Can Bluetooth Audio Replace the Wire?

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Abstract

Bluetooth is becoming more and more popular in consumer electronic devices, and with advances allowing for transfer of higher quality audio Bluetooth speaker and headphone sales are growing year on year. New developments such as the aptX HD and LDAC audio codecs are permitting better than CD quality audio to be transmitted wirelessly with Bluetooth, and the aptX Low Latency codec, has made a start at reducing the high latencies that are often associated to Bluetooth devices. Bluetooth is still however limited by interference from IEEE 802.11 and other Bluetooth networks. Methods for reducing interference are discussed and further research into hybrid schemes is suggested. Bluetooth 5 is expected to be released in early 2017, with increased performance statistics. The transmission of high resolution audio, at faster speeds and over greater distances than ever before may be possible. However, with higher latencies than its wired counterparts, and the limitations due to its susceptibility to interference Bluetooth still has a long way to go before it becomes a real contender in the professional audio industry.

1. Introduction

Millions of users around the world use networking daily to communicate with friends, family, and colleagues. Computers are able to connect in more ways than ever before, and with technology improving day by day, almost all consumer electronic devices have network capabilities.

Fixed connection networks are less susceptible to interference and are consequently more reliable than their wireless counterparts. However, wireless communications enable users to seamlessly connect personal computers to peripheral devices, without the constraints associated with wired connections.

Bluetooth and Wi-Fi are widely used wireless communications networks. The operational speed and distance of Wi-Fi is ten times greater than Bluetooth's and both have similar costs. However, Bluetooth consumes much less energy than Wi-Fi, making it ideal for use in portable devices such as headphones, hard drives, wearables and cars, where batteries need to be kept as small as possible.

ZigBee is another low power wireless communications network, with a range 10 times greater than Bluetooth, however with just a quarter of the data speed it isn't suitable for file transfers [Abinayaa and Jayan 2014]. It is mainly used for home automation systems, and is often found in remote controls.

Bluetooth is a Wireless Personal Area Network (WPAN), developed in 1994, by the Swedish mobile phone company Ericsson, with the intention of replacing cables connecting personal computers and peripheral devices [Bluetooth SIG 2001]. In 1998 IBM, Intel, Nokia and Toshiba joined the study forming the Bluetooth Special Interest Group (SIG), which now has over 30,000 member companies [Bluetooth SIG 2016b].

Since its creation the development of Bluetooth has been continuous, allowing new capabilities such as stereo audio to be introduced [McClintock 2016]. It was one of the main technologies behind the audio steaming revolution, disconnecting inconvenient wires from between headsets and speakers, and phones and computers, giving users reliable, convenient access to their music anywhere [Bluetooth SIG 2016a].

Consumer demand for devices with the ability to receive transmitted audio via Bluetooth is increasing. A total of €1.6 billion was spent on Bluetooth enabled docking speakers in 2014. In the same year the Western European market purchased 7.6 million Bluetooth speakers. Sales of these devices continue to grow, up by 40 percent in the first six months of 2015, compared with the same period in 2014 [GfK Global 2015]. With such demand for Bluetooth devices, the quality of distributed audio and ability to prevent interference is of upmost importance. With manufacturers continuously developing ways of improving the system, will Bluetooth ever be able to replace the wire?

This paper focuses on the features and limitations of Bluetooth and the overall suitability of the system for professional audio applications. In section 2 the paper looks at Bluetooth's main features and their suitability for audio transmission in professional work flows. Section 3-6 focus on Bluetooth's current limitations, including network interference, latency and operational range as well as the quality of transmitted audio. Section 7 will look at the imminent release of Bluetooth 5, and what possibilities it may bring to the audio industry.

2. Bluetooth Features

The Bluetooth system is robust, has low power, low complexity and low cost [Bluetooth SIG 2001]. Bluetooth enables numerous devices such as personal computers, mobile phones and entertainment systems to communicate using low power, short distance wireless links [Verma et al. 2015].

2.1. Universal

Bluetooth is universal, making previously impossible connections between devices with various proprietary connectors and pin arrangements possible [Bisdikian 2001]. Devices such as headphones can connect to a mobile phone with the same ease as connecting to a laptop or tablet, irrelevant of manufacturer. Likewise, computer peripherals including keyboards, hard drives, printers and speakers can be easily connected, reducing the stress and cost of sourcing and utilising potentially expensive interconnect cables.

As Bluetooth is already built into millions of products integrating new Bluetooth devices such as microphones or speakers into professional rigs may be fairly straightforward.

2.2. Low power

Bullis [2015] states that battery technology is not advancing in line with other technologies, as it is still poorly understood. There have been improvements over the last decade, but they've largely come from frequent small advances.

Bluetooth's nominal power consumption is around 100mW, whilst WiFi consumes 700mW [Lee et al. 2007]. Making Bluetooth ideal for portable devices with limited battery power. Bluetooth Low Energy, also known as Bluetooth Smart, was released in 2010 with the Bluetooth Core Specification version 4.0. Dementyev et al. [2013] found it has a nominal power consumption of 15mW, lower than standard Bluetooth. However, Bluetooth Smart has reduced data rates than standard Bluetooth, and therefore currently is not suitable for the transmission of audio.

The ability to run off small batteries would be extremely useful for wireless microphones, in live music and recording studios, which due to their size would not be able to hold larger batteries. Wireless in-ear monitors would also benefit, with the ability to remove bulky transmitter boxes that are often required with in-ear devices.

2.3. Inexpensive

Bluetooth chips replace are inexpensive when compared with the cost of the connectors and cables they replace, and therefore are attractive to manufacturers. This has led to hundreds of millions of Bluetooth equipped devices on the consumer market [Bluetooth SIG 2016a]. It would be fairly cheap and simple to incorporate Bluetooth chips into microphone and monitoring systems, or for companies to develop Bluetooth transmitters and receivers that attach to existing audio equipment.

2.4. Mobile

With the removal of cables, wireless devices give users the ability to move freely without disrupting connections. Bluetooth headphones have become a popular sports accessory, especially amongst runners, as wired headphone cables often get in the way when training and competing. The ability to move the source device, such as a smart phone, around the home is also very appealing to consumers.

A common use case for Bluetooth is streaming music from a phone or computer whilst simultaneously using it for other applications. This could also transfer to live sound, where engineers may require the ability to move freely around the venue whilst sound checking, to ensure musicians are audible in different sections. It could also be beneficial for wireless microphones and in-ear monitors, allowing performers to move freely around the stage.

2.5. Easy Instillation

Connecting a peripheral device to a personal computer is as simple as finding it from the computer and pairing the two devices. During this process the computer (verifier) sends a signal containing a random number (the challenge) to the peripheral device (claimant). The claimant then calculates a response, which is a function of the challenge, the claimant's address and a secret key [Bluetooth SIG 2001]. Once this initial connection is established, the devices will be able to connect without the need for these installation steps. Connections may be made by turning on the peripheral device.

This would be extremely useful for live sound engineers wanting to connect their desk to speakers already installed into a venue. Allowing them to easily connect via Bluetooth could speed up rigging time and reduce the need for expensive cable runs.

2.6. Stereo Audio

Most importantly for the professional audio industry is Bluetooth's ability to transmit stereo audio. Bluetooth has the ability to stream mono or stereo audio from a source device to headphones or speakers, using the Advanced Audio Distribution Profile (A2DP) [Bluetooth SIG 2015].

3. Network Interference

System reliability is extremely important for professional audio applications, as dropped packets may result in important data being lost. For example, parts of a performance not being received from a microphone by a recording or live desk, or speakers cutting out intermittently during live performances.

Bluetooth operates in the unlicensed 2.4 GHz ISM (Industrial-Scientific-Medical) band, which is split into 79 1 MHz wide channels [IEEE 802.15.2 2003], and has an operational distance of 10-100m.

A physical radio channel is shared by a group of Bluetooth devices, known as a piconet. Each piconet compromises of a single master and up to seven slave devices [Bluetooth SIG 2001]. A larger network called a scatternet can be formed when two or more piconets connect through a bridge or relay device [Pinkumphi and Phonphoem 2009]. The systems are synchronised to a common clock and use a frequency hopping spread spectrum (FHSS) scheme to combat interference. In a FHSS the 79 frequencies of the ISM band are placed in an algorithmically determined pseudo-random order, based on the device address and master clock [IEEE 802.15.1 2005]. The system hops between these frequencies using a Time Division Duplex (TDD) method dividing each second into 1600 time slots (625μs per slot) [Pinkumphi and Phonphoem 2009]. The pattern is adaptive, whereby frequencies used by interfering devices may be excluded, this technique is known as advanced frequency hopping [Nagai et al. 2012].
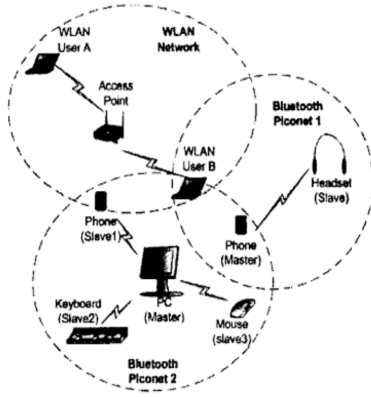
Figure 1. Coexisting piconets and WLAN in an office
scenario [Li 2007].

3.1.1. Coexisting Networks

The IEEE Std 802.11 [2005] states that the Wireless Local
Area Network (WLAN) operational frequency should also
be 2.4 GHz, and has a bandwidth that is roughly equal to 22
MHz [Chiasserini and Rao 2003]. As both the IEEE 802.11
and IEEE 802.15.1 standards specify an operational
frequency of 2.4 GHz, there can often be interference when
the two networks coexist in the same physical space [IEEE
802.15.2 2003]. Fig. 1 shows the coexistence of two
Bluetooth piconets and a WLAN. Co-channel interference
occurs when two networks collide on the same frequency.
As a result of this interference, network throughput
decreases and retransmissions can cause severe delays. The
packet error rate (PER) due to collisions, of a Bluetooth
piconet may reach 10% if seven piconets coexist, and 27%
when in the presence of a WLAN [Li 2007].

Factors that affect the interference level include; the
separation of the wireless devices, the data traffic levels
flowing over each network, the power level of each device,
and the WLAN's data. Different information types have
varying levels of sensitivity to interference. There may also
be interference from other wireless systems, such as
cordless telephones and microwaves, which could result in
severe performance degradation [Gehrmann et al. 2004].

Bluetooth uses a FHSS scheme, while IEEE 802.11
either uses FHSS (IEEE 802.11 FH) or a direct sequence
spread spectrum (DSSS) system (IEEE 802.11b)
[Chiasserini and Rao 2003]. For Bluetooth networks the
IEEE 802.11b represents a worse interferer than the IEEE
802.11 FH, because the Bluetooth packet size is so small
meaning the PER for 802.15.1 in the presence of IEEE
802.11 FH is almost insignificant [IEEE 802.15.2 2003].

3.2. Interference Reduction

Bluetooth has the ability remove channels that are
being used by interfering devices. WLAN can also detect
interference and defer transmission on channels when they
are used by other devices [Nagai et al. 2012]. However, it
has been found that these interference avoidance functions
do not work effectively [Golmie et al. 2003; Chiasserini and
Rao 2003].

The IEEE 802.15.2 standard specifies the use of
alternating wireless medium access (AWMA) and packet
traffic arbitration (PTA) to reduce interference between the
IEEE 802.11 and IEEE 802.15.1 systems [IEEE 802.15.2
2003]. Many other interference reduction techniques have
been suggested such as Li's [2007] dual channel

transmission (DCT) technique, using a Bluetooth
interference aware scheduling (BIAS) strategy or adaptive
frequency hopping (AFH) mechanism both suggested by
Golmie et al [2003], Chiasserini and Rao's [2003] overlap
avoidance schemes (OLA), and cooperative channel
segmentation (CCS) as suggested by [Nagai et al. 2012].

3.2.1. Alternating Wireless Medium Access

In AWMA, the WLAN and WPAN radios are located
within the same physical unit, and thus a wired connection
between the two radios exists. All WLAN devices
connected to the same access point (AP) share a clock. As
the WLAN and WPAN radios are physically connected they
are able to share this clock. The AWMA mechanism utilises
this so all WLAN-enabled devices connected to the same
AP, have the same common WLAN and WPAN time
intervals. This lets the devices restrict their WLAN and
WPAN traffic to non-overlapping time intervals, resulting
in zero WLAN/WPAN interference between them [IEEE
802.15.2 2003]. A major limitation of this technique is that
it does not reduce interference when multiple APs are
present, or when a WPAN device is not synchronised to an
interfering WLAN AP. Another problem with this approach
is the increased network latency [Li 2007]. Chiasserini and
Rao [2003] also found the systems throughput decreases
significantly as the number of devices operating in the
unsilenced band increases.

3.2.2. Packet Traffic Arbitration

In the PTA mechanism, all attempts to transmit by the IEEE
802.11b or the IEEE 802.15.1 require approval. The PTA is
able to predict collisions due to its knowledge of the
duration of IEEE 802.11b activity and future IEEE 802.15.1
activity. A transmit request, that would result in a collision,
may be rejected, as PTA has rules to prioritise transmissions
depending on the packets priority [IEEE 802.15.2 2003].
Even though data throughput is improved, a serious
weakness with this method, is increased network latency
due to packets not being transmitted on time because of
PTA rejections.

3.2.3. Adaptive Frequency Hopping

The main idea for AFH, is to use BIAS but use an algorithm
to adapt the frequency hopping sequence so that only 'good'
frequencies are selected, thus preventing the need to
postpone transmissions. The algorithm checks each
frequency, and if 'bad' replaces it with a 'good' one, see
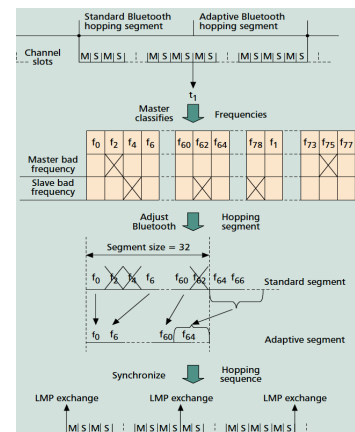Fig. 2 [Golmie et al. 2003]. AFH has been demonstrated

Figure 2. Adaptive Hopping Technique
[Golmie, Chevrollier, et al. 2003].

effective in dealing with static WLAN interference, improving throughput by up to 25%. However, it is not relevant for multiple co-located Bluetooth piconets, as channel frequencies are constantly changing and therefore, piconet hopping patterns are not known by one another [Li 2007].

3.2.4. Cooperative Channel Segmentation

The CCS algorithm builds on the AFH mechanism to avoid frequency overlap, sharing mutual interference channel information, and dividing operational channels between the Bluetooth and WLAN. The CCS block creates a new channel map by multiplying the Bluetooth AFH channel map by the current WLAN channel. It also takes any adjacent channel interference into consideration when creating the new map [Nagai et al. 2012]. Their results show that the CCS mechanism reduces interference between WLAN and Bluetooth, and significantly improve the throughput of the two systems, compared with AFH, AWMA and PTA schemes performance. However, similarly to the AFH algorithm, the CCS mechanism cannot improve interference between co-located Bluetooth piconets as their hopping patterns are not know by one another.

3.2.5. Dual Channel Transmission

With DCT simultaneous transmission of the same packet occurs on two separate channels. There is at least a 22MHz separation between the two channels to combat WLAN interference. It was shown that DCT can not completely avoid frequency collisions. Li [2007] developed an expectation maximisation algorithm, which estimates the hop timing and frequencies of the FHSS scheme. It is used in conjunction with DCT to resolve packet collisions. One major drawback of this joint method requires the use of an antenna array which is often not possible for devices with size constraints such as microphones and headphones.

3.2.6. Bluetooth Interference Aware Scheduling

In the BIAS method, the master uses a predefined criterion, to continuously categorizes frequencies as good or bad. The master will transmit in a slot if it has verified that both the slave's receiving frequency, and its own receiving frequency are 'good'. If either of the frequencies are 'bad', the transmission slot is skipped and the procedure repeated at the next transmission opportunity [Golmie et al. 2003]. Golmie's [2004] results show that BIAS eradicates packet loss due to interference, even when 75% of the frequency spectrum is occupied by other networks. One key limitation to this technique however, is increased network latency by an average of 1-5ms.

3.2.7. Overlap Avoidance

OLA assumes that the Bluetooth master has information about WLAN occupied frequency bands. The Bluetooth master will transmit a long packet on the current carrier frequency, if the next frequency falls into the 22 MHz WLAN band, eliminating co-channel interference (CCI) [Chiasserini and Rao 2003]. Fig. 3 shows this. Supposing frequency $f(k+3)$ lies in the WLAN band. Instead of transmitting a single-slot packet the master transmits a three-slot packet, avoiding transmission on $f(k+3)$ [Li
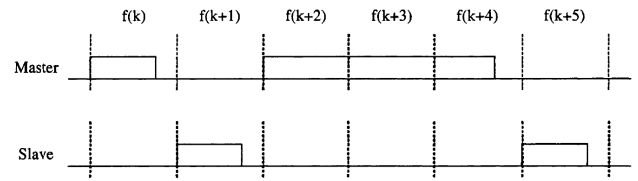
Figure 3. Example of OLA transmission [Li 2007].

2007]. Chiasserini and Rao [2003] show that Bluetooth throughput is significantly improved when using OLA, and that it can also reduce interference from microwave ovens. A limitation with this method however, is that it works on the condition that enough data is buffered for transmission, otherwise it may be postponed, resulting in additional network latency. Chiasserini and Rao fail to account for when the master does not have information about WLAN occupied frequency bands. Suggesting as with the AFH and CCS schemes the becomes redundant when the interference is between co-located Bluetooth piconets. The study would have been far more useful if they had addressed this issue.

3.3. Discussion

It could be argued that interference is Bluetooth's principal limitation. Many techniques have been developed to reduce the interference between the Bluetooth and other wireless systems. However, all the previously mentioned methods suffer from key weaknesses, making them unusable in the professional audio industry.

The AWMA, PTA and BIAS schemes, all result in significant increases to the network latency, which will be discussed later in more detail, but makes them unsuitable for professional audio. AFH has been shown to reduce interference and the CCS mechanism builds on this, resulting in higher reductions. However, both of these systems cannot be used to combat interference from co-existing Bluetooth piconets.

DCT is the only method of those discussed that is only limited due to size constraints. Investigation into antenna array design should be made to see if there are possibilities to reduce the size, and make them more suitable for portable devices.

Other than DCT, the CCS and OLA methods would seem to be the most effective of the discussed techniques at reducing interference without the addition of large latencies. However, as they are ineffective for co-existing Bluetooth piconets a hybrid scheme is suggested combining one of the two with another technique such as DTC. Further investigation should take place in order to assess the abilities for such hybrid methodologies to improve rejection between co-existing networks.

4. Audio Quality

Professionals in the audio industry require high bit depths and sampling frequencies. CD quality audio is 44.1kHz/16 bit, equivalent to a bit rate of 1.4Mbps. This is already higher than Bluetooth's 1Mbps maximum data rate. High resolution audio requires a bit rate of 4.6Mbps as it uses a sampling frequency of 96 kHz/24 bit. Audio codecs are used to compress these large data files, so they can be transmitted over the Bluetooth network. However, this method can potentially lower the audio quality.

Acording to Sayood [2012] there are two data compression schemes, lossy and lossless. If losslessly

compressed, the original data can be recovered exactly from the compressed data. This technique is generally used in applications where differences between the original and reconstructed data are not acceptable. In lossy compression techniques parts of the data are discarded, meaning encoded audio is not identical to the original file. Lossless compression generally obtains much higher compression ratios than lossless compression.

As previously stated the Bluetooth system uses A2DP, to stream stereo audio across its wireless networks. To ensure interoperability, A2DP uses the mandatory low complexity subband codec (SBC) [Bluetooth SIG 2015]. McClintock [2016] states that one major drawback of the SBC codec is that for most implementations it delivers suboptimal audio performance. Optional codecs may be used instead, if supported by both source and sink devices. These include MPEG 1 & 2 Audio, MPEG 3 & 4 AAC, and ATRAC. Vendor specific codecs can also be used if certain information and parameters are defined [Bluetooth SIG 2015].

4.1. Optional Codecs

Most audio files stored on phones or streamed using internet services are already compressed to MP3 or AAC files. SBC compression is often applied, on top of the compression already present in these files, by Bluetooth systems [Butterworth 2016]. If audio devices made use of these optional codecs, additional compression could be avoided, thus improving the quality of received audio [Bluetooth SIG 2015]. However, MP3 and AAC are lossy compression formats. MP3 bit rates vary but are usually around 256kbps, significantly lower than the 1.4Mbps rate required for lossless CD quality audio. These formats may be suitable for consumers, but aren't acceptable for the professional industry.

4.2. Vendor Specific Codecs

Many vendor specific codecs have been developed to improve the audio quality transmitted over Bluetooth, including aptX, aptX HD, and LDAC. aptX HD claims 'better than CD' audio quality [McClintock 2016], Sony Corporation [2016] state LDAC has the ability to 'maintain maximum bit depth and frequency of 96kHz/24bit audio'.

Table 1 SBC Performance [McClintock 2016]

SBC Summary	Count	Sum	Average	Variance
Dtraits_Latest Trick	30	-5.100	-0.170	0.659
GrandmasHands	30	-2.600	-0.087	1.282
Humouresque	30	-3.700	-0.123	1.118
UnderMilk Wood	30	-12.900	-0.430	0.890
Mozart_Violin	30	-0.600	-0.020	0.753
Total	150	-24.900	-0.166	0.940

Note: Scale goes from 0 to -5.0, any value between 0 and -1.0 is deemed imperceptible.

Table 2 AptX Performance [McClintock 2016]

AptX Summary	Count	Sum	Average	Variance
Dtraits_Latest Trick	30	-5.700	-0.190	0.542
GrandmasHands	30	-2.800	-0.093	0.804
Humouresque	30	0.200	0.007	0.914
UnderMilk Wood	30	-1.900	-0.063	1.279
Mozart_Violin	30	0.200	0.007	0.445
Total	150	-10.000	-0.067	0.797

4.2.1. AptX

AptX was initially used by broadcasters to store CD-quality audio on computer HDDs. It is a non-destructive compression algorithm, and supports 48 kHz/16 bit audio using adaptive differential pulse-code modulation, at a data rate of 354kbps [McClintock 2016]. It has subsequently become a popular professional audio standard and is used worldwide by more than 50,000 radio stations and cinemas. In 2009, the aptX codec started replacing SBC in Bluetooth products, and is now used in the majority of Bluetooth enabled wireless devices. It is estimated that there are now more than 1 billion aptX enabled smartphones, tablets, PCs and TVs, and over 50 million aptX Bluetooth headsets and speakers [Qualcomm Technologies International 2015].

Salford University used the perceptual evaluation of audio quality (PEAQ) algorithm to evaluate the performance of aptX at 354kbps against SBC at 328kbps. A sample base of 30 listeners evaluated the formats. The results in Tables 1 and 2 show aptX outperformed SBC by a factor of 2.5 [McClintock 2016].

4.2.2. AptX HD

The aptX HD codec format, built on the previous aptX codec, was launched in January 2016, and offers 48 kHz/24 bit audio. A pilot study was conducted by Salford University comparing aptX HD against 44.1 kHz/16 bit and 96 kHz/24 bit audio. For the test several pieces were commissioned and recorded at 96 kHz/24 bit. The content was then processed in 2 ways;
- down-sampled to 44.1 kHz/16 bit, and
- passed through an aptX HD encode/decode cycle.

Results indicated that over 50% of the participants could not hear a perceivable difference between aptX HD and the 96 kHz/24 bit content, but could hear differences between the 44.1 kHz/16 bit and 96 kHz/24 bit content [McClintock 2016]. It should be noted that this information was provided by the Director of aptX sales and marketing, and that the full study results are not yet available.

4.2.3. LDAC

Sony's LDAC, claims to have the highest audio quality out all of the codecs we have looked at so far, 96 kHz/24 bit. This is achieved by using a 990kbps transfer rate, three times greater than SBC and aptX. Ford [2015] shows that this is impossible, unless lossy compression is used. Current

lossless techniques can achieve a roughly halved bit-rate. So for a 96 kHz/24 bit file, a 2.25Mbps data rate could theoretically be achieved using lossless compression. To get 96 kHz/24 bit into 990kbps would require a lossless compression that achieved 20% of the original file size, more than doubling the maximum compression factor achieved previously.

After questioning a Sony Asia Engineer [Ford 2015] explains that LDAC is in fact a lossy codec, as it cannot fully reconstruct a 24-bit 96kHz signal. It works by trying to recreate the closest possible version of the 96 kHz/24 bit signal. It is also worth noting that LDAC adds to the bit-rate of A2DP, as the A2DP standard does not allow for such high data rates. Even with its lossy compression LDAC still delivers the highest quality audio out of the codecs we have analysed.

4.3. Discussion

Vendor specific codecs such as aptX have improved the performance of stereo audio transmitted across Bluetooth networks. With audio quality matching that of the CD systems are now good enough for most consumer usage. Further developments such as aptX HD and LDAC have significantly increased the performance of the transmitted audio, allowing 'better than CD' quality 48 kHz/24 bit and higher LDAC audio to be transferred between compatible devices.

These formats are probably of a suitable standard for use in professional audio applications, and thus would suggest that the audio quality of Bluetooth is already good enough to replace wired connections, when these codecs are used.

5. Network Latencies

Low deterministic latency is another requirement for most professional audio applications. High end networked audio systems for example typically operate with latencies between 150μs to 1ms depending on the network size [Audinate Pty Ltd 2016].

The SBC codec was used for most early Bluetooth devices. However, SBC is frame based and results in network latencies between 100-500ms. This latency is a largely due to the codec delay; delays when encoding the data, and the transport delay; many codecs split data across two Bluetooth packets to reduce interference, which results in additional transport times [McClintock 2014].

Companies such as CSR, saw the need for low latency in Bluetooth applications such as audio for video, and introduced the aptX Low Latency codec in 2012. For such applications the European Broadcast Recommendation R37-2007 [EBU 2007] states that for audio and video applications the limits of an audio component relative to its corresponding picture component are: Sound before picture ≤ 40 ms and Sound after picture ≤ 60 ms.

The aptX Low Latency codec has a codec delay of 1.89ms; and, does not use a frame format [Qualcomm Technologies International 2016]. This results in packets being populated more efficiently and removes the need for additional latency during transport [McClintock 2014]. The algorithmic delay of aptX Low Latency is 32ms, with end to end latency of 40ms [Qualcomm Technologies International 2016; McClintock 2016].

aptX Low Latency is currently the best performing codec, in terms of end to end latency, for Bluetooth. It meets the EBU requirements for audio with video, and therefore makes Bluetooth suitable for most consumer applications. The key problem with this method however, is that the latencies achieved are still vast compared to wired networked techniques, and thus not acceptable for usage in the professional audio industry.

As latency is often not as important as throughput to many engineers, a trade-off may be possible, by reducing costs of long cables for increased latency. However, it would be preferable to reduce transfer times further, so research into improving the encode/decode phases should be conducted, with the aim of achieving a faster end to end latency, closing in on wired network performance.

6. Network Range

Another key weakness with the Bluetooth technology is its limited range, of just 10m [Abinayaa and Jayan 2014]. This is not suitable for most professional audio applications, where signals need to be transported over much greater distances. For example music venues and festivals that can often have large spaces between the staging and sound desks, and studio complexes such as Abbey Road, with live rooms requiring cable runs of up to 50m [Abbey Road Studios 2016].

7. Bluetooth 5

Bluetooth version 5.0 is due to launch in early 2017, with quadrupled range, doubled speed and a 800% increase in data broadcasting capacity [Bluetooth SIG 2016b]. These system improvements may provide a more suitable technology for professional audio applications.

The increased data broadcasting capacity, will allow for an 8Mbps transfer rate. As previously stated the bit rate of 96 kHz/24 bit high resolution audio is 4.6Mbps, which would easily fit into Bluetooth 5's capabilities without the need for lossy compression. Therefore, allowing the transfer of high resolution audio.

By quadrupling the range of Bluetooth operation from 10m to 40m the system may become more appropriate for live music and studio needs. With most small to medium music venues, a 40m range will be sufficient to cover the area between stage and desk. It would also be suitable for the majority of studios, and allow for the removal of long expensive cable runs.

The main weaknesses with Bluetooth 5 are network latency and interference, which will still be unacceptable for professional audio. Despite the increased network speeds, with the current low latency codecs, the system still may only achieve 15-20ms end to end latency. This is not acceptable for professional usage, when compared against the alternative wired solutions. Interference would also continue be a major disadvantage, especially in live audio situations, where there is potential for thousands of Bluetooth enabled mobile devices, as well as a number of 802.11b networks, to be present within the same physical space.

8. Conclusions

Bluetooth currently has many benefits for the consumer market, especially for low power portable products. It would seem that it has already become a big player in electronic devices. With the audio quality already being more than adequate for the majority of consumers, it should continue to grow until it eventually dominates the headphone and portable speaker market.

Systems such as WLAN, are already present in the majority of homes. Greater speeds and throughput, suggest these networks have superior reliability over Bluetooth systems. Therefore, for applications where power consumption is not an issue WLAN enabled wireless products may be more suitable.

As Bluetooth continues to advance its ability to compete in the professional audio market becomes more and more plausible. With Bluetooth 5 offering the ability to transfer high resolution audio, over greater distances and at faster speeds than ever before, it seems to be making movements in the right direction. However, there are still key areas where improvements are required, including latency and throughput.

As throughput may be Bluetooth's main limitation, research into hybrid schemes for interference rejection should now be conducted. By using current methods together, to improve rejection for both Bluetooth in the presence of WLAN networks, as well as another Bluetooth piconet, the systems data throughput has the potential to be improved.

Network latencies are another issue, however with codecs such as aptX Low Latency combined with Bluetooth 5, end to end Bluetooth latencies of 15ms may be achievable. It would be preferable to reduce this latency too under 10ms. Further research into the encode/decode phases should be conducted to refine and reduce the delay induced by the codec.

In summary Bluetooth is taking the consumer market by storm, with further improvement of its network latency and data throughput, it has the potential to become a real contender in the professional audio industry.

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