



PolarFire® SoC FPGA: Opus Codec Benchmarking

Introduction

Microchip's PolarFire® SoC FPGAs include the industry's RISC-V based Microprocessor Subsystem (MSS) and FPGA fabric that inherits all the features of the PolarFire family. The PolarFire SoC MSS includes 5x 64-bit RISC-V processor cores, AXI Switch, DDR Controller, Fabric Interface Controllers (FIC), and a rich set of peripherals. It also offers an unparalleled combination of low power consumption, thermal efficiency, and defense-grade security for smart, connected systems. It is the first SoC FPGA with a deterministic L2 memory subsystem enabling real-time applications. Built on the award-winning, mid-range, and low-power PolarFire FPGA architecture, PolarFire SoC devices deliver up to 50% lower power than alternative FPGAs, span from 25k to 460k logic elements, and feature 12.7G transceivers.

Microchip's PolarFire SoC Icicle kit features an MPFS250T PolarFire SoC device and on-board memories, such as LPDDR4, SPI, and eMMC flash for running Linux. For more information, see [UG0882: PolarFire SoC FPGA ICICLE Kit User Guide](#).

Opus codec is an open-source interactive speech and audio codec that scales from low bitrate for narrowband speech to very high-quality stereo music. It targets a wide range of real-time Internet applications. Opus codec uses both Linear Prediction (LP) (based on the SILK codec) and the Modified Discrete Cosine Transform (MDCT) (based on the CELT codec) to achieve excellent compression for both speech and music. Opus codec is critical for interactive speech and music transmission over the Internet, and is used for streaming and storage applications.

Opus codec is also suitable for non-real-time stored-file applications, such as music distribution, game soundtracks, portable music players, jukeboxes, and other applications, such as MP3, AAC, or Vorbis. For more information, see [Opus codec](#) web page.

Opus codec supports the following features:

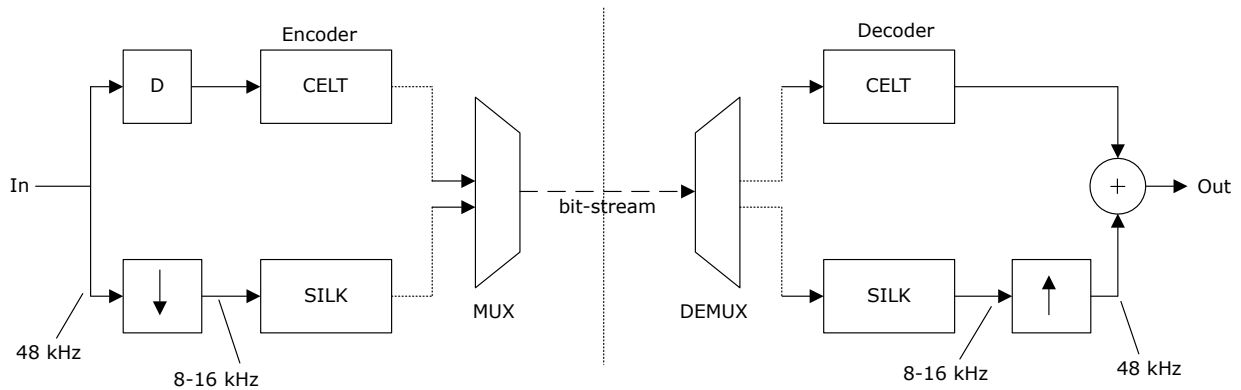
- Sampling rates from 8 kHz (narrowband) to 48 kHz (full band).
- Variable bitrates from 6 Kbytes/s to 510 Kbytes/s.
- Variable frame sizes from 2.5 ms to 60 ms.
- Support for both Constant Bitrate (CBR) and Variable Bitrate (VBR).
- Audio bandwidth from narrowband to full band.
- Support for speech and music.
- Support for mono and stereo.
- Support for up to 255 channels (multistream frames).
- Dynamically adjustable bitrate, audio bandwidth, and frame size.
- Good loss robustness and Packet Loss Concealment (PLC).
- Floating point and fixed-point implementation.

This white paper describes CPU performance results in terms of throughput. These results are based on the industry-standard mode of operations, such as Skype's SILK and Xiph.Org's CELT. The throughput is calculated by executing the standard audio test vectors with Opus audio codec on the PolarFire SoC Icicle kit. This benchmark runs on Linux (DDR) and requires only one application processor core from MSS. For more information about PolarFire SoC Icicle Kit, see [UG0882: PolarFire SoC FPGA ICICLE Kit User Guide](#).

Opus operates in SILK only (Speech to Wideband), CELT only (Music), and Hybrid (Both SILK and CELT) modes. The standard audio test vector is executed in Hybrid mode to get the performance outcome in terms of throughput.

Figure 1 shows the top-level block diagram of Opus codec. The source image is captured from arxiv.org/pdf/1602.04845.pdf.

Figure 1. Opus Codec Top-level Block Diagram



CELT operates at a sampling rate of 48 kHz, while SILK operates at 8 kHz, 12 kHz, or 16 kHz. In the Hybrid mode of operation, the crossover frequency is 8 kHz, with SILK operating at 16 kHz and CELT discarding all frequencies below the 8 kHz Nyquist rate.

Opus codec utilizes lossy compression, which is designed to efficiently code audio with a low latency, making it suitable for real time communication. Opus codec replaces both the Vorbis and Speex codecs. Opus codec's low complexity allows it to run efficiently on the PolarFire SoC Icicle kit with high throughput in the Hybrid mode. The following table lists the system configuration used to measure benchmark values for Opus codecs.

Table 1. System Configuration

System Configuration	Description
Product and Architecture	PolarFire SoC FPGA, RISC-V 64-bit
Platform	Linux
CPU Core Frequency	600 MHz
External Memory Access	eMMC/SD, LPDDR4
LPDDR4 Frequency	800 MHz
Compiler	GCC
Toolchain	riscv64-oe-linux-gcc (v9.3.0)

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1. Procedure and Execution of Opus Codec Benchmark

Opus codec is based on the IETF RFC 6716 standard. An opus-tools package provides encoding and decoding of Ogg encapsulated Opus files and includes many useful features. For more information, see [Opus codec web page](#).

[Git clone](#) is the Opus codec repository for the libopus and test vectors.

Compile the source code by executing `/autogen.sh`, `./configure`, and make commands with necessary porting on to the RISC-V architecture.

Install the codec libraries with `make install`.

To execute and get the throughput, compare the code with the following test vectors:

- `curl -OL`. See [Opus codec test vectors](#).
- `tar -zxvf opus_testvectors-rfc8251.tar.gz`.
- `/tests/run_vectors.sh / opus_newvectors 48000` (execute test vectors with various sampling rates ranging from 8000, 12000, 16000, 24000, or 48000).

2. Results

In this white paper, the benchmarking results are derived by executing both CELT and SILK mode, that is, Hybrid mode simultaneously on the PolarFire SoC Icicle kit. The following table lists the benchmarking results.

Table 2-1. Benchmarking Results

Benchmarking		Result
CELT and SILK (Hybrid mode)	Code Space	194.142 Kbytes
	Data Space	53.37 bytes (BSS + Sdata + Read only data)
	Throughput	99%

The following table lists the benchmarking values of the code and data section for riscv64 architecture by Opus Interactive Audio codec.

Table 2-2. Benchmarking Values of Code and Data

Section	Size
Text	194142
Read Only Data (rodata)	52048
Segment Data (sdata)	1310
Block Started by Symbol (BSS)	16

The Opus codec test suite has 14 test cases, such as CELT, SILK, Opus_api, Opus_decode, Opus_encode, padding, project test cases ref RFC 6716, and so on. All these standard test cases are executed on the PolarFire SoC Icicle kit with the throughput of 99%.

The following figure shows the Opus codec test suite summary for PolarFire SoC Icicle Kit.

Figure 2-1. Opus Codec Test Suite Summary for PolarFire SoC Icicle Kit

```

PASS: celt/tests/test_unit_cwrs32
PASS: celt/tests/test_unit_dft
PASS: celt/tests/test_unit_entropy
PASS: celt/tests/test_unit_laplace
PASS: celt/tests/test_unit_mathops
PASS: celt/tests/test_unit_mdct
PASS: celt/tests/test_unit_rotation
PASS: celt/tests/test_unit_types
PASS: silk/tests/test_unit_LPC_inv_pred_gain
PASS: tests/test_opus_api
PASS: tests/test_opus_decode
PASS: tests/test_opus_encode
PASS: tests/test_opus_padding
PASS: tests/test_opus_projection
=====
Testsuite summary for opus 1.3.1-91-g7b05f44f
=====
# TOTAL: 14
# PASS: 14
# SKIP: 0
# XFAIL: 0
# FAIL: 0
# XPASS: 0
# ERROR: 0
=====

```

The following figure shows the log for Mono-Opus Audio Codec.

Figure 2-2. Mono-Opus Audio Codec Log

```

Decoding with 48000 Hz output (1 channels)
average bitrate:      22.084 kb/s
maximum bitrate:     144.426 kb/s
bitrate standard deviation: 24.566 kb/s
Test vector PASSES
Opus quality metric: 96.2 % (internal weighted error is 0.009403)
libopus 1.3.1-91-g7b05f44f
Decoding with 48000 Hz output (1 channels)
average bitrate:      25.287 kb/s
maximum bitrate:     151.410 kb/s
bitrate standard deviation: 26.808 kb/s
Test vector PASSES
Opus quality metric: 96.7 % (internal weighted error is 0.008038)
libopus 1.3.1-91-g7b05f44f
Decoding with 48000 Hz output (1 channels)
average bitrate:      22.220 kb/s
maximum bitrate:     114.059 kb/s
bitrate standard deviation: 19.000 kb/s
Test vector PASSES
Opus quality metric: 96.5 % (internal weighted error is 0.008508)
Internal weighted error is 8.870150
libopus 1.3.1-91-g7b05f44f
Internal weighted error is 4.076123
libopus 1.3.1-91-g7b05f44f
Decoding with 48000 Hz output (1 channels)
average bitrate:      62.721 kb/s
maximum bitrate:     618.255 kb/s
bitrate standard deviation: 84.010 kb/s
Test vector FAILS
Internal weighted error is 2.724740
libopus 1.3.1-91-g7b05f44f
Internal weighted error is 7.318658
libopus 1.3.1-91-g7b05f44f
Internal weighted error is 0.813325
libopus 1.3.1-91-g7b05f44f
Decoding with 48000 Hz output (1 channels)
average bitrate:      182.195 kb/s
maximum bitrate:     715.397 kb/s
bitrate standard deviation: 179.946 kb/s
Test vector PASSES
Opus quality metric: 97.7 % (internal weighted error is 0.005626)
libopus 1.3.1-91-g7b05f44f
Decoding with 48000 Hz output (1 channels)
average bitrate:      95.104 kb/s
maximum bitrate:     218.902 kb/s
bitrate standard deviation: 62.045 kb/s
Test vector PASSES
Opus quality metric: 93.5 % (internal weighted error is 0.016106)
libopus 1.3.1-91-g7b05f44f
Decoding with 48000 Hz output (1 channels)
average bitrate:      13.828 kb/s
maximum bitrate:     28.800 kb/s
bitrate standard deviation: 5.660 kb/s
Test vector PASSES
Opus quality metric: 99.9 % (internal weighted error is 0.000365)

Test vector PASSES
Opus quality metric: 98.2 % (internal weighted error is 0.004328)
Test vector PASSES
Opus quality metric: 96.2 % (internal weighted error is 0.009403)
Test vector PASSES
Opus quality metric: 96.7 % (internal weighted error is 0.008038)
Test vector PASSES
Opus quality metric: 96.5 % (internal weighted error is 0.008508)
Test vector PASSES
Opus quality metric: 96.3 % (internal weighted error is 0.009183)
Test vector PASSES
Opus quality metric: 96.3 % (internal weighted error is 0.009020)
Test vector PASSES
Opus quality metric: 98.1 % (internal weighted error is 0.004616)
Test vector PASSES
Opus quality metric: 96.5 % (internal weighted error is 0.008574)
Test vector PASSES
Opus quality metric: 98.1 % (internal weighted error is 0.004609)
Test vector PASSES
Opus quality metric: 97.7 % (internal weighted error is 0.005626)
Test vector PASSES
Opus quality metric: 98.5 % (internal weighted error is 0.003645)
Test vector PASSES
Opus quality metric: 99.9 % (internal weighted error is 0.000365)

```

The following figure shows the log for Stereo-Opus Audio Codec.

Figure 2-3. Stereo-Opus Audio Codec Log

```

libopus 1.3.1-91-g7b05f44f
Decoding with 48000 Hz output (2 channels)
average bitrate:      178.980 kb/s
maximum bitrate:      716.722 kb/s
bitrate standard deviation: 119.625 kb/s
Test vector PASSES
Opus quality metric: 99.9 % (internal weighted error is 0.000258)
libopus 1.3.1-91-g7b05f44f
Decoding with 48000 Hz output (2 channels)
average bitrate:      22.084 kb/s
maximum bitrate:      144.426 kb/s
bitrate standard deviation: 24.566 kb/s
Test vector PASSES
Opus quality metric: 100.0 % (internal weighted error is 0.000000)
libopus 1.3.1-91-g7b05f44f
Decoding with 48000 Hz output (2 channels)
average bitrate:      25.287 kb/s
maximum bitrate:      151.410 kb/s
bitrate standard deviation: 26.808 kb/s
Test vector PASSES
Opus quality metric: 100.0 % (internal weighted error is 0.000000)
libopus 1.3.1-91-g7b05f44f
Decoding with 48000 Hz output (2 channels)
average bitrate:      22.220 kb/s
maximum bitrate:      114.059 kb/s
bitrate standard deviation: 19.000 kb/s
Test vector PASSES
Opus quality metric: 100.0 % (internal weighted error is 0.000000)
libopus 1.3.1-91-g7b05f44f
Decoding with 48000 Hz output (2 channels)
average bitrate:      41.210 kb/s
maximum bitrate:      99.000 kb/s
bitrate standard deviation: 18.671 kb/s
Test vector PASSES
Opus quality metric: 99.8 % (internal weighted error is 0.000408)
libopus 1.3.1-91-g7b05f44f
Decoding with 48000 Hz output (2 channels)
average bitrate:      42.388 kb/s
maximum bitrate:      114.000 kb/s
bitrate standard deviation: 21.559 kb/s
Test vector PASSES
Opus quality metric: 99.8 % (internal weighted error is 0.000397)
libopus 1.3.1-91-g7b05f44f
Decoding with 48000 Hz output (2 channels)
average bitrate:      62.721 kb/s
maximum bitrate:      618.255 kb/s
bitrate standard deviation: 84.010 kb/s
Test vector PASSES
Opus quality metric: 99.8 % (internal weighted error is 0.000405)
libopus 1.3.1-91-g7b05f44f
Decoding with 48000 Hz output (2 channels)
average bitrate:      38.127 kb/s
maximum bitrate:      201.509 kb/s
bitrate standard deviation: 44.458 kb/s
Test vector PASSES
Opus quality metric: 99.8 % (internal weighted error is 0.000397)
libopus 1.3.1-91-g7b05f44f
Decoding with 48000 Hz output (2 channels)
average bitrate:      228.550 kb/s
maximum bitrate:      495.434 kb/s
bitrate standard deviation: 193.402 kb/s
Test vector PASSES
Opus quality metric: 99.8 % (internal weighted error is 0.000545)
libopus 1.3.1-91-g7b05f44f
Decoding with 48000 Hz output (2 channels)
average bitrate:      182.195 kb/s
maximum bitrate:      715.397 kb/s
bitrate standard deviation: 179.946 kb/s
Test vector PASSES
Opus quality metric: 99.8 % (internal weighted error is 0.000486)
libopus 1.3.1-91-g7b05f44f
Decoding with 48000 Hz output (2 channels)
average bitrate:      95.104 kb/s
maximum bitrate:      218.902 kb/s
bitrate standard deviation: 62.045 kb/s
Test vector PASSES
Opus quality metric: 99.8 % (internal weighted error is 0.000435)
libopus 1.3.1-91-g7b05f44f
Decoding with 48000 Hz output (2 channels)
average bitrate:      13.828 kb/s
maximum bitrate:      28.800 kb/s
bitrate standard deviation: 5.660 kb/s
Test vector PASSES
Opus quality metric: 99.9 % (internal weighted error is 0.000363)

Test vector PASSES
Opus quality metric: 66.3 % (internal weighted error is 0.085926)
Test vector PASSES
Opus quality metric: 100.0 % (internal weighted error is 0.000000)
Test vector PASSES
Opus quality metric: 100.0 % (internal weighted error is 0.000000)
Test vector PASSES
Opus quality metric: 100.0 % (internal weighted error is 0.000000)
Test vector PASSES
Opus quality metric: 33.4 % (internal weighted error is 0.176919)
Test vector PASSES
Opus quality metric: 45.0 % (internal weighted error is 0.143813)
Test vector FAILS
Internal weighted error is 0.347141
Test vector PASSES
Opus quality metric: 13.2 % (internal weighted error is 0.236407)
Test vector PASSES
Opus quality metric: 40.7 % (internal weighted error is 0.155938)
Test vector PASSES
Opus quality metric: 99.8 % (internal weighted error is 0.000486)
Test vector PASSES
Opus quality metric: 97.0 % (internal weighted error is 0.007255)
Test vector PASSES
Opus quality metric: 99.9 % (internal weighted error is 0.000363)

```

3. Conclusion

This white paper describes the toolchain, the compiler, and the process for executing the standard Opus audio codec test vectors using the PolarFire SoC Icicle kit. The best performance results are achieved for utilization of code, data space, and throughput.

4. References

- For information about high quality low-delay music coding in the Opus codec, see https://www.researchgate.net/publication/286609722_High-Quality_Low-Delay_Music_Coding_in_the_Opus_Codec.
- For information about Opus codec, see <http://opus-codec.org/>.
- J.-M. Valin, K. Vos, and T. B. Terriberry. Definition of the Opus Audio Codec. RFC 6716, www.ietf.org/rfc/rfc6716.txt, September 2012.

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