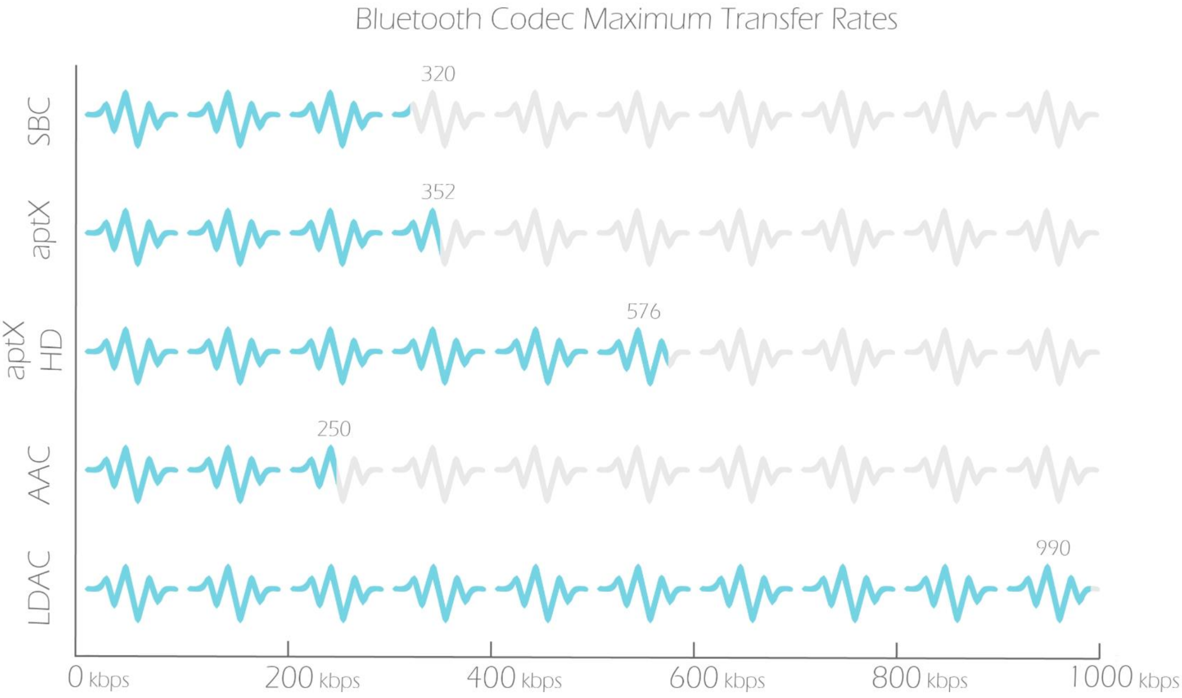

Fig. 3: Max transfer rate (kbps) of each Bluetooth codec (higher the better). [5]

5.2 Real-world Codec Performance Measurements

According to research conducted by Vanessa McCuaig at RTINGS [8], significant variations in codec performance exist across different devices. McCuaig's tests, performed using Samsung Galaxy S23 Ultra, iPhone 14 Pro, and Google Pixel 7 Pro paired with various Bluetooth headphones, showcase the real-world implications of different codec implementations. Their testing methodology involved standardized audio-video sync tests and battery consumption monitoring under controlled conditions.

In their latency testing, SBC showed the highest delay ranging from 220-270 msec on Samsung devices and 180-230 msec on iPhones. AAC performed better with latency between 160-200ms on Samsung and 140-180 msec on iPhone devices, demonstrating Apple's optimization of the AAC codec. aptX and aptX HD, available only on Android devices, showed improved performance with latency ranges of 130-170 msec and 150-190 msec respectively on Samsung devices. LDAC, despite its high-quality audio transmission, exhibited relatively high latency at 200-240 msec on Samsung devices.

Power consumption measurements by RTINGS revealed a clear correlation between codec complexity and battery drain. During continuous audio playback, SBC proved most efficient, consuming 3.2% battery per hour on Samsung and 2.8% on iPhone devices. AAC showed moderate power usage at 3.8% (Samsung) and 3.1% (iPhone) per hour. The high-quality codecs demonstrated significantly higher power demands, with aptX consuming 4.2%, aptX HD 4.8%, and LDAC 5.5% battery per hour on Samsung devices.

As noted in ValdikSS's comprehensive analysis [9], codec performance varies significantly based on environmental factors. In scenarios with high RF interference, latency increased by 15-25% across all codecs. Distance testing showed that latency and power consumption increased proportionally with distance, particularly notable beyond 5 meters. These findings suggest that real-world performance can deviate substantially from laboratory measurements.

The RTINGS testing environment was carefully controlled with display off and background apps closed, maintaining room temperature at 22°C. Signal strength was maintained at -60dBm with consistent device distance of 1 meter. Audio content comprised mixed music genres encoded at 320kbps to ensure comprehensive codec evaluation across various audio types and frequencies.

6 Bluetooth Classic: Limitations With Multi Channel Support

The Bluetooth Classic protocol with A2DP , while widely adopted for audio streaming, faces inherent limitations that hinder its ability to fully support modern multi-channel audio applications. A2DP is designed for unidirectional stereo audio streaming. This means that audio data is transmitted from a single source device to a single receiving device, and only in a two-channel stereo format. This design fundamentally restricts its capacity to handle true multi-channel surround sound experiences, such as those found in 5.1 or 7.1 systems.

Furthermore, Bluetooth Classic operates on a master-slave architecture, where a single master device manages connections and data distribution to multiple slave devices. While this architecture works well for basic audio streaming, it can introduce bottlenecks when attempting to handle multiple, simultaneous high-quality audio streams. The master device becomes a central point of congestion, potentially limiting the overall performance and scalability of multi-channel audio applications.

Although A2DP has seen some advancements through proprietary extensions developed by manufacturers to address specific use cases, it still lacks native support for true wireless stereo (TWS). TWS has become increasingly popular with the rise of true wireless earbuds, which, unlike traditional Bluetooth headphones, have no physical connection between the left and right earpieces. A2DP, in its original design, streams a single audio signal to a single receiving device, which then typically splits the audio channels via a wired connection to the left and right speakers. TWS, on the other hand, requires two independent audio streams to be transmitted wirelessly to each earbud, enabling completely untethered operation. This functionality is not included in the standard A2DP specification, necessitating the development and implementation of additional technologies to achieve synchronized audio playback in true wireless earbuds [10].

These limitations highlight the challenges faced by Bluetooth Classic in meeting the evolving demands of multi-channel audio applications. While proprietary solutions have emerged to extend its capabilities, the underlying architecture and A2DP profile remain constrained by their original design.

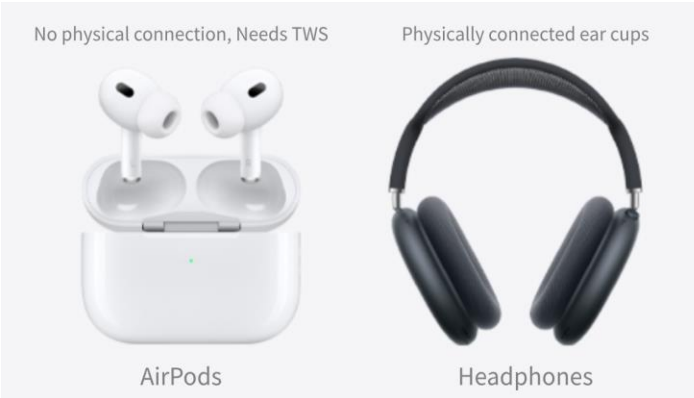

Fig 4: Airpods need True Wireless Stereo support

7. LE Audio: A New Era for Bluetooth Audio

LE Audio revolutionizes wireless audio with enhanced quality, power efficiency, and multi-stream capabilities. This unlocks innovation for hearing aids, wearables, AR/VR, public information systems, and live entertainment. Developers can leverage LE Audio to create products with extended battery life, smaller form factors, and superior sound, ushering in a new era of wireless audio experiences.

7.1 Classic Audio vs LE Audio:

While A2DP, also known as Bluetooth classic audio, is a peer to peer connection which is more suitable for stereo and continuous audio streaming to earbuds, headphones, and personal speakers. It is power-hungry and not suitable for ultra-low power applications like hearing aids. In contrast, Bluetooth LE is targeted at applications where power consumption is a key consideration and limited amounts of data are sent on an occasional basis, such as with energy-efficient sensor devices. Whilst sharing the same branding and core specification, Bluetooth Classic and Bluetooth LE are not compatible, and for this reason smartphones and other mobiles devices have to implement dual radios to support both protocols.

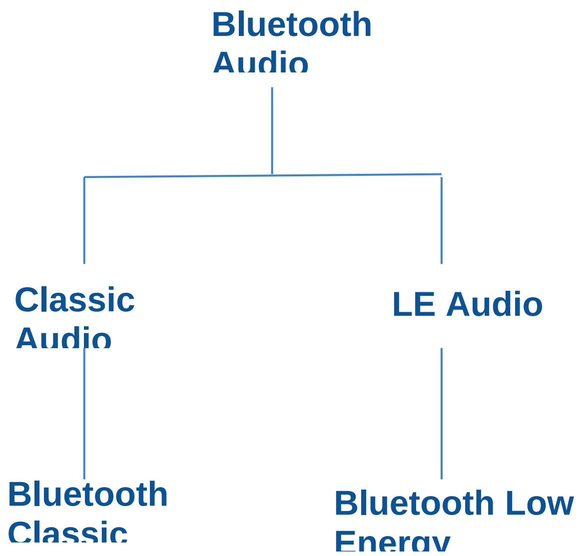

Fig 5. Bluetooth audio classification[12]

LE Audio differs from Classic Audio in that it operates on the Bluetooth Low Energy radio. This is made possible by LE Isochronous Channels, a feature introduced in Bluetooth Core Specification version 5.2 that adds isochronous data transport on the Bluetooth Low Energy radio.

LE Audio will support the development of the same audio device types and use cases as Classic Audio. In addition, LE Audio introduces several key new features that will enable development of new device types and new use cases.

Not only does support for audio on LE allow for lower power consumption, it also enables the development of devices capable of both wireless data transfer and audio streaming using a single mode Bluetooth LE radio, rather than the current need to have dual radios. However it is anticipated that mobile devices will still support Classic Audio for at least a few years, but that support will eventually be phased out. [12]

7.2 Energy-Efficient Codec

LE audio includes a new high-quality, low-power audio codec called LC3 or Low Complexity Communication Codec, LE Audio achieves similar quality to SBC at bit rates between 40-256 kbps while consuming substantially less power. This efficiency enables much longer battery life in small devices like hearing aids, making Bluetooth audio streaming viable for all-day use in these applications. Thanks to these characteristics, the codec was adopted by multiple Bluetooth audio working groups for use in other fields and selected as the mandatory audio codec for Bluetooth LE Audio in September 2020. [15] The following graph shows results graded using ITU-R BS 1116.3, which presents methods for the subjective assessment of small impairments in audio systems. [12, 13]

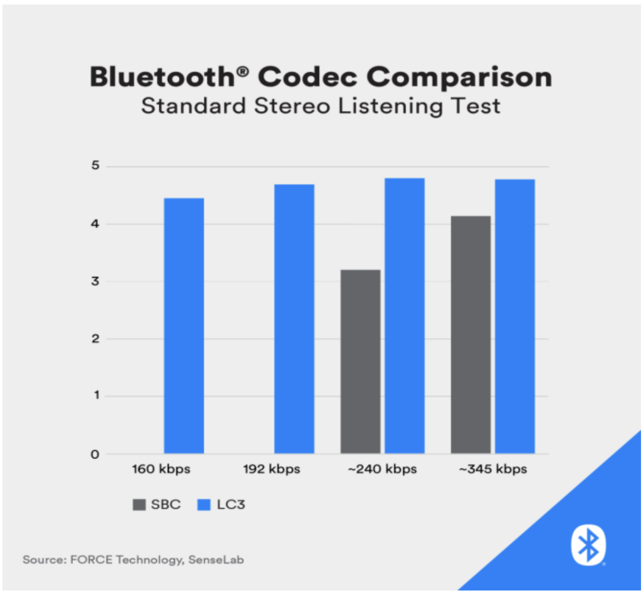

Fig 6. Listening tests results of SBC vs LC3 [14]

As shown in the Fig 6, extensive listening tests demonstrate that LC3 provides superior audio quality over the SBC codec included with Bluetooth Classic Audio for typical use cases such as listening to music, even at a 50% lower bit rate. For example, LC3 at 160 kbps outperforms the SBC 345 kbps which means ~54% of bits saved, which is directly proportional to the battery saving.

LC3 codec gets this efficiency because of new coding characterization. It employs block-based coding, utilizing a modified Discrete Cosine Transform (DCT) with frame intervals of 10 msec and 7.5 msec [16]. Also one standout difference of LC3 is, it only codes single audio channels. Stereo or multi-channel streams are assembled by aggregating single audio channel instances. Because the audio channels are kept independent, it is possible to send the individual channels to dedicated left and right audio devices, such as untethered earbuds or separate Speakers. For untethered devices, independent channel coding minimizes the overhead of receiving data and decoding complexity compared to a joint coding approach. Joint coding implies that all channels need to be decoded at one device, which results in higher computational complexity. Additionally, a jointly coded payload is larger than a single-channel payload, which means more data needs to be received by the device, leading to higher power consumption and an increased vulnerability to interference.

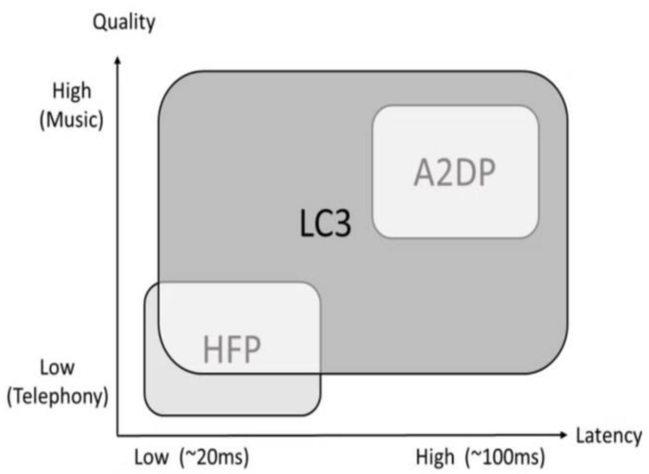

Fig 7: Latency comparisons across HFP, A2DP and LC3[17]

Fig 7 shows LC3's key superiority over HFP and A2DP profiles with respect to the lower latency values for the given quality constraints. Due to the low latency demands of hands-free calling applications, the Hands-Free Profile (HFP) traditionally suffers from poor audio quality. However, with advancements in telecommunications, such as VoIP, we now achieve high-quality audio even over wireless telephone calls. Despite this, the limitations of HFP cause audio quality to degrade when using a Bluetooth headset for hands-free calls. This is where the LC3 codec makes a significant difference, as it enables the transmission of high-quality audio between the earphone's microphone and the phone, and vice versa, while maintaining low latency.

7.3. Multi-Stream Audio

LE Audio introduces Multi-Stream Audio, a new feature that enables the transmission of multiple, independent, synchronised audio streams between an audio source device and one or more audio sink devices. Using this new feature, developers can improve performance of truly wireless earbuds, including better stereo imaging experience, more seamless voice control services, and smoother switching between multiple audio source devices, such as when a headset is simultaneously connected to both a smartphone and laptop.

7.3.1. Classic Audio Streaming

In the relay method employed by True Wireless Stereo (TWS) implementation in Classic Audio, the source device first connects to the primary sink using the standard Bluetooth A2DP, which then relays the transmission to the secondary sink device for the other channel of the stereo pair. As well as the additional transmitter for the relay link, the primary sink device needs to provide data buffering to maintain synchronization with the secondary sink, which in turn increases overall link latency. This added functional requirement for TWS sink device implementations represent increased material cost, weight and power consumption compared with the far more efficient and lower latency solutions offered by LE audio Unicast and Broadcast isochronous data transmission techniques.

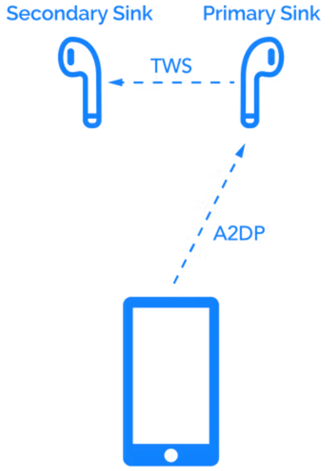

Fig.8. Classic Audio Relay Streaming [12]

7.3.2 Unicast Streaming

Unicast Connected Isochronous Streams (CIS) enable the transfer of audio data between two devices with an acknowledgement scheme to provide flow control. An Asynchronous Connection-Oriented Link (ACL) control channel is used to set up the CIS stream and maintain the flow control until the stream is terminated.

A Connected Isochronous Group (CIG) contains one or more CIS streams, and in the case of multiple streams, these may flow in the same or opposite directions. The left and right channels of a stereo pair are each implemented as a CIS and contained within a CIG, each stream connecting directly to the wireless earbud, or other sink device, for that channel. The respective ACL flow controls ensure that both streams, being in the same direction, remain time-synchronised for the duration of the connection to maintain the stereo image. This allows the sink devices for the left and right channels of a stereo pair to operate independently and without any need to know about the existence of one another.

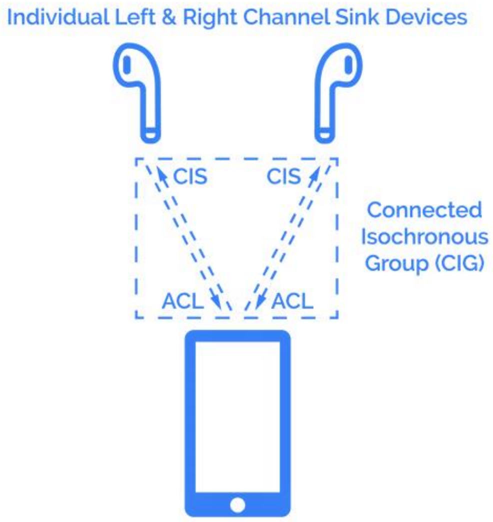

Fig. 9. Unicast Connected Streaming [12]

7.3.4 Auracast Broadcast Streaming

Auracast is Bluetooth SIG's trade name for LE Audio broadcast streaming. This technology enables multiple sink devices to connect to a single source in either mono or stereo.

Broadcast Isochronous Streams (BIS) are Connectionless in that they do not include ACL control channels to allow acknowledgements from sink devices back to the source device, and so a source device operating in Broadcast mode has no information about how many of a potentially unlimited number of receiving sink devices are subscribed to a BIS. Broadcasts can be configured to be open for any sink device to subscribe, or secured with a pass key to protect against unauthorised access.

As with Unicast connected streams, multiple BIS streams can be grouped together. The Broadcast Audio Source Endpoint (BASE) structure is a three tier hierarchy with the individual BIS streams as the bottom tier. At the middle tier, BIS streams with common features such as the left and right channels of a stereo pair are contained in Subgroups. The Subgroups are then aggregated into a Broadcast Isochronous Group (BIG) at the top tier.

The use of Unicast and Broadcast streams is not mutually exclusive in LE Audio, indeed implementations may switch between them, or use them in combination, to fulfil the requirements of a particular application.

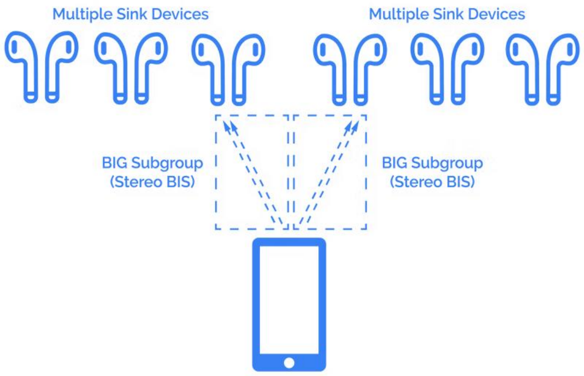

Fig. 10. Broadcast Connectionless Streaming [12]

Conclusion

Bluetooth audio streaming technology has evolved significantly through various iterations, with A2DP and AVRCP profiles serving as fundamental components for wireless audio transmission. While Bluetooth classic offers diverse codec options catering to different needs, from basic audio streaming to high-resolution audio, however certain limitations persist, particularly in multi-channel support and power efficiency. The introduction of LE Audio marks a promising direction for future developments, especially for power-sensitive applications like hearing aids, while maintaining comparable audio quality to traditional Bluetooth classic audio streaming.

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