FRAUNHOFER-INSTITUT FOR INTEGRATED CIRCUITS IIS

LC3PLUS IMPLEMENTATION PRODUCT SHEET

Version: 2024-05

LC3plus has been standardized by ETSI as TS 103 634 as a highly flexible audio codec suitable for speech and music content, providing high quality, low delay and low complexity at medium compression. The LC3plus codec is a superset of LC3 as specified by Bluetooth (LC3BT).
The codec can be used in any wireless transmission environment, such as (but not limited to) DECT, Bluetooth, UWB, WiSA etc. For the usage of LC3plus in Bluetooth as vendor-specific codec, please refer to section 6.4 of this document.
LC3plus brings additional functionalities for transmission robustness, extremely low-delay modes, and high-resolution audio transmission.

To improve robustness, LC3plus contains a high-performance packet loss concealment algorithm for speech and music signals. Furthermore, LC3plus includes forward error correction schemes such as channel coding for bit error protection or redundancy frame modes for transmissions within network congestions.

LC3plus offers several low-delay modes for optimal support of a wide range of applications spanning from voice calls to applications with extremely challenging latency requirements such as gaming. The codec features the frame durations 10ms, 7.5 ms, 5ms and 2.5ms leading to a total delay of 12.5ms, 11.5ms, 7.5ms and 5ms.

LC3plus also includes dedicated high-resolution audio modes for transmitting high-resolution audio content, e.g. over Bluetooth, at 96 kHz and 24 bits per sample. This mode improves the measurable audio quality beyond perceptual transparency. More details are provided in section 6.

Fraunhofer-Institute for
Integrated Circuits IIS

Licensing and technical
inqueries:
Manfred Lutzky
lc3-licensing@iis.fraunhofer.de

Am Wolfsmantel 33
91058 Erlangen, Germany
www.iis.fraunhofer.de/audio

1. LC3plus – Overview and Compatibility with LC3

LC3plus is a superset of the LC3 codec as standardized in Bluetooth – meaning that LC3plus can operate in an LC3-compliant mode and also decode all bitstreams created with LC3. A single LC3plus implementation can thus cover both Bluetooth-LC3 and LC3plus use-cases.
The following tables show the supported features of both codecs as well as the compatibility of LC3, LC3plus and LC3plus High-Resolution.

NOTE: One single library can cover LC3, LC3plus and LC3plus High-Resolution use-cases while being efficient in terms of memory usage.

Sample Rates	Frame Durations	Features
8 kHz	10 ms	Advanced Packet Loss Concealment
16 kHz	7.5 ms	Low-Delay Modes
24 kHz	5 ms	High-Resolution Mode
32 kHz	2.5 ms	
44.1/48 kHz	1.25 ms*	
96 kHz		*in development
LC3 and LC3plus		**LC3plus-only**

Table 1: Feature Overview of LC3 and LC3plus

	LC3 Decoder	LC3plus Decoder	LC3plus High-Resolution Decoder
LC3 Encoder	X	X	---
LC3plus Encoder	X Limited to 10 ms and 7.5 ms frame duration	X	---
LC3plus High-Resolution Encoder	---	---	X

NOTE: The LC3plus High-Resolution mode is a dedicated mode for transmission of High-Resolution audio and is not compatible with LC3 and LC3plus Normal Resolution.

Table 2: Compatibility of LC3, LC3plus and LC3plus High-Resolution

1. LC3plus – Software Implementations

Fraunhofer IIS offers several LC3plus implementations designed for different target platforms in C source code:

- floating-point arithmetic
- fixed-point arithmetic
- fixed-point arithmetic with optimizations for ARM platforms
- fixed-point arithmetic with optimizations for Tensilica HiFi-3z and HiFi5

Further details regarding computational and memory requirements are provided below.

General notes:

- The computational complexity for the WB operation mode (16 kHz, 32 kbps) is roughly 60 % of the SWB operation mode (32 kHz, 64 kbps).
- For dynamic memory measurements, it is assumed that encoder and decoder do not run simultaneously on the same device, i.e. the scratch memory can be shared between the encoder and the decoder. Therefore, the "codec" value refers to the maximum of these two.
- To achieve a comparable audio quality when operating in the low-delay modes of LC3plus (5 ms and 2.5 ms frame duration), an increase of the bitrate is required: 20 % additional bitrate for 5 ms, and 60 % additional bitrate for 2.5 ms. For the 32 kHz operation point where the 10 ms frame duration operates at 64 kbit/s, 76.8 kbit/s are required for the 5 ms frame duration and 102 kbit/s are required for the 2.5 ms frame duration.
- Unless otherwise specified, the tables show the complexity/memory requirements of a single mono channel. Stereo is achieved by using two mono channels.
- The ROM requirements do not increase with the number of channels. They include all supported frame duration (10 ms, 5 ms and 2.5 ms). The codec can be configured to support a subset of the features only, e.g., to support only the 32 kHz operation mode. Such configurations will result in a smaller ROM size.

2. Performance: LC3plus Normal Resolution

Table 3 shows the computational complexity of the LC3plus codec.
The performance was measured using the following devices:

- x86 (measured on Intel® Core™ i5-8279U@2.4 GHz)
- ARMv7 (measured on Raspberry Pi BCM2835 with Cortex-A53@1.2 GHz in ARMv7 mode)
- ARMv8 (measured on Jetson Tx1 with Cortex-A57@1.9 GHz)

		Encoder				Decoder			
Frame Duration [ms]		10	7.5	5	2.5	10	7.5	5	2.5
Fixed-point C source code with Hifi3 and HiFi5 optimizations:									
HiFi-3z/ HiFi-5	32 kHz 64 kbps	11.7	13.1	15.9	23.8	5.8	6.1	7	9
	48 kHz 320 kbps	18.6	21.1	22.1	29.6	12.6	13.0	13.3	13.5
C source code in fixed-point arithmetic:									
x86	32 kHz 64 kbps	12.5	13.1	14.2	18.1	5.2	5.8	6	7.5
	48 kHz 320 kbps	18.5	19.3	20	25.4	7.6	7.7	8	8.9
C source code in floating-point arithmetic:									
x86	32 kHz 64 kbps	13.9	14.3	15.1	20.4	4.2	4.6	4.9	6.2
	48 kHz 320 kbps	20.2	20.9	21.8	26.3	6.8	7.2	8.1	8.1
Fixed-point C source code with optimizations for ARM:									
ARMv8-NEON	32 kHz 64 kbps	16.9	17.4	17.9	24.1	6.2	7.0	7.2	9.7
	48 kHz 320 kbps	21.4	23.3	27.7	33.8	10.5	10.9	11.7	19.2
ARMv7-NEON	32 kHz 64 kbps	24.6	30.1	32.8	45.4	12.7	13.4	15.2	19.2
	48 kHz 320 kbps	43.8	47.4	50.3	61.9	30.8	31.4	32.3	34.7
ARMv7-Core	32 kHz 64 kbps	38.1	41.4	44.9	61.9	15.0	17.1	18.0	24.6
	48 kHz 320 kbps	58.2	60.1	64.2	83.2	28.5	30.0	30.6	35.2

Table 3: Computational complexity per channel in MHz of LC3plus C-code in different arithmetics and optimizations for different CPUs

3. Memory Requirements

Table 4 shows the memory requirements of the LC3plus codec.

The ROM numbers include both Code and Table ROM and are independent of the number of channels.

Static RAM corresponds to the states of the Encoder and the Decoder that must not be changed on a frame-by-frame basis. Dynamic RAM

corresponds to the scratch buffer which can also be used for other applications than LC3plus inbetween coding frames.

Both static and dynamic RAM are given per channel. In case of sequential processing, dynamic RAM can be re-used and is independent of the number of channels.

	ROM	Static RAM	Dynamic RAM
C source code in floating-point arithmetic:			
Encoder	125.0	8.6	11.8
Decoder	168.2	29.8	26.1
Codec	217.8	38.4	26.1
C source code in fixed-point arithmetic:			
Encoder	235.1	2.9	7.2
Decoder	268.5	14.0	16.6
Codec	308.2	16.9	16.6

Table 4: Memory requirements in kB of LC3plus C-code supporting sampling rates up to 48 kHz. See chapter 6 for memory requirements of LC3plus High-Resolution.

Figure 1 below shows a detailed memory distribution of the LC3plus codec and it's features.

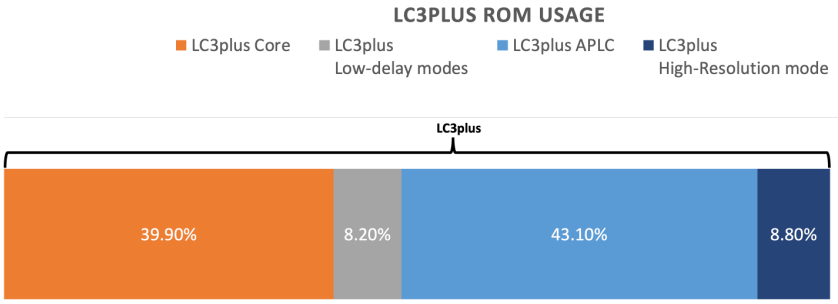

Figure 1: ROM break-up for LC3plus

4 APLC – Advanced Packet Loss Concealment

LC3plus contains a very efficient and powerful Advanced packet loss concealment (APLC) algorithm providing significantly better audio quality in case of packet losses. The purpose of the APLC is to conceal unavailable or corrupted frame data at decoder side. The LC3plus APLC algorithm can enhance both speech and music signals.

Figures 2 and 3 show the results of listening tests performed according to ITU-T Rec. P.800/P.808 on speech signals for a 16 kHz sampling frequency and music signals for a 48 kHz sampling frequency. The plots demonstrate, that at any packet loss rate (PLR), the LC3plus Advanced PLC scores significantly higher than the Bluetooth standard PLC. LC3plus Advanced PLC at 12 % packet loss rate performs comparable to Bluetooth standard PLC at 3 % packet loss rate and thus quadruples the allowed packet loss rate for same audio quality.

In terms of complexity, the reconstruction of a concealed frame using the advanced PLC algorithm is comparable to the decoding of a regular frame.

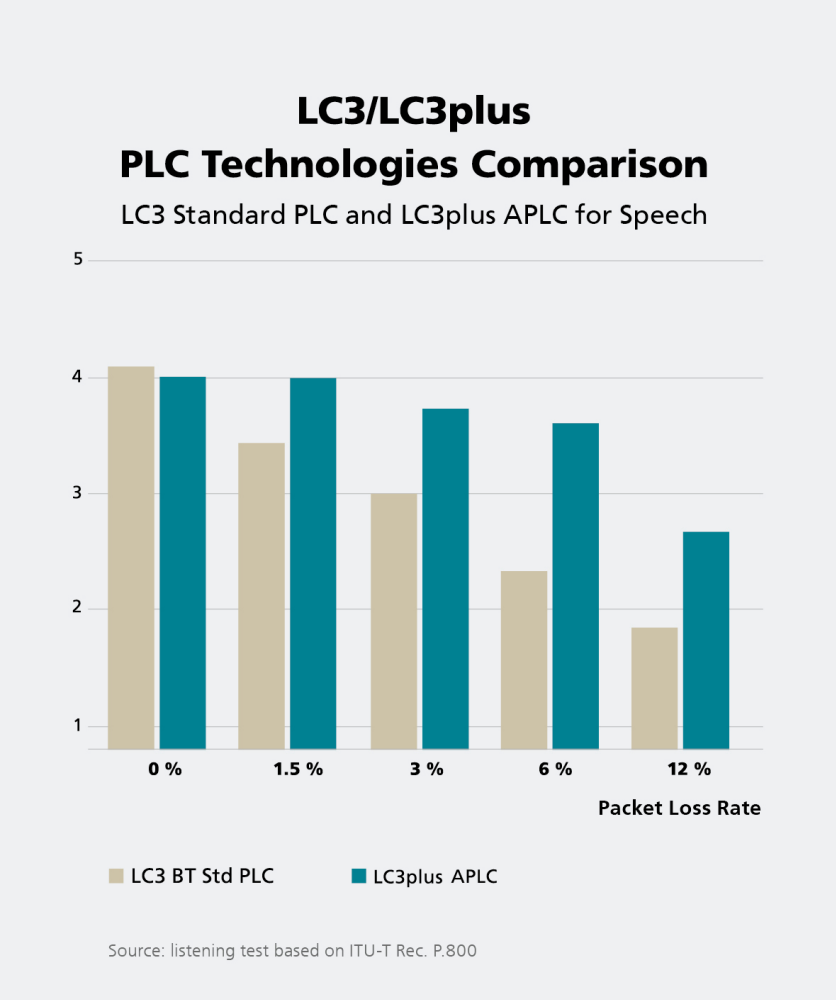

Figure 2: Test results from Wideband P.800 listening test comparing different PLC techniques among different codecs for speech signals

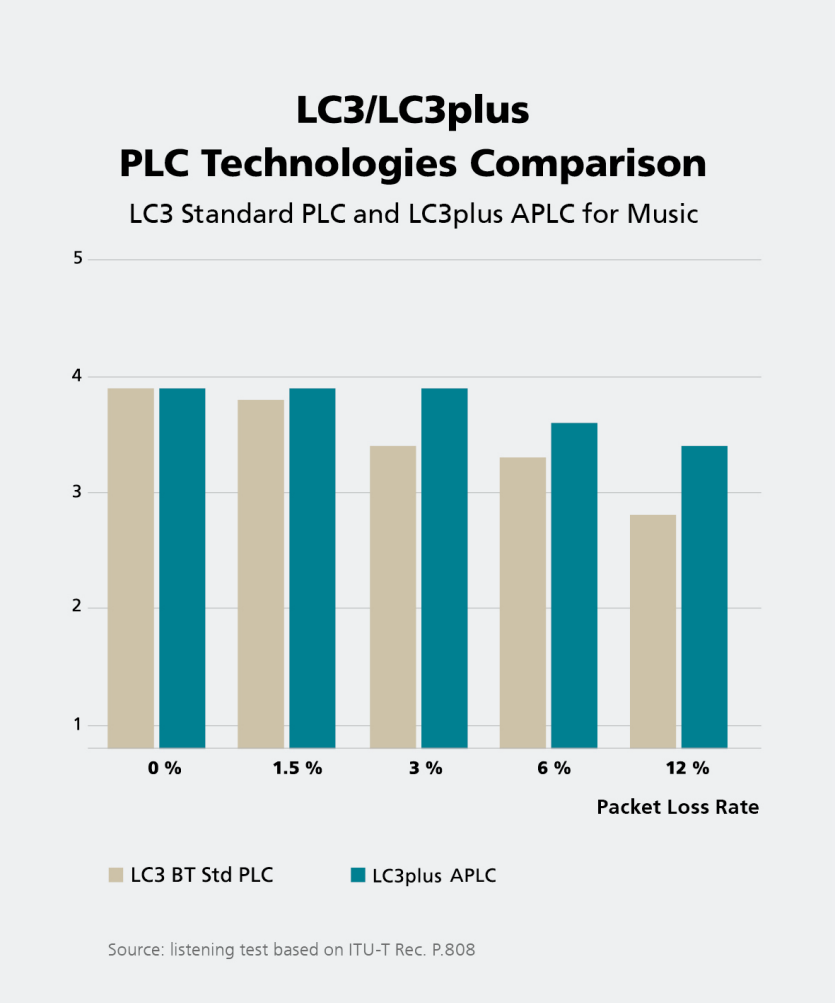

Figure 3: Test results from Fullband P.808 listening test comparing different PLC techniques among different codecs for music signals

5 Forward Error Correction and Redundancy Frames

The LC3plus codec features a channel coder designed for the DECT environment supporting gross rates from 40 to 300 bytes per frame. It offers four error protection class in order to adapt to different channel characteristics. To achieve low complexity, it uses Reed-Solomon (RS) Codes capable of correcting 1, 2 or 3 symbols. To serve different frame sizes, the data is split and encoded into multitude of truncated RS codes, which are subsequently interleaved.

For an optimal performance of the Forward Error Correction (FEC), LC3plus comes with an example FEC control unit which is based on real measured DECT error statistics. The FEC control unit is responsible for choosing the appropriate protection class by analyzing the bi-directional transmission error charachteristics.

LC3plus can use timewise delayed redundancy frames to fill the missing frame or guide the Advanced Packet Loss Concealment. The redundant frame might be identical to the main frame or contains only a lower audio bandwidth. In the latter case, whenever a redundancy frame is available for concealment, a partial concealment algorithm assembles a concealed frame consting of the available low bandwidth data and conceals the remaining upper spectrum.

The FEC adds roughly 7% of additional complexity in the highest error protection mode. Similarly, correcting the maximum amount of bit-errors in the highest protection class adds roughly 12% of additional workload on the decoder side of LC3plus.

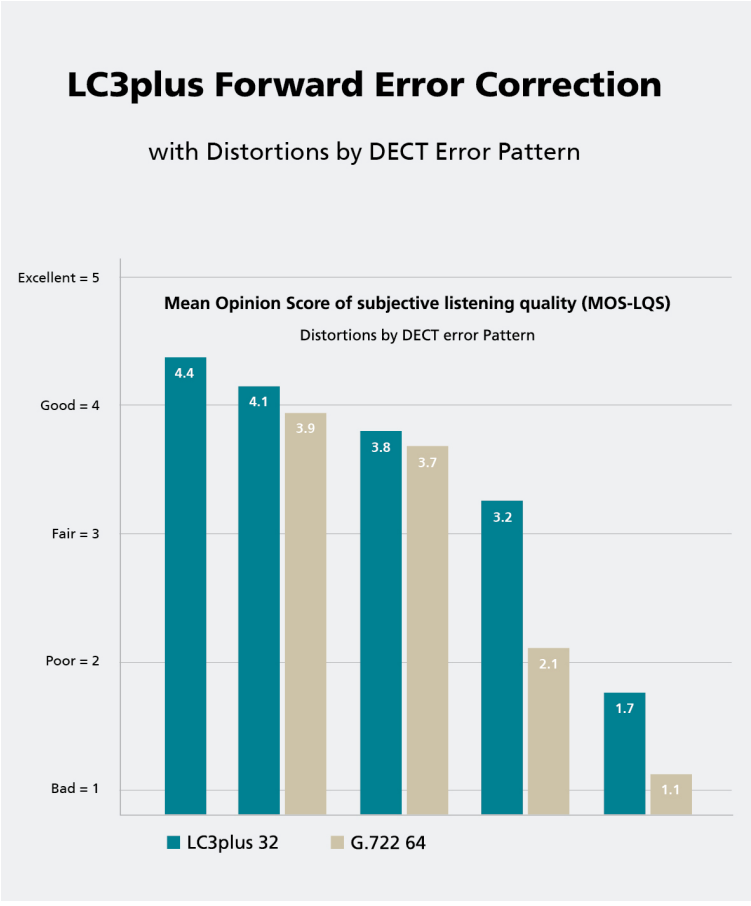

Figure 4: Test results from Wideband P.800 listening test comparing LC3plus with active FEC at 32 kbit/s and G.722 at 64 kbit/s

6 LC3plus High-Resolution

6.1 Performance: THD+N

The LC3plus offers a dedicated high-resolution audio mode with higher precision and higher dynamic range. Thus, it supports high-resolution audio content with sample rates of up to 96 kHz. The LC3plus High-Resolution mode is available for sampling rates of 48 kHz and 96 kHz, all frame sizes (10 ms, 7.5 ms, 5 ms, and 2.5 ms) at bitrates at least up to 500 kbit/s per channel.

Compared to LC3BT in Bluetooth, LC3plus High-Resolution can achieve a significantly lower Total Harmonic Distortion plus Noise (THD+N) of around -130 dB (equal to soundcard level).

The following figure provides a comparison of the THD+N for typical codecs used in the Bluetooth environment including LC3plus High-Resolution.

LC3plus High-Resolution can not only provide a much better THD+N than any other solution, but it provides the same THD+N as the LDAC codec while using only 1/3 of LDAC's bitrate. Further increase of the bitrate for LC3plus High-Resolution beyond 250 kbit/s per channel shows marginal improvements of the THD+N.

NOTE: For LC3, SBC, LC3plus and LDAC, the data was measured using the AudioPrecision APx500 Analyzer with a stepped frequency sweep. The measurement point for LHDC is acquired using a file-based measurement with APx500. The measurement points for aptX are referenced from the aptX product sheet.

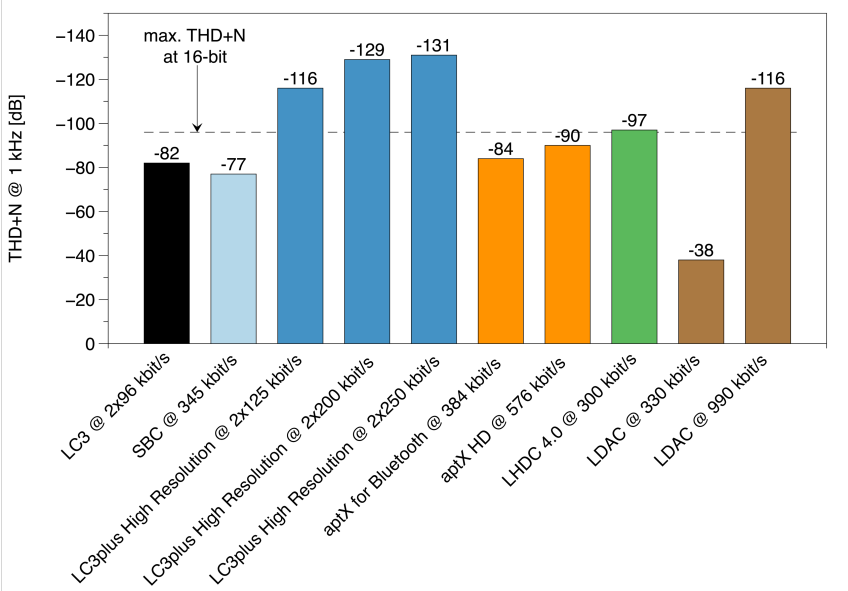

Figure 5: THD+N for LC3plus High-Resolution and other codecs at sampling rate of 48 kHz

The following figures show the THD+N for LC3plus High-Resolution over the full frequency range for sampling rates of 48 kHz and 96 kHz.

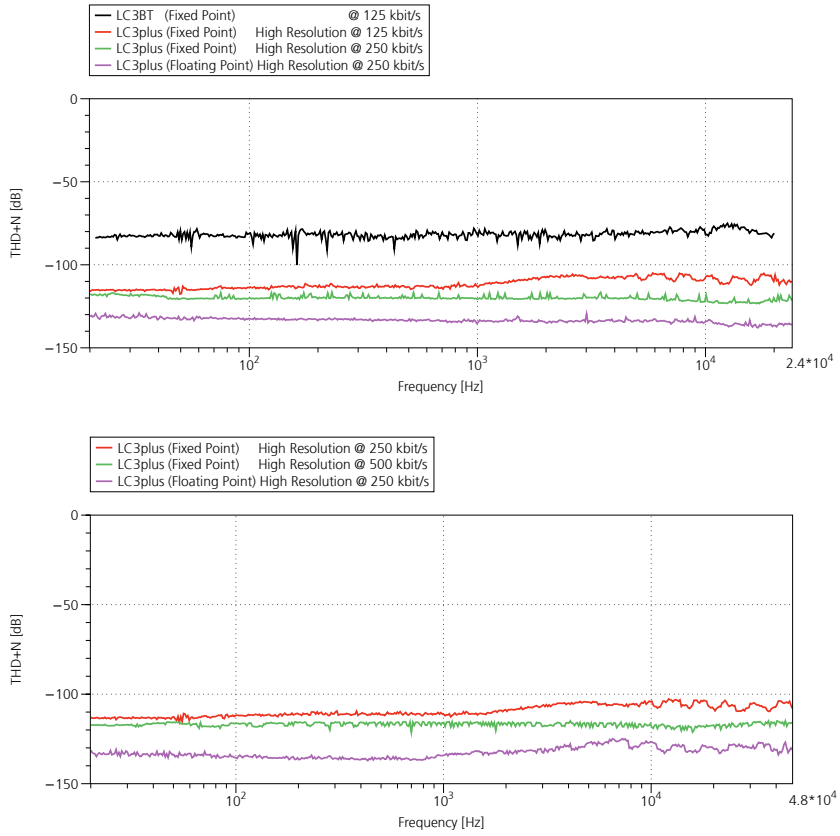

Figure 6: THD+N for LC3plus High-Resolution over full frequency range for 48 kHz and 96 kHz sampling frequency

6.2 Fallback bitrates for critical conditions

In critical conditions, e.g., when only limited bandwidth is available, the amount of collisions and thus the amount of packet losses increases with the size of the packet. It is therefore crucial to reduce the bitrate under such conditions in order to prevent drop-outs and other coding artifacts.

The LC3plus High-Resolution audio mode can also be used at lower bitrates down to 62.4 kbit/s per channel (for the 10 ms frame duration) to prevent such collisions. LC3plus allows a seamless switching of the bitrate which makes it possible to dynamically adapt the bitrate of the codec based on the current channel conditions.

NOTE: the critical bitrate threshold for such conditions is approx. 250 kbit/s. No other High-Resolution codec besides LC3plus supports bitrates below that threshold. LDAC's lowest bitrate is 330 kbit/s.

6.3 Performance: Computational complexity and memory requirements

Table 5 shows the computational complexity of the LC3plus codec performing in the High-Resolution mode for a stereo configuration, each channel operating at 250 kbps.
The performance was measured using the following devices:

- x86 (measured on Intel® Core™ i5-8279U@2.4 GHz)
- ARMv7 (measured on Raspberry Pi BCM2835 with Cortex-A53@1.2 GHz in ARMv7 mode)
- ARMv8 (measured on Jetson Tx1 with Cortex-A57@1.9 GHz)

		Encoder				Decoder			
Frame Duration [ms]		10	7.5	5	2.5	10	7.5	5	2.5
C source code in fixed-point arithmetic:									
x86 2x250 kbps (stereo)	48 kHz	37.6	38.9	40.5	46.6	18.5	19.0	19.3	21.8
	96 kHz	59.8	65.1	69.3	74.0	26.1	226.9	27.3	28.8
C source code in floating -point arithmetic:									
x86 2x250 kbps (stereo)	48 kHz	41.6	42.4	43.4	49.9	16.4	17.1	18	18.7
	96 kHz	64.3	64.9	65.2	77.8	20.7	21.3	22.7	26.6
C source code with Hifi3 and HiFi5 optimizations:									
HiFi-3z/ HiFi-5 2x250 kbps (stereo)	48 kHz	63.4	67.0	69.5	83.3	52.0	52.5	53.5	56.7
	96 kHz	94.5	97.1	102.8	123.7	77.2	77.5	78.3	83.0
Fixed-point C source code with optimizations for ARM:									
ARMv8-NEON 2x250 kbps (stereo)	48 kHz	52.4	64.3	78.0	112.7	29.5	30.1	32.4	39.8
	96 kHz	80.6	93.1	111.2	145.6	38.5	40.1	45.5	51.1
ARMv7-NEON 2x250 kbps (stereo)	48 kHz	84.4	90.5	97.4	116.6	52.0	55.1	60.7	68.8
	96 kHz	132.1	138.1	140.6	151.0	85.0	93.7	97.4	103.1
ARMv7-Core 2x250 kbps (stereo)	48 kHz	119.5	124.1	127.3	148.5	53.8	54.0	54.4	59.8
	96 kHz	149.0	153.1	157.1	189.5	68.4	71.3	75.6	78.8

Table 5: Computational complexity for stereo configuration (2x250 kbps) in MHz of LC3plus C-code running in the High-Resolution mode in different arithmetics and optimizations for different CPUs

Table 6 shows the memory requirements of the LC3plus codec.

The ROM numbers include both Code and Table ROM and are independent of the number of channels.

Static RAM corresponds to the states of the Encoder and the Decoder that must not be changed on a frame-by-frame basis. Dynamic RAM corresponds to the scratch buffer which can also be used for other applications than LC3plus inbetween coding frames.

Both static and dynamic RAM are given per channel. In case of sequential processing, dynamic RAM can be re-used and is independent of the number of channels.

	ROM	Static RAM	Dynamic RAM
C source code in floating-point arithmetic:			
Encoder	101.7	13.6	23.5
Decoder	93.0	44.5	38.8
Codec	130.5	58.1	38.8
C source code in fixed-point arithmetic:			
Encoder	158.1	4.1	15.3
Decoder	151.7	22.8	17.4
Codec	211.8	26.9	17.4

Table 6: Memory requirements in kB of LC3plus C-code exclusively capable of running in the High-Resolution mode with support for 48 kHz and 96 kHz sampling rates

6.4 LC3plus High-Resolution for Bluetooth LE Audio and A2DP

The LC3plus High-Resolution codec can be used for transport over any kind of wireless link.

For transport over the Bluetooth Low Energy Audio and over Bluetooth Classic profile A2DP, Fraunhofer has prepared dedicated transport specifications that explain the signalling and the transport of LC3plus High-Resolution as a vendor-specific codec over Bluetooth LE Audio and over the A2DP profile using the Fraunhofer Vendor-ID. This specifications is available online.
An open-source implementation of the A2DP-specification can be found in the repository of bluez-alsa.

On request, Fraunhofer can provide software patches to enable this functionality on Android smartphones.