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Bluetooth Audio: Technology, Advancements, Challenges and a road toward Wi-Fi.

White Paper

Revision

1.2

Bluetooth technology has transformed the way we consume and enjoy audio content. From wireless headphones and speakers to car audio systems and smart devices, Bluetooth audio has become ubiquitous.

This white paper delves into the technology, advancements, and challenges associated with Bluetooth audio.

1. Bluetooth Audio Technology: Bluetooth is a short-range wireless packet-based protocol with a master/slave architecture. standard used for exchanging data over short distances typically <10 metres employing UHF radio waves in the ISM bands, from 2.402 GHz to 2.48 GHz.

Formerly standardized the IEEE as IEEE 802.15.1 Bluetooth is managed by the Bluetooth Special Interest Group (SIG), initially formed in February 1998, comprising of Ericsson, Intel, IBM, Toshiba and Nokia and now has more than 35,000 member companies.

While widely used for audio purposes, Bluetooth also supports a wide range of radio data options, including printers, keyboards and peripherals.

2. Advancements in Bluetooth Audio: Bluetooth audio functionality is defined by specific profiles, which are sets of rules and protocols that govern how devices communicate and interact with each other.

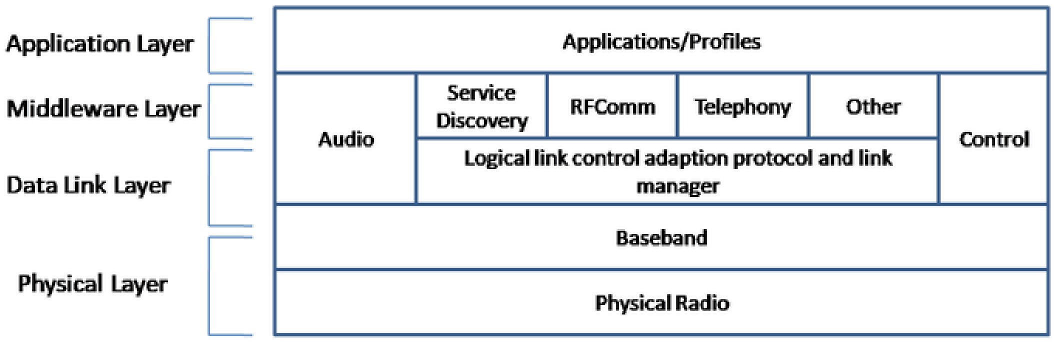

Figure 1 - Profiles within Bluetooth Stack

The most common Bluetooth audio profiles include:

Advanced Audio Distribution Profile (A2DP): A2DP is used for streaming high-quality stereo audio from a source device (e.g., smartphone, tablet) to a receiving device (e.g., headphones, speakers). It supports various audio codecs for encoding and decoding audio data.

Hands-Free Profile (HFP): HFP is used for enabling hands-free communication in vehicles. It allows for the transmission of audio between a mobile phone and a car's audio system, as well as for voice calls and control functions.

Headset Profile (HSP): HSP is similar to HFP but is primarily used for enabling communication between a mobile phone and a mono headset, typically for making phone calls.

Audio/Video Remote Control Profile (AVRCP): AVRCP enables remote control functions for audio and video playback. It allows devices like headphones or car stereos to control playback (play, pause, skip tracks) on a connected source device.

A2DP is the principal profile for sharing music and is widely supported by most Bluetooth-enabled devices, including smartphones, tablets, headphones, speakers, and car stereos. This ensures interoperability and allows users to seamlessly stream audio between different devices regardless of the manufacturer.

A2DP further supports multiple audio codecs for encoding and decoding audio data.Common codecs include SBC (Subband Coding), AAC (Advanced Audio Coding), aptX, and LDAC (Low-Complexity Subband Coding). The choice of codec depends on factors such as device compatibility, audio quality, and latency requirements.

Mechanisms for ensuring Quality of Service (QoS), safeguarding a reliable audio streaming experience are integrated. These mechanisms prioritize audio data transmission, minimize latency, and reduce the likelihood of audio dropouts, ensuring a consistent and uninterrupted listening experience.

A2DP also supports basic control functions such as play, pause, skip track, and volume control. These control functions are facilitated through the Audio/Video Remote Control Profile (AVRCP).

Bluetooth audio has undergone significant advancements over the years, enhancing its capabilities and performance. The introduction of Bluetooth versions like Bluetooth 4.0 (with Low Energy) and Bluetooth 5.0 has provided improved power efficiency, extended range, and increased data transfer rates. These advancements have resulted in better audio quality, reduced latency, and enhanced overall user experience.

3. Limitations for Audio Quality: In music recording and playback the industry standard has long been CD quality, 16 bit resolution, 44.1kHz sampling, 1.4Mbps bandwidth.

With restricted bandwidth Bluetooth relies on audio codecs for compression and decompression of audio signals. Different codecs, such as SBC, AAC, aptX, and LDAC, offer varying levels of audio quality. The choice of codec can impact the overall audio fidelity.

These codecs are “lossy” as they discard most of the audio data, typically reducing a 1.4Mbps source to around 300 kbps, with codecs like AAC running at a maximum of 250 kbps.

The discarded data generally is audio that the human ear is less likely to detect, such as a soft sound in the presence of a similar but louder sound, but it is widely perceived as a less rich and tonal sound.

This compression and processing comes at another cost, latency.

Latency is the time taken for a digital signal processor to decode or encoded the audio into the Bluetooth standard. This is one piece of a complex series of steps which result in a total transmisson delay from sound source to reception at the listener.

With Bluetooth this latency varies by how complex the codec is, generally there is trade off between compression, quality, reliability and bandwidth.

SBC can run at data rates as high as 345 kilobits per second but the latency has been measured at around 200 milliseconds (300ms with wireless earphones). aptX is measured at typically around 120 ms and aptX Low Latency below 40 ms.

There are multiple scenarios where latency will not matter, playback of recorded audio, non-real time monitoring etc, however these levels of delay are unacceptable for many applications.

Lip-sync is a solid benchmark for the impact of latency.

The recognized industry standard adopted ITU-T Recommendation G.1080, is an audio/video delay threshold between plus 15ms and minus 45ms.

The EN 301549 information and communication technology public procurement standard specifies a maximum time difference of 100 ms between the audio and the video, noting that the decline in intelligibility is greater if the audio is ahead of, rather than behind, the video track. Whereas Studies using high quality audiovisual content at much faster frame rates have shown that lip synchronization mismatch of 20 ms or less is imperceptible.

4. Bluetooth Range and Radio Spectrum: Bluetooth operates on the 2.4GHz Instruments, Scientific and Medical (ISM) band. This radio band is shared with other technologies, including Wi-Fi access points, cordless phones, amateur radios, garage door openers and more. Because different technologies share the same radio frequencies there is potential for conflict between devices.

More specifically, Bluetooth operates on the 2,402 MHz to 2,480 MHz frequencies. This band is divided into seventy-nine 1MHz channels. In operation, a Bluetooth headset hops among the 79 channels 1,600 times per second in a pseudo-random sequence known only to the transmitter and receiver. From Bluetooth 4.0, the physical channel is 40 with FH (Frequency Hopping).

The widespread adoption of Bluetooth-enabled gadgets, including smartphones, smartwatches, and IoT devices, has significantly increased the number of devices contending for bandwidth within the 2.4 GHz spectrum as has co-existence with Wi-Fi Networks.

Legacy Wi-Fi networks operating in the 2.4 GHz band lead to interference and congestion due to overlapping channels and competing transmissions.

For this reason modern Wi-Fi standards have moved towards away from the 2.4G spectrum

IEEE standard	Radio frequency (GHz)
802.11bn	2.4, 5, 6, 42, 71
802.11be	2.4, 5, 6
802.11ax	2.4, 5, 6
802.11ac	5
802.11n	2.4, 5
802.11g	2.4
802.11b	2.4

Table 1: Wi-Fi radio frequency bands.

Inherent protocol overheads in Bluetooth, such as device discovery and frequency hopping, contribute to increased congestion and reduced throughput in densely populated Bluetooth environments.

Congestion in the 2.4 GHz band results in increased interference, leading to packet collisions, signal degradation, and reduced communication range in Bluetooth networks. High levels of congestion can cause frequent disconnections and reconnections between Bluetooth devices, impacting the overall reliability and user experience, and congestion-induced collisions and contention for the wireless medium lead to decreased data rates and slower performance in Bluetooth communication.

The primary mitigations for this congestion are frequency hopping and channel management techniques such as channel switching and dynamic channel selection helps optimize spectrum usage and reduce interference from neighbouring.

Newer Bluetooth specifications, such as Bluetooth Low Energy (BLE) and Bluetooth 5.0, offer improved coexistence mechanisms and higher data rates, enhances the resilience of Bluetooth communication in congested environments.

Part of Bluetooth's success has been due to it's low power operation and that is partly due to a transmission power limited to 2.5mW compared to WiFi in a typical laptop or smartphone of generally 10mW or a Indoor home or office router of 100mW.

This has an impact on maximum range. While the theoretical outdoor range of Bluetooth is 100m in practical indoor settings with attenuating factors such as walls the maximum range is generally 10m.

5. Future Possibilities: Bluetooth audio continues to evolve, and future advancements hold promising possibilities:

Enhanced Codecs: Newer and more efficient audio codecs are being developed to deliver higher audio quality and lower latency.

Increased Compatibility: Bluetooth technology is expected to become more compatible with emerging audio standards, enabling seamless integration with advanced audio devices

Improved Power Efficiency: Bluetooth is continually improving its power efficiency, allowing for longer battery life in wireless audio devices

Wi-Fi as a successor in the High Performance space

Bluetooth provides an excellent common platform for audio and non-audio wireless connection, but many Bluetooth devices are equipped with another wireless radio platform, who's standard and capabilities has steadily increased – Wi-Fi.

Wi-Fi particularly with advancements in the 802.11 specification for increased capacity, range and focus on multimedia – offers a proven platform for audio sharing, with the potential to overcome the challenges of Bluetooth's, restrictive range, bandwidth and latency and recent evolutions in the 802.11 specification show the massive opportunity for real time audio applications.

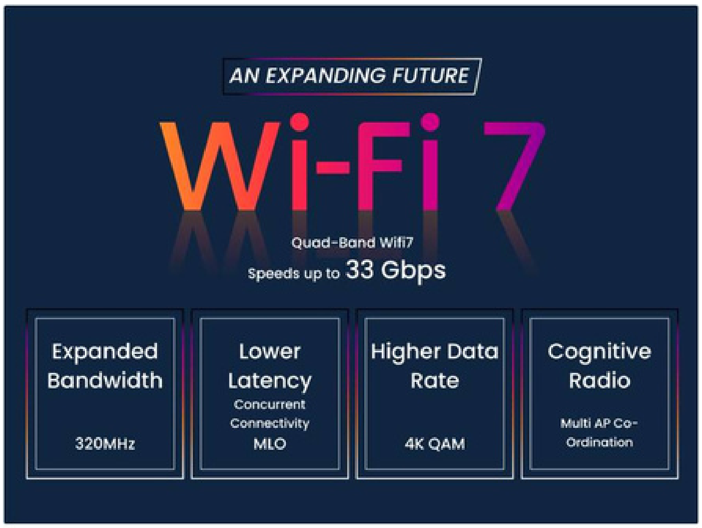

Figure 2 – Key features of Wi-Fi 7 that will benefit Fi-Live(TM) style audio.

Fi-Live(TM) offers a live real time system for converting analog sources such as instruments into real time Wi-Fi packets on a self-generated Wi-Fi network.

As an open framework, as the 802.11 standard progressively adds more range and bandwidth, so Fi-Live(TM) can grow and adapt a range of effects and codecs for error correction and audio tuning. Crucially by levering the 10 billion Wi-Fi capable phones, tablets and PCs in use today Fi-Live offers a common platform for audio recording and distribution with a ready to go audience.

Conclusion

Bluetooth audio has revolutionized the way we experience audio on a daily basis. With its convenience, compatibility, and advancements in audio quality, Bluetooth technology has become a go-to solution for wireless audio transmission, however the considerations for audio quality, range and latency, make Bluetooth unsuitable for high performance or live audio applications. As such while Bluetooth will remain a pervasive standard for general consumer audio there is huge scope for Wi-Fi based audio systems such as Fi-Live to offer a superior solution for key applications.

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