The Linley Group

MICROPROCESSOR report

Insightful Analysis of Processor Technology

Ceva Bluebud Streams Wireless Stereo

Low Energy Audio Design Extends Battery Life

By Mike Demler (April 5, 2021)

Ceva's Bluebud is a turnkey solution for implementing so-called true-wireless-stereo (TWS) earbuds. The intellectual property (IP) supports Bluetooth Classic as well as the new Bluetooth Low Energy Audio (LE Audio) of version 5.2, which the Special Interest Group (SIG) ratified last year. Because earlier Bluetooth specifications only allow pairing of a single transmitter and receiver, the wireless industry adopted the TWS label to describe proprietary techniques that enable two earbuds to deliver stereo audio. The LE Audio standard introduces a new method based on isochronous channels, permitting an audio source to broadcast one or more streams to an unlimited number of receivers.

LE Audio devices can more easily separate left and right channels or simulcast in different languages. Allowing several of them to share the same source enables new applications, such as letting sports-bar patrons choose the game they want to watch, transmitting messages to airline passengers in several languages, and broadcasting audio for a movie or theatrical production to the hearing aids of attendees.

The Bluebud package combines several licensable Ceva cores and a complete software stack. As Figure 1 shows, the hardware is a single-core processor that employs the Ceva BX1 hybrid DSP to run the Bluetooth protocol, application code, and audio codecs. Because the processor can run standalone, the host-CPU interface is optional. The DSP works with a baseband controller from the company's Riviera-Waves product line, which supports Bluetooth Classic as well as BLE 5.2. The Bluebud hardware and software IP is now available for licensing.

A Small DSP Runs Audio and Neural Networks

Ceva's BX1 is a four-way SIMD/VLIW DSP with 11 stages; it runs general-purpose code as well (see *MPR 2/4/19,* "Ceva's BX Hybrid Boosts DSP Engine"). Since releasing the design, the company increased its throughput specification to 4.4 CoreMarks per megahertz, similar to that of Arm's Cortex-M55 (see *MPR 3/9/20,* "Cortex-M55 Supports Tiny-AI Ethos").

The DSP has five multiply-accumulate (MAC) units: one single or dual 32x32-bit unit and four 16x16-bit units. The latter four also execute 16x8- and 8x8-bit MACs. The BX1 supports optional half-, single-, and double-precision floating-point units, as Figure 2 shows. Data and instruction caches are optional, too, as are the buffer (B) and queue (Q) managers, which connect to custom accelerators. The independent B and Q managers enable tasks to run on the accelerators without consuming DSP resources.

The Bluebud IP package comes with a power-management unit (PMU) and audio-peripheral interfaces. To complete the radio, designers must separately license or

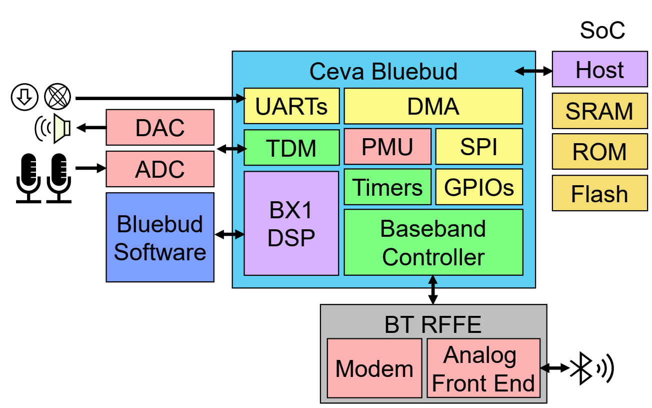

Figure 1. Ceva Bluebud IP. The turnkey package includes a Bluetooth baseband controller, a BX1 DSP, standard audio interfaces, and a power-management unit. Customers can add a Ceva RF front end or third-party IP. They must license the ADC and DAC separately.

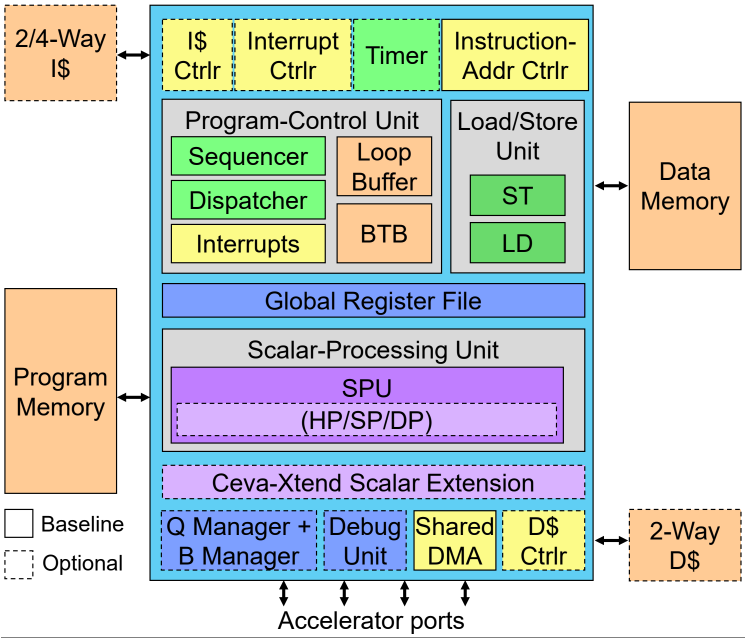

Figure 2. Ceva BX1 DSP. The 11-stage SIMD/VLIW design serves as Bluebud's main compute engine, also providing one or two 32x32-bit MAC units and four 16x16-bit MAC units.

integrate their own audio analog-to-digital and digital-to-analog converters (ADCs and DACs), modems, and RF front ends (RFFEs). The company supplies RFFEs for manufacture in TSMC's 40nm ULP technology, but customers can license hard IP from third parties instead. For example, Swiss research organization CSEM offers RFFE IP for 22nm. In that IC technology, the Bluebud processor consumes just 0.5mm^2, excluding the data converters, memories, and RFFE.

The Bluebud software includes audio codecs, drivers, a reference earbud application, and an RTOS. Along with the stereo codecs, Bluebud ships with codecs that improve voice calls—for anyone who still talks on the phone. The health and wellness profiles work with sports watches and smartphones.

Designers can optionally use the Ceva Sensling software platform to add other features, including 3D-audio synthesis. There's even a graphics equalizer that lets users adjust the sound to their liking. The company's ClearVox software performs echo and noise reduction, MotionEngine Hear handles sensor processing and touch control, and WhisPro provides biometrics and speech-recognition neural networks. The IP supports the TensorFlow Lite Micro framework, so customers can add their own neural-network models.

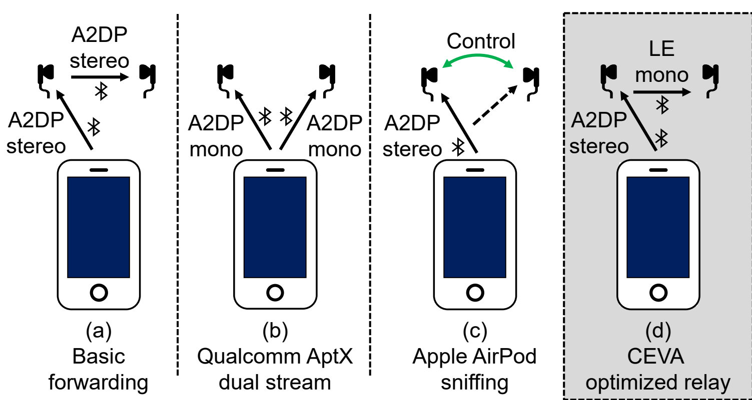

Figure 3. Ways to implement TWS earbuds. Manufacturers employ a variety of proprietary methods in wireless-stereo earbuds. Qualcomm's dual-stream AptX delivers 70% longer battery life than the Bluetooth Classic A2DP forwarding method, whereas Apple's "sniffing" method gains 28%. Using the new LE Audio standard, however, Bluebud enables 80% longer battery life.

Getting to the Stem of the Problem

Before ratification of the LE Audio standard, device manufacturers implemented various workarounds to enable TWS earbuds. Bluetooth Classic's Advanced Audio Distribution Profile (A2DP) defines the packet structure for transmitting stereo content, but because it's strictly a point-to-point protocol, the receiving earbud must forward the signal to the other earbud, as Figure 3(a) shows. Each earbud only decodes one channel. That technique is adequate for left/right speakers connected by wires, but because the two wireless earbuds are unsynchronized, interchannel delay can corrupt the stereo image.

Qualcomm pioneered the use of dual-monophonic transmissions, as Figure 3(b) shows. Because this technique eliminates synchronization issues, it produces better stereo sound than Bluetooth Classic. It's proprietary, however, and the two transmitters double transmission power. To get the benefit, both the transmitter and receiver must have AptX-equipped radios; otherwise, the devices must fall back to the forwarding method.

Figure 3(c) shows the technique Apple developed for its AirPods (see *MPR 10/24/16,* "Apple W1 Processor Powers AirPods"). The phone uses a single point-to-point A2DP transmission, but the left and right earbuds operate as a master/slave pair. By employing a bidirectional link, the master enables the slave to "sniff" the transmission for its own packets rather than wait for the master to forward them. This proprietary technique requires no additional transmit power, but the master/slave link is critical for synchronization. For that reason, AirPods have an antenna stem that allows the link to travel through the user's jaw rather than through the denser path from the ear canal through the brain.

For Bluebud, Ceva developed a technique it calls an optimized relay, as Figure 3(d) shows. It's similar to the original A2DP technique, but the receiver only forwards the necessary monophonic packets using the Bluetooth Low Energy protocol. Like Apple's AirPods, the two earbuds synchronize playback through a bidirectional control signal. The optimized relay introduces less than a 5-microsecond delay between earbuds, and the latency from RF to audio playback is less than 20 milliseconds, ensuring the audio and video appear synchronized. By comparison, Qualcomm specifies 40ms latency for its AptX technology.

To balance power consumption between the left and right earbuds, Bluebud implements automatic role switching, periodically reversing the receiver and relay responsibilities. Ceva used a reference chip and simulations to compare Bluebud's power savings with those of each Bluetooth Classic alternative. Bluebud's battery life is about the same as AirPods, providing 22% longer operation than A2DP. Although Qualcomm's technique requires greater handset power, it extends earbud battery life by 70%. AptX enables longer operation by eliminating the transmissions between earbuds, which have tiny batteries. For an LE Audio transmission, Bluebud's battery life was at least 80% longer than the Classic method's.

Perception Becomes Reality

Ceva developed the Bluebud hardware by integrating components from its catalog, but the software stack was a greater challenge. A turnkey solution must support numerous audio formats and device configurations that appear in Bluetooth products. In addition to implementing both the Classic and new LE Audio protocols, the Bluebud software includes a comprehensive set of codecs, application profiles, and UI functions.

All Bluetooth products handle the Classic A2DP standard, which employs a sub-band-code (SBC) codec that applies lossy compression to stereo signals transmitted at up to 345kbps. Although the Bluetooth SIG describes A2DP transmissions as "high quality," the compression is just one-fourth the bit rate of a compact disc, potentially degrading fidelity.

To improve fidelity, many Bluetooth-chip vendors and device manufacturers use alternative codecs, some license-free and others proprietary (such as Qualcomm's AptX—see *MPR 8/21/17,* "Qualcomm Makes Play for Audiophiles"). The MP3 codec, developed at the Fraunhofer Institute, was the first to implement a psychoacoustic (or perceptual) model, reducing file size and bandwidth requirements by exploiting limitations in human hearing. Such models aggressively compress elements that most people can't hear, such as low-amplitude high-frequency tones, but they apply less compression to more-audible midrange tones. Audiophiles have debated the perceptibility of psychoacoustic compression since Apple first adopted it for iPods, but most listeners don't notice the difference.

Few Bluetooth devices employ MP3 codecs, but many employ its successor: the license-free Advanced Audio Coding (AAC). Apple implements AAC in AirPods and iPhones, but despite a slower 250kbps data rate, decoding that format requires more compute horsepower and memory than SBC. Because AAC consumes more power, some OEMs fall back to SBC. The Bluebud software includes a sample-rate converter that can handle such differences between source and sink devices.

Along with these legacy codecs, Bluebud offers the new Low Complexity Communications Codec (LC3) that all LE Audio devices must implement. LC3 is a perceptual codec that supports 16-, 24-, and 32-bit audio samples and an unlimited number of channels. It allows 8-, 16-, 24-, 32-, 44.1-, and 48kHz sampling rates, with either 7.5ms or 10ms frames. The bit rate for 10ms frames is 16–320kbps; for 7.5ms frames, it's 21–427kbps. Bluebud supports the new specification's packet-loss-concealment (PLC) technique, which hides the effect of unavailable data and corrupted frames.

Beware Audio Myths

The Bluetooth SIG tested LC3 using the ITU standard *Methods for the Subjective Assessment of Small Impairments in Audio Systems*, comparing it with SBC operating at the same bit rate. In testing with 160–345kbps bit streams, LC3 received subjective scores ranging from 4.4 to 4.8 out of 5.0, as Figure 4 shows. A 4.0 rating indicates the compression is perceptible but not annoying, and 5.0 indicates no perceptible differences from the (unspecified) reference. SBC's highest score at the maximum sample rate was 4.1.

Although these tests indicate LC3 offers a subjectively better perceptual model than its predecessor, it unfortunately revives decades-old audio myths as well. Since the first CD shipped nearly 40 years ago, some critics have treated the Fourier transform and Nyquist sampling theorem like fake news. Harry Nyquist proved that sampling at twice a signal's highest frequency is sufficient to exactly reproduce the original waveform, but these critics continue to claim

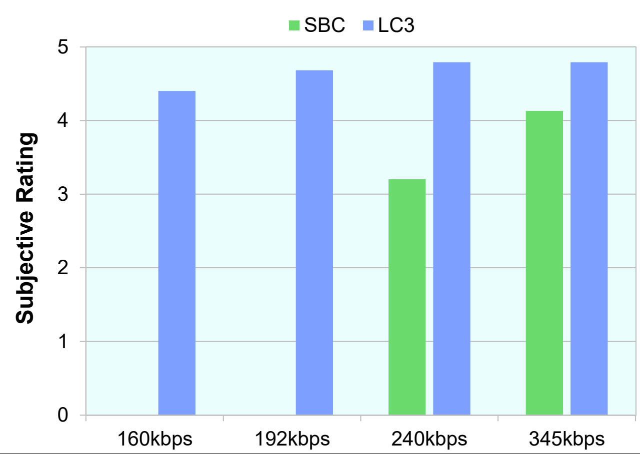

Figure 4. Comparison of Bluetooth LE Audio and Classic codecs. Operating at the same sampling rate as the Classic SBC codec, the new LC3 codec improves fidelity in subjective evaluations. It also offers superior fidelity for low bit rates. (Data source: Force Technology SenseLab)

Price and Availability

Production Bluebud hardware and software IP is available for licensing. Ceva doesn't disclose pricing. For more information, access *www.ceva-dsp.com/product/ceva-bluebud*.

that greater than 16-bit quantization and higher sampling rates will capture missing details.

By supporting 24- and 32-bit audio samples in addition to a 48kHz sampling frequency, the LC3 codec beats CD-audio standards (16 bits and 44.1kHz). Although a faster sampling frequency enables designers to employ less complex antialiasing filters, which are necessary to prevent distortion by out-of-band signals, it adds nothing to the audio waveform. The upper limit of human hearing is generally considered to be 20kHz, and for most adults it's much lower, so there's no reason to sample at the 192kHz maximum frequency Amazon promotes in its "Ultra HD" audio service.

Adding bits to a perceptual model is a dubious proposition, because these models achieve their efficiency by eliminating many low-level details. The highest-resolution audiophile DACs claim to deliver true 24-bit precision (–146dBV), but such a device won't fit in an earbud. Even if it could, earbud transducers and the tiny amplifiers that drive them have a much smaller dynamic range. That's a good thing, because a 120dB sound-pressure level (SPL) is the threshold of pain. Moreover, in a typical earbud transducer operating at room temperature (20°C), the thermal noise is about –135dBV masking low-level signals.

Sound Reasons to Upgrade

Many TWS promoters point to the rapid growth in sales of Bluetooth earbuds as a sign of success, but the leading phone makers have already removed the wired-earphone jack from their flagship smartphones, encouraging consumers to switch to Bluetooth earbuds or use an adapter that only works when the phone isn't charging. Although going wireless eliminates tangles, it also creates additional revenues for these companies.

The LE Audio standard offers a number of new capabilities, however, including dynamic power management between transmitters and receivers, multichannel/multiuser broadcasts, and more-precise synchronization. Although combining Bluebud with LE Audio may not satisfy audiophiles, the new codec can subjectively boost sound quality. The new optimized-relay technique will improve the stereo-listening experience, and the latency reductions will ensure video watchers don't see lips move before the words reach their ears. Consumers will especially appreciate having battery life that's nearly twice as long as with Bluetooth Classic.

Apple's AirPods have the largest share of the TWS market, but the Android market's fragmentation creates numerous opportunities for Bluebud IP. The turnkey hardware and software package offers everything an LE Audio designer needs, except for the analog and RF components. The software stack handles the legacy Classic protocol as well, and the extensive library of software plugins lets customers differentiate their products. Ceva's Bluebud is emerging just as the industry begins its transition to LE audio, but we expect it will become a popular platform. ♦