Bit-Accurate CD Audio From aptX Lossless

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Bit-Accurate CD Audio From aptX Lossless

Thanks to the development of Bluetooth audio technology, wireless streaming has largely replaced physical media, and smartphone users no longer need to struggle with tangled earphone wires. But to accommodate Bluetooth's limited bandwidth, the industry adopted a variety of lossy compression techniques that sacrifice audio fidelity. This white paper describes the benefits of the aptX Lossless codec, which enables wireless Bluetooth earbuds and speakers to stream audio that's bit accurate to the original CD recording. The Linley Group prepared this paper, which Qualcomm sponsored, but the opinions and analysis are those of the author.

Introduction

In 1998, Bluetooth technology debuted in a wireless earpiece that enabled hands-free cellular phone calls. That first mobile headset was a clunky monophonic device, but ever since its introduction, the industry has strived to improve wireless-audio quality. The compact-disc (CD) standard has served as the high-fidelity benchmark for this effort. More than 20 years later, Bluetooth has successfully eliminated the wires that connect audio sources to earbuds and loudspeakers, and it has allowed streaming to replace most physical media as well.

Accomplishing that feat required innovations in two fields: the codec algorithms that format audio signals and the radio components that maintain reliable wireless links between the source and output devices. Developing a codec that can stream CD-quality audio over a Bluetooth connection proved difficult owing to the low bandwidth of that short-range wireless protocol. To overcome this limitation, the Bluetooth SIG and consumer-electronics manufacturers developed a variety of compression techniques, which achieve streaming compatibility by reducing the codec bit rate.

Unfortunately, most of these compression techniques come at a cost: reduced audio fidelity. The codecs that employ them are called lossy, because they achieve their bit-rate savings by eliminating components from the original CD recording deemed imperceptible to most listeners. Everyone's hearing is different, however, as is their acoustic environment and playback equipment, so no lossy system can satisfy all listeners—especially audiophiles who prize high accuracy.

The solution to delivering bit-accurate audio is lossless codecs, which until recently have only served in PCs, smartphones, and other devices. Such devices don't require compression because they support wired or wireless broadband connections that are hundreds of times faster than Bluetooth, although they do so at the expense of many times more power consumption. The challenge to using a lossless codec with Bluetooth is the codec must be compatible with the peak 1.0Mbps Bluetooth basic rate (BR), and it must also be adaptive, working with the radio circuits to scale seamlessly and match variable wireless-link conditions.

A complete lossless-streaming solution requires co-development of the codec algorithm, DSP hardware and software, and associated Bluetooth radio components. Few companies possess all the necessary expertise, but Qualcomm is an exception. Products based on its aptX codec, Bluetooth chipsets, and Kalimba DSPs have won numerous plaudits from the audiophile community. And the company recently announced aptX Lossless, which operates with its Bluetooth High Speed Link (QHS) technology to deliver streaming audio that's a bit-accurate match with the original CD recording. Consumers will be able to enjoy aptX Lossless in earbuds and headphones scheduled to ship by year-end.

Perception Shapes Lossy Models

Codec developers can address Bluetooth's low bandwidth and variable link conditions using lossy or lossless techniques. The CD recording standard specifies a 44.1kHz sampling rate, employing linear pulse-code modulation (PCM) to digitize stereo channels at 16-bit precision. At that rate, a CD audio stream requires about 1.4Mbps, whereas Bluetooth BR supports a maximum 1.0Mbps. Therefore, the codec must handle compression ratios of at least 1.4:1.

Because lossy codecs achieve 4:1 or greater compression, they may appear to be an obvious choice for wireless streaming. For example, MPEG4 reduces the bit rate to a maximum 60kbps per channel—substantially less than even a degraded Bluetooth link can support. Higher compression also yields smaller files that are easier to download and store.

But MPEG and other lossy codecs rely on so-called perceptual or psychoacoustic models, which employ a sophisticated combination of time-frequency analyses that demand greater compute and memory resources than lossless codecs do. Executing such algorithms consumes more power, sapping battery life in earbuds and other portable devices. The complex processing can also introduce latency, a critical factor that can impair gaming response and cause audio/video content to go out of synch.

Researchers develop psychoacoustic models by subjectively testing human auditory perception. The ITU published a standard that recommends a double-blind hidden-reference testing process in which subjects compare three consecutive audio samples. The first sample (A) is always the reference, whereas subjects must identify the randomly alternating samples B and C as the hidden reference or the encoded sample. Subjects grade the differences they perceive using the absolute scale in Table 1. The test system calculates the differential grade by subtracting the score assigned to the hidden reference from the score assigned to the encoded sample. If a subject correctly identifies the hidden reference, the test yields a negative differential grade, and vice versa if the subject misidentifies the reference.

Codec developers employ such tests to assess the quality impairment their algorithms introduce. Perceptual models comprise a set of rules that the codec applies to audio material, such as delete signals below an absolute hearing threshold and remove certain tones on the basis of critical frequency-band analysis. Hearing-threshold models assume the sound-pressure level (SPL) in the tests matches that of the end-user system, a highly unlikely assumption. Hearing acuity varies greatly with volume, the listener's age, earbud fit, the speaker system, and numerous other factors. Critical-bandwidth rules aim to model how the human ear responds to dynamic amplitude and frequency changes; that sensitivity also varies by individual.

The bottom line for perceptual modeling is that to reduce the bit rate, it must sacrifice accuracy. Developing a model that's appropriate for the vast range of musical genres is impossible, but either way, removing portions of the source yields audio that differs from the artist's intent. Nevertheless, most consumers are probably unaware of the effects lossy codecs can introduce, because it's all they've ever heard. Perceptual models constitute a least-common-denominator approach to sound reproduction.

Absolute Grade	Impairment Rating	Differential Grade
5.0	Imperceptible	0.0
4.9 ↕ 4.0	Perceptible but not annoying	-0.1 ↕ -1.0
3.9 ↕ 3.0	Slightly annoying	-1.1 ↕ -2.0
2.9 ↕ 2.0	Annoying	-2.1 ↕ -3.0
1.9 ↕ 1.0	Very annoying	-3.1 ↕ -4.0

Table 1. ITU subjective listening metric. ***In this double-blind hidden-reference test, subjects use the 41-point absolute scale to grade the random samples. The test system calculates the differential, with a negative score indicating the subject correctly identified the hidden reference. The specification allows for elimination of scores from subjects who are unable to identify the reference.***

In addition to the BoW interface, ODSA has workgroups developing BoW test requirements, a link layer, proof-of-concept prototypes, a format for chiplet physical descriptions, and chiplet business workflows. By creating interfaces, reference designs, and workflows, ODSA is laying the groundwork for an open chiplet marketplace that will enable chip vendors to source interoperable chiplets from multiple suppliers.

Real-Time Analysis Enables Lossless

Rather than apply predefined rules to remove presumably inaudible content, aptX Lossless reduces the bit rate through real-time audio analysis. Qualcomm's technology originated in the late 1980s, when researchers at Queen's University in Belfast developed techniques to reduce the audio bit rate for the film, music, and radio-broadcast industries. Before its adoption by wireless-headset manufacturers, the technology primarily served in professional audio equipment. In the 1990s, aptX gained a huge endorsement from Steven Spielberg, who chose it to record the soundtracks for several of his award-winning movies. The technology's first Bluetooth design win was with Sennheiser, a well-known developer of audiophile-grade headphones.

Although CDs employ 44kHz linear PCM, which can accurately reproduce 98dB peak-to-peak harmonics at up to the 22kHz Nyquist limit, audio recordings are unlikely to contain such high-amplitude and high-frequency tones. To prevent distortion, recording engineers must keep sound levels below the peak limit. The highest fundamental tone produced by a musical instrument is around 4kHz, whereas the remainder of the Nyquist bandwidth contains lesser-amplitude harmonics.

Therefore, applying fixed 16-bit PCM consumes greater bandwidth than necessary to produce bit-accurate audio. Instead, aptX analyzes the real-time audio dynamics, employing a more efficient modulation technique called adaptive differential PCM (ADPCM). For example, sampling a 4kHz fundamental tone at 44kHz yields 10 samples per cycle. Even if it hits a 98dB peak, the difference between successive samples covers just a portion of that dynamic range, requiring fewer bits to encode the entire waveform.

Encoding just the differential value reduces the bit rate, but the aptX Lossless codec delivers additional saving by applying more-sophisticated analysis as well. As Figure 2 shows, the first step in the encoding process is to collect small data blocks from both stereo channels. In the second step, the encoder analyzes the samples, measuring their correlation and identifying redundancies. This technique allows encoding of each block in a more compact format relative to linear PCM, and the decoder can invert that format with no data loss.

In the next encoding step, aptX uses digital prediction filters to further compress the data in each channel by estimating the correlation between consecutive samples. Feedback in the digital filters improves accuracy, and encoding just the prediction error requires fewer bits than encoding the actual data. Employing lookup tables for that step increases processing efficiency.

The final step applies entropy-coding methods, which exploit residual statistical dependence between samples. This technique implements variable-length coding, further reducing the bit rate by applying short codes to frequently occurring amplitude values and reserving long codes for infrequent ones.

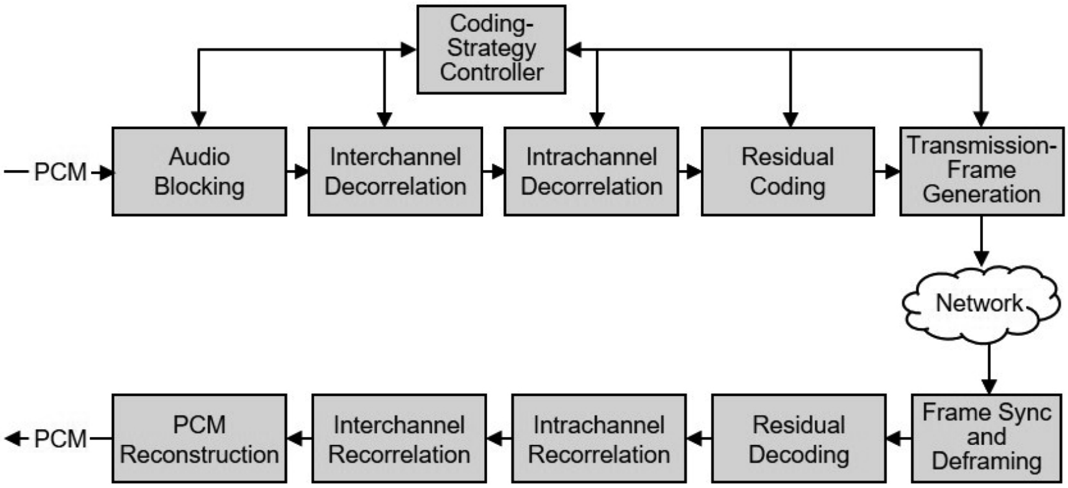

Figure 2. Qualcomm aptX Lossless codec. ***The technology uses both audio and environmental information. The coding-strategy controller collects real-time statistics, optimizing the encoding process on the basis of time-domain audio analysis, including sample amplitudes and sample correlation between and within channels, as well as environmental parameters such as Bluetooth link quality.***

Adaptive Methods Optimize Audio Quality

As with all wireless technologies, Bluetooth signal strength varies with distance between the receiver and transmitter as well as the presence of objects in the signal path, since they reduce the link speed. Since Bluetooth operates in the same band as Wi-Fi and other unlicensed protocols, it's also subject to interference.

Because they're autonomously adaptive, aptX codecs adjust seamlessly to such quality-of-service (QoS) issues, optimizing the bit rate on the fly in response to dynamic signal conditions. The coding-strategy controller (CSC) in Figure 2 collects statistics from the input audio-data blocks, as well as from the various encoder blocks, and uses them to select the best parameters for each function. The choice depends on both the data and Bluetooth link quality, as well as other external factors such as the compute resources available for audio processing.

During encoding, the controller can select from a toolbox of compression algorithms with different properties, depending on the performance metric it must optimize. Because the dynamic factors may correspond to several candidate algorithms, the codec runs the same data through each one, applying only the best result to the actual transmission. The encoder can communicate the selection directly or indirectly to the decoder, which need only run the selected algorithm. The DSP can execute the algorithms in hard-wired logic or in software, enabling chip designers to customize aptX for a particular platform.

By applying its adaptive capabilities, the aptX codec can employ lossless methods when the Bluetooth link is of sufficient quality, and it can seamlessly adjust the bit rate if the signal deteriorates. Because aptX performs the entire analysis in the time domain, it requires fewer compute and memory resources than the complex time-frequency-based techniques of lossy psychoacoustic models.

Conclusion

Thanks to Bluetooth earbuds, smartphone users no longer need to untangle wires every time they want to make a hands-free call or stream their favorite music. These tiny devices have become so popular that many phones omit the earphone jack. They allow headphone wearers to move around without being tethered to a receiver, and portable Bluetooth speakers make it easy to stream music anywhere, indoors or out. Previously, these conveniences came at the expense of lower audio fidelity, but aptX Lossless removes that limitation as well.

Although Qualcomm isn't the first to develop a lossless codec, its ability to design a complete solution for Bluetooth streaming is an advantage over most competitors. The company's extensive catalog includes low-power devices for smartphones and wearables as well as chipsets for audiophile headphones, automotive, smart speakers, and other applications. The adaptive capabilities of its technology ensure that users get optimum audio quality under all conditions, but the new aptX Lossless codec can deliver the same quality as the nearly obsolete CD player without the hassle of carrying and storing the physical media.

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