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Definition of the Opus Audio Codec
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Abstract

This document defines the Opus interactive speech and audio codec. Opus is designed to handle a wide range of interactive audio applications, including Voice over IP, videoconferencing, in-game chat, and even live, distributed music performances. It scales from low bit-rate narrowband speech at 6 kb/s to very high quality stereo music at 510 kb/s. Opus uses both linear prediction (LP) and the Modified Discrete Cosine Transform (MDCT) to achieve good compression of both speech and music.

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1. Introduction

The Opus codec is a real-time interactive audio codec designed to meet the requirements described in [requirements]. It is composed of a linear prediction (LP)-based layer and a Modified Discrete Cosine Transform (MDCT)-based layer. The main idea behind using two layers is that in speech, linear prediction techniques (such as CELP) code low frequencies more efficiently than transform (e.g., MDCT) domain techniques, while the situation is reversed for music and higher speech frequencies. Thus a codec with both layers available can operate over a wider range than either one alone and, by combining them, achieve better quality than either one individually.

The primary normative part of this specification is provided by the source code in Appendix A. Only the decoder portion of this software is normative, though a significant amount of code is shared by both the encoder and decoder. The decoder contains significant amounts of integer and fixed-point arithmetic which must be performed exactly, including all rounding considerations, so any useful specification must make extensive use of domain-specific symbolic language to adequately define these operations. Additionally, any conflict between the symbolic representation and the included reference implementation must be resolved. For the practical reasons of compatibility and testability it would be advantageous to give the reference implementation priority in any disagreement. The C language is also one of the most widely understood human-readable symbolic representations for machine behavior. For these reasons this RFC uses the reference implementation as the sole symbolic representation of the codec.

While the symbolic representation is unambiguous and complete it is not always the easiest way to understand the codec's operation. For this reason this document also describes significant parts of the codec in English and takes the opportunity to explain the rationale behind many of the more surprising elements of the design. These descriptions are intended to be accurate and informative, but the limitations of common English sometimes result in ambiguity, so it is expected that the reader will always read them alongside the symbolic representation. Numerous references to the implementation are provided for this purpose. The descriptions sometimes differ from the reference in ordering or through mathematical simplification wherever such deviation makes an explanation easier to understand. For example, the right shift and left shift operations in the reference implementation are often described using division and multiplication in the text. In general, the text is focused on the "what" and "why" while the symbolic representation most clearly provides the "how".

1.1. Notation and Conventions

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in RFC 2119 [rfc2119].

Even when using floating-point, various operations in the codec require bit-exact fixed-point behavior. The notation "Q<n>", where n is an integer, denotes the number of binary digits to the right of the decimal point in a fixed-point number. For example, a signed Q14 value in a 16-bit word can represent values from -2.0 to 1.99993896484375, inclusive. This notation is for informational purposes only. Arithmetic, when described, always operates on the underlying integer. E.g., the text will explicitly indicate any shifts required after a multiplication.

Expressions, where included in the text, follow C operator rules and precedence, with the exception that the syntax "x**y" is used to indicate x raised to the power y. The text also makes use of the following functions:

1.1.1. min(x,y)

The smallest of two values x and y.

1.1.2. max(x,y)

The largest of two values x and y.

1.1.3. clamp(lo,x,hi)

$$\text{clamp}(\text{lo}, \text{x}, \text{hi}) = \text{max}(\text{lo}, \text{min}(\text{x}, \text{hi}))$$

With this definition, if $\text{lo} > \text{hi}$, the lower bound is the one that is enforced.

1.1.4. sign(x)

The sign of x, i.e.,

$$\text{sign}(\text{x}) = \begin{cases} -1, & \text{x} < 0 \\ 0, & \text{x} == 0 \\ 1, & \text{x} > 0 \end{cases}$$

1.1.5. $\log_2(f)$

The base-two logarithm of f .

1.1.6. $\text{ilog}(n)$

The minimum number of bits required to store a positive integer n in two's complement notation, or 0 for a non-positive integer n .

$$\text{ilog}(n) = \begin{cases} 0, & n \leq 0, \\ \lfloor \log_2(n) \rfloor + 1, & n > 0 \end{cases}$$

Examples:

- o $\text{ilog}(-1) = 0$
- o $\text{ilog}(0) = 0$
- o $\text{ilog}(1) = 1$
- o $\text{ilog}(2) = 2$
- o $\text{ilog}(3) = 2$
- o $\text{ilog}(4) = 3$
- o $\text{ilog}(7) = 3$

2. Opus Codec Overview

The Opus codec scales from 6 kb/s narrowband mono speech to 510 kb/s fullband stereo music, with algorithmic delays ranging from 5 ms to 65.2 ms. At any given time, either the LP layer, the MDCT layer, or both, may be active. It can seamlessly switch between all of its various operating modes, giving it a great deal of flexibility to adapt to varying content and network conditions without renegotiating the current session. The codec allows input and output of various audio bandwidths, defined as follows:

Abbreviation	Audio Bandwidth	Sample Rate (Effective)
NB (narrowband)	4 kHz	8 kHz
MB (medium-band)	6 kHz	12 kHz
WB (wideband)	8 kHz	16 kHz
SWB (super-wideband)	12 kHz	24 kHz
FB (fullband)	20 kHz (*)	48 kHz

Table 1

(*) Although the sampling theorem allows a bandwidth as large as half the sampling rate, Opus never codes audio above 20 kHz, as that is the generally accepted upper limit of human hearing.

Opus defines super-wideband (SWB) with an effective sample rate of 24 kHz, unlike some other audio coding standards that use 32 kHz. This was chosen for a number of reasons. The band layout in the MDCT layer naturally allows skipping coefficients for frequencies over 12 kHz, but does not allow cleanly dropping just those frequencies over 16 kHz. A sample rate of 24 kHz also makes resampling in the MDCT layer easier, as 24 evenly divides 48, and when 24 kHz is sufficient, it can save computation in other processing, such as Acoustic Echo Cancellation (AEC). Experimental changes to the band layout to allow a 16 kHz cutoff (32 kHz effective sample rate) showed potential quality degradations at other sample rates, and at typical bitrates the number of bits saved by using such a cutoff instead of coding in fullband (FB) mode is very small. Therefore, if an application wishes to process a signal sampled at 32 kHz, it should just use FB.

The LP layer is based on the SILK [1] codec [SILK]. It supports NB,

MB, or WB audio and frame sizes from 10 ms to 60 ms, and requires an additional 5 ms look-ahead for noise shaping estimation. A small additional delay (up to 1.2 ms) may be required for sampling rate conversion. Like Vorbis and many other modern codecs, SILK is inherently designed for variable-bitrate (VBR) coding, though the encoder can also produce constant-bitrate (CBR) streams. The version of SILK used in Opus is substantially modified from, and not compatible with, the stand-alone SILK codec previously deployed by Skype. This document does not serve to define that format, but those interested in the original SILK codec should see [SILK] instead.

The MDCT layer is based on the CELT [2] codec [CELT]. It supports NB, WB, SWB, or FB audio and frame sizes from 2.5 ms to 20 ms, and requires an additional 2.5 ms look-ahead due to the overlapping MDCT windows. The CELT codec is inherently designed for CBR coding, but unlike many CBR codecs it is not limited to a set of predetermined rates. It internally allocates bits to exactly fill any given target budget, and an encoder can produce a VBR stream by varying the target on a per-frame basis. The MDCT layer is not used for speech when the audio bandwidth is WB or less, as it is not useful there. On the other hand, non-speech signals are not always adequately coded using linear prediction, so for music only the MDCT layer should be used.

A "Hybrid" mode allows the use of both layers simultaneously with a frame size of 10 or 20 ms and a SWB or FB audio bandwidth. Each frame is split into a low frequency signal and a high frequency signal, with a cutoff of 8 kHz. The LP layer then codes the low frequency signal, followed by the MDCT layer coding the high frequency signal. In the MDCT layer, all bands below 8 kHz are discarded, so there is no coding redundancy between the two layers.

The sample rate (in contrast to the actual audio bandwidth) can be chosen independently on the encoder and decoder side, e.g., a fullband signal can be decoded as wideband, or vice versa. This approach ensures a sender and receiver can always interoperate, regardless of the capabilities of their actual audio hardware. Internally, the LP layer always operates at a sample rate of twice the audio bandwidth, up to a maximum of 16 kHz, which it continues to use for SWB and FB. The decoder simply resamples its output to support different sample rates. The MDCT layer always operates internally at a sample rate of 48 kHz. Since all the supported sample rates evenly divide this rate, and since the the decoder may easily zero out the high frequency portion of the spectrum in the frequency domain, it can simply decimate the MDCT layer output to achieve the other supported sample rates very cheaply.

After conversion to the common, desired output sample rate, the decoder simply adds the output from the two layers together. To

compensate for the different look-ahead required by each layer, the CELT encoder input is delayed by an additional 2.7 ms. This ensures that low frequencies and high frequencies arrive at the same time. This extra delay may be reduced by an encoder by using less look-ahead for noise shaping or using a simpler resampler in the LP layer, but this will reduce quality. However, the base 2.5 ms look-ahead in the CELT layer cannot be reduced in the encoder because it is needed for the MDCT overlap, whose size is fixed by the decoder.

Both layers use the same entropy coder, avoiding any waste from "padding bits" between them. The hybrid approach makes it easy to support both CBR and VBR coding. Although the LP layer is VBR, the bit allocation of the MDCT layer can produce a final stream that is CBR by using all the bits left unused by the LP layer.

2.1. Control Parameters

The Opus codec includes a number of control parameters which can be changed dynamically during regular operation of the codec, without interrupting the audio stream from the encoder to the decoder. These parameters only affect the encoder since any impact they have on the bit-stream is signalled in-band such that a decoder can decode any Opus stream without any out-of-band signalling. Any Opus implementation can add or modify these control parameters without affecting interoperability. The most important encoder control parameters in the reference encoder are listed below.

2.1.1. Bitrate

Opus supports all bitrates from 6 kb/s to 510 kb/s. All other parameters being equal, higher bit-rate results in higher quality. For a frame size of 20 ms, these are the bitrate "sweet spots" for Opus in various configurations:

- o 8-12 kb/s for narrowband speech
- o 16-20 kb/s for wideband speech
- o 28-40 kb/s for fullband speech
- o 48-64 kb/s for fullband mono music
- o 64-128 kb/s for fullband stereo music

2.1.2. Number of channels (mono/stereo)

Opus can transmit either mono or stereo audio within one stream. When decoding a mono stream in stereo, the left and right channels will be identical and when decoding a stereo channel in mono, the mono output will be the average of the encoded left and right channels. In some cases it is desirable to encode a stereo input stream in mono (e.g. because the bit-rate is insufficient for good quality stereo). The number of channels encoded can be selected in real-time, but by default the reference encoder attempts to make the best decision possible given the current bitrate.

2.1.3. Audio bandwidth

The audio bandwidths supported by Opus are listed in Table 1. Just like for the number of channels, any decoder can decode audio encoded at any bandwidth. For example, any Opus decoder operating at 8 kHz can decode a fullband Opus stream and any Opus decoder operating at 48 kHz can decode a narrowband stream. Similarly, the reference encoder can take a 48 kHz input signal and encode it in narrowband. The higher the audio bandwidth, the higher the required bitrate to achieve acceptable quality. The audio bandwidth can be explicitly specified in real-time, but by default the reference encoder attempts to make the best bandwidth decision possible given the current bitrate.

2.1.4. Frame duration

Opus can encode frames of 2.5, 5, 10, 20, 40 or 60 ms. It can also combine multiple frames into packets of up to 120 ms. Because of the overhead from IP/UDP/RTP headers, sending fewer packets per second reduces the bitrate, but increases latency and sensitivity to packet losses as losing one packet constitutes a loss of a bigger chunk of audio signal. Increasing the frame duration also slightly improves coding efficiency, but the gain becomes small for frame sizes above 20 ms. For this reason, 20 ms frames tend to be a good choice for most applications.

2.1.5. Complexity

There are various aspects of the Opus encoding process where trade-offs can be made between CPU complexity and quality/bitrate. In the reference encoder, the complexity is selected using an integer from 0 to 10, where 0 is the lowest complexity and 10 is the highest. Examples of computations for which such trade-offs may occur are:

- o the filter order of the pitch analysis whitening filter the short-term noise shaping filter;

- o The number of states in delayed decision quantization of the residual signal;
- o The use of certain bit-stream features such as variable time-frequency resolution and pitch post-filter.

2.1.6. Packet loss resilience

Audio codecs often exploit inter-frame correlations to reduce the bitrate at a cost in error propagation: after losing one packet several packets need to be received before the decoder is able to accurately reconstruct the speech signal. The extent to which Opus exploits inter-frame dependencies can be adjusted on the fly to choose a trade-off between bitrate and amount of error propagation.

2.1.7. Forward error correction (FEC)

Another mechanism providing robustness against packet loss is the in-band Forward Error Correction (FEC). Packets that are determined to contain perceptually important speech information, such as onsets or transients, are encoded again at a lower bitrate and this re-encoded information is added to a subsequent packet.

2.1.8. Constant/variable bit-rate

Opus is more efficient when operating with variable bitrate (VBR), which is the default. However, in some (rare) applications, constant bit-rate (CBR) is required. There are two main reasons to operate in CBR mode:

- o When the transport only supports a fixed size for each compressed frame
- o When security is important and the input audio not a normal conversation but is highly constrained (e.g. yes/no, recorded prompts) [SRTP-VBR]

When low-latency transmission is required over a relatively slow connection, then constrained VBR can also be used. This uses VBR in a way that simulates a "bit reservoir" and is equivalent to what MP3 and AAC call CBR (i.e. not true CBR due to the bit reservoir).

2.1.9. Discontinuous transmission (DTX)

Discontinuous Transmission (DTX) reduces the bitrate during silence or background noise. When DTX is enabled, only one frame is encoded every 400 milliseconds.

3. Internal Framing

The Opus encoder produces "packets", which are each a contiguous set of bytes meant to be transmitted as a single unit. The packets described here do not include such things as IP, UDP, or RTP headers which are normally found in a transport-layer packet. A single packet may contain multiple audio frames, so long as they share a common set of parameters, including the operating mode, audio bandwidth, frame size, and channel count (mono vs. stereo). This section describes the possible combinations of these parameters and the internal framing used to pack multiple frames into a single packet. This framing is not self-delimiting. Instead, it assumes that a higher layer (such as UDP or RTP or Ogg or Matroska) will communicate the length, in bytes, of the packet, and it uses this information to reduce the framing overhead in the packet itself. A decoder implementation **MUST** support the framing described in this section. An alternative, self-delimiting variant of the framing is described in Appendix B. Support for that variant is **OPTIONAL**.

3.1. The TOC Byte

An Opus packet begins with a single-byte table-of-contents (TOC) header that signals which of the various modes and configurations a given packet uses. It is composed of a frame count code, "c", a stereo flag, "s", and a configuration number, "config", arranged as illustrated in Figure 1. A description of each of these fields follows.

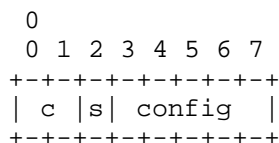


Figure 1: The TOC byte

The top five bits of the TOC byte, labeled "config", encode one of 32 possible configurations of operating mode, audio bandwidth, and frame size. As described, the LP layer and MDCT layer can be combined in three possible operating modes:

1. An LP-only mode for use in low bitrate connections with an audio bandwidth of WB or less,
2. A Hybrid (LP+MDCT) mode for SWB or FB speech at medium bitrates, and

3. An MDCT-only mode for very low delay speech transmission as well as music transmission (NB to FB).

The 32 possible configurations each identify which one of these operating modes the packet uses, as well as the audio bandwidth and the frame size. Table 2 lists the parameters for each configuration.

Configuration Number(s)	Mode	Bandwidth	Frame Sizes
0...3	SILK-only	NB	10, 20, 40, 60 ms
4...7	SILK-only	MB	10, 20, 40, 60 ms
8...11	SILK-only	WB	10, 20, 40, 60 ms
12...13	Hybrid	SWB	10, 20 ms
14...15	Hybrid	FB	10, 20 ms
16...19	CELT-only	NB	2.5, 5, 10, 20 ms
20...23	CELT-only	WB	2.5, 5, 10, 20 ms
24...27	CELT-only	SWB	2.5, 5, 10, 20 ms
28...31	CELT-only	FB	2.5, 5, 10, 20 ms

Table 2: TOC Byte Configuration Parameters

The configuration numbers in each range (e.g., 0...3 for NB SILK-only) correspond to the various choices of frame size, in the same order. For example, configuration 0 has a 10 ms frame size and configuration 3 has a 60 ms frame size.

One additional bit, labeled "s", is used to signal mono vs. stereo, with 0 indicating mono and 1 indicating stereo.

The remaining two bits of the TOC byte, labeled "c", code the number of frames per packet (codes 0 to 3) as follows:

- o 0: 1 frame in the packet
- o 1: 2 frames in the packet, each with equal compressed size

- o 2: 2 frames in the packet, with different compressed sizes
- o 3: an arbitrary number of frames in the packet

This draft refers to a packet as a code 0 packet, code 1 packet, etc., based on the value of "c".

A well-formed Opus packet MUST contain at least one byte with the TOC information, though the frame(s) within a packet MAY be zero bytes long.

3.2. Frame Packing

This section describes how frames are packed according to each possible value of "c" in the TOC byte.

3.2.1. Frame Length Coding

When a packet contains multiple VBR frames (i.e., code 2 or 3), the compressed length of one or more of these frames is indicated with a one or two byte sequence, with the meaning of the first byte as follows:

- o 0: No frame (discontinuous transmission (DTX) or lost packet)
- o 1...251: Length of the frame in bytes
- o 252...255: A second byte is needed. The total length is $(len[1]*4)+len[0]$

The maximum representable length is $255*4+255=1275$ bytes. For 20 ms frames, this represents a bitrate of 510 kb/s, which is approximately the highest useful rate for lossily compressed fullband stereo music. Beyond this point, lossless codecs are more appropriate. It is also roughly the maximum useful rate of the MDCT layer, as shortly thereafter quality no longer improves with additional bits due to limitations on the codebook sizes.

No length is transmitted for the last frame in a VBR packet, or for any of the frames in a CBR packet, as it can be inferred from the total size of the packet and the size of all other data in the packet. However, the length of any individual frame MUST NOT exceed 1275 bytes, to allow for repacketization by gateways, conference bridges, or other software.

3.2.2. Code 0: One Frame in the Packet

For code 0 packets, the TOC byte is immediately followed by N-1 bytes of compressed data for a single frame (where N is the size of the packet), as illustrated in Figure 2.

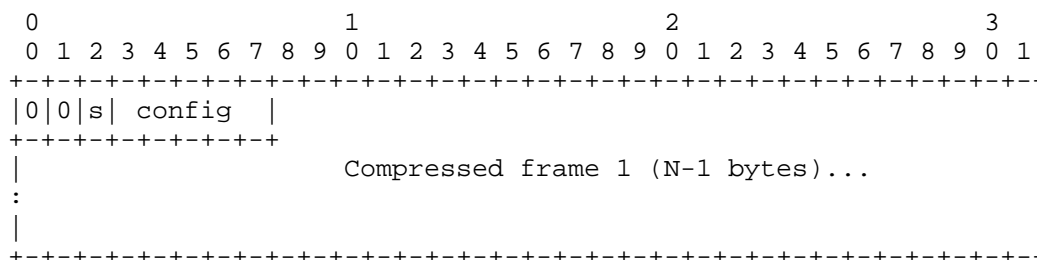


Figure 2: A Code 0 Packet

3.2.3. Code 1: Two Frames in the Packet, Each with Equal Compressed Size

For code 1 packets, the TOC byte is immediately followed by the (N-1)/2 bytes of compressed data for the first frame, followed by (N-1)/2 bytes of compressed data for the second frame, as illustrated in Figure 3. The number of payload bytes available for compressed data, N-1, MUST be even for all code 1 packets.

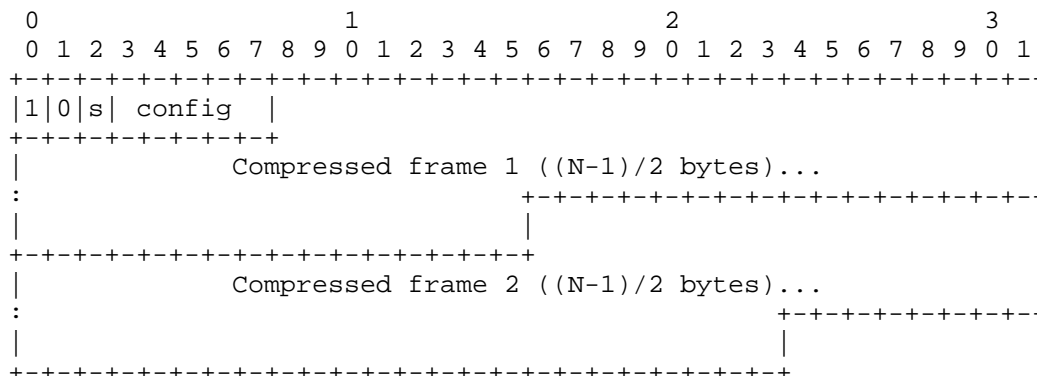


Figure 3: A Code 1 Packet

3.2.4. Code 2: Two Frames in the Packet, with Different Compressed Sizes

For code 2 packets, the TOC byte is followed by a one or two byte sequence indicating the length of the first frame (marked N1 in the

figure below), followed by N_1 bytes of compressed data for the first frame. The remaining $N-N_1-2$ or $N-N_1-3$ bytes are the compressed data for the second frame. This is illustrated in Figure 4. A code 2 packet MUST contain enough bytes to represent a valid length. For example, a 1-byte code 2 packet is always invalid, and a 2-byte code 2 packet whose second byte is in the range 252...255 is also invalid. The length of the first frame, N_1 , MUST also be no larger than the size of the payload remaining after decoding that length for all code 2 packets. This makes, for example, a 2-byte code 2 packet with a second byte in the range 1...250 invalid as well (the only valid 2-byte code 2 packet is one where the length of both frames is zero).

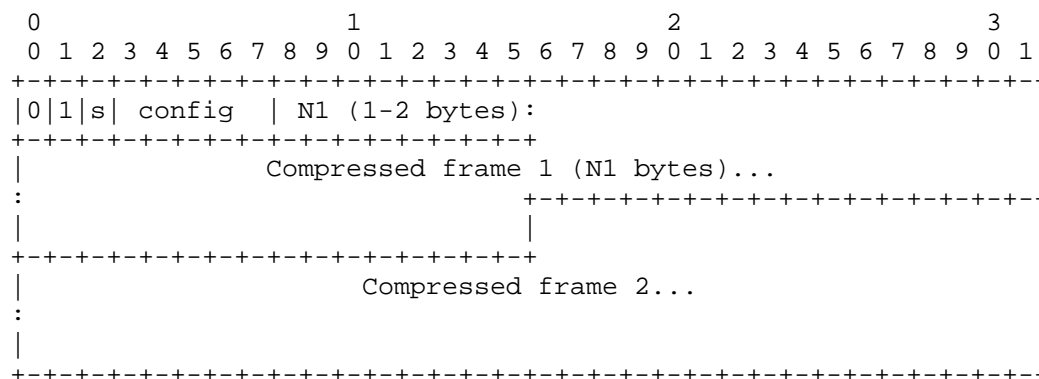


Figure 4: A Code 2 Packet

3.2.5. Code 3: An Arbitrary Number of Frames in the Packet

Code 3 packets may encode an arbitrary number of frames, as well as additional padding, called "Opus padding" to indicate that this padding is added at the Opus layer, rather than at the transport layer. Code 3 packets MUST have at least 2 bytes. The TOC byte is followed by a byte encoding the number of frames in the packet in bits 0 to 5 (marked "M" in the figure below), with bit 6 indicating whether or not Opus padding is inserted (marked "p" in the figure below), and bit 7 indicating VBR (marked "v" in the figure below). M MUST NOT be zero, and the audio duration contained within a packet MUST NOT exceed 120 ms. This limits the maximum frame count for any frame size to 48 (for 2.5 ms frames), with lower limits for longer frame sizes. Figure 5 illustrates the layout of the frame count byte.

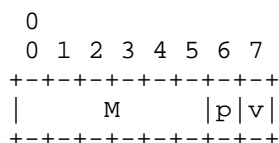


Figure 5: The frame count byte

When Opus padding is used, the number of bytes of padding is encoded in the bytes following the frame count byte. Values from 0...254 indicate that 0...254 bytes of padding are included, in addition to the byte(s) used to indicate the size of the padding. If the value is 255, then the size of the additional padding is 254 bytes, plus the padding value encoded in the next byte. There MUST be at least one more byte in the packet in this case. By using the value 255 multiple times, it is possible to create a packet of any specific, desired size. The additional padding bytes appear at the end of the packet, and MUST be set to zero by the encoder to avoid creating a covert channel. The decoder MUST accept any value for the padding bytes, however. Let P be the total amount of padding, including both the trailing padding bytes themselves and the header bytes used to indicate how many trailing bytes there are. Then P MUST be no more than $N-2$.

In the CBR case, the compressed length of each frame in bytes is equal to the number of remaining bytes in the packet after subtracting the (optional) padding, $(N-2-P)$, divided by M . This number MUST be an integer multiple of M . The compressed data for all M frames then follows, each of size $(N-2-P)/M$ bytes, as illustrated in Figure 6.

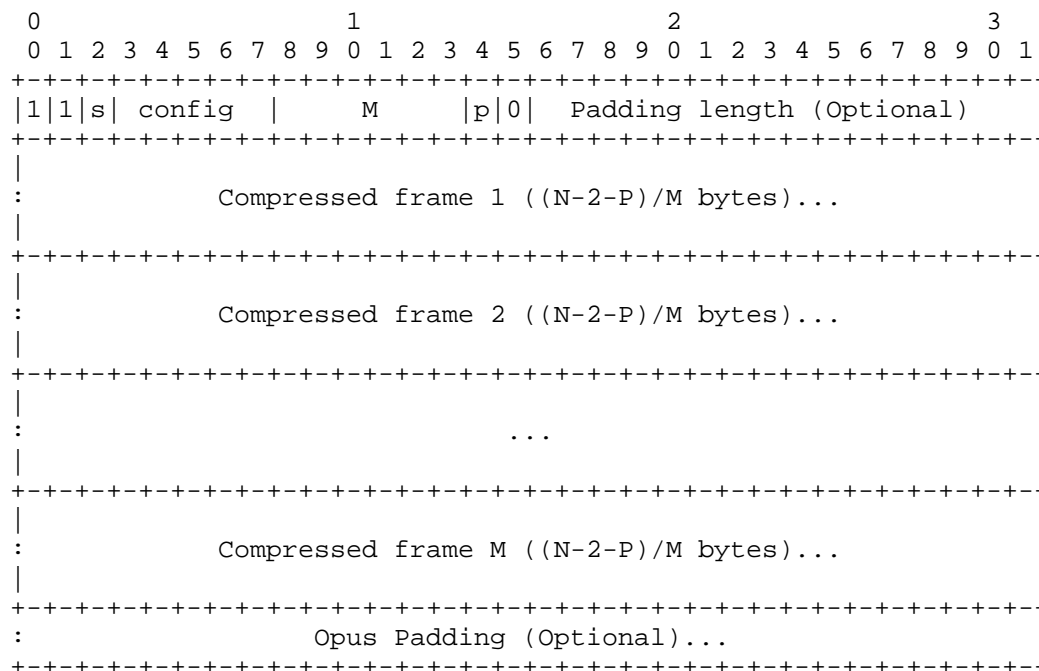


Figure 6: A CBR Code 3 Packet

In the VBR case, the (optional) padding length is followed by M-1 frame lengths (indicated by "N1" to "N[M-1]" in the figure below), each encoded in a one or two byte sequence as described above. The packet MUST contain enough data for the M-1 lengths after removing the (optional) padding, and the sum of these lengths MUST be no larger than the number of bytes remaining in the packet after decoding them. The compressed data for all M frames follows, each frame consisting of the indicated number of bytes, with the final frame consuming any remaining bytes before the final padding, as illustrated in Figure 6. The number of header bytes (TOC byte, frame count byte, padding length bytes, and frame length bytes), plus the length of the first M-1 frames themselves, plus the length of the padding MUST be no larger than N, the total size of the packet.

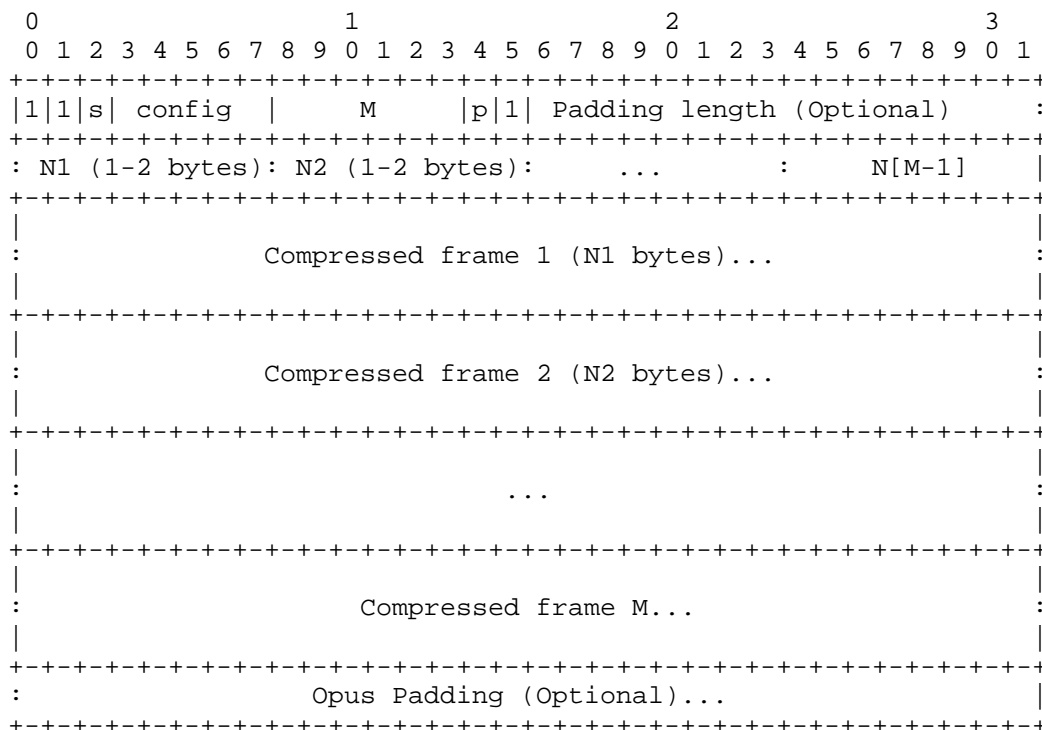
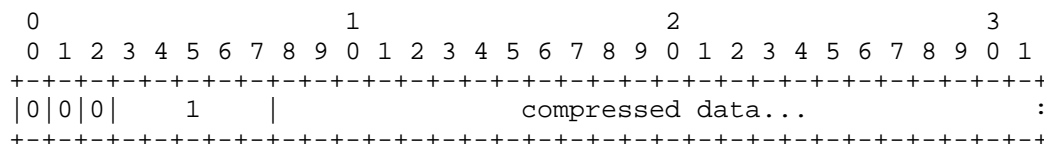


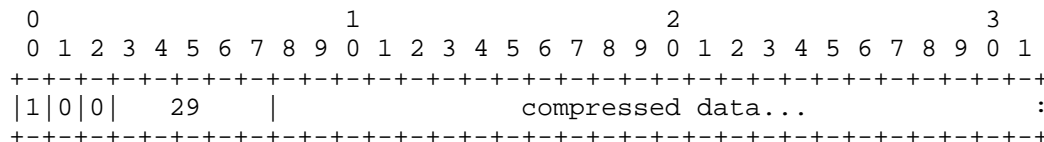
Figure 7: A VBR Code 3 Packet

3.3. Examples

Simplest case, one NB mono 20 ms SILK frame:



Two FB mono 5 ms CELT frames of the same compressed size:



Two FB mono 20 ms Hybrid frames of different compressed size:

```

      0                               1                               2                               3
      0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-----+-----+-----+-----+-----+-----+-----+-----+-----+
|1|1|0|      15      |      2      |0|1|      N1      |      |
+-----+-----+-----+-----+-----+-----+-----+-----+
|                                     compressed data...      :
+-----+-----+-----+-----+-----+-----+-----+-----+

```

Four FB stereo 20 ms CELT frames of the same compressed size:

```

      0                               1                               2                               3
      0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-----+-----+-----+-----+-----+-----+-----+-----+-----+
|1|1|1|      31      |      4      |0|0|      compressed data... :
+-----+-----+-----+-----+-----+-----+-----+-----+

```

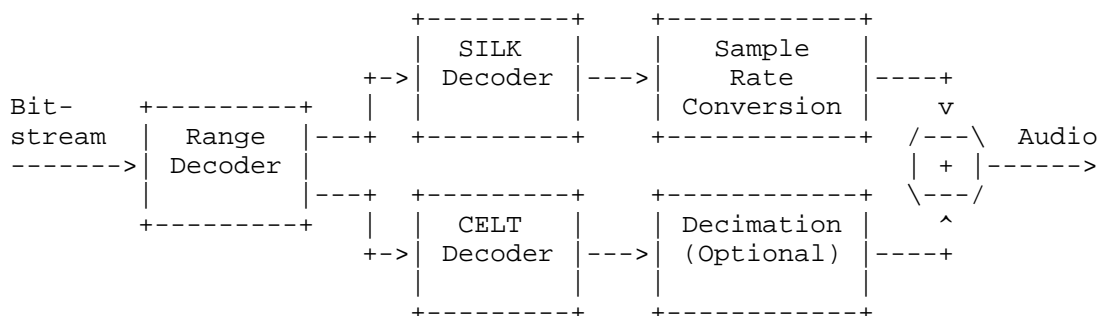
3.4. Extending Opus

A receiver MUST NOT process packets which violate any of the rules above as normal Opus packets. They are reserved for future applications, such as in-band headers (containing metadata, etc.). These constraints are summarized here for reference:

- o Packets are at least one byte.
- o No implicit frame length is larger than 1275 bytes.
- o Code 1 packets have an odd total length, N , so that $(N-1)/2$ is an integer.
- o Code 2 packets have enough bytes after the TOC for a valid frame length, and that length is no larger than the number of bytes remaining in the packet.
- o Code 3 packets contain at least one frame, but no more than 120 ms of audio total.
- o The length of a CBR code 3 packet, N , is at least two bytes, the size of the padding, P (including both the padding length bytes in the header and the trailing padding bytes) is no more than $N-2$, and the frame count, M , satisfies the constraint that $(N-2-P)$ is an integer multiple of M .
- o VBR code 3 packets are large enough to contain all the header bytes (TOC byte, frame count byte, any padding length bytes, and any frame length bytes), plus the length of the first $M-1$ frames, plus any trailing padding bytes.

4. Opus Decoder

The Opus decoder consists of two main blocks: the SILK decoder and the CELT decoder. At any given time, one or both of the SILK and CELT decoders may be active. The output of the Opus decode is the sum of the outputs from the SILK and CELT decoders with proper sample rate conversion and delay compensation on the SILK side, and optional decimation (when decoding to sample rates less than 48 kHz) on the CELT side, as illustrated in the block diagram below.



4.1. Range Decoder

Opus uses an entropy coder based on [range-coding], which is itself a rediscovery of the FIFO arithmetic code introduced by [coding-thesis]. It is very similar to arithmetic encoding, except that encoding is done with digits in any base instead of with bits, so it is faster when using larger bases (i.e., an octet). All of the calculations in the range coder must use bit-exact integer arithmetic.

Symbols may also be coded as "raw bits" packed directly into the bitstream, bypassing the range coder. These are packed backwards starting at the end of the frame, as illustrated in Figure 8. This reduces complexity and makes the stream more resilient to bit errors, as corruption in the raw bits will not desynchronize the decoding process, unlike corruption in the input to the range decoder. Raw bits are only used in the CELT layer.

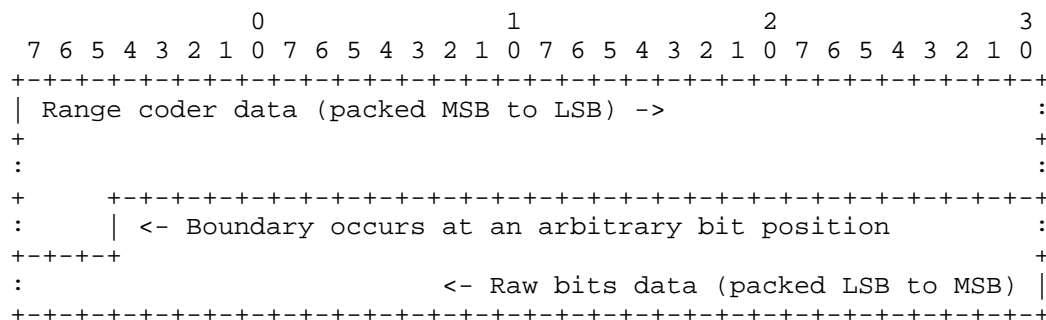


Figure 8: Illustrative example of packing range coder and raw bits data

Each symbol coded by the range coder is drawn from a finite alphabet and coded in a separate "context", which describes the size of the alphabet and the relative frequency of each symbol in that alphabet.

Suppose there is a context with n symbols, identified with an index that ranges from 0 to $n-1$. The parameters needed to encode or decode symbol k in this context are represented by a three-tuple $(fl[k], fh[k], ft)$, with $0 \leq fl[k] < fh[k] \leq ft \leq 65535$. The values of this tuple are derived from the probability model for the symbol, represented by traditional "frequency counts". Because Opus uses static contexts these are not updated as symbols are decoded. Let $f[i]$ be the frequency of symbol i . Then the three-tuple corresponding to symbol k is given by

$$fl[k] = \sum_{i=0}^{k-1} f[i], \quad fh[k] = fl[k] + f[k], \quad ft[k] = \sum_{i=0}^{n-1} f[i]$$

The range decoder extracts the symbols and integers encoded using the range encoder in Section 5.1. The range decoder maintains an internal state vector composed of the two-tuple (val, rng) , representing the difference between the high end of the current range and the actual coded value, minus one, and the size of the current range, respectively. Both val and rng are 32-bit unsigned integer values. The decoder initializes rng to 128 and initializes val to 127 minus the top 7 bits of the first input octet. It saves the remaining bit for use in the renormalization procedure described in Section 4.1.1.1, which the decoder invokes immediately after initialization to read additional bits and establish the invariant that $rng > 2^{*23}$.

4.1.1. Decoding Symbols

Decoding a symbol is a two-step process. The first step determines a 16-bit unsigned value *fs*, which lies within the range of some symbol in the current context. The second step updates the range decoder state with the three-tuple (*fl*[*k*], *fh*[*k*], *ft*) corresponding to that symbol.

The first step is implemented by `ec_decode()` (`entdec.c`), which computes

$$fs = ft - \min(val/(rng/ft)+1, ft) .$$

The divisions here are exact integer division.

The decoder then identifies the symbol in the current context corresponding to *fs*; i.e., the value of *k* whose three-tuple (*fl*[*k*], *fh*[*k*], *ft*) satisfies *fl*[*k*] ≤ *fs* < *fh*[*k*]. It uses this tuple to update *val* according to

$$val = val - (rng/ft)*(ft-fh[k]) .$$

If *fl*[*k*] is greater than zero, then the decoder updates *rng* using

$$rng = (rng/ft)*(fh[k]-fl[k]) .$$

Otherwise, it updates *rng* using

$$rng = rng - (rng/ft)*(ft-fh[k]) .$$

Using a special case for the first symbol (rather than the last symbol, as is commonly done in other arithmetic coders) ensures that all the truncation error from the finite precision arithmetic accumulates in symbol 0. This makes the cost of coding a 0 slightly smaller, on average, than its estimated probability indicates and makes the cost of coding any other symbol slightly larger. When contexts are designed so that 0 is the most probable symbol, which is often the case, this strategy minimizes the inefficiency introduced by the finite precision. It also makes some of the special-case decoding routines in Section 4.1.2 particularly simple.

After the updates, implemented by `ec_dec_update()` (`entdec.c`), the decoder normalizes the range using the procedure in the next section, and returns the index *k*.

4.1.1.1. Renormalization

To normalize the range, the decoder repeats the following process, implemented by `ec_dec_normalize()` (`entdec.c`), until `rng > 2**23`. If `rng` is already greater than 2^{23} , the entire process is skipped. First, it sets `rng` to $(rng \ll 8)$. Then it reads the next octet of the payload and combines it with the left-over bit buffered from the previous octet to form the 8-bit value `sym`. It takes the left-over bit as the high bit (bit 7) of `sym`, and the top 7 bits of the octet it just read as the other 7 bits of `sym`. The remaining bit in the octet just read is buffered for use in the next iteration. If no more input octets remain, it uses zero bits instead. Then, it sets

```
val = ((val<<8) + (255-sym)) & 0x7FFFFFFF .
```

It is normal and expected that the range decoder will read several bytes into the raw bits data (if any) at the end of the packet by the time the frame is completely decoded, as illustrated in Figure 9. This same data **MUST** also be returned as raw bits when requested. The encoder is expected to terminate the stream in such a way that the decoder will decode the intended values regardless of the data contained in the raw bits. Section 5.1.4 describes a procedure for doing this. If the range decoder consumes all of the bytes belonging to the current frame, it **MUST** continue to use zero when any further input bytes are required, even if there is additional data in the current packet from padding or other frames.

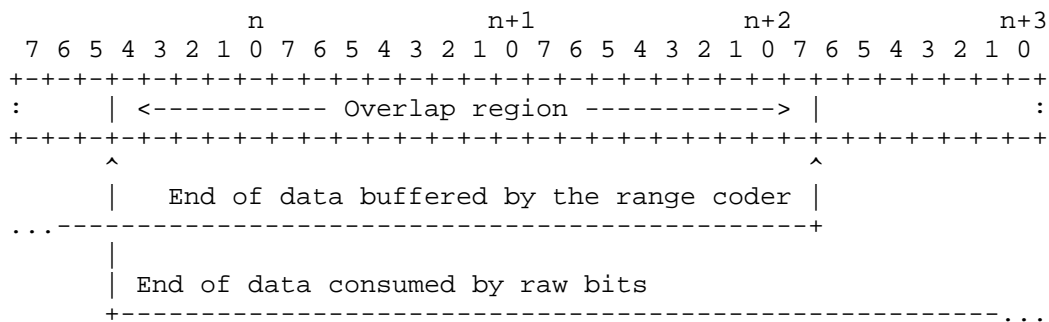


Figure 9: Illustrative example of raw bits overlapping range coder data

4.1.2. Alternate Decoding Methods

The reference implementation uses three additional decoding methods that are exactly equivalent to the above, but make assumptions and simplifications that allow for a more efficient implementation.

4.1.2.1. `ec_decode_bin()`

The first is `ec_decode_bin()` (`entdec.c`), defined using the parameter `ftb` instead of `ft`. It is mathematically equivalent to calling `ec_decode()` with `ft = (1<<ftb)`, but avoids one of the divisions.

4.1.2.2. `ec_dec_bit_logp()`

The next is `ec_dec_bit_logp()` (`entdec.c`), which decodes a single binary symbol, replacing both the `ec_decode()` and `ec_dec_update()` steps. The context is described by a single parameter, `logp`, which is the absolute value of the base-2 logarithm of the probability of a "1". It is mathematically equivalent to calling `ec_decode()` with `ft = (1<<logp)`, followed by `ec_dec_update()` with the 3-tuple (`fl[k] = 0`, `fh[k] = (1<<logp)-1`, `ft = (1<<logp)`) if the returned value of `fs` is less than `(1<<logp)-1` (a "0" was decoded), and with (`fl[k] = (1<<logp)-1`, `fh[k] = ft = (1<<logp)`) otherwise (a "1" was decoded). The implementation requires no multiplications or divisions.

4.1.2.3. `ec_dec_icdf()`

The last is `ec_dec_icdf()` (`entdec.c`), which decodes a single symbol with a table-based context of up to 8 bits, also replacing both the `ec_decode()` and `ec_dec_update()` steps, as well as the search for the decoded symbol in between. The context is described by two parameters, an `icdf` ("inverse" cumulative distribution function) table and `ftb`. As with `ec_decode_bin()`, `(1<<ftb)` is equivalent to `ft`. `icdf[k]`, on the other hand, stores `(1<<ftb)-fh[k]`, which is equal to `(1<<ftb)-fl[k+1]`. `fl[0]` is assumed to be 0, and the table is terminated by a value of 0 (where `fh[k] == ft`).

The function is mathematically equivalent to calling `ec_decode()` with `ft = (1<<ftb)`, using the returned value `fs` to search the table for the first entry where `fs < (1<<ftb)-icdf[k]`, and calling `ec_dec_update()` with `fl[k] = (1<<ftb)-icdf[k-1]` (or 0 if `k == 0`), `fh[k] = (1<<ftb)-icdf[k]`, and `ft = (1<<ftb)`. Combining the search with the update allows the division to be replaced by a series of multiplications (which are usually much cheaper), and using an inverse CDF allows the use of an `ftb` as large as 8 in an 8-bit table without any special cases. This is the primary interface with the range decoder in the SILK layer, though it is used in a few places in the CELT layer as well.

Although `icdf[k]` is more convenient for the code, the frequency counts, `f[k]`, are a more natural representation of the probability distribution function (PDF) for a given symbol. Therefore this draft lists the latter, not the former, when describing the context in

which a symbol is coded as a list, e.g., {4, 4, 4, 4}/16 for a uniform context with four possible values and $ft=16$. The value of ft after the slash is always the sum of the entries in the PDF, but is included for convenience. Contexts with identical probabilities, $f[k]/ft$, but different values of ft (or equivalently, ftb) are not the same, and cannot, in general, be used in place of one another. An icdf table is also not capable of representing a PDF where the first symbol has 0 probability. In such contexts, `ec_dec_icdf()` can decode the symbol by using a table that drops the entries for any initial zero-probability values and adding the constant offset of the first value with a non-zero probability to its return value.

4.1.3. Decoding Raw Bits

The raw bits used by the CELT layer are packed at the end of the packet, with the least significant bit of the first value packed in the least significant bit of the last byte, filling up to the most significant bit in the last byte, continuing on to the least significant bit of the penultimate byte, and so on. The reference implementation reads them using `ec_dec_bits()` (`entdec.c`). Because the range decoder must read several bytes ahead in the stream, as described in Section 4.1.1.1, the input consumed by the raw bits MAY overlap with the input consumed by the range coder, and a decoder MUST allow this. The format should render it impossible to attempt to read more raw bits than there are actual bits in the frame, though a decoder MAY wish to check for this and report an error.

4.1.4. Decoding Uniformly Distributed Integers

The `ec_dec_uint()` (`entdec.c`) function decodes one of ft equiprobable values in the range 0 to $ft-1$, inclusive, each with a frequency of 1, where ft may be as large as $2^{32}-1$. Because `ec_decode()` is limited to a total frequency of $2^{16}-1$, this is split up into a range coded symbol representing up to 8 of the high bits of the value, and, if necessary, raw bits representing the remaining bits. The limit of 8 bits in the range coded symbol is a trade-off between implementation complexity, modeling error (since the symbols no longer truly have equal coding cost), and rounding error introduced by the range coder itself (which gets larger as more bits are included). Using raw bits reduces the maximum number of divisions required in the worst case, but means that it may be possible to decode a value outside the range 0 to $ft-1$, inclusive.

`ec_dec_uint()` takes a single, positive parameter, ft , which is not necessarily a power of two, and returns an integer, t , whose value lies between 0 and $ft-1$, inclusive. Let $ftb = \text{ilog}(ft-1)$, i.e., the number of bits required to store $ft-1$ in two's complement notation. If ftb is 8 or less, then t is decoded with $t = \text{ec_decode}(ft)$, and

the range coder state is updated using the three-tuple $(t, t+1, ft)$.

If ftb is greater than 8, then the top 8 bits of t are decoded using $t = ec_decode((ft-1 \gg ftb-8)+1)$, the decoder state is updated using the three-tuple $(t, t+1, (ft-1 \gg ftb-8)+1)$, and the remaining bits are decoded as raw bits, setting $t = t \ll ftb-8 | ec_dec_bits(ftb-8)$. If, at this point, $t \geq ft$, then the current frame is corrupt. In that case, the decoder should assume there has been an error in the coding, decoding, or transmission and SHOULD take measures to conceal the error and/or report to the application that a problem has occurred.

4.1.5. Current Bit Usage

The bit allocation routines in the CELT decoder need a conservative upper bound on the number of bits that have been used from the current frame thus far, including both range coder bits and raw bits. This drives allocation decisions that must match those made in the encoder. The upper bound is computed in the reference implementation to whole-bit precision by the function `ec_tell()` (`entcode.h`) and to fractional 1/8th bit precision by the function `ec_tell_frac()` (`entcode.c`). Like all operations in the range coder, it must be implemented in a bit-exact manner, and must produce exactly the same value returned by the same functions in the encoder after encoding the same symbols.

`ec_tell()` is guaranteed to return `ceil(ec_tell_frac()/8.0)`. In various places the codec will check to ensure there is enough room to contain a symbol before attempting to decode it. In practice, although the number of bits used so far is an upper bound, decoding a symbol whose probability model suggests it has a worst-case cost of p 1/8th bits may actually advance the return value of `ec_tell_frac()` by $p-1$, p , or $p+1$ 1/8th bits, due to approximation error in that upper bound, truncation error in the range coder, and for large values of ft , modeling error in `ec_dec_uint()`.

However, this error is bounded, and periodic calls to `ec_tell()` or `ec_tell_frac()` at precisely defined points in the decoding process prevent it from accumulating. For a range coder symbol that requires a whole number of bits (i.e., for which $ft/(fh[k]-fl[k])$ is a power of two), where there are at least p 1/8th bits available, decoding the symbol will never cause `ec_tell()` or `ec_tell_frac()` to exceed the size of the frame ("bust the budget"). In this case the return value of `ec_tell_frac()` will only advance by more than p 1/8th bits if there was an additional, fractional number of bits remaining, and it will never advance beyond the next whole-bit boundary, which is safe, since frames always contain a whole number of bits. However, when p is not a whole number of bits, an extra 1/8th bit is required to

ensure that decoding the symbol will not bust the budget.

The reference implementation keeps track of the total number of whole bits that have been processed by the decoder so far in the variable `nbits_total`, including the (possibly fractional) number of bits that are currently buffered, but not consumed, inside the range coder. `nbits_total` is initialized to 33 just after the initial range renormalization process completes (or equivalently, it can be initialized to 9 before the first renormalization). The extra two bits over the actual amount buffered by the range coder guarantees that it is an upper bound and that there is enough room for the encoder to terminate the stream. Each iteration through the range coder's renormalization loop increases `nbits_total` by 8. Reading raw bits increases `nbits_total` by the number of raw bits read.

4.1.5.1. `ec_tell()`

The whole number of bits buffered in `rng` may be estimated via `l = ilog(rng)`. `ec_tell()` then becomes a simple matter of removing these bits from the total. It returns `(nbits_total - l)`.

In a newly initialized decoder, before any symbols have been read, this reports that 1 bit has been used. This is the bit reserved for termination of the encoder.

4.1.5.2. `ec_tell_frac()`

`ec_tell_frac()` estimates the number of bits buffered in `rng` to fractional precision. Since `rng` must be greater than 2^{23} after renormalization, `l` must be at least 24. Let

$$r_{Q15} = rng \gg (l-16) ,$$

so that $32768 \leq r_{Q15} < 65536$, an unsigned Q15 value representing the fractional part of `rng`. Then the following procedure can be used to add one bit of precision to `l`. First, update

$$r_{Q15} = (r_{Q15} * r_{Q15}) \gg 15 .$$

Then add the 16th bit of `r_Q15` to `l` via

$$l = 2 * l + (r_{Q15} \gg 16) .$$

Finally, if this bit was a 1, reduce `r_Q15` by a factor of two via

$$r_{Q15} = r_{Q15} \gg 1 ,$$

so that it once again lies in the range $32768 \leq r_{Q15} < 65536$.

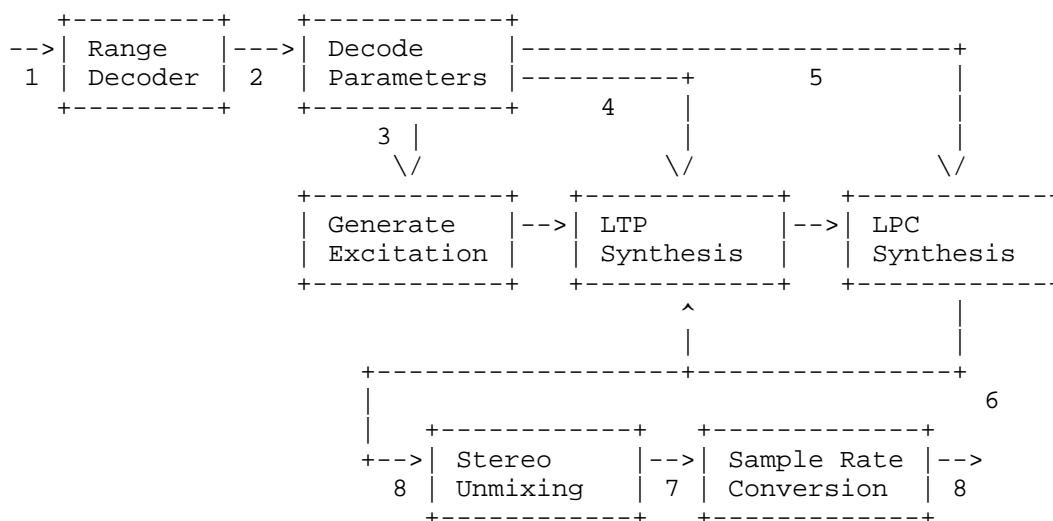
This procedure is repeated three times to extend 1 to 1/8th bit precision. `ec_tell_frac()` then returns $(\text{nbits_total} * 8 - 1)$.

4.2. SILK Decoder

The decoder's LP layer uses a modified version of the SILK codec (herein simply called "SILK"), which runs a decoded excitation signal through adaptive long-term and short-term prediction synthesis filters. It runs at NB, MB, and WB sample rates internally. When used in a SWB or FB Hybrid frame, the LP layer itself still only runs in WB.

4.2.1. SILK Decoder Modules

An overview of the decoder is given in Figure 10.



- 1: Range encoded bitstream
- 2: Coded parameters
- 3: Pulses, LSBs, and signs
- 4: Pitch lags, LTP coefficients
- 5: LPC coefficients and gains
- 6: Decoded signal (mono or mid-side stereo)
- 7: Unmixed signal (mono or left-right stereo)
- 8: Resampled signal

Decoder block diagram.

Figure 10

The decoder feeds the bitstream (1) to the range decoder from Section 4.1, and then decodes the parameters in it (2) using the procedures detailed in Sections 4.2.3 through 4.2.7.8.5. These parameters (3, 4, 5) are used to generate an excitation signal (see Section 4.2.7.8.6), which is fed to an optional long-term prediction (LTP) filter (voiced frames only, see Section 4.2.7.9.1) and then a short-term prediction filter (see Section 4.2.7.9.2), producing the decoded signal (6). For stereo streams, the mid-side representation is converted to separate left and right channels (7). The result is finally resampled to the desired output sample rate (e.g., 48 kHz) so that the resampled signal (8) can be mixed with the CELT layer.

4.2.2. LP Layer Organization

Internally, the LP layer of a single Opus frame is composed of either a single 10 ms regular SILK frame or between one and three 20 ms regular SILK frames. A stereo Opus frame may double the number of regular SILK frames (up to a total of six), since it includes separate frames for a mid channel and, optionally, a side channel. Optional Low Bit-Rate Redundancy (LBRR) frames, which are reduced-bitrate encodings of previous SILK frames, may be included to aid in recovery from packet loss. If present, these appear before the regular SILK frames. They are in most respects identical to regular, active SILK frames, except that they are usually encoded with a lower bitrate. This draft uses "SILK frame" to refer to either one and "regular SILK frame" if it needs to draw a distinction between the two.

Logically, each SILK frame is in turn composed of either two or four 5 ms subframes. Various parameters, such as the quantization gain of the excitation and the pitch lag and filter coefficients can vary on a subframe-by-subframe basis. Physically, the parameters for each subframe are interleaved in the bitstream, as described in the relevant sections for each parameter.

All of these frames and subframes are decoded from the same range coder, with no padding between them. Thus packing multiple SILK frames in a single Opus frame saves, on average, half a byte per SILK frame. It also allows some parameters to be predicted from prior SILK frames in the same Opus frame, since this does not degrade packet loss robustness (beyond any penalty for merely using fewer, larger packets to store multiple frames).

Stereo support in SILK uses a variant of mid-side coding, allowing a mono decoder to simply decode the mid channel. However, the data for the two channels is interleaved, so a mono decoder must still unpack the data for the side channel. It would be required to do so anyway for Hybrid Opus frames, or to support decoding individual 20 ms frames.

Table 3 summarizes the overall grouping of the contents of the LP layer. Figures 11 and 12 illustrate the ordering of the various SILK frames for a 60 ms Opus frame, for both mono and stereo, respectively.

Symbol(s)	PDF(s)	Condition
VAD flags	{1, 1}/2	
LBRR flag	{1, 1}/2	
Per-frame LBRR flags	Table 4	Section 4.2.4
LBRR Frame(s)	Section 4.2.7	Section 4.2.4
Regular SILK Frame(s)	Section 4.2.7	

Organization of the SILK layer of an Opus frame.

Table 3

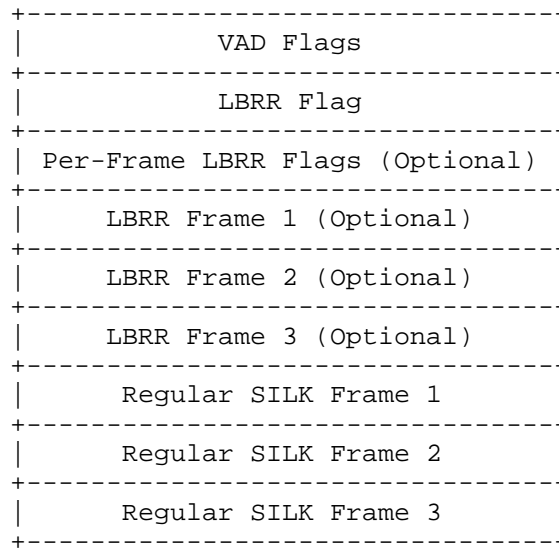


Figure 11: A 60 ms Mono Frame

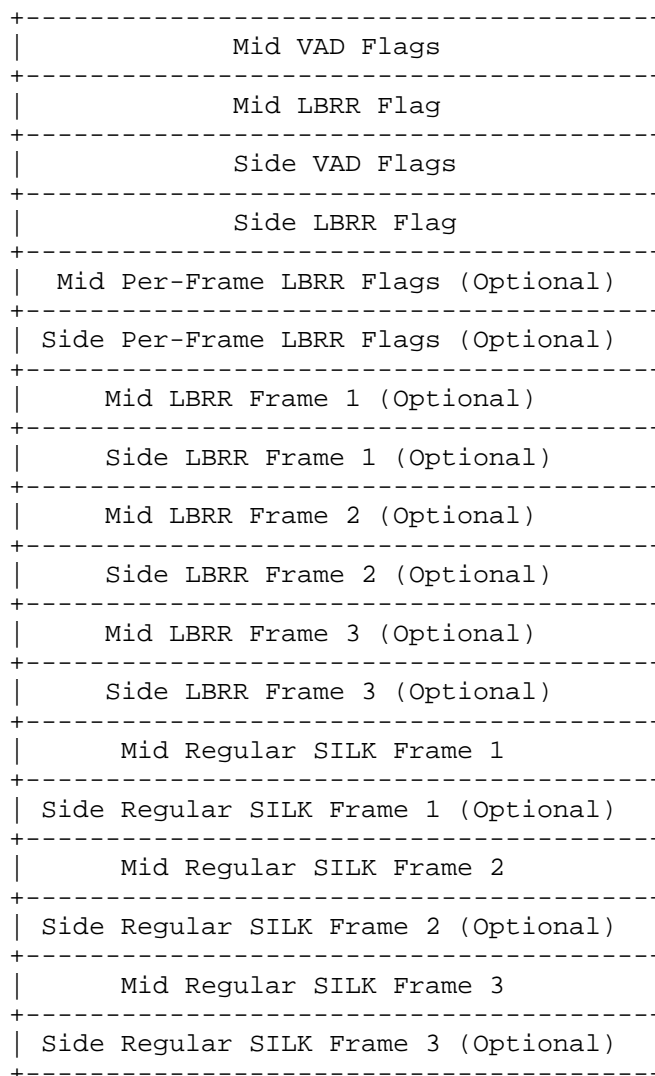


Figure 12: A 60 ms Stereo Frame

4.2.3. Header Bits

The LP layer begins with two to eight header bits, decoded in `silk_Decode()` (`dec_API.c`). These consist of one Voice Activity Detection (VAD) bit per frame (up to 3), followed by a single flag indicating the presence of LBRR frames. For a stereo packet, these first flags correspond to the mid channel, and a second set of flags is included for the side channel.

Because these are the first symbols decoded by the range coder and because they are coded as binary values with uniform probability, they can be extracted directly from the most significant bits of the first byte of compressed data. Thus, a receiver can determine if an Opus frame contains any active SILK frames without the overhead of using the range decoder.

4.2.4. Per-Frame LBRR Flags

For Opus frames longer than 20 ms, a set of LBRR flags is decoded for each channel that has its LBRR flag set. Each set contains one flag per 20 ms SILK frame. 40 ms Opus frames use the 2-frame LBRR flag PDF from Table 4, and 60 ms Opus frames use the 3-frame LBRR flag PDF. For each channel, the resulting 2- or 3-bit integer contains the corresponding LBRR flag for each frame, packed in order from the LSB to the MSB.

Frame Size	PDF
40 ms	{0, 53, 53, 150}/256
60 ms	{0, 41, 20, 29, 41, 15, 28, 82}/256

Table 4: LBRR Flag PDFs

A 10 or 20 ms Opus frame does not contain any per-frame LBRR flags, as there may be at most one LBRR frame per channel. The global LBRR flag in the header bits (see Section 4.2.3) is already sufficient to indicate the presence of that single LBRR frame.

4.2.5. LBRR Frames

The LBRR frames, if present, contain an encoded representation of the signal immediately prior to the current Opus frame as if it were encoded with the current mode, frame size, audio bandwidth, and channel count, even if those differ from the prior Opus frame. When one of these parameters changes from one Opus frame to the next, this implies that the LBRR frames of the current Opus frame may not be simple drop-in replacements for the contents of the previous Opus frame.

For example, when switching from 20 ms to 60 ms, the 60 ms Opus frame may contain LBRR frames covering up to three prior 20 ms Opus frames, even if those frames already contained LBRR frames covering some of the same time periods. When switching from 20 ms to 10 ms, the 10 ms Opus frame can contain an LBRR frame covering at most half the prior

20 ms Opus frame, potentially leaving a hole that needs to be concealed from even a single packet loss. When switching from mono to stereo, the LBRR frames in the first stereo Opus frame MAY contain a non-trivial side channel.

In order to properly produce LBRR frames under all conditions, an encoder might need to buffer up to 60 ms of audio and re-encode it during these transitions. However, the reference implementation opts to disable LBRR frames at the transition point for simplicity.

The LBRR frames immediately follow the LBRR flags, prior to any regular SILK frames. Section 4.2.7 describes their exact contents. LBRR frames do not include their own separate VAD flags. LBRR frames are only meant to be transmitted for active speech, thus all LBRR frames are treated as active.

In a stereo Opus frame longer than 20 ms, although the per-frame LBRR flags for the mid channel are coded as a unit before the per-frame LBRR flags for the side channel, the LBRR frames themselves are interleaved. The decoder parses an LBRR frame for the mid channel of a given 20 ms interval (if present) and then immediately parses the corresponding LBRR frame for the side channel (if present), before proceeding to the next 20 ms interval.

4.2.6. Regular SILK Frames

The regular SILK frame(s) follow the LBRR frames (if any). Section 4.2.7 describes their contents, as well. Unlike the LBRR frames, a regular SILK frame is coded for each time interval in an Opus frame, even if the corresponding VAD flags are unset. For stereo Opus frames longer than 20 ms, the regular mid and side SILK frames for each 20 ms interval are interleaved, just as with the LBRR frames. The side frame may be skipped by coding an appropriate flag, as detailed in Section 4.2.7.2.

4.2.7. SILK Frame Contents

Each SILK frame includes a set of side information that encodes

- o The frame type and quantization type (Section 4.2.7.3),
- o Quantization gains (Section 4.2.7.4),
- o Short-term prediction filter coefficients (Section 4.2.7.5),
- o An LSF interpolation weight (Section 4.2.7.5.5),

- o Long-term prediction filter lags and gains (Section 4.2.7.6), and
- o A linear congruential generator (LCG) seed (Section 4.2.7.7).

The quantized excitation signal (see Section 4.2.7.8) follows these at the end of the frame. Table 5 details the overall organization of a SILK frame.

Symbol(s)	PDF(s)	Condition
Stereo Prediction Weights	Table 6	Section 4.2.7.1
Mid-only Flag	Table 8	Section 4.2.7.2
Frame Type	Section 4.2.7.3	
Subframe Gains	Section 4.2.7.4	
Normalized LSF Stage 1 Index	Table 14	
Normalized LSF Stage 2 Residual	Section 4.2.7.5.2	
Normalized LSF Interpolation Weight	Table 26	Section 4.2.7.5.5
Primary Pitch Lag	Section 4.2.7.6.1	Voiced frame
Subframe Pitch Contour	Table 32	Voiced frame
Periodicity Index	Table 37	Voiced frame
LTP Filter	Table 38	Voiced frame
LTP Scaling	Table 42	Section 4.2.7.6.3
LCG Seed	Table 43	
Excitation Rate Level	Table 45	
Excitation Pulse Counts	Table 46	
Excitation Pulse Locations	Section 4.2.7.8.3	Non-zero pulse count
Excitation LSBs	Table 51	Section 4.2.7.8.2
Excitation Signs	Table 52	Section 4.2.7.8.5

Order of the symbols in an individual SILK frame.

Table 5

4.2.7.1. Stereo Prediction Weights

A SILK frame corresponding to the mid channel of a stereo Opus frame begins with a pair of side channel prediction weights, designed such that zeros indicate normal mid-side coupling. Since these weights can change on every frame, the first portion of each frame linearly interpolates between the previous weights and the current ones, using zeros for the previous weights if none are available. These prediction weights are never included in a mono Opus frame, and the previous weights are reset to zeros on any transition from mono to stereo. They are also not included in an LBRR frame for the side channel, even if the LBRR flags indicate the corresponding mid channel was not coded. In that case, the previous weights are used, again substituting in zeros if no previous weights are available since the last decoder reset (see Section 4.5).

To summarize, these weights are coded if and only if

- o This is a stereo Opus frame (Section 3.1), and
- o The current SILK frame corresponds to the mid channel.

The prediction weights are coded in three separate pieces, which are decoded by `silk_stereo_decode_pred()` (`decode_stereo_pred.c`). The first piece jointly codes the high-order part of a table index for both weights. The second piece codes the low-order part of each table index. The third piece codes an offset used to linearly interpolate between table indices. The details are as follows.

Let n be an index decoded with the 25-element stage-1 PDF in Table 6. Then let i_0 and i_1 be indices decoded with the stage-2 and stage-3 PDFs in Table 6, respectively, and let i_2 and i_3 be two more indices decoded with the stage-2 and stage-3 PDFs, all in that order.

Stage	PDF
Stage 1	{7, 2, 1, 1, 1, 10, 24, 8, 1, 1, 3, 23, 92, 23, 3, 1, 1, 8, 24, 10, 1, 1, 1, 2, 7}/256
Stage 2	{85, 86, 85}/256
Stage 3	{51, 51, 52, 51, 51}/256

Table 6: Stereo Weight PDFs

Then use n , i_0 , and i_2 to form two table indices, wi_0 and wi_1 , according to

$$\begin{aligned} wi_0 &= i_0 + 3*(n/5) \\ wi_1 &= i_2 + 3*(n\%5) \end{aligned}$$

where the division is exact integer division. The range of these indices is 0 to 14, inclusive. Let $w[i]$ be the i 'th weight from Table 7. Then the two prediction weights, $w0_Q13$ and $w1_Q13$, are

$$\begin{aligned} w1_Q13 &= w_Q13[wi_1] \\ &\quad + ((w_Q13[wi_1+1] - w_Q13[wi_1])*6554) >> 16)*(2*i_3 + 1) \end{aligned}$$
$$\begin{aligned} w0_Q13 &= w_Q13[wi_0] \\ &\quad + ((w_Q13[wi_0+1] - w_Q13[wi_0])*6554) >> 16)*(2*i_1 + 1) \\ &\quad - w1_Q13 \end{aligned}$$

N.b., $w1_Q13$ is computed first here, because $w0_Q13$ depends on it.

Index	Weight (Q13)
0	-13732
1	-10050
2	-8266
3	-7526
4	-6500
5	-5000
6	-2950
7	-820
8	820
9	2950
10	5000
11	6500
12	7526
13	8266
14	10050
15	13732

Table 7: Stereo Weight Table

4.2.7.2. Mid-only Flag

A flag appears after the stereo prediction weights that indicates if only the mid channel is coded for this time interval. It appears only when

- o This is a stereo Opus frame (see Section 3.1),
- o The current SILK frame corresponds to the mid channel, and

- o Either

- * This is a regular SILK frame where the VAD flags (see Section 4.2.3) indicate that the corresponding side channel is not active.
- * This is an LBRR frame where the LBRR flags (see Section 4.2.3 and Section 4.2.4) indicate that the corresponding side channel is not coded.

It is omitted when there are no stereo weights, for all of the same reasons. It is also omitted for a regular SILK frame when the VAD flag of the corresponding side channel frame is set (indicating it is active). The side channel must be coded in this case, making the mid-only flag redundant. It is also omitted for an LBRR frame when the corresponding LBRR flags indicate the side channel is coded.

When the flag is present, the decoder reads a single value using the PDF in Table 8, as implemented in `silk_stereo_decode_mid_only()` (`decode_stereo_pred.c`). If the flag is set, then there is no corresponding SILK frame for the side channel, the entire decoding process for the side channel is skipped, and zeros are fed to the stereo unmixing process (see Section 4.2.8) instead. As stated above, LBRR frames still include this flag when the LBRR flag indicates that the side channel is not coded. In that case, if this flag is zero (indicating that there should be a side channel), then Packet Loss Concealment (PLC, see Section 4.4) SHOULD be invoked to recover a side channel signal.

+-----+
PDF
+-----+
{192, 64}/256
+-----+

Table 8: Mid-only Flag PDF

4.2.7.3. Frame Type

Each SILK frame contains a single "frame type" symbol that jointly codes the signal type and quantization offset type of the corresponding frame. If the current frame is a regular SILK frame whose VAD bit was not set (an "inactive" frame), then the frame type symbol takes on a value of either 0 or 1 and is decoded using the first PDF in Table 9. If the frame is an LBRR frame or a regular SILK frame whose VAD flag was set (an "active" frame), then the value of the symbol may range from 2 to 5, inclusive, and is decoded using the second PDF in Table 9. Table 10 translates between the value of

the frame type symbol and the corresponding signal type and quantization offset type.

VAD Flag	PDF
Inactive	$\{26, 230, 0, 0, 0, 0\}/256$
Active	$\{0, 0, 24, 74, 148, 10\}/256$

Table 9: Frame Type PDFs

Frame Type	Signal Type	Quantization Offset Type
0	Inactive	Low
1	Inactive	High
2	Unvoiced	Low
3	Unvoiced	High
4	Voiced	Low
5	Voiced	High

Table 10: Signal Type and Quantization Offset Type from Frame Type

4.2.7.4. Subframe Gains

A separate quantization gain is coded for each 5 ms subframe. These gains control the step size between quantization levels of the excitation signal and, therefore, the quality of the reconstruction. They are independent of the pitch gains coded for voiced frames. The quantization gains are themselves uniformly quantized to 6 bits on a log scale, giving them a resolution of approximately 1.369 dB and a range of approximately 1.94 dB to 88.21 dB.

The subframe gains are either coded independently, or relative to the gain from the most recent coded subframe in the same channel. Independent coding is used if and only if

- o This is the first subframe in the current SILK frame, and

- o Either
 - * This is the first SILK frame of its type (LBRR or regular) for this channel in the current Opus frame, or
 - * The previous SILK frame of the same type (LBRR or regular) for this channel in the same Opus frame was not coded.

In an independently coded subframe gain, the 3 most significant bits of the quantization gain are decoded using a PDF selected from Table 11 based on the decoded signal type (see Section 4.2.7.3).

Signal Type	PDF
Inactive	$\{32, 112, 68, 29, 12, 1, 1, 1\}/256$
Unvoiced	$\{2, 17, 45, 60, 62, 47, 19, 4\}/256$
Voiced	$\{1, 3, 26, 71, 94, 50, 9, 2\}/256$

Table 11: PDFs for Independent Quantization Gain MSB Coding

The 3 least significant bits are decoded using a uniform PDF:

PDF
$\{32, 32, 32, 32, 32, 32, 32, 32\}/256$

Table 12: PDF for Independent Quantization Gain LSB Coding

For subframes which do not have an independent gain (including the first subframe of frames not listed as using independent coding above), the quantization gain is coded relative to the gain from the previous subframe (in the same channel). The PDF in Table 13 yields a delta gain index between 0 and 40, inclusive.

[illegible]

Table 13: PDF for Delta Quantization Gain Coding

The following formula translates this index into a quantization gain for the current subframe using the gain from the previous subframe:

$$\text{log_gain} = \min(\max(2 * \text{gain_index} - 16, \text{previous_log_gain} + \text{gain_index} - 4), 63) .$$

The value here is not clamped at 0, and may reach values as low as -16 over the course of consecutive subframes within a single Opus frame.

`silk_gains_dequant()` (`gain_quant.c`) dequantizes `log_gain` for the *k*'th subframe and converts it into a linear Q16 scale factor via

$$\text{gain_Q16}[k] = \text{silk_log2lin}((0 \times 1 \text{D1C71} * \text{log_gain} \gg 16) + 2090)$$

The function `silk_log2lin()` (`log2lin.c`) computes an approximation of $2^{*(\text{inLog_Q7}/128.0)}$, where `inLog_Q7` is its Q7 input. Let *i* = `inLog_Q7 >> 7` be the integer part of `inLog_Q7` and *f* = `inLog_Q7 & 127` be the fractional part. If *i* < 16, then

$$(1 \ll i) + (((-174 * f * (128 - f) \gg 16) + f) \gg 7) * (1 \ll i)$$

yields the approximate exponential. Otherwise, `silk_log2lin` uses

$$(1 \ll i) + ((-174 * f * (128 - f) \gg 16) + f) * ((1 \ll i) \gg 7) .$$

The final Q16 gain values lies between 4096 and 1686110208, inclusive (representing scale factors of 0.0625 to 25728, respectively).

4.2.7.5. Normalized Line Spectral Frequency (LSF) and Linear Predictive Coding (LPC) Coefficients

A set of normalized Line Spectral Frequency (LSF) coefficients follow the quantization gains in the bitstream, and represent the Linear Predictive Coding (LPC) coefficients for the current SILK frame. Once decoded, the normalized LSFs form an increasing list of Q15 values between 0 and 1. These represent the interleaved zeros on the unit circle between 0 and π (hence "normalized") in the standard decomposition of the LPC filter into a symmetric part and an anti-symmetric part (P and Q in Section 4.2.7.5.6). Because of non-linear effects in the decoding process, an implementation SHOULD match the fixed-point arithmetic described in this section exactly. An encoder SHOULD also use the same process.

The normalized LSFs are coded using a two-stage vector quantizer (VQ) (Section 4.2.7.5.1 and Section 4.2.7.5.2). NB and MB frames use an

order-10 predictor, while WB frames use an order-16 predictor, and thus have different sets of tables. After reconstructing the normalized LSFs (Section 4.2.7.5.3), the decoder runs them through a stabilization process (Section 4.2.7.5.4), interpolates them between frames (Section 4.2.7.5.5), converts them back into LPC coefficients (Section 4.2.7.5.6), and then runs them through further processes to limit the range of the coefficients (Section 4.2.7.5.7) and the gain of the filter (Section 4.2.7.5.8). All of this is necessary to ensure the reconstruction process is stable.

4.2.7.5.1. Stage 1 Normalized LSF Decoding

The first VQ stage uses a 32-element codebook, coded with one of the PDFs in Table 14, depending on the audio bandwidth and the signal type of the current SILK frame. This yields a single index, *l1*, for the entire frame. This indexes an element in a coarse codebook, selects the PDFs for the second stage of the VQ, and selects the prediction weights used to remove intra-frame redundancy from the second stage. The actual codebook elements are listed in Table 23 and Table 24, but they are not needed until the last stages of reconstructing the LSF coefficients.

Audio Bandwidth	Signal Type	PDF
NB or MB	Inactive or unvoiced	{44, 34, 30, 19, 21, 12, 11, 3, 3, 2, 16, 2, 2, 1, 5, 2, 1, 3, 3, 1, 1, 2, 2, 2, 3, 1, 9, 9, 2, 7, 2, 1}/256
NB or MB	Voiced	{1, 10, 1, 8, 3, 8, 8, 14, 13, 14, 1, 14, 12, 13, 11, 11, 12, 11, 10, 10, 11, 8, 9, 8, 7, 8, 1, 1, 6, 1, 6, 5}/256
WB	Inactive or unvoiced	{31, 21, 3, 17, 1, 8, 17, 4, 1, 18, 16, 4, 2, 3, 1, 10, 1, 3, 16, 11, 16, 2, 2, 3, 2, 11, 1, 4, 9, 8, 7, 3}/256
WB	Voiced	{1, 4, 16, 5, 18, 11, 5, 14, 15, 1, 3, 12, 13, 14, 14, 6, 14, 12, 2, 6, 1, 12, 12, 11, 10, 3, 10, 5, 1, 1, 1, 3}/256

Table 14: PDFs for Normalized LSF Index Stage-1 Decoding

4.2.7.5.2. Stage 2 Normalized LSF Decoding

A total of 16 PDFs are available for the LSF residual in the second stage: the 8 (a...h) for NB and MB frames given in Table 15, and the 8 (i...p) for WB frames given in Table 16. Which PDF is used for which coefficient is driven by the index, I1, decoded in the first stage. Table 17 lists the letter of the corresponding PDF for each normalized LSF coefficient for NB and MB, and Table 18 lists the same information for WB.

Codebook	PDF
a	{1, 1, 1, 15, 224, 11, 1, 1, 1}/256
b	{1, 1, 2, 34, 183, 32, 1, 1, 1}/256
c	{1, 1, 4, 42, 149, 55, 2, 1, 1}/256
d	{1, 1, 8, 52, 123, 61, 8, 1, 1}/256
e	{1, 3, 16, 53, 101, 74, 6, 1, 1}/256
f	{1, 3, 17, 55, 90, 73, 15, 1, 1}/256
g	{1, 7, 24, 53, 74, 67, 26, 3, 1}/256
h	{1, 1, 18, 63, 78, 58, 30, 6, 1}/256

Table 15: PDFs for NB/MB Normalized LSF Index Stage-2 Decoding

Codebook	PDF
i	{1, 1, 1, 9, 232, 9, 1, 1, 1}/256
j	{1, 1, 2, 28, 186, 35, 1, 1, 1}/256
k	{1, 1, 3, 42, 152, 53, 2, 1, 1}/256
l	{1, 1, 10, 49, 126, 65, 2, 1, 1}/256
m	{1, 4, 19, 48, 100, 77, 5, 1, 1}/256
n	{1, 1, 14, 54, 100, 72, 12, 1, 1}/256
o	{1, 1, 15, 61, 87, 61, 25, 4, 1}/256
p	{1, 7, 21, 50, 77, 81, 17, 1, 1}/256

Table 16: PDFs for WB Normalized LSF Index Stage-2 Decoding

l1	Coefficient
	0 1 2 3 4 5 6 7 8 9
0	a a a a a a a a a a
1	b d b c c b c b b b
2	c b b b b b b b b b
3	b c c c c b c b b b
4	c d d d d c c c c c
5	a f d d c c c c b b
g	a c c c c c c c c b
7	c d g e e e f e f f
8	c e f f e f e g e e
9	c e e h e f e f f e
10	e d d d c d c c c c

11	b f f g e f e f f f
12	c h e g f f f f f f
13	c h f f f f f g f e
14	d d f e e f e f e e
15	c d d f f e e e e e
16	c e e g e f e f f f
17	c f e g f f f e f e
18	c h e f e f e f f f
19	c f e g h g f g f e
20	d g h e g f f g e f
21	c h g e e e f e f f
22	e f f e g g f g f e
23	c f f g f g e g e e
24	e f f f d h e f f e
25	c d e f f g e f f e
26	c d c d d e c d d d
27	b b c c c c c d c c
28	e f f g g g f g e f
29	d f f e e e e d d c
30	c f d h f f e e f e
31	e e f e f g f g f e

Table 17: Codebook Selection for NB/MB Normalized LSF Index Stage 2 Decoding

I1	Coefficient															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	i	i	i	i	i	i	i	i	i	i	i	i	i	i	i	i
1	k	l	l	l	l	l	k	k	k	k	k	j	j	j	i	l
2	k	n	n	l	p	m	m	n	k	n	m	n	n	m	l	l
3	i	k	j	k	k	j	j	j	j	j	i	i	i	i	i	j
4	i	o	n	m	o	m	p	n	m	m	m	n	n	m	m	l
5	i	l	n	n	m	l	l	n	l	l	l	l	l	l	k	m
6	i	i	i	i	i	i	i	i	i	i	i	i	i	i	i	i
7	i	k	o	l	p	k	n	l	m	n	n	m	l	l	k	l
8	i	o	k	o	o	m	n	m	o	n	m	m	n	l	l	l
9	k	j	i	i	i	i	i	i	i	i	i	i	i	i	i	i
j0	i	j	i	i	i	i	i	i	i	i	i	i	i	i	i	j
11	k	k	l	m	n	l	l	l	l	l	l	l	k	k	j	l
12	k	k	l	l	m	l	l	l	l	l	l	l	l	k	j	l
13	l	m	m	m	o	m	m	n	l	n	m	m	n	m	l	m
14	i	o	m	n	m	p	n	k	o	n	p	m	m	l	n	l
15	i	j	i	j	j	j	j	j	j	j	i	i	i	i	j	i
16	j	o	n	p	n	m	n	l	m	n	m	m	m	l	l	m
17	j	l	l	m	m	l	l	n	k	l	l	n	n	n	l	m
18	k	l	l	k	k	k	l	k	j	k	j	k	j	j	j	m
19	i	k	l	n	l	l	k	k	k	j	j	i	i	i	i	i
20	l	m	l	n	l	l	k	k	j	j	j	j	j	k	k	m
21	k	o	l	p	p	m	n	m	n	l	n	l	l	k	l	l

22	k	l	n	o	o	l	n	l	m	m	l	l	l	l	k	m
23	j	l	l	m	m	m	m	l	n	n	n	l	j	j	j	j
24	k	n	l	o	o	m	p	m	m	n	l	m	m	l	l	l
25	i	o	j	j	i	i	i	i	i	i	i	i	i	i	i	i
26	i	o	o	l	n	k	n	n	l	m	m	p	p	m	m	m
27	l	l	p	l	n	m	l	l	l	k	k	l	l	l	k	l
28	i	i	j	i	i	i	k	j	k	j	j	k	k	k	j	j
29	i	l	k	n	l	l	k	l	k	j	i	i	j	i	i	j
30	l	n	n	m	p	n	l	l	k	l	k	k	j	i	j	i
31	k	l	n	l	m	l	l	l	k	j	k	o	m	i	i	i

Table 18: Codebook Selection for WB Normalized LSF Index Stage 2 Decoding

Decoding the second stage residual proceeds as follows. For each coefficient, the decoder reads a symbol using the PDF corresponding to I1 from either Table 17 or Table 18, and subtracts 4 from the result to give an index in the range -4 to 4, inclusive. If the index is either -4 or 4, it reads a second symbol using the PDF in Table 19, and adds the value of this second symbol to the index, using the same sign. This gives the index, I2[k], a total range of -10 to 10, inclusive.

PDF
{156, 60, 24, 9, 4, 2, 1}/256

Table 19: PDF for Normalized LSF Index Extension Decoding

The decoded indices from both stages are translated back into normalized LSF coefficients in `silk_NLSF_decode()` (`NLSF_decode.c`). The stage-2 indices represent residuals after both the first stage of the VQ and a separate backwards-prediction step. The backwards prediction process in the encoder subtracts a prediction from each residual formed by a multiple of the coefficient that follows it. The decoder must undo this process. Table 20 contains lists of

prediction weights for each coefficient. There are two lists for NB and MB, and another two lists for WB, giving two possible prediction weights for each coefficient.

Coefficient	A	B	C	D
0	179	116	175	68
1	138	67	148	62
2	140	82	160	66
3	148	59	176	60
4	151	92	178	72
5	149	72	173	117
6	153	100	174	85
7	151	89	164	90
8	163	92	177	118
9			174	136
10			196	151
11			182	142
12			198	160
13			192	142
14			182	155

Table 20: Prediction Weights for Normalized LSF Decoding

The prediction is undone using the procedure implemented in `silk_NLSF_residual_dequant()` (`NLSF_decode.c`), which is as follows. Each coefficient selects its prediction weight from one of the two lists based on the stage-1 index, `l1`. Table 21 gives the selections for each coefficient for NB and MB, and Table 22 gives the selections for WB. Let `d_LPC` be the order of the codebook, i.e., 10 for NB and MB, and 16 for WB, and let `pred_Q8[k]` be the weight for the k 'th coefficient selected by this process for $0 \leq k < d_LPC-1$. Then, the

stage-2 residual for each coefficient is computed via

```
res_Q10[k] = (k+1 < d_LPC ? (res_Q10[k+1]*pred_Q8[k])>>8 : 0)
             + (((I2[k]<<10) + sign(I2[k])*102)*qstep)>>16) ,
```

where qstep is the Q16 quantization step size, which is 11796 for NB and MB and 9830 for WB (representing step sizes of approximately 0.18 and 0.15, respectively).

I1	Coefficient
	0 1 2 3 4 5 6 7 8
0	A B A A A A A A A
1	B A A A A A A A A
2	A A A A A A A A A
3	B B B A A A A B A
4	A B A A A A A A A
5	A B A A A A A A A
6	B A B B A A A B A
7	A B B A A B B A A
8	A A B B A B A B B
9	A A B B A A B B B
10	A A A A A A A A A
11	A B A B B B B B A
12	A B A B B B B B A
13	A B B B B B B B A
14	B A B B A B B B B
15	A B B B B B A B A
16	A A B B A B A B A

17	A A B B B A B B B
18	A B B A A B B B A
19	A A A B B B A B A
20	A B B A A B A B A
21	A B B A A A B B A
22	A A A A A B B B B
23	A A B B A A A B B
24	A A A B A B B B B
25	A B B B B B B B A
26	A A A A A A A A A
27	A A A A A A A A A
28	A A B A B B A B A
29	A A A B A A A A A
30	A A A B B A B A B
31	B A B B A B B B B

Table 21: Prediction Weight Selection for NB/MB Normalized LSF Decoding

I1	Coefficient														
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
0	C	C	C	C	C	C	C	C	C	C	C	C	C	C	D
1	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
2	C	C	D	C	C	D	D	D	C	D	D	D	D	C	C
3	C	C	C	C	C	C	C	C	C	C	C	C	D	C	C
4	C	D	D	C	D	C	D	D	C	D	D	D	D	D	C

5	C	D	C	C	C	C	C	C	C	C	C	C	C	C	C
6	D	C	C	C	C	C	C	C	C	C	C	D	C	D	C
7	C	D	D	C	C	C	D	C	D	D	D	C	D	C	D
8	C	D	C	D	D	C	D	C	D	C	D	D	D	D	D
9	C	C	C	C	C	C	C	C	C	C	C	C	C	C	D
10	C	D	C	C	C	C	C	C	C	C	C	C	C	C	C
11	C	C	D	C	D	D	D	D	D	D	D	C	D	C	C
12	C	C	D	C	C	D	C	D	C	D	C	C	D	C	C
13	C	C	C	C	D	D	C	D	C	D	D	D	D	C	C
14	C	D	C	C	C	D	D	C	D	D	D	C	D	D	D
15	C	C	D	D	C	C	C	C	C	C	C	C	D	D	C
16	C	D	D	C	D	C	D	D	D	D	D	C	D	C	C
17	C	C	D	C	C	C	C	D	C	C	D	D	D	C	C
18	C	C	C	C	C	C	C	C	C	C	C	C	C	C	D
19	C	C	C	C	C	C	C	C	C	C	C	C	D	C	C
20	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
21	C	D	C	D	C	D	D	C	D	C	D	C	D	D	C
22	C	C	D	D	D	D	C	D	D	C	C	D	D	C	C
23	C	D	D	C	D	C	D	C	D	C	C	C	C	D	C
24	C	C	C	D	D	C	D	C	D	D	D	D	D	D	D
25	C	C	C	C	C	C	C	C	C	C	C	C	C	C	D
26	C	D	D	C	C	C	D	D	C	C	D	D	D	D	D
27	C	C	C	C	C	D	C	D	D	D	D	C	D	D	D
28	C	C	C	C	C	C	C	C	C	C	C	C	C	C	D

29	C	C	C	C	C	C	C	C	C	C	C	C	C	C	D
30	D	C	C	C	C	C	C	C	C	C	C	D	C	C	C
31	C	C	D	C	C	D	D	D	C	C	D	C	C	D	C

Table 22: Prediction Weight Selection for WB Normalized LSF Decoding

4.2.7.5.3. Reconstructing the Normalized LSF Coefficients

Once the stage-1 index `l1` and the stage-2 residual `res_Q10[]` have been decoded, the final normalized LSF coefficients can be reconstructed.

The spectral distortion introduced by the quantization of each LSF coefficient varies, so the stage-2 residual is weighted accordingly, using the low-complexity Inverse Harmonic Mean Weighting (IHMW) function proposed in [laroia-icassp]. The weights are derived directly from the stage-1 codebook vector. Let `cb1_Q8[k]` be the k 'th entry of the stage-1 codebook vector from Table 23 or Table 24. Then for $0 \leq k < d_LPC$ the following expression computes the square of the weight as a Q18 value:

$$w2_Q18[k] = (1024 / (cb1_Q8[k] - cb1_Q8[k-1]) + 1024 / (cb1_Q8[k+1] - cb1_Q8[k])) \ll 16 ,$$

where `cb1_Q8[-1] = 0` and `cb1_Q8[d_LPC] = 256`, and the division is exact integer division. This is reduced to an unsquared, Q9 value using the following square-root approximation:

```
i = ilog(w2_Q18[k])
f = (w2_Q18[k] >> (i-8)) & 127
y = ((i&1) ? 32768 : 46214) >> ((32-i)>>1)
w_Q9[k] = y + ((213*f*y)>>16)
```

The `cb1_Q8[]` vector completely determines these weights, and they may be tabulated and stored as 13-bit unsigned values (with a range of 1819 to 5227, inclusive) to avoid computing them when decoding. The reference implementation already requires code to compute these weights on unquantized coefficients in the encoder, in `silk_NLSF_VQ_weights_laroia()` (`NLSF_VQ_weights_laroia.c`) and its callers, so it reuses that code in the decoder instead of using a pre-computed table to reduce the amount of ROM required.

I1	Codebook (Q8)									
	0	1	2	3	4	5	6	7	8	9
0	12	35	60	83	108	132	157	180	206	228
1	15	32	55	77	101	125	151	175	201	225
2	19	42	66	89	114	137	162	184	209	230
3	12	25	50	72	97	120	147	172	200	223
4	26	44	69	90	114	135	159	180	205	225
5	13	22	53	80	106	130	156	180	205	228
6	15	25	44	64	90	115	142	168	196	222
7	19	24	62	82	100	120	145	168	190	214
8	22	31	50	79	103	120	151	170	203	227
9	21	29	45	65	106	124	150	171	196	224
10	30	49	75	97	121	142	165	186	209	229
11	19	25	52	70	93	116	143	166	192	219
12	26	34	62	75	97	118	145	167	194	217
13	25	33	56	70	91	113	143	165	196	223
14	21	34	51	72	97	117	145	171	196	222
15	20	29	50	67	90	117	144	168	197	221
16	22	31	48	66	95	117	146	168	196	222
17	24	33	51	77	116	134	158	180	200	224
18	21	28	70	87	106	124	149	170	194	217
19	26	33	53	64	83	117	152	173	204	225
20	27	34	65	95	108	129	155	174	210	225
21	20	26	72	99	113	131	154	176	200	219

22	34	43	61	78	93	114	155	177	205	229
23	23	29	54	97	124	138	163	179	209	229
24	30	38	56	89	118	129	158	178	200	231
25	21	29	49	63	85	111	142	163	193	222
26	27	48	77	103	133	158	179	196	215	232
27	29	47	74	99	124	151	176	198	220	237
28	33	42	61	76	93	121	155	174	207	225
29	29	53	87	112	136	154	170	188	208	227
30	24	30	52	84	131	150	166	186	203	229
31	37	48	64	84	104	118	156	177	201	230

Table 23: Codebook Vectors for NB/MB Normalized LSF Stage 1 Decoding

I1	Codebook (Q8)															
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	7	23	38	54	69	85	100	116	131	147	162	178	193	208	223	239
1	13	25	41	55	69	83	98	112	127	142	157	171	187	203	220	236
2	15	21	34	51	61	78	92	106	126	136	152	167	185	205	225	240
3	10	21	36	50	63	79	95	110	126	141	157	173	189	205	221	237
4	17	20	37	51	59	78	89	107	123	134	150	164	184	205	224	240
5	10	15	32	51	67	81	96	112	129	142	158	173	189	204	220	236
6	8	21	37	51	65	79	98	113	126	138	155	168	179	192	209	218
7	12	15	34	55	63	78	87	108	118	131	148	167	185	203	219	236
8	16	19	32	36	56	79	91	108	118	136	154	171	186	204	220	237
9	11	28	43	58	74	89	105	120	135	150	165	180	196	211	226	241

10	6	16	33	46	60	75	92	107	123	137	156	169	185	199	214	225
11	11	19	30	44	57	74	89	105	121	135	152	169	186	202	218	234
12	12	19	29	46	57	71	88	100	120	132	148	165	182	199	216	233
13	17	23	35	46	56	77	92	106	123	134	152	167	185	204	222	237
14	14	17	45	53	63	75	89	107	115	132	151	171	188	206	221	240
15	9	16	29	40	56	71	88	103	119	137	154	171	189	205	222	237
16	16	19	36	48	57	76	87	105	118	132	150	167	185	202	218	236
17	12	17	29	54	71	81	94	104	126	136	149	164	182	201	221	237
18	15	28	47	62	79	97	115	129	142	155	168	180	194	208	223	238
19	8	14	30	45	62	78	94	111	127	143	159	175	192	207	223	239
20	17	30	49	62	79	92	107	119	132	145	160	174	190	204	220	235
21	14	19	36	45	61	76	91	108	121	138	154	172	189	205	222	238
22	12	18	31	45	60	76	91	107	123	138	154	171	187	204	221	236
23	13	17	31	43	53	70	83	103	114	131	149	167	185	203	220	237
24	17	22	35	42	58	78	93	110	125	139	155	170	188	206	224	240
25	8	15	34	50	67	83	99	115	131	146	162	178	193	209	224	239
26	13	16	41	66	73	86	95	111	128	137	150	163	183	206	225	241
27	17	25	37	52	63	75	92	102	119	132	144	160	175	191	212	231
28	19	31	49	65	83	100	117	133	147	161	174	187	200	213	227	242
29	18	31	52	68	88	103	117	126	138	149	163	177	192	207	223	239
30	16	29	47	61	76	90	106	119	133	147	161	176	193	209	224	240
31	15	21	35	50	61	73	86	97	110	119	129	141	175	198	218	237

Table 24: Codebook Vectors for WB Normalized LSF Stage 1 Decoding

Given the stage-1 codebook entry `cb1_Q8[]`, the stage-2 residual

res_Q10[], and their corresponding weights, w_Q9[], the reconstructed normalized LSF coefficients are

$$\text{NLSF_Q15}[k] = (\text{cbl_Q8}[k] \ll 7) + (\text{res_Q10}[k] \ll 14) / \text{w_Q9}[k] ,$$

where the division is exact integer division. However, nothing in either the reconstruction process or the quantization process in the encoder thus far guarantees that the coefficients are monotonically increasing and separated well enough to ensure a stable filter. When using the reference encoder, roughly 2% of frames violate this constraint. The next section describes a stabilization procedure used to make these guarantees.

4.2.7.5.4. Normalized LSF Stabilization

The normalized LSF stabilization procedure is implemented in `silk_NLSF_stabilize()` (`NLSF_stabilize.c`). This process ensures that consecutive values of the normalized LSF coefficients, `NLSF_Q15[]`, are spaced some minimum distance apart (predetermined to be the 0.01 percentile of a large training set). Table 25 gives the minimum spacings for NB and MB and those for WB, where row *k* is the minimum allowed value of `NLSF_Q[k]-NLSF_Q[k-1]`. For the purposes of computing this spacing for the first and last coefficient, `NLSF_Q15[-1]` is taken to be 0, and `NLSF_Q15[d_LPC]` is taken to be 32768.

Coefficient	NB and MB	WB
0	250	100
1	3	3
2	6	40
3	3	3
4	3	3
5	3	3
6	4	5
7	3	14
8	3	14
9	3	10
10	461	11
11		3
12		8
13		9
14		7
15		3
16		347

Table 25: Minimum Spacing for Normalized LSF Coefficients

The procedure starts off by trying to make small adjustments which attempt to minimize the amount of distortion introduced. After 20 such adjustments, it falls back to a more direct method which guarantees the constraints are enforced but may require large adjustments.

Let $\text{NDeltaMin_Q15}[k]$ be the minimum required spacing for the current audio bandwidth from Table 25. First, the procedure finds the index

i where $\text{NLSF_Q15}[i] - \text{NLSF_Q15}[i-1] - \text{NDeltaMin_Q15}[i]$ is the smallest, breaking ties by using the lower value of i . If this value is non-negative, then the stabilization stops; the coefficients satisfy all the constraints. Otherwise, if $i == 0$, it sets $\text{NLSF_Q15}[0]$ to $\text{NDeltaMin_Q15}[0]$, and if $i == d_LPC$, it sets $\text{NLSF_Q15}[d_LPC-1]$ to $(32768 - \text{NDeltaMin_Q15}[d_LPC])$. For all other values of i , both $\text{NLSF_Q15}[i-1]$ and $\text{NLSF_Q15}[i]$ are updated as follows:

$$\begin{aligned} \text{min_center_Q15} &= (\text{NDeltaMin}[i] \gg 1) + \frac{\sum_{k=0}^{i-1} \text{NDeltaMin}[k]}{i} \\ \text{max_center_Q15} &= 32768 - (\text{NDeltaMin}[i] \gg 1) - \frac{\sum_{k=i+1}^{d_LPC} \text{NDeltaMin}[k]}{d_LPC - i} \\ \text{center_freq_Q15} &= \text{clamp}(\text{min_center_Q15}[i], \\ &\quad (\text{NLSF_Q15}[i-1] + \text{NLSF_Q15}[i] + 1) \gg 1, \\ &\quad \text{max_center_Q15}[i]) \\ \text{NLSF_Q15}[i-1] &= \text{center_freq_Q15} - (\text{NDeltaMin_Q15}[i] \gg 1) \\ \text{NLSF_Q15}[i] &= \text{NLSF_Q15}[i-1] + \text{NDeltaMin_Q15}[i] . \end{aligned}$$

Then the procedure repeats again, until it has either executed 20 times or has stopped because the coefficients satisfy all the constraints.

After the 20th repetition of the above procedure, the following fallback procedure executes once. First, the values of $\text{NLSF_Q15}[k]$ for $0 \leq k < d_LPC$ are sorted in ascending order. Then for each value of k from 0 to d_LPC-1 , $\text{NLSF_Q15}[k]$ is set to

$$\max(\text{NLSF_Q15}[k], \text{NLSF_Q15}[k-1] + \text{NDeltaMin_Q15}[k]) .$$

Next, for each value of k from d_LPC-1 down to 0, $\text{NLSF_Q15}[k]$ is set to

$$\min(\text{NLSF_Q15}[k], \text{NLSF_Q15}[k+1] - \text{NDeltaMin_Q15}[k+1]) .$$

4.2.7.5.5. Normalized LSF Interpolation

For 20 ms SILK frames, the first half of the frame (i.e., the first two subframes) may use normalized LSF coefficients that are interpolated between the decoded LSFs for the most recent coded frame

(in the same channel) and the current frame. A Q2 interpolation factor follows the LSF coefficient indices in the bitstream, which is decoded using the PDF in Table 26. This happens in `silk_decode_indices()` (`decode_indices.c`). For the first frame after a decoder reset (see Section 4.5), when no prior LSF coefficients are available, the decoder still decodes this factor, but ignores its value and always uses 4 instead. For 10 ms SILK frames, this factor is not stored at all.

PDF
{13, 22, 29, 11, 181}/256

Table 26: PDF for Normalized LSF Interpolation Index

Let $n2_Q15[k]$ be the normalized LSF coefficients decoded by the procedure in Section 4.2.7.5, $n0_Q15[k]$ be the LSF coefficients decoded for the prior frame, and w_Q2 be the interpolation factor. Then the normalized LSF coefficients used for the first half of a 20 ms frame, $n1_Q15[k]$, are

$$n1_Q15[k] = n0_Q15[k] + (w_Q2 * (n2_Q15[k] - n0_Q15[k]) \gg 2) .$$

This interpolation is performed in `silk_decode_parameters()` (`decode_parameters.c`).

4.2.7.5.6. Converting Normalized LSFs to LPC Coefficients

Any LPC filter $A(z)$ can be split into a symmetric part $P(z)$ and an anti-symmetric part $Q(z)$ such that

$$A(z) = 1 - \sum_{k=1}^{d_LPC} a[k] * z^{-k} = \frac{1}{2} * (P(z) + Q(z))$$

with

$$P(z) = A(z) + z^{-d_LPC-1} * A(z^{-1})$$

$$Q(z) = A(z) - z^{-d_LPC-1} * A(z^{-1}) .$$

The even normalized LSF coefficients correspond to a pair of

conjugate roots of $P(z)$, while the odd coefficients correspond to a pair of conjugate roots of $Q(z)$, all of which lie on the unit circle. In addition, $P(z)$ has a root at π and $Q(z)$ has a root at 0. Thus, they may be reconstructed mathematically from a set of normalized LSF coefficients, $n[k]$, as

$$P(z) = (1 + z^{-1}) * \prod_{k=0}^{d_{\text{LPC}}/2-1} (1 - 2*\cos(\pi*n[2*k])*z^{-1} + z^{-2})$$

$$Q(z) = (1 - z^{-1}) * \prod_{k=0}^{d_{\text{LPC}}/2-1} (1 - 2*\cos(\pi*n[2*k+1])*z^{-1} + z^{-2})$$

However, SILK performs this reconstruction using a fixed-point approximation so that all decoders can reproduce it in a bit-exact manner to avoid prediction drift. The function `silk_NLSF2A()` (`NLSF2A.c`) implements this procedure.

To start, it approximates $\cos(\pi*n[k])$ using a table lookup with linear interpolation. The encoder SHOULD use the inverse of this piecewise linear approximation, rather than the true inverse of the cosine function, when deriving the normalized LSF coefficients. These values are also re-ordered to improve numerical accuracy when constructing the LPC polynomials.

Coefficient	NB and MB	WB
0	0	0
1	9	15
2	6	8
3	3	7
4	4	4
5	5	11
6	8	12
7	1	3
8	2	2
9	7	13
10		10
11		5
12		6
13		9
14		14
15		1

Table 27: LSF Ordering for Polynomial Evaluation

The top 7 bits of each normalized LSF coefficient index a value in the table, and the next 8 bits interpolate between it and the next value. Let $i = (n[k] \gg 8)$ be the integer index and $f = (n[k] \& 255)$ be the fractional part of a given coefficient. Then the re-ordered, approximated cosine, $c_{Q17}[\text{ordering}[k]]$, is

$$c_{Q17}[\text{ordering}[k]] = (\cos_{Q13}[i]*256 + (\cos_{Q13}[i+1]-\cos_{Q13}[i])*f + 8) \gg 4 ,$$

where $\text{ordering}[k]$ is the k 'th entry of the column of Table 27

corresponding to the current audio bandwidth and $\cos_Q13[i]$ is the i 'th entry of Table 28.

i	+0	+1	+2	+3
0	8192	8190	8182	8170
4	8152	8130	8104	8072
8	8034	7994	7946	7896
12	7840	7778	7714	7644
16	7568	7490	7406	7318
20	7226	7128	7026	6922
24	6812	6698	6580	6458
28	6332	6204	6070	5934
32	5792	5648	5502	5352
36	5198	5040	4880	4718
40	4552	4382	4212	4038
44	3862	3684	3502	3320
48	3136	2948	2760	2570
52	2378	2186	1990	1794
56	1598	1400	1202	1002
60	802	602	402	202
64	0	-202	-402	-602
68	-802	-1002	-1202	-1400
72	-1598	-1794	-1990	-2186
76	-2378	-2570	-2760	-2948
80	-3136	-3320	-3502	-3684

84	-3862	-4038	-4212	-4382
88	-4552	-4718	-4880	-5040
92	-5198	-5352	-5502	-5648
96	-5792	-5934	-6070	-6204
100	-6332	-6458	-6580	-6698
104	-6812	-6922	-7026	-7128
108	-7226	-7318	-7406	-7490
112	-7568	-7644	-7714	-7778
116	-7840	-7896	-7946	-7994
120	-8034	-8072	-8104	-8130
124	-8152	-8170	-8182	-8190
128	-8192			

Table 28: Q13 Cosine Table for LSF Conversion

Given the list of cosine values, `silk_NLSF2A_find_poly()` (NLSF2A.c) computes the coefficients of P and Q, described here via a simple recurrence. Let `p_Q16[k][j]` and `q_Q16[k][j]` be the coefficients of the products of the first (k+1) root pairs for P and Q, with j indexing the coefficient number. Only the first (k+2) coefficients are needed, as the products are symmetric. Let `p_Q16[0][0] = q_Q16[0][0] = 1 << 16`, `p_Q16[0][1] = -c_Q17[0]`, `q_Q16[0][1] = -c_Q17[1]`, and `d2 = d_LPC/2`. As boundary conditions, assume `p_Q16[k][j] = q_Q16[k][j] = 0` for all `j < 0`. Also, assume `p_Q16[k][k+2] = p_Q16[k][k]` and `q_Q16[k][k+2] = q_Q16[k][k]` (because of the symmetry). Then, for `0 < k < d2` and `0 <= j <= k+1`,

$$\begin{aligned}
 p_Q16[k][j] &= p_Q16[k-1][j] + p_Q16[k-1][j-2] \\
 &\quad - ((c_Q17[2*k]*p_Q16[k-1][j-1] + 32768) >> 16) , \\
 q_Q16[k][j] &= q_Q16[k-1][j] + q_Q16[k-1][j-2] \\
 &\quad - ((c_Q17[2*k+1]*q_Q16[k-1][j-1] + 32768) >> 16) .
 \end{aligned}$$

The use of Q17 values for the cosine terms in an otherwise Q16 expression implicitly scales them by a factor of 2. The multiplications in this recurrence may require up to 48 bits of

precision in the result to avoid overflow. In practice, each row of the recurrence only depends on the previous row, so an implementation does not need to store all of them.

`silk_NLSF2A()` uses the values from the last row of this recurrence to reconstruct a 32-bit version of the LPC filter (without the leading 1.0 coefficient), `a32_Q17[k]`, $0 \leq k < d2$:

$$\begin{aligned} a32_Q17[k] &= -(q_Q16[d2-1][k+1] - q_Q16[d2-1][k]) \\ &\quad - (p_Q16[d2-1][k+1] + p_Q16[d2-1][k])) , \\ a32_Q17[d_LPC-k-1] &= (q_Q16[d2-1][k+1] - q_Q16[d2-1][k]) \\ &\quad - (p_Q16[d2-1][k+1] + p_Q16[d2-1][k])) . \end{aligned}$$

The sum and difference of two terms from each of the `p_Q16` and `q_Q16` coefficient lists reflect the $(1 + z^{-1})$ and $(1 - z^{-1})$ factors of `P` and `Q`, respectively. The promotion of the expression from `Q16` to `Q17` implicitly scales the result by $1/2$.

4.2.7.5.7. Limiting the Range of the LPC Coefficients

The `a32_Q17[]` coefficients are too large to fit in a 16-bit value, which significantly increases the cost of applying this filter in fixed-point decoders. Reducing them to `Q12` precision doesn't incur any significant quality loss, but still does not guarantee they will fit. `silk_NLSF2A()` applies up to 10 rounds of bandwidth expansion to limit the dynamic range of these coefficients. Even floating-point decoders SHOULD perform these steps, to avoid mismatch.

For each round, the process first finds the index `k` such that `abs(a32_Q17[k])` is largest, breaking ties by choosing the lowest value of `k`. Then, it computes the corresponding `Q12` precision value, `maxabs_Q12`, subject to an upper bound to avoid overflow in subsequent computations:

$$\text{maxabs_Q12} = \min((\text{maxabs_Q17} + 16) \gg 5, 163838) .$$

If this is larger than 32767, the procedure derives the chirp factor, `sc_Q16[0]`, to use in the bandwidth expansion as

$$\text{sc_Q16}[0] = 65470 - \frac{(\text{maxabs_Q12} - 32767) \ll 14}{(\text{maxabs_Q12} * (k+1)) \gg 2} ,$$

where the division here is exact integer division. This is an approximation of the chirp factor needed to reduce the target coefficient to 32767, though it is both less than 0.999 and, for $k > 0$ when `maxabs_Q12` is much greater than 32767, still slightly too

large.

`silk_bwexpander_32()` (`bwexpander_32.c`) performs the bandwidth expansion (again, only when `maxabs_Q12` is greater than 32767) using the following recurrence:

```
a32_Q17[k] = (a32_Q17[k]*sc_Q16[k]) >> 16
sc_Q16[k+1] = (sc_Q16[0]*sc_Q16[k] + 32768) >> 16
```

The first multiply may require up to 48 bits of precision in the result to avoid overflow. The second multiply must be unsigned to avoid overflow with only 32 bits of precision. The reference implementation uses a slightly more complex formulation that avoids the 32-bit overflow using signed multiplication, but is otherwise equivalent.

After 10 rounds of bandwidth expansion are performed, they are simply saturated to 16 bits:

```
a32_Q17[k] = clamp(-32768, (a32_Q17[k]+16) >> 5, 32767) << 5 .
```

Because this performs the actual saturation in the Q12 domain, but converts the coefficients back to the Q17 domain for the purposes of prediction gain limiting, this step must be performed after the 10th round of bandwidth expansion, regardless of whether or not the Q12 version of any coefficient still overflows a 16-bit integer. This saturation is not performed if `maxabs_Q12` drops to 32767 or less prior to the 10th round.

4.2.7.5.8. Limiting the Prediction Gain of the LPC Filter

The prediction gain of an LPC synthesis filter is the square-root of the output energy when the filter is excited by a unit-energy impulse. Even if the Q12 coefficients would fit, the resulting filter may still have a significant gain (especially for voiced sounds), making the filter unstable. `silk_NLSF2A()` applies up to 18 additional rounds of bandwidth expansion to limit the prediction gain. Instead of controlling the amount of bandwidth expansion using the prediction gain itself (which may diverge to infinity for an unstable filter), `silk_NLSF2A()` uses `silk_LPC_inverse_pred_gain_QA()` (`LPC_inv_pred_gain.c`) to compute the reflection coefficients associated with the filter. The filter is stable if and only if the magnitude of these coefficients is sufficiently less than one. The reflection coefficients, `rc[k]`, can be computed using a simple Levinson recurrence, initialized with the LPC coefficients `a[d_LPC-1][n] = a[n]`, and then updated via

$$rc[k] = -a[k][k] ,$$

$$a[k-1][n] = \frac{a[k][n] - a[k][k-n-1]*rc[k]}{1 - rc[k]^2} .$$

However, `silk_LPC_inverse_pred_gain_QA()` approximates this using fixed-point arithmetic to guarantee reproducible results across platforms and implementations. Since small changes in the coefficients can make a stable filter unstable, it takes the real Q12 coefficients that will be used during reconstruction as input. Thus, let

$$a32_Q12[n] = (a32_Q17[n] + 16) \gg 5$$

be the Q12 version of the LPC coefficients that will eventually be used. As a simple initial check, the decoder computes the DC response as

$$DC_resp = \frac{\sum_{n=0}^{d_PLC-1} a32_Q12[n]}{d_PLC}$$

and if `DC_resp > 4096`, the filter is unstable.

Increasing the precision of these Q12 coefficients to Q24 for intermediate computations allows more accurate computation of the reflection coefficients, so the decoder initializes the recurrence via

$$a32_Q24[d_LPC-1][n] = a32_Q12[n] \ll 12 .$$

Then for each `k` from `d_LPC-1` down to 0, if `abs(a32_Q24[k][k]) > 16773022`, the filter is unstable and the recurrence stops. Otherwise, row `k-1` of `a32_Q24` is computed from row `k` as

```

    rc_Q31[k] = -a32_Q24[k][k] << 7 ,

    div_Q30[k] = (1<<30) - (rc_Q31[k]*rc_Q31[k] >> 32) ,

    b1[k] = ilog(div_Q30[k]) ,

    b2[k] = b1[k] - 16 ,

    inv_Qb2[k] = (1<<29) - 1
                ----- ,
                div_Q30[k] >> (b2[k]+1)

    err_Q29[k] = (1<<29)
                - ((div_Q30[k]<<(15-b2[k]))*inv_Qb2[k] >> 16) ,

    gain_Qb1[k] = ((inv_Qb2[k] << 16)
                  + (err_Q29[k]*inv_Qb2[k] >> 13)) ,

    num_Q24[k-1][n] = a32_Q24[k][n]
                    - ((a32_Q24[k][k-n-1]*rc_Q31[k] + (1<<30)) >> 31) ,

    a32_Q24[k-1][n] = (num_Q24[k-1][n]*gain_Qb1[k]
                    + (1<<(b1[k]-1))) >> b1[k] ,

```

where $0 \leq n < k-1$. Here, $rc_Q30[k]$ are the reflection coefficients. $div_Q30[k]$ is the denominator for each iteration, and $gain_Qb1[k]$ is its multiplicative inverse (with $b1[k]$ fractional bits, where $b1[k]$ ranges from 20 to 31). $inv_Qb2[k]$, which ranges from 16384 to 32767, is a low-precision version of that inverse (with $b2[k]$ fractional bits). $err_Q29[k]$ is the residual error, ranging from -32763 to 32392, which is used to improve the accuracy. The values $t_Q24[k-1][n]$ for each n are the numerators for the next row of coefficients in the recursion, and $a32_Q24[k-1][n]$ is the final version of that row. Every multiply in this procedure except the one used to compute $gain_Qb1[k]$ requires more than 32 bits of precision, but otherwise all intermediate results fit in 32 bits or less. In practice, because each row only depends on the next one, an implementation does not need to store them all.

If $\text{abs}(a32_Q24[k][k]) \leq 16773022$ for $0 \leq k < d_LPC$, then the filter is considered stable. However, the problem of determining stability is ill-conditioned when the filter contains several reflection coefficients whose magnitude is very close to one. This fixed-point algorithm is not mathematically guaranteed to correctly classify filters as stable or unstable in this case, though it does very well in practice.

On round i , $1 \leq i \leq 18$, if the filter passes these stability

checks, then this procedure stops, and the final LPC coefficients to use for reconstruction in Section 4.2.7.9.2 are

$$a_{Q12}[k] = (a_{32_Q17}[k] + 16) \gg 5 \text{ .}$$

Otherwise, a round of bandwidth expansion is applied using the same procedure as in Section 4.2.7.5.7, with

$$sc_{Q16}[0] = 65536 - i*(i+9) \text{ .}$$

If, after the 18th round, the filter still fails these stability checks, then $a_{Q12}[k]$ is set to 0 for all k .

4.2.7.6. Long-Term Prediction (LTP) Parameters

After the normalized LSF indices and, for 20 ms frames, the LSF interpolation index, voiced frames (see Section 4.2.7.3) include additional LTP parameters. There is one primary lag index for each SILK frame, but this is refined to produce a separate lag index per subframe using a vector quantizer. Each subframe also gets its own prediction gain coefficient.

4.2.7.6.1. Pitch Lags

The primary lag index is coded either relative to the primary lag of the prior frame in the same channel, or as an absolute index. Absolute coding is used if and only if

- o This is the first SILK frame of its type (LBRR or regular) for this channel in the current Opus frame,
- o The previous SILK frame of the same type (LBRR or regular) for this channel in the same Opus frame was not coded, or
- o That previous SILK frame was coded, but was not voiced (see Section 4.2.7.3).

With absolute coding, the primary pitch lag may range from 2 ms (inclusive) up to 18 ms (exclusive), corresponding to pitches from 500 Hz down to 55.6 Hz, respectively. It is comprised of a high part and a low part, where the decoder reads the high part using the 32-entry codebook in Table 29 and the low part using the codebook corresponding to the current audio bandwidth from Table 30. The final primary pitch lag is then

$$\text{lag} = \text{lag_high} * \text{lag_scale} + \text{lag_low} + \text{lag_min}$$

where lag_high is the high part, lag_low is the low part, and

lag_scale and lag_min are the values from the "Scale" and "Minimum Lag" columns of Table 30, respectively.

PDF
{3, 3, 6, 11, 21, 30, 32, 19, 11, 10, 12, 13, 13, 12, 11, 9, 8, 7, 6, 4, 2, 2, 2, 1, 1, 1, 1, 1, 1, 1, 1}/256

Table 29: PDF for High Part of Primary Pitch Lag

Audio Bandwidth	PDF	Scale	Minimum Lag	Maximum Lag
NB	{64, 64, 64, 64}/256	4	16	144
MB	{43, 42, 43, 43, 42, 43}/256	6	24	216
WB	{32, 32, 32, 32, 32, 32, 32, 32, 32}/256	8	32	288

Table 30: PDF for Low Part of Primary Pitch Lag

All frames that do not use absolute coding for the primary lag index use relative coding instead. The decoder reads a single delta value using the 21-entry PDF in Table 31. If the resulting value is zero, it falls back to the absolute coding procedure from the prior paragraph. Otherwise, the final primary pitch lag is then

$$\text{lag} = \text{lag_prev} + (\text{delta_lag_index} - 9)$$

where lag_prev is the primary pitch lag from the most recent frame in the same channel and delta_lag_index is the value just decoded. This allows a per-frame change in the pitch lag of -8 to +11 samples. The decoder does no clamping at this point, so this value can fall outside the range of 2 ms to 18 ms, and the decoder must use this unclamped value when using relative coding in the next SILK frame (if any). However, because an Opus frame can use relative coding for at most two consecutive SILK frames, integer overflow should not be an issue.

PDF
{46, 2, 2, 3, 4, 6, 10, 15, 26, 38, 30, 22, 15, 10, 7, 6, 4, 4, 2, 2, 2}/256

Table 31: PDF for Primary Pitch Lag Change

After the primary pitch lag, a "pitch contour", stored as a single entry from one of four small VQ codebooks, gives lag offsets for each subframe in the current SILK frame. The codebook index is decoded using one of the PDFs in Table 32 depending on the current frame size and audio bandwidth. Tables 33 through 36 give the corresponding offsets to apply to the primary pitch lag for each subframe given the decoded codebook index.

Audio Bandwidth	SILK Frame Size	Codebook Size	PDF
NB	10 ms	3	{143, 50, 63}/256
NB	20 ms	11	{68, 12, 21, 17, 19, 22, 30, 24, 17, 16, 10}/256
MB or WB	10 ms	12	{91, 46, 39, 19, 14, 12, 8, 7, 6, 5, 5, 4}/256
MB or WB	20 ms	34	{33, 22, 18, 16, 15, 14, 14, 13, 13, 10, 9, 9, 8, 6, 6, 6, 5, 4, 4, 4, 3, 3, 3, 2, 2, 2, 2, 2, 2, 2, 1, 1, 1, 1}/256

Table 32: PDFs for Subframe Pitch Contour

Index	Subframe Offsets
0	0 0
1	1 0
2	0 1

Table 33: Codebook Vectors for Subframe Pitch Contour: NB, 10 ms Frames

Index	Subframe Offsets
0	0 0 0 0
1	2 1 0 -1
2	-1 0 1 2
3	-1 0 0 1
4	-1 0 0 0
5	0 0 0 1
6	0 0 1 1
7	1 1 0 0
8	1 0 0 0
9	0 0 0 -1
10	1 0 0 -1

Table 34: Codebook Vectors for Subframe Pitch Contour: NB, 20 ms Frames

Index	Subframe Offsets
0	0 0
1	0 1
2	1 0
3	-1 1
4	1 -1
5	-1 2
6	2 -1
7	-2 2
8	2 -2
9	-2 3
10	3 -2
11	-3 3

Table 35: Codebook Vectors for Subframe Pitch Contour: MB or WB,
10 ms Frames

Index	Subframe Offsets
0	0 0 0 0
1	0 0 1 1
2	1 1 0 0
3	-1 0 0 0
4	0 0 0 1
5	1 0 0 0
6	-1 0 0 1

7	0	0	0	-1
8	-1	0	1	2
9	1	0	0	-1
10	-2	-1	1	2
11	2	1	0	-1
12	-2	0	0	2
13	-2	0	1	3
14	2	1	-1	-2
15	-3	-1	1	3
16	2	0	0	-2
17	3	1	0	-2
18	-3	-1	2	4
19	-4	-1	1	4
20	3	1	-1	-3
21	-4	-1	2	5
22	4	2	-1	-3
23	4	1	-1	-4
24	-5	-1	2	6
25	5	2	-1	-4
26	-6	-2	2	6
27	-5	-2	2	5
28	6	2	-1	-5
29	-7	-2	3	8
30	6	2	-2	-6

31	5	2	-2	-5
32	8	3	-2	-7
33	-9	-3	3	9

Table 36: Codebook Vectors for Subframe Pitch Contour: MB or WB, 20 ms Frames

The final pitch lag for each subframe is assembled in `silk_decode_pitch()` (`decode_pitch.c`). Let `lag` be the primary pitch lag for the current SILK frame, `contour_index` be index of the VQ codebook, and `lag_cb[contour_index][k]` be the corresponding entry of the codebook from the appropriate table given above for the k 'th subframe. Then the final pitch lag for that subframe is

```
pitch_lags[k] = clamp(lag_min, lag + lag_cb[contour_index][k],
                      lag_max)
```

where `lag_min` and `lag_max` are the values from the "Minimum Lag" and "Maximum Lag" columns of Table 30, respectively.

4.2.7.6.2. LTP Filter Coefficients

SILK uses a separate 5-tap pitch filter for each subframe, selected from one of three codebooks. The three codebooks each represent different rate-distortion trade-offs, with average rates of 1.61 bits/subframe, 3.68 bits/subframe, and 4.85 bits/subframe, respectively.

The importance of the filter coefficients generally depends on two factors: the periodicity of the signal and relative energy between the current subframe and the signal from one period earlier. Greater periodicity and decaying energy both lead to more important filter coefficients, and thus should be coded with lower distortion and higher rate. These properties are relatively stable over the duration of a single SILK frame, hence all of the subframes in a SILK frame choose their filter from the same codebook. This is signaled with an explicitly-coded "periodicity index". This immediately follows the subframe pitch lags, and is coded using the 3-entry PDF from Table 37.

PDF
{77, 80, 99}/256

Table 37: Periodicity Index PDF

The indices of the filters for each subframe follow. They are all coded using the PDF from Table 38 corresponding to the periodicity index. Tables 39 through 41 contain the corresponding filter taps as signed Q7 integers.

Periodicity Index	Codebook Size	PDF
0	8	{185, 15, 13, 13, 9, 9, 6, 6}/256
1	16	{57, 34, 21, 20, 15, 13, 12, 13, 10, 10, 9, 10, 9, 8, 7, 8}/256
2	32	{15, 16, 14, 12, 12, 12, 11, 11, 11, 10, 9, 9, 9, 9, 8, 8, 8, 8, 7, 7, 6, 6, 5, 4, 5, 4, 4, 4, 3, 4, 3, 2}/256

Table 38: LTP Filter PDFs

Index	Filter Taps (Q7)				
0	4	6	24	7	5
1	0	0	2	0	0
2	12	28	41	13	-4
3	-9	15	42	25	14
4	1	-2	62	41	-9
5	-10	37	65	-4	3
6	-6	4	66	7	-8
7	16	14	38	-3	33

Table 39: Codebook Vectors for LTP Filter, Periodicity Index 0

Index	Filter Taps (Q7)				
0	13	22	39	23	12
1	-1	36	64	27	-6
2	-7	10	55	43	17
3	1	1	8	1	1
4	6	-11	74	53	-9
5	-12	55	76	-12	8
6	-3	3	93	27	-4
7	26	39	59	3	-8
8	2	0	77	11	9
9	-8	22	44	-6	7
10	40	9	26	3	9
11	-7	20	101	-7	4
12	3	-8	42	26	0
13	-15	33	68	2	23
14	-2	55	46	-2	15
15	3	-1	21	16	41

Table 40: Codebook Vectors for LTP Filter, Periodicity Index 1

Index	Filter Taps (Q7)				
0	-6	27	61	39	5
1	-11	42	88	4	1
2	-2	60	65	6	-4
3	-1	-5	73	56	1

4	-9	19	94	29	-9
5	0	12	99	6	4
6	8	-19	102	46	-13
7	3	2	13	3	2
8	9	-21	84	72	-18
9	-11	46	104	-22	8
10	18	38	48	23	0
11	-16	70	83	-21	11
12	5	-11	117	22	-8
13	-6	23	117	-12	3
14	3	-8	95	28	4
15	-10	15	77	60	-15
16	-1	4	124	2	-4
17	3	38	84	24	-25
18	2	13	42	13	31
19	21	-4	56	46	-1
20	-1	35	79	-13	19
21	-7	65	88	-9	-14
22	20	4	81	49	-29
23	20	0	75	3	-17
24	5	-9	44	92	-8
25	1	-3	22	69	31
26	-6	95	41	-12	5
27	39	67	16	-4	1

28	0	-6	120	55	-36
29	-13	44	122	4	-24
30	81	5	11	3	7
31	2	0	9	10	88

Table 41: Codebook Vectors for LTP Filter, Periodicity Index 2

4.2.7.6.3. LTP Scaling Parameter

An LTP scaling parameter appears after the LTP filter coefficients if and only if

- o This is a voiced frame (see Section 4.2.7.3), and
- o Either
 - * This SILK frame corresponds to the first time interval of the current Opus frame for its type (LBRR or regular), or
 - * This is an LBRR frame where the LBRR flags (see Section 4.2.4) indicate the previous LBRR frame in the same channel is not coded.

This allows the encoder to trade off the prediction gain between packets against the recovery time after packet loss. Unlike absolute-coding for pitch lags, regular SILK frames that are not at the start of an Opus frame (i.e., that do not correspond to the first 20 ms time interval in Opus frames of 40 or 60 ms) do not include this field, even if the prior frame was not voiced, or (in the case of the side channel) not even coded. After an uncoded frame in the side channel, the LTP buffer (see Section 4.2.7.9.1) is cleared to zero, and is thus in a known state. In contrast, LBRR frames do include this field when the prior frame was not coded, since the LTP buffer contains the output of the PLC, which is non-normative.

If present, the decoder reads a value using the 3-entry PDF in Table 42. The three possible values represent Q14 scale factors of 15565, 12288, and 8192, respectively (corresponding to approximately 0.95, 0.75, and 0.5). Frames that do not code the scaling parameter use the default factor of 15565 (approximately 0.95).

PDF
{128, 64, 64}/256

Table 42: PDF for LTP Scaling Parameter

4.2.7.7. Linear Congruential Generator (LCG) Seed

As described in Section 4.2.7.8.6, SILK uses a linear congruential generator (LCG) to inject pseudorandom noise into the quantized excitation. To ensure synchronization of this process between the encoder and decoder, each SILK frame stores a 2-bit seed after the LTP parameters (if any). The encoder may consider the choice of seed during quantization, and the flexibility of this choice lets it reduce distortion, helping to pay for the bit cost required to signal it. The decoder reads the seed using the uniform 4-entry PDF in Table 43, yielding a value between 0 and 3, inclusive.

PDF
{64, 64, 64, 64}/256

Table 43: PDF for LCG Seed

4.2.7.8. Excitation

SILK codes the excitation using a modified version of the Pyramid Vector Quantization (PVQ) codebook [PVQ]. The PVQ codebook is designed for Laplace-distributed values and consists of all sums of K signed, unit pulses in a vector of dimension N , where two pulses at the same position are required to have the same sign. Thus the codebook includes all integer codevectors y of dimension N that satisfy

$$\sqrt{\sum_{j=0}^{N-1} \text{abs}(y[j])} = K.$$

Unlike regular PVQ, SILK uses a variable-length, rather than fixed-length, encoding. This encoding is better suited to the more Gaussian-like distribution of the coefficient magnitudes and the non-uniform distribution of their signs (caused by the quantization

offset described below). SILK also handles large codebooks by coding the least significant bits (LSBs) of each coefficient directly. This adds a small coding efficiency loss, but greatly reduces the computation time and ROM size required for decoding, as implemented in `silk_decode_pulses()` (`decode_pulses.c`).

SILK fixes the dimension of the codebook to $N = 16$. The excitation is made up of a number of "shell blocks", each 16 samples in size. Table 44 lists the number of shell blocks required for a SILK frame for each possible audio bandwidth and frame size. 10 ms MB frames nominally contain 120 samples (10 ms at 12 kHz), which is not a multiple of 16. This is handled by coding 8 shell blocks (128 samples) and discarding the final 8 samples of the last block. The decoder contains no special case that prevents an encoder from placing pulses in these samples, and they must be correctly parsed from the bitstream if present, but they are otherwise ignored.

Audio Bandwidth	Frame Size	Number of Shell Blocks
NB	10 ms	5
MB	10 ms	8
WB	10 ms	10
NB	20 ms	10
MB	20 ms	15
WB	20 ms	20

Table 44: Number of Shell Blocks Per SILK Frame

4.2.7.8.1. Rate Level

The first symbol in the excitation is a "rate level", which is an index from 0 to 8, inclusive, coded using the PDF in Table 45 corresponding to the signal type of the current frame (from Section 4.2.7.3). The rate level selects the PDF used to decode the number of pulses in the individual shell blocks. It does not directly convey any information about the bitrate or the number of pulses itself, but merely changes the probability of the symbols in Section 4.2.7.8.2. Level 0 provides a more efficient encoding at low rates generally, and level 8 provides a more efficient encoding at high rates generally, though the most efficient level for a particular SILK frame may depend on the exact distribution of the

coded symbols. An encoder should, but is not required to, use the most efficient rate level.

Signal Type	PDF
Inactive or Unvoiced	{15, 51, 12, 46, 45, 13, 33, 27, 14}/256
Voiced	{33, 30, 36, 17, 34, 49, 18, 21, 18}/256

Table 45: PDFs for the Rate Level

4.2.7.8.2. Pulses Per Shell Block

The total number of pulses in each of the shell blocks follows the rate level. The pulse counts for all of the shell blocks are coded consecutively, before the content of any of the blocks. Each block may have anywhere from 0 to 16 pulses, inclusive, coded using the 18-entry PDF in Table 46 corresponding to the rate level from Section 4.2.7.8.1. The special value 17 indicates that this block has one or more additional LSBs to decode for each coefficient. If the decoder encounters this value, it decodes another value for the actual pulse count of the block, but uses the PDF corresponding to the special rate level 9 instead of the normal rate level. This process repeats until the decoder reads a value less than 17, and it then sets the number of extra LSBs used to the number of 17's decoded for that block. If it reads the value 17 ten times, then the next iteration uses the special rate level 10 instead of 9. The probability of decoding a 17 when using the PDF for rate level 10 is zero, ensuring that the number of LSBs for a block will not exceed 10. The cumulative distribution for rate level 10 is just a shifted version of that for 9 and thus does not require any additional storage.

Rate Level	PDF
0	{131, 74, 25, 8, 3, 3, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1}/256
1	{58, 93, 60, 23, 7, 3, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1}/256
2	{43, 51, 46, 33, 24, 16, 11, 8, 6, 3, 3, 3, 2, 1, 1, 2, 1, 2}/256
3	{17, 52, 71, 57, 31, 12, 5, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1}/256
4	{6, 21, 41, 53, 49, 35, 21, 11, 6, 3, 2, 2, 1, 1, 1, 1, 1, 1}/256
5	{7, 14, 22, 28, 29, 28, 25, 20, 17, 13, 11, 9, 7, 5, 4, 4, 3, 10}/256
6	{2, 5, 14, 29, 42, 46, 41, 31, 19, 11, 6, 3, 2, 1, 1, 1, 1, 1}/256
7	{1, 2, 4, 10, 19, 29, 35, 37, 34, 28, 20, 14, 8, 5, 4, 2, 2, 2}/256
8	{1, 2, 2, 5, 9, 14, 20, 24, 27, 28, 26, 23, 20, 15, 11, 8, 6, 15}/256
9	{1, 1, 1, 6, 27, 58, 56, 39, 25, 14, 10, 6, 3, 3, 2, 1, 1, 2}/256
10	{2, 1, 6, 27, 58, 56, 39, 25, 14, 10, 6, 3, 3, 2, 1, 1, 2, 0}/256

Table 46: PDFs for the Pulse Count

4.2.7.8.3. Pulse Location Decoding

The locations of the pulses in each shell block follow the pulse counts, as decoded by `silk_shell_decoder()` (`shell_coder.c`). As with the pulse counts, these locations are coded for all the shell blocks before any of the remaining information for each block. Unlike many other codecs, SILK places no restriction on the distribution of pulses within a shell block. All of the pulses may be placed in a

single location, or each one in a unique location, or anything in between.

The location of pulses is coded by recursively partitioning each block into halves, and coding how many pulses fall on the left side of the split. All remaining pulses must fall on the right side of the split. The process then recurses into the left half, and after that returns, the right half (preorder traversal). The PDF to use is chosen by the size of the current partition (16, 8, 4, or 2) and the number of pulses in the partition (1 to 16, inclusive). Tables 47 through 50 list the PDFs used for each partition size and pulse count. This process skips partitions without any pulses, i.e., where the initial pulse count from Section 4.2.7.8.2 was zero, or where the split in the prior level indicated that all of the pulses fell on the other side. These partitions have nothing to code, so they require no PDF.

Pulse Count	PDF
1	$\{126, 130\}/256$
2	$\{56, 142, 58\}/256$
3	$\{25, 101, 104, 26\}/256$
4	$\{12, 60, 108, 64, 12\}/256$
5	$\{7, 35, 84, 87, 37, 6\}/256$
6	$\{4, 20, 59, 86, 63, 21, 3\}/256$
7	$\{3, 12, 38, 72, 75, 42, 12, 2\}/256$
8	$\{2, 8, 25, 54, 73, 59, 27, 7, 1\}/256$
9	$\{2, 5, 17, 39, 63, 65, 42, 18, 4, 1\}/256$
10	$\{1, 4, 12, 28, 49, 63, 54, 30, 11, 3, 1\}/256$
11	$\{1, 4, 8, 20, 37, 55, 57, 41, 22, 8, 2, 1\}/256$
12	$\{1, 3, 7, 15, 28, 44, 53, 48, 33, 16, 6, 1, 1\}/256$
13	$\{1, 2, 6, 12, 21, 35, 47, 48, 40, 25, 12, 5, 1, 1\}/256$
14	$\{1, 1, 4, 10, 17, 27, 37, 47, 43, 33, 21, 9, 4, 1, 1\}/256$
15	$\{1, 1, 1, 8, 14, 22, 33, 40, 43, 38, 28, 16, 8, 1, 1, 1\}/256$
16	$\{1, 1, 1, 1, 13, 18, 27, 36, 41, 41, 34, 24, 14, 1, 1, 1, 1\}/256$

Table 47: PDFs for Pulse Count Split, 16 Sample Partitions

Pulse Count	PDF
1	$\{127, 129\}/256$
2	$\{53, 149, 54\}/256$
3	$\{22, 105, 106, 23\}/256$
4	$\{11, 61, 111, 63, 10\}/256$
5	$\{6, 35, 86, 88, 36, 5\}/256$
6	$\{4, 20, 59, 87, 62, 21, 3\}/256$
7	$\{3, 13, 40, 71, 73, 41, 13, 2\}/256$
8	$\{3, 9, 27, 53, 70, 56, 28, 9, 1\}/256$
9	$\{3, 8, 19, 37, 57, 61, 44, 20, 6, 1\}/256$
10	$\{3, 7, 15, 28, 44, 54, 49, 33, 17, 5, 1\}/256$
11	$\{1, 7, 13, 22, 34, 46, 48, 38, 28, 14, 4, 1\}/256$
12	$\{1, 1, 11, 22, 27, 35, 42, 47, 33, 25, 10, 1, 1\}/256$
13	$\{1, 1, 6, 14, 26, 37, 43, 43, 37, 26, 14, 6, 1, 1\}/256$
14	$\{1, 1, 4, 10, 20, 31, 40, 42, 40, 31, 20, 10, 4, 1, 1\}/256$
15	$\{1, 1, 3, 8, 16, 26, 35, 38, 38, 35, 26, 16, 8, 3, 1, 1\}/256$
16	$\{1, 1, 2, 6, 12, 21, 30, 36, 38, 36, 30, 21, 12, 6, 2, 1, 1\}/256$

Table 48: PDFs for Pulse Count Split, 8 Sample Partitions

Pulse Count	PDF
1	$\{127, 129\}/256$
2	$\{49, 157, 50\}/256$
3	$\{20, 107, 109, 20\}/256$
4	$\{11, 60, 113, 62, 10\}/256$
5	$\{7, 36, 84, 87, 36, 6\}/256$
6	$\{6, 24, 57, 82, 60, 23, 4\}/256$
7	$\{5, 18, 39, 64, 68, 42, 16, 4\}/256$
8	$\{6, 14, 29, 47, 61, 52, 30, 14, 3\}/256$
9	$\{1, 15, 23, 35, 51, 50, 40, 30, 10, 1\}/256$
10	$\{1, 1, 21, 32, 42, 52, 46, 41, 18, 1, 1\}/256$
11	$\{1, 6, 16, 27, 36, 42, 42, 36, 27, 16, 6, 1\}/256$
12	$\{1, 5, 12, 21, 31, 38, 40, 38, 31, 21, 12, 5, 1\}/256$
13	$\{1, 3, 9, 17, 26, 34, 38, 38, 34, 26, 17, 9, 3, 1\}/256$
14	$\{1, 3, 7, 14, 22, 29, 34, 36, 34, 29, 22, 14, 7, 3, 1\}/256$
15	$\{1, 2, 5, 11, 18, 25, 31, 35, 35, 31, 25, 18, 11, 5, 2, 1\}/256$
16	$\{1, 1, 4, 9, 15, 21, 28, 32, 34, 32, 28, 21, 15, 9, 4, 1, 1\}/256$

Table 49: PDFs for Pulse Count Split, 4 Sample Partitions

Pulse Count	PDF
1	$\{128, 128\}/256$
2	$\{42, 172, 42\}/256$
3	$\{21, 107, 107, 21\}/256$
4	$\{12, 60, 112, 61, 11\}/256$
5	$\{8, 34, 86, 86, 35, 7\}/256$
6	$\{8, 23, 55, 90, 55, 20, 5\}/256$
7	$\{5, 15, 38, 72, 72, 36, 15, 3\}/256$
8	$\{6, 12, 27, 52, 77, 47, 20, 10, 5\}/256$
9	$\{6, 19, 28, 35, 40, 40, 35, 28, 19, 6\}/256$
10	$\{4, 14, 22, 31, 37, 40, 37, 31, 22, 14, 4\}/256$
11	$\{3, 10, 18, 26, 33, 38, 38, 33, 26, 18, 10, 3\}/256$
12	$\{2, 8, 13, 21, 29, 36, 38, 36, 29, 21, 13, 8, 2\}/256$
13	$\{1, 5, 10, 17, 25, 32, 38, 38, 32, 25, 17, 10, 5, 1\}/256$
14	$\{1, 4, 7, 13, 21, 29, 35, 36, 35, 29, 21, 13, 7, 4, 1\}/256$
15	$\{1, 2, 5, 10, 17, 25, 32, 36, 36, 32, 25, 17, 10, 5, 2, 1\}/256$
16	$\{1, 2, 4, 7, 13, 21, 28, 34, 36, 34, 28, 21, 13, 7, 4, 2, 1\}/256$

Table 50: PDFs for Pulse Count Split, 2 Sample Partitions

4.2.7.8.4. LSB Decoding

After the decoder reads the pulse locations for all blocks, it reads the LSBs (if any) for each block in turn. Inside each block, it reads all the LSBs for each coefficient in turn, even those where no

pulses were allocated, before proceeding to the next one. They are coded from most significant to least significant, and they all use the PDF in Table 51.

PDF
{136, 120}/256

Table 51: PDF for Excitation LSBs

The number of LSBs read for each coefficient in a block is determined in Section 4.2.7.8.2. The magnitude of the coefficient is initially equal to the number of pulses placed at that location in Section 4.2.7.8.3. As each LSB is decoded, the magnitude is doubled, and then the value of the LSB added to it, to obtain an updated magnitude.

4.2.7.8.5. Sign Decoding

After decoding the pulse locations and the LSBs, the decoder knows the magnitude of each coefficient in the excitation. It then decodes a sign for all coefficients with a non-zero magnitude, using one of the PDFs from Table 52. If the value decoded is 0, then the coefficient magnitude is negated. Otherwise, it remains positive.

The decoder chooses the PDF for the sign based on the signal type and quantization offset type (from Section 4.2.7.3) and the number of pulses in the block (from Section 4.2.7.8.2). The number of pulses in the block does not take into account any LSBs. Most PDFs are skewed towards negative signs because of the quantization offset, but the PDFs for zero pulses are highly skewed towards positive signs. If a block contains many positive coefficients, it is sometimes beneficial to code it solely using LSBs (i.e., with zero pulses), since the encoder may be able to save enough bits on the signs to justify the less efficient coefficient magnitude encoding.

Signal Type	Quantization Offset Type	Pulse Count	PDF
Inactive	Low	0	{2, 254}/256
Inactive	Low	1	{207, 49}/256
Inactive	Low	2	{189, 67}/256

Inactive	Low	3	{179, 77}/256
Inactive	Low	4	{174, 82}/256
Inactive	Low	5	{163, 93}/256
Inactive	Low	6 or more	{157, 99}/256
Inactive	High	0	{58, 198}/256
Inactive	High	1	{245, 11}/256
Inactive	High	2	{238, 18}/256
Inactive	High	3	{232, 24}/256
Inactive	High	4	{225, 31}/256
Inactive	High	5	{220, 36}/256
Inactive	High	6 or more	{211, 45}/256
Unvoiced	Low	0	{1, 255}/256
Unvoiced	Low	1	{210, 46}/256
Unvoiced	Low	2	{190, 66}/256
Unvoiced	Low	3	{178, 78}/256
Unvoiced	Low	4	{169, 87}/256
Unvoiced	Low	5	{162, 94}/256
Unvoiced	Low	6 or more	{152, 104}/256
Unvoiced	High	0	{48, 208}/256
Unvoiced	High	1	{242, 14}/256
Unvoiced	High	2	{235, 21}/256
Unvoiced	High	3	{224, 32}/256
Unvoiced	High	4	{214, 42}/256
Unvoiced	High	5	{205, 51}/256

Unvoiced	High	6 or more	{190, 66}/256
Voiced	Low	0	{1, 255}/256
Voiced	Low	1	{162, 94}/256
Voiced	Low	2	{152, 104}/256
Voiced	Low	3	{147, 109}/256
Voiced	Low	4	{144, 112}/256
Voiced	Low	5	{141, 115}/256
Voiced	Low	6 or more	{138, 118}/256
Voiced	High	0	{8, 248}/256
Voiced	High	1	{203, 53}/256
Voiced	High	2	{187, 69}/256
Voiced	High	3	{176, 80}/256
Voiced	High	4	{168, 88}/256
Voiced	High	5	{161, 95}/256
Voiced	High	6 or more	{154, 102}/256

Table 52: PDFs for Excitation Signs

4.2.7.8.6. Reconstructing the Excitation

After the signs have been read, there is enough information to reconstruct the complete excitation signal. This requires adding a constant quantization offset to each non-zero sample, and then pseudorandomly inverting and offsetting every sample. The constant quantization offset varies depending on the signal type and quantization offset type (see Section 4.2.7.3).

Signal Type	Quantization Offset Type	Quantization Offset (Q25)
Inactive	Low	100
Inactive	High	240
Unvoiced	Low	100
Unvoiced	High	240
Voiced	Low	32
Voiced	High	100

Table 53: Excitation Quantization Offsets

Let `e_raw[i]` be the raw excitation value at position `i`, with a magnitude composed of the pulses at that location (see Section 4.2.7.8.3) combined with any additional LSBs (see Section 4.2.7.8.4), and with the corresponding sign decoded in Section 4.2.7.8.5. Additionally, let `seed` be the current pseudorandom seed, which is initialized to the value decoded from Section 4.2.7.7 for the first sample in the current SILK frame, and updated for each subsequent sample according to the procedure below. Finally, let `offset_Q25` be the quantization offset from Table 53. Then the following procedure produces the final reconstructed excitation value, `e_Q25[i]`:

```

e_Q25[i] = (e_raw[i] << 10) - sign(e_raw[i])*80 + offset_Q25;
seed = (196314165*seed + 907633515) & 0xFFFFFFFF;
e_Q25[i] = (seed & 0x80000000) ? -(e_Q25[i] + 1) : e_Q25[i];
seed = (seed + e_raw[i]) & 0xFFFFFFFF;

```

When `e_raw[i]` is zero, `sign()` returns 0 by the definition in Section 1.1.4, so the 80 term does not get added. `offset` does not get added. The final `e_Q25[i]` value may require more than 16 bits per sample, but will not require more than 25, including the sign.

4.2.7.9. SILK Frame Reconstruction

The remainder of the reconstruction process for the frame does not need to be bit-exact, as small errors should only introduce proportionally small distortions. Although the reference implementation only includes a fixed-point version of the remaining steps, this section describes them in terms of a floating-point

version for simplicity. This produces a signal with a nominal range of -1.0 to 1.0.

`silk_decode_core()` (`decode_core.c`) contains the code for the main reconstruction process. It proceeds subframe-by-subframe, since quantization gains, LTP parameters, and (in 20 ms SILK frames) LPC coefficients can vary from one to the next.

Let `a_Q12[k]` be the LPC coefficients for the current subframe. If this is the first or second subframe of a 20 ms SILK frame and the LSF interpolation factor, `w_Q2` (see Section 4.2.7.5.5), is less than 4, then these correspond to the final LPC coefficients produced by Section 4.2.7.5.8 from the interpolated LSF coefficients, `n1_Q15[k]` (computed in Section 4.2.7.5.5). Otherwise, they correspond to the final LPC coefficients produced from the uninterpolated LSF coefficients for the current frame, `n2_Q15[k]`.

Also, let `n` be the number of samples in a subframe (40 for NB, 60 for MB, and 80 for WB), `s` be the index of the current subframe in this SILK frame (0 or 1 for 10 ms frames, or 0 to 3 for 20 ms frames), and `j` be the index of the first sample in the residual corresponding to the current subframe.

4.2.7.9.1. LTP Synthesis

Voiced SILK frames (see Section 4.2.7.3) pass the excitation through an LTP filter using the parameters decoded in Section 4.2.7.6 to produce an LPC residual. The LTP filter requires LPC residual values from before the current subframe as input. However, since the LPCs may have changed, it obtains this residual by "rewhitening" the corresponding output signal using the LPCs from the current subframe. Let `e_Q25[i]` be the excitation, and `out[i]` be the fully reconstructed output signal from previous subframes (see Section 4.2.7.9.2), or zeros in the first subframe for this channel after either

- o An uncoded regular SILK frame in the side channel, or
- o A decoder reset (see Section 4.5).

Let `LTP_scale_Q14` be the LTP scaling parameter from Section 4.2.7.6.3 for the first two subframes in any SILK frame, as well as the last two subframes in a 20 ms SILK frame where `w_Q2 == 4`. Otherwise let `LTP_scale_Q14` be 16384 (corresponding to 1.0). Then, for `i` such that $(j - \text{pitch_lags}[s] - d_LPC - 2) \leq i < j$, where `pitch_lags[s]` is the pitch lag for the current subframe from Section 4.2.7.6.1, `out[i]` is rewhitened into an LPC residual, `res[i]`, via

$$\text{res}[i] = \frac{4.0 * \text{LTP_scale_Q14}}{\text{max}(\text{gain_Q16}[s], 131076)} * \text{clamp}(-1.0, \frac{\text{d_LPC}-1}{\sum_{k=0}^{\text{d_LPC}-1} \text{out}[i-k-1] * \frac{\text{a_Q12}[k]}{4096.0}}, 1.0) .$$

This requires storage to buffer up to 306 values of $\text{out}[i]$ from previous subframes. This corresponds to WB with a maximum of 18 ms * 16 kHz samples of pitch lag, plus 2 samples for the width of the LTP filter, plus 16 samples for d_LPC .

Let $\text{b_Q7}[k]$ be the coefficients of the LTP filter taken from the codebook entry in one of Tables 39 through 41 corresponding to the index decoded for the current subframe in Section 4.2.7.6.2. Then for i such that $j \leq i < (j + n)$, the LPC residual is

$$\text{res}[i] = \frac{\text{e_Q25}[i]}{33554432.0} + \frac{\sum_{k=0}^4 \text{res}[i - \text{pitch_lags}[s] + 2 - k] * \frac{\text{b_Q7}[k]}{128.0}}{\sum_{k=0}^4 1}$$

For unvoiced frames, the LPC residual for $j \leq i < (j + n)$ is simply a normalized copy of the excitation signal, i.e.,

$$\text{res}[i] = \frac{\text{e_Q25}[i]}{33554432.0}$$

4.2.7.9.2. LPC Synthesis

LPC synthesis uses the short-term LPC filter to predict the next output coefficient. For i such that $(j - \text{d_LPC}) \leq i < j$, let $\text{lpc}[i]$ be the result of LPC synthesis from the previous subframe, or zeros in the first subframe for this channel after either

- o An uncoded regular SILK frame in the side channel, or
- o A decoder reset (see Section 4.5).

Then for i such that $j \leq i < (j + n)$, the result of LPC synthesis for the current subframe is

$$\text{lpc}[i] = \frac{\text{gain_Q16}[i]}{65536.0} * \text{res}[i] + \sum_{k=0}^{\text{d_LPC}-1} \text{lpc}[i-k-1] * \frac{\text{a_Q12}[k]}{4096.0} .$$

The decoder saves the final d_LPC values, i.e., lpc[i] such that (j + n - d_LPC) <= i < (j + n), to feed into the LPC synthesis of the next subframe. This requires storage for up to 16 values of lpc[i] (for WB frames).

Then, the signal is clamped into the final nominal range:

$$\text{out}[i] = \text{clamp}(-1.0, \text{lpc}[i], 1.0) .$$

This clamping occurs entirely after the LPC synthesis filter has run. The decoder saves the unclamped values, lpc[i], to feed into the LPC filter for the next subframe, but saves the clamped values, out[i], for rewhitening in voiced frames.

4.2.8. Stereo Unmixing

For stereo streams, after decoding a frame from each channel, the decoder must convert the mid-side (MS) representation into a left-right (LR) representation. The function `silk_stereo_MS_to_LR` (`stereo_MS_to_LR.c`) implements this process. In it, the decoder predicts the side channel using a) a simple low-passed version of the mid channel, and b) the unfiltered mid channel, using the prediction weights decoded in Section 4.2.7.1. This simple low-pass filter imposes a one-sample delay, and the unfiltered mid channel is also delayed by one sample. In order to allow seamless switching between stereo and mono, mono streams must also impose the same one-sample delay. The encoder requires an additional one-sample delay for both mono and stereo streams, though an encoder may omit the delay for mono if it knows it will never switch to stereo.

The unmixing process operates in two phases. The first phase lasts for 8 ms, during which it interpolates the prediction weights from the previous frame, `prev_w0_Q13` and `prev_w1_Q13`, to the values for the current frame, `w0_Q13` and `w1_Q13`. The second phase simply uses these weights for the remainder of the frame.

Let `mid[i]` and `side[i]` be the contents of `out[i]` (from Section 4.2.7.9.2) for the current mid and side channels, respectively, and let `left[i]` and `right[i]` be the corresponding stereo output channels. If the side channel is not coded (see Section 4.2.7.2), then `side[i]` is set to zero. Also let `j` be defined as in Section 4.2.7.9, `n1` be the number of samples in phase 1 (64 for

NB, 96 for MB, and 128 for WB), and n_2 be the total number of samples in the frame. Then for i such that $j \leq i < (j + n_2)$, the left and right channel output is

$$w_0 = \frac{\text{prev_w0_Q13}}{8192.0} + \min(i - j, n_1) * \frac{(w_0_Q13 - \text{prev_w0_Q13})}{8192.0 * n_1} ,$$

$$w_1 = \frac{\text{prev_w1_Q13}}{8192.0} + \min(i - j, n_1) * \frac{(w_1_Q13 - \text{prev_w1_Q13})}{8192.0 * n_1} ,$$

$$p_0 = \frac{\text{mid}[i-2] + 2 * \text{mid}[i-1] + \text{mid}[i]}{4.0} ,$$

$$\text{left}[i] = \text{clamp}(-1.0, (1 + w_1) * \text{mid}[i-1] + \text{side}[i-1] + w_0 * p_0, 1.0) ,$$

$$\text{right}[i] = \text{clamp}(-1.0, (1 - w_1) * \text{mid}[i-1] - \text{side}[i-1] - w_0 * p_0, 1.0) .$$

These formulas require two samples prior to index j , the start of the frame, for the mid channel, and one prior sample for the side channel. For the first frame after a decoder reset, zeros are used instead.

4.2.9. Resampling

After stereo unmixing (if any), the decoder applies resampling to convert the decoded SILK output to the sample rate desired by the application. This is necessary when decoding a Hybrid frame at SWB or FB sample rates, or whenever the decoder wants the output at a different sample rate than the internal SILK sampling rate (e.g., to allow a constant sample rate when the audio bandwidth changes, or to allow mixing with audio from other applications). The resampler itself is non-normative, and a decoder can use any method it wants to perform the resampling.

However, a minimum amount of delay is imposed to allow the resampler to operate, and this delay is normative, so that the corresponding delay can be applied to the MDCT layer in the encoder. A decoder is always free to use a resampler which requires more delay than allowed for here (e.g., to improve quality), but then it must delay the output of the MDCT layer by this extra amount. Keeping as much delay as possible on the encoder side allows an encoder which knows it will never use any of the SILK or Hybrid modes to skip this delay. By contrast, if it were all applied by the decoder, then a decoder which processes audio in fixed-size blocks would be forced to delay the output of CELT frames just in case of a later switch to a SILK or

Hybrid mode.

Table 54 gives the maximum resampler delay in samples at 48 kHz for each SILK audio bandwidth. The reference implementation is able to resample to any of the supported output sampling rates (8, 12, 16, 24, or 48 kHz) within or near this delay constraint. Because the actual output rate may not be 48 kHz, it may not be possible to achieve exactly these delays while using a whole number of input or output samples. Some resampling filters (including those used by the reference implementation) may add a delay that is not itself an exact integer at either rate. However, such deviations are unlikely to be perceptible. The delays listed here are the ones that should be targeted by the encoder.

Audio Bandwidth	Delay in Samples at 48 kHz
NB	18
MB	32
WB	24

Table 54: SILK Resampler Delay Allocations

4.3. CELT Decoder

An overview of the decoder is given in Figure 13.

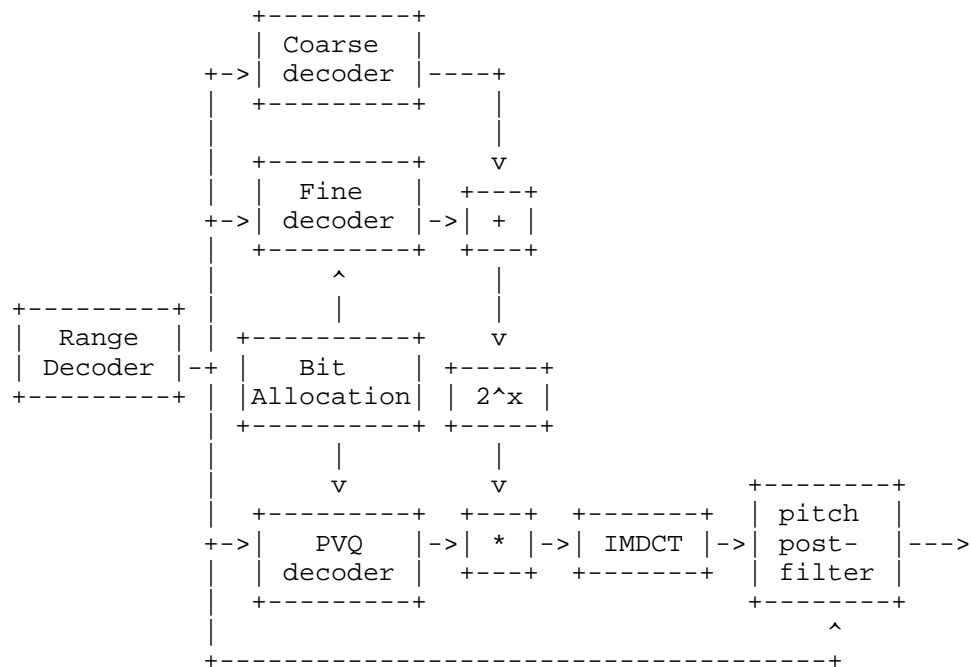


Figure 13: Structure of the CELT decoder

The decoder is based on the following symbols and sets of symbols:

Symbol(s)	PDF	Condition
silence	$\{32767, 1\}/32768$	
post-filter	$\{1, 1\}/2$	
octave	uniform (6)	post-filter
period	raw bits (4+octave)	post-filter
gain	raw bits (3)	post-filter
tapset	$\{2, 1, 1\}/4$	post-filter
transient	$\{7, 1\}/8$	
intra	$\{7, 1\}/8$	
coarse energy	Section 4.3.2	

tf_change	Section 4.3.1	
tf_select	{1, 1}/2	Section 4.3.1
spread	{7, 2, 21, 2}/32	
dyn. alloc.	Section 4.3.3	
alloc. trim	{2, 2, 5, 10, 22, 46, 22, 10, 5, 2, 2}/128	
skip	{1, 1}/2	Section 4.3.3
intensity	uniform	Section 4.3.3
dual	{1, 1}/2	
fine energy	Section 4.3.2	
residual	Section 4.3.4	
anti-collapse	{1, 1}/2	Section 4.3.5
finalize	Section 4.3.2	

Order of the symbols in the CELT section of the bitstream.

Table 55

The decoder extracts information from the range-coded bitstream in the order described in the figure above. In some circumstances, it is possible for a decoded value to be out of range due to a very small amount of redundancy in the encoding of large integers by the range coder. In that case, the decoder should assume there has been an error in the coding, decoding, or transmission and SHOULD take measures to conceal the error and/or report to the application that a problem has occurred.

4.3.1. Transient Decoding

The "transient" flag encoded in the bitstream has a probability of 1/8. When it is set, then the MDCT coefficients represent multiple short MDCTs in the frame. When not set, the coefficients represent a single long MDCT for the frame. In addition to the global transient flag is a per-band binary flag to change the time-frequency (tf) resolution independently in each band. The change in tf resolution is defined in `tf_select_table[][]` in `celt.c` and depends on the frame

size, whether the transient flag is set, and the value of `tf_select`. The `tf_select` flag uses a 1/2 probability, but is only decoded if it can have an impact on the result knowing the value of all per-band `tf_change` flags.

4.3.2. Energy Envelope Decoding

It is important to quantize the energy with sufficient resolution because any energy quantization error cannot be compensated for at a later stage. Regardless of the resolution used for encoding the shape of a band, it is perceptually important to preserve the energy in each band. CELT uses a three-step coarse-fine-fine strategy for encoding the energy in the base-2 log domain, as implemented in `quant_bands.c`

4.3.2.1. Coarse energy decoding

Coarse quantization of the energy uses a fixed resolution of 6 dB (integer part of base-2 log). To minimize the bitrate, prediction is applied both in time (using the previous frame) and in frequency (using the previous bands). The part of the prediction that is based on the previous frame can be disabled, creating an "intra" frame where the energy is coded without reference to prior frames. The decoder first reads the intra flag to determine what prediction is used. The 2-D z-transform of the prediction filter is:

$$A(z_l, z_b) = \frac{(1 - \alpha z_l^{-1})(1 - z_b^{-1})}{1 - \beta z_b^{-1}}$$

where `b` is the band index and `l` is the frame index. The prediction coefficients applied depend on the frame size in use when not using intra energy and are `alpha=0`, `beta=4915/32768` when using intra energy. The time-domain prediction is based on the final fine quantization of the previous frame, while the frequency domain (within the current frame) prediction is based on coarse quantization only (because the fine quantization has not been computed yet). The prediction is clamped internally so that fixed point implementations with limited dynamic range do not suffer desynchronization. We approximate the ideal probability distribution of the prediction error using a Laplace distribution with separate parameters for each frame size in intra- and inter-frame modes. The coarse energy quantization is performed by `unquant_coarse_energy()` and `unquant_coarse_energy_impl()` (`quant_bands.c`). The encoding of the Laplace-distributed values is implemented in `ec_laplace_decode()` (`laplace.c`).

4.3.2.2. Fine energy quantization

The number of bits assigned to fine energy quantization in each band is determined by the bit allocation computation described in Section 4.3.3. Let B_i be the number of fine energy bits for band i ; the refinement is an integer f in the range $[0, 2^{B_i}-1]$. The mapping between f and the correction applied to the coarse energy is equal to $(f+1/2)/2^{B_i} - 1/2$. Fine energy quantization is implemented in `quant_fine_energy()` (`quant_bands.c`).

When some bits are left "unused" after all other flags have been decoded, these bits are assigned to a "final" step of fine allocation. In effect, these bits are used to add one extra fine energy bit per band per channel. The allocation process determines two "priorities" for the final fine bits. Any remaining bits are first assigned only to bands of priority 0, starting from band 0 and going up. If all bands of priority 0 have received one bit per channel, then bands of priority 1 are assigned an extra bit per channel, starting from band 0. If any bits are left after this, they are left unused. This is implemented in `unquant_energy_finalise()` (`quant_bands.c`).

4.3.3. Bit Allocation

Many codecs transmit significant amounts of side information for the purpose of controlling bit allocation within a frame. Often this side information controls bit usage indirectly and must be carefully selected to achieve the desired rate constraints.

The band-energy normalized structure of Opus MDCT mode ensures that a constant bit allocation for the shape content of a band will result in a roughly constant tone to noise ratio, which provides for fairly consistent perceptual performance. The effectiveness of this approach is the result of two factors: that the band energy, which is understood to be perceptually important on its own, is always preserved regardless of the shape precision, and because the constant tone-to-noise ratio implies a constant intra-band noise to masking ratio. Intra-band masking is the strongest of the perceptual masking effects. This structure means that the ideal allocation is more consistent from frame to frame than it is for other codecs without an equivalent structure.

Because the bit allocation is used to drive the decoding of the range-coder stream, it MUST be recovered exactly so that identical coding decisions are made in the encoder and decoder. Any deviation from the reference's resulting bit allocation will result in corrupted output, though implementers are free to implement the procedure in any way which produces identical results.

Because all of the information required to decode a frame must be derived from that frame alone in order to retain robustness to packet loss, the overhead of explicitly signaling the allocation would be considerable, especially for low-latency (small frame size) applications, even though the allocation is relatively static.

For this reason, in the MDCT mode Opus uses a primarily implicit bit allocation. The available bitstream capacity is known in advance to both the encoder and decoder without additional signaling, ultimately from the packet sizes expressed by a higher-level protocol. Using this information the codec interpolates an allocation from a hard-coded table.

While the band-energy structure effectively models intra-band masking, it ignores the weaker inter-band masking, band-temporal masking, and other less significant perceptual effects. While these effects can often be ignored, they can become significant for particular samples. One mechanism available to encoders would be to simply increase the overall rate for these frames, but this is not possible in a constant rate mode and can be fairly inefficient. As a result three explicitly signaled mechanisms are provided to alter the implicit allocation:

- o Band boost
- o Allocation trim
- o Band skipping

The first of these mechanisms, band boost, allows an encoder to boost the allocation in specific bands. The second, allocation trim, works by biasing the overall allocation towards higher or lower frequency bands. The third, band skipping, selects which low-precision high frequency bands will be allocated no shape bits at all.

In stereo mode there are two additional parameters potentially coded as part of the allocation procedure: a parameter to allow the selective elimination of allocation for the 'side' in jointly coded bands, and a flag to deactivate joint coding. These values are not signaled if they would be meaningless in the overall context of the allocation.

Because every signaled adjustment increases overhead and implementation complexity, none were included speculatively: the reference encoder makes use of all of these mechanisms. While the decision logic in the reference was found to be effective enough to justify the overhead and complexity, further analysis techniques may be discovered which increase the effectiveness of these parameters.

As with other signaled parameters, an encoder is free to choose the values in any manner, but unless a technique is known to deliver superior perceptual results the methods used by the reference implementation should be used.

The allocation process consists of the following steps: determining the per-band maximum allocation vector, decoding the boosts, decoding the tilt, determining the remaining capacity of the frame, searching the mode table for the entry nearest but not exceeding the available space (subject to the tilt, boosts, band maximums, and band minimums), linear interpolation, reallocation of unused bits with concurrent skip decoding, determination of the fine-energy vs. shape split, and final reallocation. This process results in a per-band shape allocation (in 1/8th bit units), a per-band fine-energy allocation (in 1 bit per channel units), a set of band priorities for controlling the use of remaining bits at the end of the frame, and a remaining balance of unallocated space, which is usually zero except at very high rates.

The maximum allocation vector is an approximation of the maximum space that can be used by each band for a given mode. The value is approximate because the shape encoding is variable rate (due to entropy coding of splitting parameters). Setting the maximum too low reduces the maximum achievable quality in a band while setting it too high may result in waste: bitstream capacity available at the end of the frame which can not be put to any use. The maximums specified by the codec reflect the average maximum. In the reference the maximums are provided in partially computed form, in order to fit in less memory as a static table (see `cache_caps50[]` in `static_modes_float.h`). Implementations are expected to simply use the same table data, but the procedure for generating this table is included in `rate.c` as part of `compute_pulse_cache()`.

To convert the values in `cache.caps` into the actual maximums: first set `nbBands` to the maximum number of bands for this mode, and `stereo` to zero if stereo is not in use and one otherwise. For each band set `N` to the number of MDCT bins covered by the band (for one channel), set `LM` to the shift value for the frame size (e.g. 0 for 120, 1 for 240, 3 for 480), then set `i` to `nbBands*(2*LM+stereo)`. Then set the maximum for the band to the `i`-th index of `cache.caps + 64` and multiply by the number of channels in the current frame (one or two) and by `N`, then divide the result by 4 using truncating integer division. The resulting vector will be called `cap[]`. The elements fit in signed 16-bit integers but do not fit in 8 bits. This procedure is implemented in the reference in the function `init_caps()` in `celt.c`.

The band boosts are represented by a series of binary symbols which

are coded with very low probability. Each band can potentially be boosted multiple times, subject to the frame actually having enough room to obey the boost and having enough room to code the boost symbol. The default coding cost for a boost starts out at six bits, but subsequent boosts in a band cost only a single bit and every time a band is boosted the initial cost is reduced (down to a minimum of two). Since the initial cost of coding a boost is 6 bits, the coding cost of the boost symbols when completely unused is 0.48 bits/frame for a 21 band mode ($21 * -\log_2(1 - 1/2^6)$).

To decode the band boosts: First set 'dynalloc_logp' to 6, the initial amount of storage required to signal a boost in bits, 'total_bits' to the size of the frame in 8th bits, 'total_boost' to zero, and 'tell' to the total number of 8th bits decoded so far. For each band from the coding start (0 normally, but 17 in Hybrid mode) to the coding end (which changes depending on the signaled bandwidth): set 'width' to the number of MDCT bins in this band for all channels. Take the larger of width and 64, then the minimum of that value and the width times eight and set 'quanta' to the result. This represents a boost step size of six bits subject to limits of 1/bit/sample and 1/8th bit/sample. Set 'boost' to zero and 'dynalloc_loop_logp' to dynalloc_logp. While dynalloc_loop_log (the current worst case symbol cost) in 8th bits plus tell is less than total_bits plus total_boost and boost is less than cap[] for this band: Decode a bit from the bitstream with a with dynalloc_loop_logp as the cost of a one, update tell to reflect the current used capacity, if the decoded value is zero break the loop otherwise add quanta to boost and total_boost, subtract quanta from total_bits, and set dynalloc_loop_log to 1. When the while loop finishes boost contains the boost for this band. If boost is non-zero and dynalloc_logp is greater than 2, decrease dynalloc_logp. Once this process has been executed on all bands, the band boosts have been decoded. This procedure is implemented around line 2352 of celt.c.

At very low rates it is possible that there won't be enough available space to execute the inner loop even once. In these cases band boost is not possible but its overhead is completely eliminated. Because of the high cost of band boost when activated, a reasonable encoder should not be using it at very low rates. The reference implements its dynalloc decision logic around line 1269 of celt.c.

The allocation trim is a integer value from 0-10. The default value of 5 indicates no trim. The trim parameter is entropy coded in order to lower the coding cost of less extreme adjustments. Values lower than 5 bias the allocation towards lower frequencies and values above 5 bias it towards higher frequencies. Like other signaled parameters, signaling of the trim is gated so that it is not included if there is insufficient space available in the bitstream. To decode

the trim, first set the trim value to 5, then iff the count of decoded 8th bits so far (`ec_tell_frac`) plus 48 (6 bits) is less than or equal to the total frame size in 8th bits minus `total_boost` (a product of the above band boost procedure), decode the trim value using the inverse CDF {127, 126, 124, 119, 109, 87, 41, 19, 9, 4, 2, 0}.

For 10 ms and 20 ms frames using short blocks and that have at least `LM+2` bits left prior to the allocation process, then one anti-collapse bit is reserved in the allocation process so it can be decoded later. Following the the anti-collapse reservation, one bit is reserved for skip if available.

For stereo frames, bits are reserved for intensity stereo and for dual stereo. Intensity stereo requires $\text{ilog2}(\text{end}-\text{start})$ bits. Those bits are reserved if there is enough bits left. Following this, one bit is reserved for dual stereo if available.

The allocation computation begins by setting up some initial conditions. 'total' is set to the remaining available 8th bits, computed by taking the size of the coded frame times 8 and subtracting `ec_tell_frac()`. From this value, one (8th bit) is subtracted to ensure that the resulting allocation will be conservative. 'anti_collapse_rsv' is set to 8 (8th bits) iff the frame is a transient, `LM` is greater than 1, and total is greater than or equal to $(\text{LM}+2) * 8$. Total is then decremented by `anti_collapse_rsv` and clamped to be equal to or greater than zero. 'skip_rsv' is set to 8 (8th bits) if total is greater than 8, otherwise it is zero. Total is then decremented by `skip_rsv`. This reserves space for the final skipping flag.

If the current frame is stereo, `intensity_rsv` is set to the conservative \log_2 in 8th bits of the number of coded bands for this frame (given by the table `LOG2_FRAC_TABLE`). If `intensity_rsv` is greater than total then `intensity_rsv` is set to zero. Otherwise total is decremented by `intensity_rsv`, and if total is still greater than 8, `dual_stereo_rsv` is set to 8 and total is decremented by `dual_stereo_rsv`.

The allocation process then computes a vector representing the hard minimum amounts allocation any band will receive for shape. This minimum is higher than the technical limit of the PVQ process, but very low rate allocations produce an excessively sparse spectrum and these bands are better served by having no allocation at all. For each coded band, set `thresh[band]` to twenty-four times the number of MDCT bins in the band and divide by 16. If 8 times the number of channels is greater, use that instead. This sets the minimum allocation to one bit per channel or 48 128th bits per MDCT bin,

whichever is greater. The band-size dependent part of this value is not scaled by the channel count, because at the very low rates where this limit is applicable there will usually be no bits allocated to the side.

The previously decoded allocation trim is used to derive a vector of per-band adjustments, 'trim_offsets[]'. For each coded band take the alloc_trim and subtract 5 and LM. Then multiply the result by the number of channels, the number of MDCT bins in the shortest frame size for this mode, the number of remaining bands, $2 \times \text{LM}$, and 8. Then divide this value by 64. Finally, if the number of MDCT bins in the band per channel is only one, 8 times the number of channels is subtracted in order to diminish the allocation by one bit, because width 1 bands receive greater benefit from the coarse energy coding.

4.3.4. Shape Decoding

In each band, the normalized "shape" is encoded using a vector quantization scheme called a "pyramid vector quantizer".

In the simplest case, the number of bits allocated in Section 4.3.3 is converted to a number of pulses as described by Section 4.3.4.1. Knowing the number of pulses and the number of samples in the band, the decoder calculates the size of the codebook as detailed in Section 4.3.4.2. The size is used to decode an unsigned integer (uniform probability model), which is the codeword index. This index is converted into the corresponding vector as explained in Section 4.3.4.2. This vector is then scaled to unit norm.

4.3.4.1. Bits to Pulses

Although the allocation is performed in 1/8th bit units, the quantization requires an integer number of pulses K . To do this, the encoder searches for the value of K that produces the number of bits nearest to the allocated value (rounding down if exactly halfway between two values), not to exceed the total number of bits available. For efficiency reasons, the search is performed against a precomputed allocation table which only permits some K values for each N . The number of codebook entries can be computed as explained in Section 4.3.4.2. The difference between the number of bits allocated and the number of bits used is accumulated to a "balance" (initialized to zero) that helps adjust the allocation for the next bands. One third of the balance is applied to the bit allocation of each band to help achieve the target allocation. The only exceptions are the band before the last and the last band, for which half the balance and the whole balance are applied, respectively.

4.3.4.2. PVQ Decoding

Decoding of PVQ vectors is implemented in `decode_pulses()` (`cwrs.c`). The unique codeword index is decoded as a uniformly-distributed integer value between 0 and $V(N,K)-1$, where $V(N,K)$ is the number of possible combinations of K pulses in N samples. The index is then converted to a vector in the same way specified in [PVQ]. The indexing is based on the calculation of $V(N,K)$ (denoted $N(L,K)$ in [PVQ]).

The number of combinations can be computed recursively as $V(N,K) = V(N-1,K) + V(N,K-1) + V(N-1,K-1)$, with $V(N,0) = 1$ and $V(0,K) = 0$, $K \neq 0$. There are many different ways to compute $V(N,K)$, including precomputed tables and direct use of the recursive formulation. The reference implementation applies the recursive formulation one line (or column) at a time to save on memory use, along with an alternate, univariate recurrence to initialize an arbitrary line, and direct polynomial solutions for small N . All of these methods are equivalent, and have different trade-offs in speed, memory usage, and code size. Implementations MAY use any methods they like, as long as they are equivalent to the mathematical definition.

The decoded vector is normalised such that its L2-norm equals one.

4.3.4.3. Spreading

The normalised vector decoded in Section 4.3.4.2 is then rotated for the purpose of avoiding tonal artefacts. The rotation gain is equal to

$$g_r = N / (N + f_r \cdot K)$$

where N is the number of dimensions, K is the number of pulses, and f_r depends on the value of the "spread" parameter in the bit-stream.

Spread value	f_r
0	infinite (no rotation)
1	15
2	10
3	5

Table 56: Spreading values

The rotation angle is then calculated as

$$\text{theta} = \frac{\pi * g_r^2}{4}$$

A 2-D rotation $R(i,j)$ between points x_i and x_j is defined as:

$$\begin{aligned} x_i' &= \cos(\text{theta}) * x_i + \sin(\text{theta}) * x_j \\ x_j' &= -\sin(\text{theta}) * x_i + \cos(\text{theta}) * x_j \end{aligned}$$

An N-D rotation is then achieved by applying a series of 2-D rotations back and forth, in the following order: $R(x_1, x_2)$, $R(x_2, x_3)$, ..., $R(x_{N-2}, x_{N-1})$, $R(x_{N-1}, x_N)$, $R(x_{N-2}, x_{N-1})$, ..., $R(x_1, x_2)$.

If the decoded vector represents more than one time block, then the following process is applied separately on each time block. Also, if each block represents 8 samples or more, then another N-D rotation, by $(\pi/2 - \text{theta})$, is applied before the rotation described above. This extra rotation is applied in an interleaved manner with a stride equal to $\text{round}(\sqrt{N/\text{nb_blocks}})$

4.3.4.4. Split decoding

To avoid the need for multi-precision calculations when decoding PVQ codevectors, the maximum size allowed for codebooks is 32 bits. When larger codebooks are needed, the vector is instead split in two sub-vectors of size $N/2$. A quantized gain parameter with precision derived from the current allocation is entropy coded to represent the relative gains of each side of the split, and the entire decoding process is recursively applied. Multiple levels of splitting may be applied up to a frame size dependent limit. The same recursive mechanism is applied for the joint coding of stereo audio.

4.3.4.5. Time-Frequency change

The time-frequency (TF) parameters are used to control the time-frequency resolution tradeoff in each coded band. For each band, there are two possible TF choices. For the first band coded, the PDF is $\{3, 1\}/4$ for frames marked as transient and $\{15, 1\}/16$ for the other frames. For subsequent bands, the TF choice is coded relative to the previous TF choice with probability $\{15, 1\}/15$ for transient frames and $\{31, 1\}/32$ otherwise. The mapping between the decoded TF choices and the adjustment in TF resolution is shown in the tables below.

Frame size (ms)	0	1
2.5	0	-1
5	0	-1
10	0	-2
20	0	-2

TF adjustments for non-transient frames and `tf_select=0`

Table 57

Frame size (ms)	0	1
2.5	0	-1
5	0	-2
10	0	-3
20	0	-3

TF adjustments for non-transient frames and `tf_select=1`

Table 58

Frame size (ms)	0	1
2.5	0	-1
5	1	0
10	2	0
20	3	0

TF adjustments for transient frames and `tf_select=0`

Table 59

Frame size (ms)	0	1
2.5	0	-1
5	1	-1
10	1	-1
20	1	-1

TF adjustments for transient frames and `tf_select=1`

Table 60

A negative TF adjustment means that the temporal resolution is increased, while a positive TF adjustment means that the frequency resolution is increased. Changes in TF resolution are implemented using the Hadamard transform. To increase the time resolution by N, N "levels" of the Hadamard transform are applied to the decoded vector for each interleaved MDCT vector. To increase the frequency resolution (assumes a transient frame), then N levels of the Hadamard transform are applied across the interleaved MDCT vector. In the case of increased time resolution the decoder uses the "sequency order" because the input vector is sorted in time.

4.3.5. Anti-Collapse Processing

When the frame has the transient bit set, an anti-collapse bit is decoded. When anti-collapse is set, the energy in each small MDCT is prevented from collapsing to zero. For each band of each MDCT where a collapse is detected, a pseudo-random signal is inserted with an energy corresponding to the min energy over the two previous frames. A renormalization step is then required to ensure that the anti-collapse step did not alter the energy preservation property.

4.3.6. Denormalization

Just like each band was normalized in the encoder, the last step of the decoder before the inverse MDCT is to denormalize the bands. Each decoded normalized band is multiplied by the square root of the decoded energy. This is done by `denormalise_bands()` (`bands.c`).

4.3.7. Inverse MDCT

The inverse MDCT implementation has no special characteristics. The input is N frequency-domain samples and the output is 2*N time-domain

samples, while scaling by 1/2. A "low-overlap" window is used to reduce the algorithmic delay. It is derived from a basic (full overlap) 240-sample version of the window used by the Vorbis codec:

$$W(n) = \left| \sin \left| \frac{\pi}{2} \left(\frac{n + 1/2}{L} \right) \right| \right|^2$$

The low-overlap window is created by zero-padding the basic window and inserting ones in the middle, such that the resulting window still satisfies power complementarity. The IMDCT and windowing are performed by `mdct_backward` (`mdct.c`).

4.3.7.1. Post-filter

The output of the inverse MDCT (after weighted overlap-add) is sent to the post-filter. Although the post-filter is applied at the end, the post-filter parameters are encoded at the beginning, just after the silence flag. The post-filter can be switched on or off using one bit (`logp=1`). If the post-filter is enabled, then the octave is decoded as an integer value between 0 and 6 of uniform probability. Once the octave is known, the fine pitch within the octave is decoded using 4+octave raw bits. The final pitch period is equal to $(16 \ll \text{octave}) + \text{fine_pitch} - 1$ so it is bounded between 15 and 1022, inclusively. Next, the gain is decoded as three raw bits and is equal to $G = 3 * (\text{int_gain} + 1) / 32$. The set of post-filter taps is decoded last, using a pdf equal to $\{2, 1, 1\} / 4$. Tapset zero corresponds to the filter coefficients $g_0 = 0.3066406250$, $g_1 = 0.2170410156$, $g_2 = 0.1296386719$. Tapset one corresponds to the filter coefficients $g_0 = 0.4638671875$, $g_1 = 0.2680664062$, $g_2 = 0$, and tapset two uses filter coefficients $g_0 = 0.7998046875$, $g_1 = 0.1000976562$, $g_2 = 0$.

The post-filter response is thus computed as:

$$y(n) = x(n) + G * (g_0 * y(n-T) + g_1 * (y(n-T+1) + y(n-T+1)) + g_2 * (y(n-T+2) + y(n-T+2)))$$

During a transition between different gains, a smooth transition is calculated using the square of the MDCT window. It is important that values of $y(n)$ be interpolated one at a time such that the past value of $y(n)$ used is interpolated.

4.3.7.2. De-emphasis

After the post-filter, the signal is de-emphasized using the inverse of the pre-emphasis filter used in the encoder:

$$\frac{1}{A(z)} = \frac{1}{1 - \alpha_p z^{-1}},$$

where $\alpha_p=0.8500061035$.

4.4. Packet Loss Concealment (PLC)

Packet loss concealment (PLC) is an optional decoder-side feature that SHOULD be included when receiving from an unreliable channel. Because PLC is not part of the bitstream, there are many acceptable ways to implement PLC with different complexity/quality trade-offs.

The PLC in the reference implementation depends on the mode of last packet received. In CELT mode, the PLC finds a periodicity in the decoded signal and repeats the windowed waveform using the pitch offset. The windowed waveform is overlapped in such a way as to preserve the time-domain aliasing cancellation with the previous frame and the next frame. This is implemented in `celt_decode_lost()` (`mdct.c`). In SILK mode, the PLC uses LPC extrapolation from the previous frame, implemented in `silk_PLC()` (`PLC.c`).

4.4.1. Clock Drift Compensation

Clock drift refers to the gradual desynchronization of two endpoints whose sample clocks run at different frequencies while they are streaming live audio. Differences in clock frequencies are generally attributable to manufacturing variation in the endpoints' clock hardware. For long-lived streams, the time difference between sender and receiver can grow without bound.

When the sender's clock runs slower than the receiver's, the effect is similar to packet loss: too few packets are received. The receiver can distinguish between drift and loss if the transport provides packet timestamps. A receiver for live streams SHOULD conceal the effects of drift, and MAY do so by invoking the PLC.

When the sender's clock runs faster than the receiver's, too many packets will be received. The receiver MAY respond by skipping any packet (i.e. not submitting the packet for decoding). This is likely to produce a less severe artifact than if the frame were dropped after decoding.

A decoder MAY employ a more sophisticated drift compensation method. For example, the NetEQ component [3] of the WebRTC.org codebase [4] compensates for drift by adding or removing one period when the signal is highly periodic. The reference implementation of Opus allows a caller to learn whether the current frame's signal is highly periodic, and if so what the period is, using the OPUS_GET_PITCH() request.

4.5. Configuration Switching

Switching between the Opus coding modes, audio bandwidths, and channel counts requires careful consideration to avoid audible glitches. Switching between any two configurations of the CELT-only mode, any two configurations of the Hybrid mode, or from WB SILK to Hybrid mode does not require any special treatment in the decoder, as the MDCT overlap will smooth the transition. Switching from Hybrid mode to WB SILK requires adding in the final contents of the CELT overlap buffer to the first SILK-only packet. This can be done by decoding a 2.5 ms silence frame with the CELT decoder using the channel count of the SILK-only packet (and any choice of audio bandwidth), which will correctly handle the cases when the channel count changes as well.

When changing the channel count for SILK-only or Hybrid packets, the encoder can avoid glitches by smoothly varying the stereo width of the input signal before or after the transition, and SHOULD do so. However, other transitions between SILK-only packets or between NB or MB SILK and Hybrid packets may cause glitches, because neither the LSF coefficients nor the LTP, LPC, stereo unmixing, and resampler buffers are available at the new sample rate. These switches SHOULD be delayed by the encoder until quiet periods or transients, where the inevitable glitches will be less audible. Additionally, the bitstream MAY include redundant side information ("redundancy"), in the form of additional CELT frames embedded in each of the Opus frames around the transition.

The other transitions that cannot be easily handled are those where the lower frequencies switch between the SILK LP-based model and the CELT MDCT model. However, an encoder may not have an opportunity to delay such a switch to a convenient point. For example, if the content switches from speech to music, and the encoder does not have enough latency in its analysis to detect this in advance, there may be no convenient silence period during which to make the transition for quite some time. To avoid or reduce glitches during these problematic mode transitions, and also between audio bandwidth changes in the SILK-only modes, transitions MAY include redundant side information ("redundancy"), in the form of an additional CELT frame embedded in the Opus frame.

A transition between coding the lower frequencies with the LP model and the MDCT model or a transition that involves changing the SILK bandwidth is only normatively specified when it includes redundancy. For those without redundancy, it is RECOMMENDED that the decoder use a concealment technique (e.g., make use of a PLC algorithm) to "fill in" the gap or discontinuity caused by the mode transition. Therefore, PLC MUST NOT be applied during any normative transition, i.e., when

- o A packet includes redundancy for this transition (as described below),
 - o The transition is between any WB SILK packet and any Hybrid packet, or vice versa,
 - o The transition is between any two Hybrid mode packets, or
 - o The transition is between any two CELT mode packets,
- unless there is actual packet loss.

4.5.1. Transition Side Information (Redundancy)

Transitions with side information include an extra 5 ms "redundant" CELT frame within the Opus frame. This frame is designed to fill in the gap or discontinuity in the different layers without requiring the decoder to conceal it. For transitions from CELT-only to SILK-only or Hybrid, the redundant frame is inserted in the first Opus frame after the transition (i.e., the first SILK-only or Hybrid frame). For transitions from SILK-only or Hybrid to CELT-only, the redundant frame is inserted in the last Opus frame before the transition (i.e., the last SILK-only or Hybrid frame).

4.5.1.1. Redundancy Flag

The presence of redundancy is signaled in all SILK-only and Hybrid frames, not just those involved in a mode transition. This allows the frames to be decoded correctly even if an adjacent frame is lost. For SILK-only frames, this signaling is implicit, based on the size of the Opus frame and the number of bits consumed decoding the SILK portion of it. After decoding the SILK portion of the Opus frame, the decoder uses `ec_tell()` (see Section 4.1.5.1) to check if there are at least 17 bits remaining. If so, then the frame contains redundancy.

For Hybrid frames, this signaling is explicit. After decoding the SILK portion of the Opus frame, the decoder uses `ec_tell()` (see Section 4.1.5.1) to ensure there are at least 37 bits remaining. If

so, it reads a symbol with the PDF in Table 61, and if the value is 1, then the frame contains redundancy. Otherwise (if there were fewer than 37 bits left or the value was 0), the frame does not contain redundancy.

+-----+
PDF
+-----+
{4095, 1}/4096
+-----+

Table 61: Redundancy Flag PDF

4.5.1.2. Redundancy Position Flag

Since the current frame is a SILK-only or a Hybrid frame, it must be at least 10 ms. Therefore, it needs an additional flag to indicate whether the redundant 5 ms CELT frame should be mixed into the beginning of the current frame, or the end. After determining that a frame contains redundancy, the decoder reads a 1 bit symbol with a uniform PDF (Table 62).

+-----+
PDF
+-----+
{1, 1}/2
+-----+

Table 62: Redundancy Position PDF

If the value is zero, this is the first frame in the transition, and the redundancy belongs at the end. If the value is one, this is the second frame in the transition, and the redundancy belongs at the beginning. There is no way to specify that an Opus frame contains separate redundant CELT frames at both the beginning and the end.

4.5.1.3. Redundancy Size

Unlike the CELT portion of a Hybrid frame, the redundant CELT frame does not use the same entropy coder state as the rest of the Opus frame, because this would break the CELT bit allocation mechanism in Hybrid frames. Thus, a redundant CELT frame always starts and ends on a byte boundary, even in SILK-only frames, where this is not strictly necessary.

For SILK-only frames, the number of bytes in the redundant CELT frame is simply the number of whole bytes remaining, which must be at least 2, due to the space check in Section 4.5.1.1. For Hybrid frames, the

number of bytes is equal to 2, plus a decoded unsigned integer less than 256 (see Section 4.1.4). This may be more than the number of whole bytes remaining in the Opus frame, in which case the frame is invalid. However, a decoder is not required to ignore the entire frame, as this may be the result of a bit error that desynchronized the range coder. There may still be useful data before the error, and a decoder MAY keep any audio decoded so far instead of invoking the PLC, but it is RECOMMENDED that the decoder stop decoding and discard the rest of the current Opus frame.

It would have been possible to avoid these invalid states in the design of Opus by limiting the range of the explicit length decoded from Hybrid frames by the actual number of whole bytes remaining. However, this would require an encoder to determine the rate allocation for the MDCT layer up front, before it began encoding that layer. By allowing some invalid sizes, the encoder is able to defer that decision until much later. When encoding Hybrid frames which do not include redundancy, the encoder must still decide up-front if it wishes to use the minimum 37 bits required to trigger encoding of the redundancy flag, but this is a much looser restriction.

After determining the size of the redundant CELT frame, the decoder reduces the size of the buffer currently in use by the range coder by that amount. The CELT layer read any raw bits from the end of this reduced buffer, and all calculations of the number of bits remaining in the buffer must be done using this new, reduced size, rather than the original size of the Opus frame.

4.5.1.4. Decoding the Redundancy

The redundant frame is decoded like any other CELT-only frame, with the exception that it does not contain a TOC byte. The frame size is fixed at 5 ms, the channel count is set to that of the current frame, and the audio bandwidth is also set to that of the current frame, with the exception that for MB SILK frames, it is set to WB.

If the redundancy belongs at the beginning (in a CELT-only to SILK-only or Hybrid transition), the final reconstructed output uses the first 2.5 ms of audio output by the decoder for the redundant frame is as-is, discarding the corresponding output from the SILK-only or Hybrid portion of the frame. The remaining 2.5 ms is cross-lapped with the decoded SILK/Hybrid signal using the CELT's power-complementary MDCT window to ensure a smooth transition.

If the redundancy belongs at the end (in a SILK-only or Hybrid to CELT-only transition), only the second half (2.5 ms) of the audio output by the decoder for the redundant frame is used. In that case, the second half of the redundant frame is cross-lapped with the end

of the SILK/Hybrid signal, again using CELT's power-complementary MDCT window to ensure a smooth transition.

4.5.2. State Reset

When a transition occurs, the state of the SILK or the CELT decoder (or both) may need to be reset before decoding a frame in the new mode. This avoids reusing "out of date" memory, which may not have been updated in some time or may not be in a well-defined state due to, e.g., PLC. The SILK state is reset before every SILK-only or Hybrid frame where the previous frame was CELT-only. The CELT state is reset every time the operating mode changes and the new mode is either Hybrid or CELT-only, except when the transition uses redundancy as described above. When switching from SILK-only or Hybrid to CELT-only with redundancy, the CELT state is reset before decoding the redundant CELT frame embedded in the SILK-only or Hybrid frame, but it is not reset before decoding the following CELT-only frame. When switching from CELT-only mode to SILK-only or Hybrid mode with redundancy, the CELT decoder is not reset for decoding the redundant CELT frame.

4.5.3. Summary of Transitions

Figure 14 illustrates all of the normative transitions involving a mode change, an audio bandwidth change, or both. Each one uses an S, H, or C to represent an Opus frames in the corresponding modes. In addition, an R indicates the presence of redundancy in the Opus frame it is cross-lapped with. Its location in the first or last 5 ms is assumed to correspond to whether it is the frame before or after the transition. Other uses of redundancy are non-normative. Finally, a c indicates the contents of the CELT overlap buffer after the previously decoded frame (i.e., as extracted by decoding a silence frame).

SILK to SILK with Redundancy:	$ \begin{array}{c} S \rightarrow S \rightarrow S \quad ; S \rightarrow S \rightarrow S \\ \quad \quad \quad \& \quad \quad \& \\ \quad \quad \quad !R \rightarrow R \end{array} $		
NB or MB SILK to Hybrid with Redundancy:	$ \begin{array}{c} S \rightarrow S \rightarrow S \\ \quad \quad \quad \& \\ \quad \quad \quad !R \rightarrow ; H \rightarrow H \rightarrow H \end{array} $		
WB SILK to Hybrid:	$S \rightarrow S \rightarrow S \rightarrow !H \rightarrow H \rightarrow H$		
SILK to CELT with Redundancy:	$ \begin{array}{c} S \rightarrow S \rightarrow S \\ \quad \quad \quad \& \\ \quad \quad \quad !R \rightarrow C \rightarrow C \rightarrow C \end{array} $		
Hybrid to NB or MB SILK with Redundancy:	$ \begin{array}{c} H \rightarrow H \rightarrow H \quad ; S \rightarrow S \rightarrow S \\ \quad \quad \quad \& \quad \quad \& \\ \quad \quad \quad !R \rightarrow R \end{array} $		
Hybrid to WB SILK:	$ \begin{array}{c} H \rightarrow H \rightarrow H \rightarrow c \\ \quad \quad \quad \quad \quad \backslash \quad + \\ \quad \quad \quad \quad \quad > S \rightarrow S \rightarrow S \end{array} $		
Hybrid to CELT with Redundancy:	$ \begin{array}{c} H \rightarrow H \rightarrow H \\ \quad \quad \quad \& \\ \quad \quad \quad !R \rightarrow C \rightarrow C \rightarrow C \end{array} $		
CELT to SILK with Redundancy:	$ \begin{array}{c} C \rightarrow C \rightarrow C \rightarrow R \\ \quad \quad \quad \& \\ \quad \quad \quad ; S \rightarrow S \rightarrow S \end{array} $		
CELT to Hybrid with Redundancy:	$ \begin{array}{c} C \rightarrow C \rightarrow C \rightarrow R \\ \quad \quad \quad \& \\ \quad \quad \quad H \rightarrow H \rightarrow H \end{array} $		
Key:			
S	SILK-only frame	;	SILK decoder reset
H	Hybrid frame		CELT and SILK decoder resets
C	CELT-only frame	!	CELT decoder reset
c	CELT overlap	+	Direct mixing
R	Redundant CELT frame	&	Windowed cross-lap

Figure 14: Normative Transitions

The first two and the last two Opus frames in each example are illustrative, i.e., there is no requirement that a stream remain in the same configuration for three consecutive frames before or after a switch.

The behavior of transitions without redundancy where PLC is allowed is non-normative. An encoder might still wish to use these transitions if, for example, it doesn't want to add the extra bitrate required for redundancy or if it makes a decision to switch after it has already transmitted the frame that would have had to contain the redundancy. Figure 15 illustrates the recommended cross-lapping and decoder resets for these transitions.

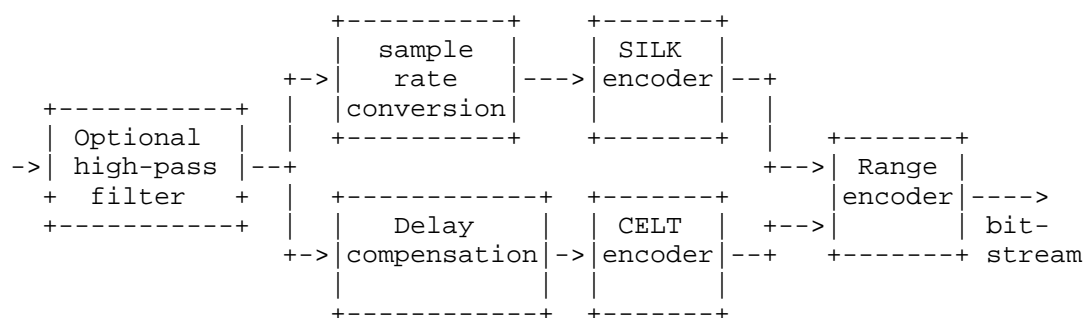
SILK to SILK (audio bandwidth change):	S -> S -> S ;S -> S -> S
NB or MB SILK to Hybrid:	S -> S -> S H -> H -> H
SILK to CELT without Redundancy:	S -> S -> S -> P & !C -> C -> C
Hybrid to NB or MB SILK:	H -> H -> H -> c + ;S -> S -> S
Hybrid to CELT without Redundancy:	H -> H -> H -> P & !C -> C -> C
CELT to SILK without Redundancy:	C -> C -> C -> P & ;S -> S -> S
CELT to Hybrid without Redundancy:	C -> C -> C -> P & H -> H -> H
Key:	
S SILK-only frame	; SILK decoder reset
H Hybrid frame	CELT and SILK decoder resets
C CELT-only frame	! CELT decoder reset
P Packet Loss Concealment	& Windowed cross-lap

Figure 15: Recommended Non-Normative Transitions

Encoders SHOULD NOT use other transitions, e.g., those that involve redundancy in ways not illustrated in Figure 14.

5. Opus Encoder

Just like the decoder, the Opus encoder also normally consists of two main blocks: the SILK encoder and the CELT encoder. However, unlike the case of the decoder, a valid (though potentially suboptimal) Opus encoder is not required to support all modes and may thus only include a SILK encoder module or a CELT encoder module. The output bit-stream of the Opus encoding contains bits from the SILK and CELT encoders, though these are not separable due to the use of a range coder. A block diagram of the encoder is illustrated below.



For a normal encoder where both the SILK and the CELT modules are included, an optimal encoder should select which coding mode to use at run-time depending on the conditions. In the reference implementation, the frame size is selected by the application, but the other configuration parameters (number of channels, bandwidth, mode) are automatically selected (unless explicitly overridden by the application) depend on the following:

- o Requested bit-rate
- o Input sampling rate
- o Type of signal (speech vs music)
- o Frame size in use

The type of signal currently needs to be provided by the application (though it can be changed in real-time). An Opus encoder implementation could also do automatic detection, but since Opus is an interactive codec, such an implementation would likely have to either delay the signal (for non-interactive application) or delay the mode switching decisions (for interactive applications).

When the encoder is configured for voice over IP applications, the input signal is filtered by a high-pass filter to remove the lowest part of the spectrum that contains little speech energy and may contain background noise. This is a second order Auto Regressive Moving Average (ARMA) filter with a cut-off frequency around 50 Hz. In the future, a music detector may also be used to lower the cut-off frequency when the input signal is detected to be music rather than speech.

5.1. Range Coder

The range coder also acts as the bit-packer for Opus. It is used in three different ways, to encode:

- o entropy-coded symbols with a fixed probability model using `ec_encode()`, (`entenc.c`)
- o integers from 0 to 2^M-1 using `ec_enc_uint()` or `ec_enc_bits()`, (`entenc.c`)
- o integers from 0 to $N-1$ (where N is not a power of two) using `ec_enc_uint()`. (`entenc.c`)

The range encoder maintains an internal state vector composed of the four-tuple (`low`, `rng`, `rem`, `ext`) representing the low end of the current range, the size of the current range, a single buffered output octet, and a count of additional carry-propagating output octets. Both `rng` and `low` are 32-bit unsigned integer values, `rem` is an octet value or the special value -1, and `ext` is an integer with at least 16 bits. This state vector is initialized at the start of each frame to the value (0, 2^{31} , -1, 0). The reference implementation re-uses the 'val' field of the entropy coder structure to hold `low`, in order to allow the same structure to be used for encoding and decoding, but we maintain the distinction here for clarity.

5.1.1. Encoding Symbols

The main encoding function is `ec_encode()` (`entenc.c`), which takes as an argument a three-tuple (`fl`, `fh`, `ft`) describing the range of the symbol to be encoded in the current context, with $0 \leq fl < fh \leq ft \leq 65535$. The values of this tuple are derived from the probability model for the symbol. Let $f(i)$ be the frequency of the i 'th symbol in the current context. Then the three-tuple corresponding to the k 'th symbol is given by $fl = \sum(f(i), i < k)$, $fh = fl + f(k)$, and $ft = \sum(f(i))$.

`ec_encode()` updates the state of the encoder as follows. If `fl` is greater than zero, then $low = low + rng - (rng/ft)*(ft-fl)$ and $rng =$

$(rng/ft)*(fh-fl)$. Otherwise, low is unchanged and $rng = rng - (rng/ft)*(fh-fl)$. The divisions here are exact integer division. After this update, the range is normalized.

To normalize the range, the following process is repeated until $rng > 2^{23}$. First, the top 9 bits of low, $(low \gg 23)$, are placed into a carry buffer. Then, low is set to $(low \ll 8 \& 0x7FFFFFFF)$ and rng is set to $(rng \ll 8)$. This process is carried out by `ec_enc_normalize()` (`entenc.c`).

The 9 bits produced in each iteration of the normalization loop consist of 8 data bits and a carry flag. The final value of the output bits is not determined until carry propagation is accounted for. Therefore the reference implementation buffers a single (non-propagating) output octet and keeps a count of additional propagating (0xFF) output octets. An implementation may choose to use any mathematically equivalent scheme to perform carry propagation.

The function `ec_enc_carry_out()` (`entenc.c`) performs this buffering. It takes a 9-bit input value, c , from the normalization: 8 bits of output and a carry bit. If c is 0xFF, then `ext` is incremented and no octets are output. Otherwise, if `rem` is not the special value -1, then the octet $(rem + (c \gg 8))$ is output. Then `ext` octets are output with the value 0 if the carry bit is set, or 0xFF if it is not, and `rem` is set to the lower 8 bits of c . After this, `ext` is set to zero.

In the reference implementation, a special version of `ec_encode()` called `ec_encode_bin()` (`entenc.c`) is defined to take a two-tuple (fl, ftb) , where $0 \leq fl < 2^{ftb}$ and $ftb < 16$. It is mathematically equivalent to calling `ec_encode()` with the three-tuple $(fl, fl+1, fl \ll ftb)$, but avoids using division.

5.1.2. Encoding Raw Bits

The CELT layer also allows directly encoding a series of raw bits, outside of the range coder, implemented in `ec_enc_bits()` (`entenc.c`). The raw bits are packed at the end of the packet, starting by storing the least significant bit of the value to be packed in the least significant bit of the last byte, filling up to the most significant bit in the last byte, and then continuing in the least significant bit of the penultimate byte, and so on. This packing may continue into the last byte output by the range coder, though the format should render it impossible to overwrite any set bit produced by the range coder when the procedure in Section 5.1.4 is followed to finalize the stream.

5.1.3. Encoding Uniformly Distributed Integers

The function `ec_enc_uint()` is based on `ec_encode()` and encodes one of N equiprobable symbols, each with a frequency of 1, where N may be as large as $2^{32}-1$. Because `ec_encode()` is limited to a total frequency of $2^{16}-1$, this is done by encoding a series of symbols in smaller contexts.

`ec_enc_uint()` (`entenc.c`) takes a two-tuple (fl, ft) , where ft is not necessarily a power of two. Let ftb be the location of the highest 1 bit in the two's-complement representation of $(ft-1)$, or -1 if no bits are set. If $ftb > 8$, then the top 8 bits of fl are encoded using `ec_encode()` with the three-tuple $(fl \gg ftb-8, (fl \gg ftb-8)+1, (ft-1 \gg ftb-8)+1)$, and the remaining bits are encoded as raw bits. Otherwise, fl is encoded with `ec_encode()` directly using the three-tuple $(fl, fl+1, ft)$.

5.1.4. Finalizing the Stream

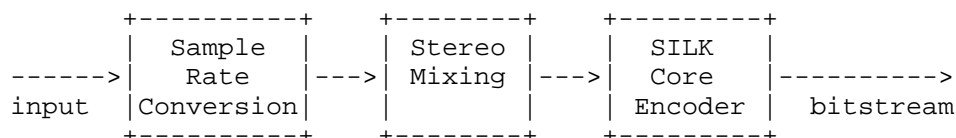
After all symbols are encoded, the stream must be finalized by outputting a value inside the current range. Let end be the integer in the interval $[low, low+rng)$ with the largest number of trailing zero bits, b , such that $end+(1 \ll b)-1$ is also in the interval $[low, low+rng)$. Then while end is not zero, the top 9 bits of end , e.g., $(end \gg 23)$, are sent to the carry buffer, and end is replaced by $(end \ll 8 \& 0x7FFFFFFF)$. Finally, if the value in carry buffer, rem , is neither zero nor the special value -1 , or the carry count, ext , is greater than zero, then 9 zero bits are sent to the carry buffer. After the carry buffer is finished outputting octets, the rest of the output buffer (if any) is padded with zero bits, until it reaches the raw bits. Finally, rem is set to the special value -1 . This process is implemented by `ec_enc_done()` (`entenc.c`).

5.1.5. Current Bit Usage

The bit allocation routines in Opus need to be able to determine a conservative upper bound on the number of bits that have been used to encode the current frame thus far. This drives allocation decisions and ensures that the range coder and raw bits will not overflow the output buffer. This is computed in the reference implementation to whole-bit precision by the function `ec_tell()` (`entcode.h`) and to fractional 1/8th bit precision by the function `ec_tell_frac()` (`entcode.c`). Like all operations in the range coder, it must be implemented in a bit-exact manner, and must produce exactly the same value returned by the same functions in the decoder after decoding the same symbols.

5.2. SILK Encoder

In many respects the SILK encoder mirrors the SILK decoder described in Section 4.2. Details such as the quantization and range coder tables can be found there, while this section describes the high-level design choices that were made. The diagram below shows the basic modules of the SILK encoder.



Silk Encoder.

5.2.1. Sample Rate Conversion

The input signal's sampling rate is adjusted by a sample rate conversion module so that it matches the SILK internal sampling rate. The input to the sample rate convertor is delayed by a number of samples depending on the sample rate ratio, such that the overall delay is constant for all input and output sample rates.

5.2.2. Stereo Mixing

The stereo mixer is only used for stereo input signals. It converts a stereo left/right signal into an adaptive mid/side representation. The first step is to compute non-adaptive mid/side signals as half the sum and difference between left and right signals. The side signal is then minimized in energy by subtracting a prediction of it based on the mid signal. This prediction works well when the left and right signals exhibit linear dependency, for instance for an amplitude-panned input signal. Like in the decoder, the prediction coefficients are linearly interpolated during the first 8 ms of the frame. The mid signal is always encoded, whereas the residual side signal is only encoded if it has sufficient energy compared to the mid signal's energy. If it has not, the "mid_only_flag" is set without encoding the side signal.

The predictor coefficients are coded regardless of whether the side signal is encoded. For each frame, two predictor coefficients are computed, one that predicts between low-passed mid and side channels, and one that predicts between high-passed mid and side channels. The low-pass filter is a simple three-tap filter and creates a delay of one sample. The high-pass filtered signal is the difference between

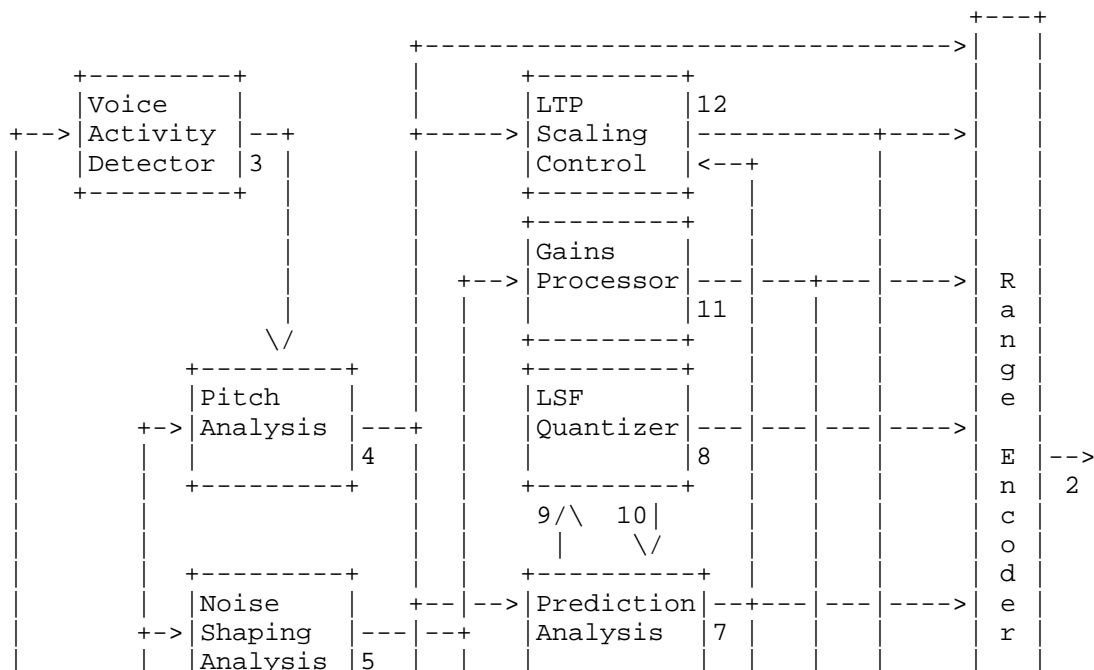
the mid signal delayed by one sample and the low-passed signal. Instead of explicitly computing the high-passed signal, it is computationally more efficient to transform the prediction coefficients before applying them to the filtered mid signal, as follows

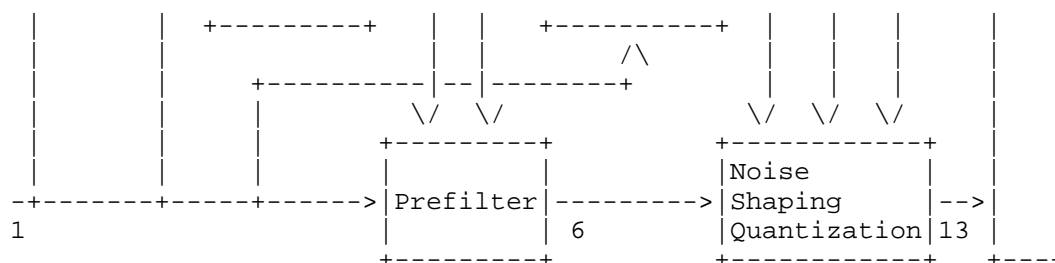
```
pred(n) = LP(n) * w0 + HP(n) * w1
         = LP(n) * w0 + (mid(n-1) - LP(n)) * w1
         = LP(n) * (w0 - w1) + mid(n-1) * w1
```

where w_0 and w_1 are the low-pass and high-pass prediction coefficients, $mid(n-1)$ is the mid signal delayed by one sample, $LP(n)$ and $HP(n)$ are the low-passed and high-passed signals and $pred(n)$ is the prediction signal that is subtracted from the side signal.

5.2.3. SILK Core Encoder

What follows is a description of the core encoder and its components. For simplicity, the core encoder is referred to simply as the encoder in the remainder of this section. An overview of the encoder is given in Figure 16.





- 1: Input speech signal
- 2: Range encoded bitstream
- 3: Voice activity estimate
- 4: Pitch lags (per 5 ms) and voicing decision (per 20 ms)
- 5: Noise shaping quantization coefficients
 - Short term synthesis and analysis noise shaping coefficients (per 5 ms)
 - Long term synthesis and analysis noise shaping coefficients (per 5 ms and for voiced speech only)
 - Noise shaping tilt (per 5 ms)
 - Quantizer gain/step size (per 5 ms)
- 6: Input signal filtered with analysis noise shaping filters
- 7: Short and long term prediction coefficients
 - LTP (per 5 ms) and LPC (per 20 ms)
- 8: LSF quantization indices
- 9: LSF coefficients
- 10: Quantized LSF coefficients
- 11: Processed gains, and synthesis noise shape coefficients
- 12: LTP state scaling coefficient. Controlling error propagation / prediction gain trade-off
- 13: Quantized signal

Silk Core Encoder.

Figure 16

5.2.3.1. Voice Activity Detection

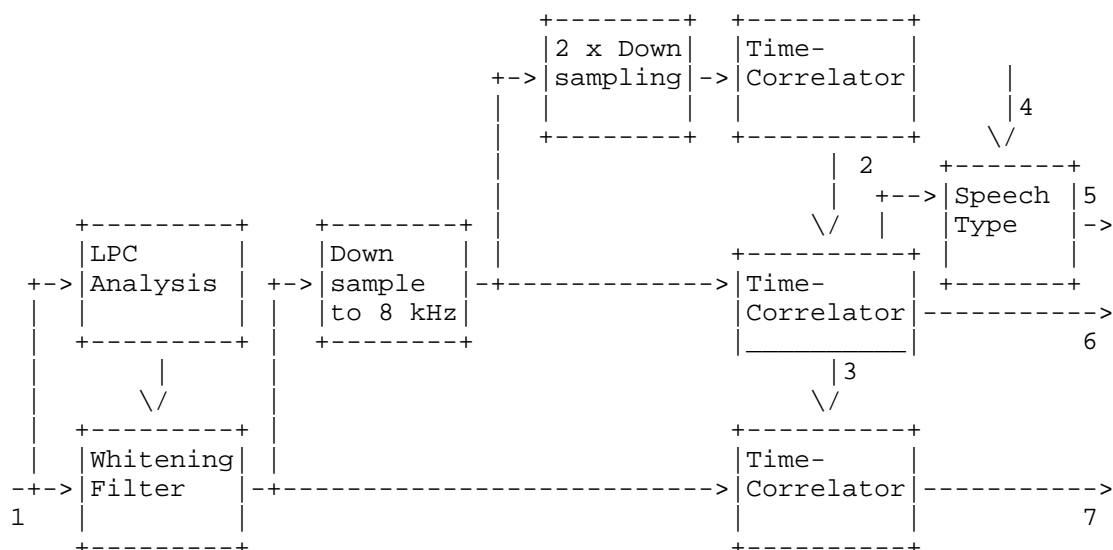
The input signal is processed by a Voice Activity Detector (VAD) to produce a measure of voice activity, spectral tilt, and signal-to-noise estimates for each frame. The VAD uses a sequence of half-band filterbanks to split the signal into four subbands: $0 \dots F_s/16$, $F_s/16 \dots F_s/8$, $F_s/8 \dots F_s/4$, and $F_s/4 \dots F_s/2$, where F_s is the sampling frequency (8, 12, 16, or 24 kHz). The lowest subband, from $0 - F_s/16$, is high-pass filtered with a first-order moving average (MA) filter (with transfer function $H(z) = 1 - z^{(-1)}$) to reduce the energy at the lowest frequencies. For each frame, the signal energy per

subband is computed. In each subband, a noise level estimator tracks the background noise level and a Signal-to-Noise Ratio (SNR) value is computed as the logarithm of the ratio of energy to noise level. Using these intermediate variables, the following parameters are calculated for use in other SILK modules:

- o Average SNR. The average of the subband SNR values.
- o Smoothed subband SNRs. Temporally smoothed subband SNR values.
- o Speech activity level. Based on the average SNR and a weighted average of the subband energies.
- o Spectral tilt. A weighted average of the subband SNRs, with positive weights for the low subbands and negative weights for the high subbands.

5.2.3.2. Pitch Analysis

The input signal is processed by the open loop pitch estimator shown in Figure 17.



- 1: Input signal
- 2: Lag candidates from stage 1
- 3: Lag candidates from stage 2
- 4: Correlation threshold
- 5: Voiced/unvoiced flag
- 6: Pitch correlation
- 7: Pitch lags

Block diagram of the pitch estimator.

Figure 17

The pitch analysis finds a binary voiced/unvoiced classification, and, for frames classified as voiced, four pitch lags per frame - one for each 5 ms subframe - and a pitch correlation indicating the periodicity of the signal. The input is first whitened using a Linear Prediction (LP) whitening filter, where the coefficients are computed through standard Linear Prediction Coding (LPC) analysis. The order of the whitening filter is 16 for best results, but is reduced to 12 for medium complexity and 8 for low complexity modes. The whitened signal is analyzed to find pitch lags for which the time correlation is high. The analysis consists of three stages for reducing the complexity:

- o In the first stage, the whitened signal is downsampled to 4 kHz (from 8 kHz) and the current frame is correlated to a signal delayed by a range of lags, starting from a shortest lag

corresponding to 500 Hz, to a longest lag corresponding to 56 Hz.

- o The second stage operates on an 8 kHz signal (downsampled from 12, 16, or 24 kHz) and measures time correlations only near the lags corresponding to those that had sufficiently high correlations in the first stage. The resulting correlations are adjusted for a small bias towards short lags to avoid ending up with a multiple of the true pitch lag. The highest adjusted correlation is compared to a threshold depending on:

- * Whether the previous frame was classified as voiced
- * The speech activity level
- * The spectral tilt.

If the threshold is exceeded, the current frame is classified as voiced and the lag with the highest adjusted correlation is stored for a final pitch analysis of the highest precision in the third stage.

- o The last stage operates directly on the whitened input signal to compute time correlations for each of the four subframes independently in a narrow range around the lag with highest correlation from the second stage.

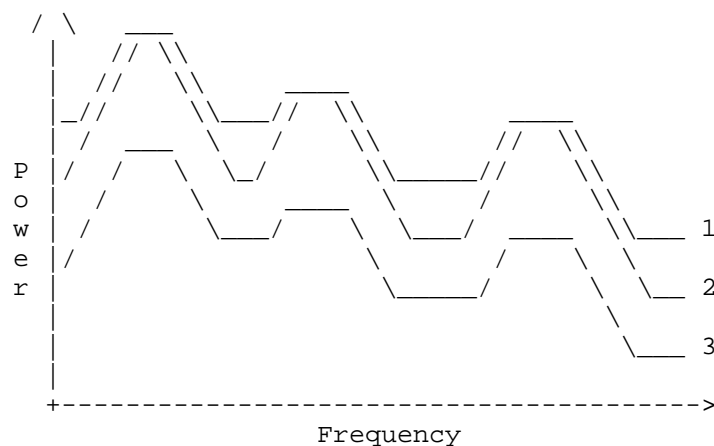
5.2.3.3. Noise Shaping Analysis

The noise shaping analysis finds gains and filter coefficients used in the prefilter and noise shaping quantizer. These parameters are chosen such that they will fulfill several requirements:

- o Balancing quantization noise and bitrate. The quantization gains determine the step size between reconstruction levels of the excitation signal. Therefore, increasing the quantization gain amplifies quantization noise, but also reduces the bitrate by lowering the entropy of the quantization indices.
- o Spectral shaping of the quantization noise; the noise shaping quantizer is capable of reducing quantization noise in some parts of the spectrum at the cost of increased noise in other parts without substantially changing the bitrate. By shaping the noise such that it follows the signal spectrum, it becomes less audible. In practice, best results are obtained by making the shape of the noise spectrum slightly flatter than the signal spectrum.
- o De-emphasizing spectral valleys; by using different coefficients in the analysis and synthesis part of the prefilter and noise

shaping quantizer, the levels of the spectral valleys can be decreased relative to the levels of the spectral peaks such as speech formants and harmonics. This reduces the entropy of the signal, which is the difference between the coded signal and the quantization noise, thus lowering the bitrate.

- o Matching the levels of the decoded speech formants to the levels of the original speech formants; an adjustment gain and a first order tilt coefficient are computed to compensate for the effect of the noise shaping quantization on the level and spectral tilt.



- 1: Input signal spectrum
- 2: De-emphasized and level matched spectrum
- 3: Quantization noise spectrum

Noise shaping and spectral de-emphasis illustration.

Figure 18

Figure 18 shows an example of an input signal spectrum (1). After de-emphasis and level matching, the spectrum has deeper valleys (2). The quantization noise spectrum (3) more or less follows the input signal spectrum, while having slightly less pronounced peaks. The entropy, which provides a lower bound on the bitrate for encoding the excitation signal, is proportional to the area between the de-emphasized spectrum (2) and the quantization noise spectrum (3). Without de-emphasis, the entropy is proportional to the area between input spectrum (1) and quantization noise (3) - clearly higher.

The transformation from input signal to de-emphasized signal can be described as a filtering operation with a filter

$$H(z) = G * (1 - c_tilt * z^{-1}) * \frac{Wana(z)}{Wsyn(z)},$$

having an adjustment gain G , a first order tilt adjustment filter with tilt coefficient c_tilt , and where

$$Wana(z) = (1 - \prod_{k=1}^{16} (a_ana(k) * z^{-k}) * (1 - z^{-L} * \prod_{k=-d}^d b_ana(k) * z^{-k})),$$

is the analysis part of the de-emphasis filter, consisting of the short-term shaping filter with coefficients $a_ana(k)$, and the long-term shaping filter with coefficients $b_ana(k)$ and pitch lag L . The parameter d determines the number of long-term shaping filter taps.

Similarly, but without the tilt adjustment, the synthesis part can be written as

$$Wsyn(z) = (1 - \prod_{k=1}^{16} (a_syn(k) * z^{-k}) * (1 - z^{-L} * \prod_{k=-d}^d b_syn(k) * z^{-k})).$$

All noise shaping parameters are computed and applied per subframe of 5 ms. First, an LPC analysis is performed on a windowed signal block of 15 ms. The signal block has a look-ahead of 5 ms relative to the current subframe, and the window is an asymmetric sine window. The LPC analysis is done with the autocorrelation method, with an order of between 8, in lowest-complexity mode, and 16, for best quality.

Optionally the LPC analysis and noise shaping filters are warped by replacing the delay elements by first-order allpass filters. This increases the frequency resolution at low frequencies and reduces it at high ones, which better matches the human auditory system and improves quality. The warped analysis and filtering comes at a cost

in complexity and is therefore only done in higher complexity modes.

The quantization gain is found by taking the square root of the residual energy from the LPC analysis and multiplying it by a value inversely proportional to the coding quality control parameter and the pitch correlation.

Next the two sets of short-term noise shaping coefficients $a_{ana}(k)$ and $a_{syn}(k)$ are obtained by applying different amounts of bandwidth expansion to the coefficients found in the LPC analysis. This bandwidth expansion moves the roots of the LPC polynomial towards the origin, using the formulas

$$a_{ana}(k) = a(k) * g_{ana}^k, \text{ and}$$

$$a_{syn}(k) = a(k) * g_{syn}^k,$$

where $a(k)$ is the k 'th LPC coefficient, and the bandwidth expansion factors g_{ana} and g_{syn} are calculated as

$$g_{ana} = 0.95 - 0.01 * C, \text{ and}$$

$$g_{syn} = 0.95 + 0.01 * C,$$

where C is the coding quality control parameter between 0 and 1. Applying more bandwidth expansion to the analysis part than to the synthesis part gives the desired de-emphasis of spectral valleys in between formants.

The long-term shaping is applied only during voiced frames. It uses three filter taps, described by

$$b_{ana} = F_{ana} * [0.25, 0.5, 0.25], \text{ and}$$

$$b_{syn} = F_{syn} * [0.25, 0.5, 0.25].$$

For unvoiced frames these coefficients are set to 0. The multiplication factors F_{ana} and F_{syn} are chosen between 0 and 1, depending on the coding quality control parameter, as well as the calculated pitch correlation and smoothed subband SNR of the lowest

subband. By having F_{ana} less than F_{syn} , the pitch harmonics are emphasized relative to the valleys in between the harmonics.

The tilt coefficient c_{tilt} is for unvoiced frames chosen as

$$c_{tilt} = 0.25,$$

and as

$$c_{tilt} = 0.25 + 0.2625 * V$$

for voiced frames, where V is the voice activity level between 0 and 1.

The adjustment gain G serves to correct any level mismatch between the original and decoded signals that might arise from the noise shaping and de-emphasis. This gain is computed as the ratio of the prediction gain of the short-term analysis and synthesis filter coefficients. The prediction gain of an LPC synthesis filter is the square root of the output energy when the filter is excited by a unit-energy impulse on the input. An efficient way to compute the prediction gain is by first computing the reflection coefficients from the LPC coefficients through the step-down algorithm, and extracting the prediction gain from the reflection coefficients as

$$\text{predGain} = \left(\prod_{k=1}^K 1 - (r_k)^2 \right)^{-0.5},$$

where r_k is the k 'th reflection coefficient.

Initial values for the quantization gains are computed as the square-root of the residual energy of the LPC analysis, adjusted by the coding quality control parameter. These quantization gains are later adjusted based on the results of the prediction analysis.

5.2.3.4. Prediction Analysis

The prediction analysis is performed in one of two ways depending on how the pitch estimator classified the frame. The processing for voiced and unvoiced speech is described in Section 5.2.3.4.1 and

Section 5.2.3.4.2, respectively. Inputs to this function include the pre-whitened signal from the pitch estimator (see Section 5.2.3.2).

5.2.3.4.1. Voiced Speech

For a frame of voiced speech the pitch pulses will remain dominant in the pre-whitened input signal. Further whitening is desirable as it leads to higher quality at the same available bitrate. To achieve this, a Long-Term Prediction (LTP) analysis is carried out to estimate the coefficients of a fifth-order LTP filter for each of four subframes. The LTP coefficients are quantized using the method described in Section 5.2.3.6, and the quantized LTP coefficients are used to compute the LTP residual signal. This LTP residual signal is the input to an LPC analysis where the LPCs are estimated using Burg's method, such that the residual energy is minimized. The estimated LPCs are converted to a Line Spectral Frequency (LSF) vector and quantized as described in Section 5.2.3.5. After quantization, the quantized LSF vector is converted back to LPC coefficients using the full procedure in Section 4.2.7.5. By using quantized LTP coefficients and LPC coefficients derived from the quantized LSF coefficients, the encoder remains fully synchronized with the decoder. The quantized LPC and LTP coefficients are also used to filter the input signal and measure residual energy for each of the four subframes.

5.2.3.4.2. Unvoiced Speech

For a speech signal that has been classified as unvoiced, there is no need for LTP filtering, as it has already been determined that the pre-whitened input signal is not periodic enough within the allowed pitch period range for LTP analysis to be worth the cost in terms of complexity and bitrate. The pre-whitened input signal is therefore discarded, and instead the input signal is used for LPC analysis using Burg's method. The resulting LPC coefficients are converted to an LSF vector and quantized as described in the following section. They are then transformed back to obtain quantized LPC coefficients, which are then used to filter the input signal and measure residual energy for each of the four subframes.

5.2.3.4.2.1. Burgs method

The main purpose of LPC coding in SILK is to reduce the bitrate by minimizing the residual energy. At least at high bitrates, perceptual aspects are handled independently by the noise shaping filter. Burg's method is used because it provides higher prediction gain than the autocorrelation method and, unlike the covariance method, produces stable filters (assuming numerical errors don't spoil that). SILK's implementation of Burg's method is also

computationally faster than the autocovariance method. The implementation of Burg's method differs from traditional implementations in two aspects. The first difference is that it operates on autocorrelations, similar to the Schur algorithm, but with a simple update to the autocorrelations after finding each reflection coefficient to make the result identical to Burg's method. This brings down the complexity of Burg's method to near that of the autocorrelation method. The second difference is that the signal in each subframe is scaled by the inverse of the residual quantization step size. Subframes with a small quantization step size will on average spend more bits for a given amount of residual energy than subframes with a large step size. Without scaling, Burg's method minimizes the total residual energy in all subframes, which doesn't necessarily minimize the total number of bits needed for coding the quantized residual. The residual energy of the scaled subframes is a better measure for that number of bits.

5.2.3.5. LSF Quantization

Unlike many other speech codecs, SILK uses variable bitrate coding for the LSFs. This improves the average rate-distortion tradeoff and reduces outliers. The variable bitrate coding minimizes a linear combination of the weighted quantization errors and the bitrate. The weights for the quantization errors are the Inverse Harmonic Mean Weighting (IHMW) function proposed by Laroia et al. (see [laroia-icassp]). These weights are referred to here as Laroia weights.

The LSF quantizer consists of two stages. The first stage is an (unweighted) vector quantizer (VQ), with a codebook size of 32 vectors. The quantization errors for the codebook vector are sorted, and for the N best vectors a second stage quantizer is run. By varying the number N a tradeoff is made between R/D performance and computational efficiency. For each of the N codebook vectors the Laroia weights corresponding to that vector (and not to the input vector) are calculated. Then the residual between the input LSF vector and the codebook vector is scaled by the square roots of these Laroia weights. This scaling partially normalizes error sensitivity for the residual vector, so that a uniform quantizer with fixed step sizes can be used in the second stage without too much performance loss. And by scaling with Laroia weights determined from the first-stage codebook vector, the process can be reversed in the decoder.

The second stage uses predictive delayed decision scalar quantization. The quantization error is weighted by Laroia weights determined from the LSF input vector. The predictor multiplies the previous quantized residual value by a prediction coefficient that depends on the vector index from the first stage VQ and on the

location in the LSF vector. The prediction is subtracted from the LSF residual value before quantizing the result, and added back afterwards. This subtraction can be interpreted as shifting the quantization levels of the scalar quantizer, and as a result the quantization error of each value depends on the quantization decision of the previous value. This dependency is exploited by the delayed decision mechanism to search for a quantization sequence with best R/D performance with a Viterbi-like algorithm. The quantizer processes the residual LSF vector in reverse order (i.e., it starts with the highest residual LSF value). This is done because the prediction works slightly better in the reverse direction.

The quantization index of the first stage is entropy coded. The quantization sequence from the second stage is also entropy coded, where for each element the probability table is chosen depending on the vector index from the first and the location of that element in the LSF vector.

5.2.3.5.1. LSF Stabilization

If the input is stable, finding the best candidate usually results in a quantized vector that is also stable. Because of the two-stage approach, however, it is possible that the best quantization candidate is unstable. Therefore we apply an LSF stabilization method which ensures that the LSF parameters are within their valid range, increasingly sorted, and have minimum distances between each other and the border values that have been predetermined as the 0.01 percentile distance values from a large training set.

5.2.3.6. LTP Quantization

For voiced frames, the prediction analysis described in Section 5.2.3.4.1 resulted in four sets (one set per subframe) of five LTP coefficients, plus four weighting matrices. The LTP coefficients for each subframe are quantized using entropy constrained vector quantization. A total of three vector codebooks are available for quantization, with different rate-distortion trade-offs. The three codebooks have 10, 20, and 40 vectors and average rates of about 3, 4, and 5 bits per vector, respectively. Consequently, the first codebook has larger average quantization distortion at a lower rate, whereas the last codebook has smaller average quantization distortion at a higher rate. Given the weighting matrix W_{ltp} and LTP vector b , the weighted rate-distortion measure for a codebook vector cb_i with rate r_i is given by

$$RD = u * (b - cb_i)' * W_{ltp} * (b - cb_i) + r_i,$$

where u is a fixed, heuristically-determined parameter balancing the distortion and rate. Which codebook gives the best performance for a given LTP vector depends on the weighting matrix for that LTP vector. For example, for a low valued W_{ltp} , it is advantageous to use the codebook with 10 vectors as it has a lower average rate. For a large W_{ltp} , on the other hand, it is often better to use the codebook with 40 vectors, as it is more likely to contain the best codebook vector. The weighting matrix W_{ltp} depends mostly on two aspects of the input signal. The first is the periodicity of the signal; the more periodic, the larger W_{ltp} . The second is the change in signal energy in the current subframe, relative to the signal one pitch lag earlier. A decaying energy leads to a larger W_{ltp} than an increasing energy. Both aspects fluctuate relatively slowly, which causes the W_{ltp} matrices for different subframes of one frame often to be similar. Because of this, one of the three codebooks typically gives good performance for all subframes, and therefore the codebook search for the subframe LTP vectors is constrained to only allow codebook vectors to be chosen from the same codebook, resulting in a rate reduction.

To find the best codebook, each of the three vector codebooks is used to quantize all subframe LTP vectors and produce a combined weighted rate-distortion measure for each vector codebook. The vector codebook with the lowest combined rate-distortion over all subframes is chosen. The quantized LTP vectors are used in the noise shaping quantizer, and the index of the codebook plus the four indices for the four subframe codebook vectors are passed on to the range encoder.

5.2.3.7. Prefilter

In the prefilter the input signal is filtered using the spectral valley de-emphasis filter coefficients from the noise shaping analysis (see Section 5.2.3.3). By applying only the noise shaping analysis filter to the input signal, it provides the input to the noise shaping quantizer.

5.2.3.8. Noise Shaping Quantizer

The noise shaping quantizer independently shapes the signal and coding noise spectra to obtain a perceptually higher quality at the same bitrate.

The prefilter output signal is multiplied with a compensation gain G computed in the noise shaping analysis. Then the output of a synthesis shaping filter is added, and the output of a prediction filter is subtracted to create a residual signal. The residual signal is multiplied by the inverse quantized quantization gain from

the noise shaping analysis, and input to a scalar quantizer. The quantization indices of the scalar quantizer represent a signal of pulses that is input to the pyramid range encoder. The scalar quantizer also outputs a quantization signal, which is multiplied by the quantized quantization gain from the noise shaping analysis to create an excitation signal. The output of the prediction filter is added to the excitation signal to form the quantized output signal $y(n)$. The quantized output signal $y(n)$ is input to the synthesis shaping and prediction filters.

Optionally the noise shaping quantizer operates in a delayed decision mode. In this mode it uses a Viterbi algorithm to keep track of multiple rounding choices in the quantizer and select the best one after a delay of 32 samples. This improves the rate/distortion performance of the quantizer.

5.2.3.9. Constant Bitrate Mode

SILK was designed to run in Variable Bitrate (VBR) mode. However the reference implementation also has a Constant Bitrate (CBR) mode for SILK. In CBR mode SILK will attempt to encode each packet with no more than the allowed number of bits. The Opus wrapper code then pads the bitstream if any unused bits are left in SILK mode, or encodes the high band with the remaining number of bits in Hybrid mode. If SILK is unable to encode the packet with less than the allowed number of bits, the Opus encoder temporarily codes the signal in CELT mode instead. The number of payload bits is adjusted by changing the quantization gains and the rate/distortion tradeoff in the noise shaping quantizer, in an iterative loop around the noise shaping quantizer and entropy coding. Compared to the SILK VBR mode, the CBR mode has lower audio quality at a given average bitrate, and also has higher computational complexity.

5.3. CELT Encoder

Most of the aspects of the CELT encoder can be directly derived from the description of the decoder. For example, the filters and rotations in the encoder are simply the inverse of the operation performed by the decoder. Similarly, the quantizers generally optimize for the mean square error (because noise shaping is part of the bit-stream itself), so no special search is required. For this reason, only the less straightforward aspects of the encoder are described here.

5.3.1. Pitch Prefilter

The pitch prefilter is applied after the pre-emphasis. It is applied in such a way as to be the inverse of the decoder's post-filter. The

main non-obvious aspect of the prefilter is the selection of the pitch period. The pitch search should be optimised for the following criteria:

- o continuity: it is important that the pitch period does not change abruptly between frames; and
- o avoidance of pitch multiples: when the period used is a multiple of the real period (lower frequency fundamental), the post-filter loses most of its ability to reduce noise

5.3.2. Bands and Normalization

The MDCT output is divided into bands that are designed to match the ear's critical bands for the smallest (2.5 ms) frame size. The larger frame sizes use integer multiples of the 2.5 ms layout. For each band, the encoder computes the energy that will later be encoded. Each band is then normalized by the square root of the *unquantized* energy, such that each band now forms a unit vector X . The energy and the normalization are computed by `compute_band_energies()` and `normalise_bands()` (`bands.c`), respectively.

5.3.3. Energy Envelope Quantization

Energy quantization (both coarse and fine) can be easily understood from the decoding process. For all useful bitrates, the coarse quantizer always chooses the quantized log energy value that minimizes the error for each band. Only at very low rate does the encoder allow larger errors to minimize the rate and avoid using more bits than are available. When the available CPU requirements allow it, it is best to try encoding the coarse energy both with and without inter-frame prediction such that the best prediction mode can be selected. The optimal mode depends on the coding rate, the available bit-rate, and the current rate of packet loss.

The fine energy quantizer always chooses the quantized log energy value that minimizes the error for each band because the rate of the fine quantization depends only on the bit allocation and not on the values that are coded.

5.3.4. Bit allocation

The encoder must use exactly the same bit allocation process as used by the decoder and described in Section 4.3.3. The three mechanisms that can be used by the encoder to adjust the bit-rate on a frame-by-frame basis are band boost, allocation trim, and band skipping.

5.3.4.1. Band boost

The reference encoder makes a decision to boost a band when the energy of that band is significantly higher than that of the neighboring bands. Let E_j be the log-energy of band j , we define

$$D_j = 2E_j - E_{j-1} - E_{j+1}$$

The allocation of band j is boosted once if $D_j > t_1$ and twice if $D_j > t_2$. For $LM \geq 1$, $t_1=2$ and $t_2=4$, while for $LM < 1$, $t_1=3$ and $t_2=5$.

5.3.4.2. Allocation trim

The allocation trim is a value between 0 and 10 (inclusively) that controls the allocation balance between the low and high frequencies. The encoder starts with a safe "default" of 5 and deviates from that default in two different ways. First the trim can deviate by ± 2 depending on the spectral tilt of the input signal. For signals with more low frequencies, the trim is increased by up to 2, while for signals with more high frequencies, the trim is decreased by up to 2. For stereo inputs, the trim value can be decreased by up to 4 when the inter-channel correlation at low frequency (first 8 bands) is high.

5.3.4.3. Band skipping

The encoder uses band skipping to ensure that the shape of the bands is only coded if there is at least 1/2 bit per sample available for the PVQ. If not, then no bit is allocated and folding is used instead. To ensure continuity in the allocation, some amount of hysteresis is added to the process, such that a band that received PVQ bits in the previous frame only needs 7/16 bit/sample to be coded for the current frame, while a band that did not receive PVQ bits in the previous frames needs at least 9/16 bit/sample to be coded.

5.3.5. Stereo decisions

Because CELT applies mid-side stereo coupling in the normalized domain, it does not suffer from important stereo image problems even when the two channels are completely uncorrelated. For this reason it is always safe to use stereo coupling on any audio frame. That being said, there are some frames for which dual (independent) stereo is still more efficient. This decision is made by comparing the estimated entropy with and without coupling over the first 13 bands, taking into account the fact that all bands with more than two MDCT bins require one extra degree of freedom when coded in mid-side. Let $L1_{ms}$ and $L1_{lr}$ be the L1-norm of the mid-side vector and the L1-norm of the left-right vector, respectively. The decision to use mid-side

is made if and only if

$$\frac{L1_{ms}}{\text{bins} + E} < \frac{L1_{lr}}{\text{bins}}$$

where bins is the number of MDCT bins in the first 13 bands and extra is the number of extra degrees of freedom for mid-side coding. For LM>1, E=13, otherwise E=5.

The reference encoder decides on the intensity stereo threshold based on the bitrate alone. After taking into account the frame size by subtracting 80 bits per frame for coarse energy, the first band using intensity coding is as follows:

bitrate (kb/s)	start band
<35	8
35-50	12
50-68	16
84-84	18
84-102	19
102-130	20
>130	disabled

Thresholds for intensity stereo

Table 63

5.3.6. Time-Frequency Decision

The choice of time-frequency resolution used in Section 4.3.4.5 is based on rate-distortion (RD) optimization. The distortion is the L1-norm (sum of absolute values) of each band after each TF resolution under consideration. The L1 norm is used because it represents the entropy for a Laplacian source. The number of bits required to code a change in TF resolution between two bands is higher than the cost of having those two bands use the same resolution, which is what requires the RD optimization. The optimal decision is computed using the Viterbi algorithm. See `tf_analysis()`

in `celt/celt.c`.

5.3.7. Spreading Values Decision

The choice of the spreading value in Table 56 has an impact on the nature of the coding noise introduced by CELT. The larger the `f_r` value, the lower the impact of the rotation, and the more tonal the coding noise. The more tonal the signal, the more tonal the noise should be, so the CELT encoder determines the optimal value for `f_r` by estimating how tonal the signal is. The tonality estimate is based on discrete pdf (4-bin histogram) of each band. Bands that have a large number of small values are considered more tonal and a decision is made by combining all bands with more than 8 samples. See `spreading_decision()` in `celt/bands.c`.

5.3.8. Spherical Vector Quantization

CELT uses a Pyramid Vector Quantization (PVQ) [PVQ] codebook for quantizing the details of the spectrum in each band that have not been predicted by the pitch predictor. The PVQ codebook consists of all sums of K signed pulses in a vector of N samples, where two pulses at the same position are required to have the same sign. Thus the codebook includes all integer codevectors y of N dimensions that satisfy $\text{sum}(\text{abs}(y(j))) = K$.

In bands where there are sufficient bits allocated the PVQ is used to encode the unit vector that results from the normalization in Section 5.3.2 directly. Given a PVQ codevector y , the unit vector X is obtained as $X = y / ||y||$, where $||.||$ denotes the L2 norm.

5.3.8.1. PVQ Search

The search for the best codevector y is performed by `alg_quant()` (`vg.c`). There are several possible approaches to the search, with a trade-off between quality and complexity. The method used in the reference implementation computes an initial codeword y_1 by projecting the normalized spectrum X onto the codebook pyramid of $K-1$ pulses:

```
y0 = truncate_towards_zero( (K-1) * X / sum(abs(X)))
```

Depending on N , K and the input data, the initial codeword y_0 may contain from 0 to $K-1$ non-zero values. All the remaining pulses, with the exception of the last one, are found iteratively with a greedy search that minimizes the normalized correlation between y and X :

T

$$J = -X * y / ||y||$$

The search described above is considered to be a good trade-off between quality and computational cost. However, there are other possible ways to search the PVQ codebook and the implementers MAY use any other search methods. See `alg_quant()` in `celt/vq.c`.

6. Conformance

It is the intention to allow the greatest possible choice of freedom in implementing the specification. For this reason, outside of a few exceptions noted in this section, conformance is defined through the reference implementation of the decoder provided in Appendix A. Although this document includes an English description of the codec, should the description contradict the source code of the reference implementation, the latter shall take precedence.

Compliance with this specification means that a decoder's output **MUST** be within the thresholds specified by the `opus_compare.c` tool (included with the code) when compared to the reference implementation for each of the test vectors provided (see Appendix A.4). Either the floating-point implementation or the fixed-point implementation can be used as a reference and being within the threshold for one of the two is sufficient. In addition, a compliant decoder implementation **MUST** have the same final range decoder state as that of the reference decoder.

6.1. Testing

Using the reference code provided in Appendix A, a mono test vector can be decoded with

```
opus_demo -d 48000 1 test_mono.bit test_mono.out
```

If the range decoder state is incorrect for one of the frames, the decoder will exit with "Error: Range coder state mismatch between encoder and decoder". If the decoder succeeds, then the output can be compared with the "reference" output with

```
opus_compare test_mono.float test_mono.out
```

or

```
opus_compare test_mono.fixed test_mono.out
```

For a stereo test vector, the command line for decoding is

```
opus_demo -d 48000 2 test_stereo.bin test_stereo.out
```

and the output can be compared with the reference output with

```
opus_compare -s test_stereo.float test_stereo.out
```

or

```
opus_compare -s test_stereo.fixed test_stereo.out
```

On POSIX environments, the `run_vectors.sh` script can be used to verify all test vectors. This can be done with

```
run_vectors.sh <exec path> <vector path>
```

where `<exec path>` is the directory where the `opus_demo` and `opus_compare` executables are built and `<vector path>` is the directory containing the test vectors.

6.2. Opus Custom

To complement the Opus specification, the "Opus Custom" codec is defined to handle special sample rates and frame rates that are not supported by the main Opus specification. Use of Opus Custom is discouraged for all but very special applications for which a frame size different from 2.5, 5, 10, or 20 ms is needed (for either complexity or latency reasons). Such applications will not be compatible with the "main" Opus codec. In Opus Custom operation, only the CELT layer is available, which is available using the `celt_*` function calls in `celt.h`.

7. Security Considerations

Implementations of the Opus codec need to take appropriate security considerations into account, as outlined in [DOS] and [SECGUIDE]. It is extremely important for the decoder to be robust against malicious payloads. Malicious payloads must not cause the decoder to overrun its allocated memory or to take an excessive amount of resources to decode. Although problems in encoders are typically rarer, the same applies to the encoder. Malicious audio streams must not cause the encoder to misbehave because this would allow an attacker to attack transcoding gateways.

The reference implementation contains no known buffer overflow or cases where a specially crafted packet or audio segment could cause a significant increase in CPU load. However, on certain CPU architectures where denormalized floating-point operations are much slower than normal floating-point operations, it is possible for some audio content (e.g., silence or near-silence) to cause a certain increase in CPU load. Denormals can be introduced by reordering operations in the compiler and depend on the target architecture, so it is difficult to guarantee that an implementation avoids them. For architectures on which denormals are problematic, adding very small floating-point offsets to the affected signals to prevent significant numbers of denormalized operations is RECOMMENDED. Alternatively, it is often possible to configure the hardware to treat denormals as zero (DAZ). No such issue exists for the fixed-point reference implementation.

The reference implementation was validated in the following conditions:

1. Sending the decoder valid packets generated by the reference encoder and verifying that the decoder's final range coder state matches that of the encoder.
2. Sending the decoder packets generated by the reference encoder and then subjected to random corruption.
3. Sending the decoder random packets.
4. Sending the decoder packets generated by a version of the reference encoder modified to make random coding decisions (internal fuzzing), including mode switching, and verifying that the range coder final states match.

In all of the conditions above, both the encoder and the decoder were run inside the Valgrind [5] memory debugger, which tracks reads and writes to invalid memory regions as well as the use of uninitialized

memory. There were no errors reported on any of the tested conditions.

8. IANA Considerations

This document has no actions for IANA.

9. Acknowledgements

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10. References

10.1. Normative References

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URIs

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- [2] <<http://www.celt-codec.org/>>
- [3] <http://code.google.com/p/webrtc/source/browse/trunk/src/modules/audio_coding/NetEQ/main/source/?r=583>
- [4] <<http://code.google.com/p/webrtc/>>
- [5] <<http://valgrind.org/>>
- [6] <[git://git.opus-codec.org/opus.git](http://git.opus-codec.org/opus.git)>

Appendix A. Reference Implementation

This appendix contains the complete source code for the reference implementation of the Opus codec written in C. By default, this implementation relies on floating-point arithmetic, but it can be compiled to use only fixed-point arithmetic by defining the `FIXED_POINT` macro. Information on building and using the reference implementation is available in the `README` file.

The implementation can be compiled with either a C89 or a C99 compiler. It is reasonably optimized for most platforms such that only architecture-specific optimizations are likely to be useful. The FFT used is a slightly modified version of the KISS-FFT library, but it is easy to substitute any other FFT library.

While the reference implementation does not rely on any `_undefined behavior_` as defined by C89 or C99, it relies on common `_implementation-defined behavior_` for two's complement architectures:

- o Right shifts of negative values are consistent with two's complement arithmetic, so that `a>>b` is equivalent to `floor(a/(2^b))`
- o For conversion to a signed integer of N bits, the value is reduced modulo 2^N to be within range of the type
- o The result of integer division of a negative values is truncated towards zero
- o The compiler provides a 64-bit integer type (a C99 requirement which is supported by most c89 compilers)

In its current form, the reference implementation also requires the following architectural characteristics to obtain acceptable performance:

- o two's complement arithmetic
- o at least a 16 bit by 16 bit integer multiplier (32-bit result)
- o at least a 32-bit adder/accumulator

A.1. Extracting the source

The complete source code can be extracted from this draft, by running the following command line:

```
o cat draft-ietf-codec-opus.txt | grep '^\\ \\ \\ ###' | sed -e
  's/\\s\\s\\s###// ' | base64 -d > opus_source.tar.gz

o tar xzvf opus_source.tar.gz

o cd opus_source

o make
```

On systems where the base64 utility is not present, the following commands can be used instead:

```
o cat draft-ietf-codec-opus.txt | grep '^\\ \\ \\ ###' | sed -e
  's/\\s\\s\\s###// ' > opus.b64

o openssl base64 -d -in opus.b64 > opus_source.tar.gz
```

A.2. Development Versions

The current development version of the source code is available in a Git repository [6]. Development snapshots are provided at <http://opus-codec.org/>.

A.3. Base64-encoded source code

```
###H4sIAEA1r04AA+w9a3PixpbzmV/RNVN1A15sAwZPJpOkgkHGGuG1COyZ2t3SlUUD
###ygiJ6GEPyd3/vud0t0TrwcNjzjz3l6rKGEndp8+7z+k+rbir0Nd9N/RMev7qK10V
###uN42Gvi3+rZRkf9G16tq9bJxcXlRa8DvSrVaq128Io2vhZB8hX5geIS8+m25u92+
###9/+ilyvJvzUYflT7naOPgQK+rNe3yb922WDyr1+C3Kt1lH+tlqi/IpWjY5Jz/T+X
###f8tdrTlrvghIDaRyWgPbIx+sleJs4M3LRPu0XlHStZZWQKdlMjADw7fMcoHkXH+n
###hnPaMzyT3Bq25ZTJ2Fq6wWJNrs7ImHqedQ//rPP7tjR1NCiTjkfnrrcmPePzI7Xt
###MvzwPpEr15tTb2o5gFBub8WzPpEpJS3DDzyXdN2VWyiM6NSCW+s+DCzXIYYzJaFP
###ieUQru3syb3lGDDezPWWfPk8WsGCuB7764ZBYelOrZllGgigTAyPkhXlgBXAC7Ly
###3Adrcj+ChRHAPxSA2Lb7CFgS03WmFnbyC9hpSYMfCoVTksTIJ+4sQsV0AfsIaCLx
###aGAAigjPuHcf8JWQT8FxA8ukZXhn+cQGSahgMxSjj4kHDGfahRWk3lne+DCORH80
###PhA2DQGNy6NAOfmFqWuGS+oERiSWc+A46Am0WBoB9SzD9jfcZSJBkDLqQM34RtWI
###Nrge3zVHCohfw9HgVm0rbXLlkYxvFIK+bKR2bsbkZtBtKyONNPtteNofj9SryXgw
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[illegible]

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###XTRDt1T2YrNV3TBsct3BrF9NjV5K5gtsVuDkveAtqxb8ti3RvCVb6DTSW3a+wIph
###qkxMakiIV1MRV2hLIqxV13LyAY2M/I9vS5UV1MGUudlWYidXRT+vn0iLGeePzhrL
###UQEz8BMmOfO/P7GEYMJENQ0WJCDQwyg6QznAHUbCz1ADVT5KBFeid5hj7LxaH2f
###EjNpOGOQQVgmIwb/FjmDaoLsesUpnLwz/rixOTR++DipJRaUHBXfblVWJEbaYIti
###gy02yThZZFw1NamqP37+ZNAla7aYcOLeEuLeq5xdyKXJJ5EeBh6hofNoU/3CBEk3
###D3UWHrQpStsVbVXKknKuLowErw5pv/ldCXgmKUhrDeS8Xz8b3zwAmxU41haY711W
###SsgunCWqYWVcHJFQtdhVys/VlJRG/GkIVzyxKQXth/2Yv+GV6P95EQ7H97X5878W
###7f80qpubDbn/s1GrVuG+EtSrlyf9nx9yJez/VDZL8NeW00i0T9BpIaXA9sMu0cMu
###0cMukXjYJXrYJfordonuI2Bj1pbTRXh+c5WwCzW/m4QLdgesN+f+b8qYK4JGpaK2
###RMgYl73BYAA5EkYLGs6inwntcBSz1/HIAeGZ2MXklYrx70GD0NyP7Is8E3Ov/pGH
###hyYdQC5Yr8KDx0aferxLuZIn6JEZiJvce+LDeEI8EWBHo8nNHADAIOm3ZCJ0YxDE
###0FOAAb3SxeroZnw9T03oh7mDrogT0Bwp6jT8O8VdpgjdQEvA20ER7N0BLJEGQ6Gw
###k1WmFlr4tSPGo8GdmIJ2wd0kKRujNIGeAb1LMklDPhP+xRLwVYRmzBrSu5h54EUP
###V0qoNrseTHccrycc9c7p7P8IREKKu0Wers+MBUp86sFady6dW/FVdiWf4rW41UxB
###hkAfUg8qq/BmxApmlmaj108ePf/y5vmXX59/6cCfw+d7UKscFLaMzFMO4sR0/JmO
###lc/H4vJmMMD7PKvfGcmZ9dstnt1qufG18SWofK1WvtQrXzYqiAG911tHIFgMZ6yS
###akVkggY1sqtSS4pd8nxEGHZTSr7RoK1A0ULHWJTZ/TTGvcLbaH4HkxTu96if7FPQ
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###IHocq6DHNQ0i0IjqQjsjeMgMpLRzLqZE9A+e36TODsHxx+1smhMF4Nh076L68xyDM
###oK8GyA3VHiKWqluK9nMW0XJs5vTU5LR57DAUQK36078IMgrj+gKlLfdgV9Nqg3Bz
###lGmftmkVfQPiWct3WxR3eQy1CFxwOJE/VdYwhOChjNaDleBjLFlerB+MnhyheZh
###JnGhm48xyv80x9MDRb45pn/9oX6mlz/4UcG8WtHeXrX+TD+inLs5eBZs5Clup31T
###lW+2vBclgqKe2QBoHBOSHVFEb+sM1LQLMG9FvDc3a3W0WQZe4WRSaFVa8ZMKFOF
###MmILPxf+q9pZLGindAXXMfrlKpVjDuG4UmjXB5VQd2JSul6KHCvmpjxLXglxPY9m
###cv3BWUQVw1ihNRkhaztkclxk8TUzf7VCCvyVs/gi/Fmxb8FfM4aV8HcCZ1G8LIWa
###FNn0+KBekOGphCoQjQ6jAWifmNUY7+Q7GT0ZgyfD3/BGPkWLZUtJDgXA08QiFrGs
###C+yVQmlmf6EluHpmf3OvfDchFDN8qnW3ez7R2UqTbKUGLvtSr49dWrdNrTezsEt7
###UfoBW8K6LDG7TP6gFxr3e7NeuI+BQbPWIdN3m0Ugnb0vfKLCJpDrok9MP9YQmZ2j
###onbuu73+vMk+Z8FIZx+jCX8lm4/Nb7WnT1lrepb6yErrMmjK/ltQtQ9I7e3ug0p2
###LmtejG+UHDTDyCVFuusC8dgvQk3/qsrb0fTKVmknGZJbc7xCWXedixfZ0NnPKPU
###xEW662IqK9xotwXm46urQWgJy7koDFkMcN0bSNu401ZUGcyNx8pYwIwtYRwWc4p
###jWPIyV+2vVEpbLBeR38UisrNu+dzGE5wYlvjARC4GA+7RmjDakfhZ31L2k40cXk
###YHFo1B9F/SMaNRMAwzRVLgcy/w7wDbErGkKuBmbLzdEEkaHYxG5pUai0S1Cc6T2Z
###KcYGEJECm0/hdAYjTnV0ziSjQ47Bepbyp1GYOOJo+PaM1B0ZKc5FmPeVhaGh6vgj
###zLksEfRFImjW7xmgDdKPePmnT4Wi8eZ90tivxwOd1kBURVktVSSse9CZtDgbeH/c
###fmvwyiRfgma7amWYkxTNRK0X3dfHv75ovd7/fbm6SZF6nH8EtTnOAK157BgiaL6w
###6jxB5H4ZTkdrFER+MrWnhHUuSBgozGKFQqLl+fnefDzLxXDhMFhGRSgcZRdeMFbY
###IrsUHrHm2NnqtOlRk7w6cQbEXgRVP9MsBJfb6R9WK1nflgnPlJv+saGQEE6ZYMq
###4aJRM9pWQAhFiWCR2YL09ZhWk0pEyE5PdbjChJmDQsXddrJd8kasNzR3Xi9ojWu2
###o51plPhimVAsBd7+u101ZMckGyhirX56/TUaNoDUEhaXcezq5Ig08eqUCGTL+5KN
###fZO1XjprJT2RiSPk2rAreWlJVAWf5UCqyXTcD2d4Ang4xE6hQ5PKdMYds6LLXKYG
```

```
###KvMArO1MwARA2SUPaJH33IwStQZHY5DfO/yC92LfFcGnFQ0WzfJWxNmMiu/C3ELx
###8PdZsKx5TQRU+9HzGM+Xl/IJKc2VyPHd6t58Q3U2X+bK1f36DdU5OSxXqazzLbXF
###02auUuXhN9Soss3wmVPbPGJz4BoJaJ20FT2b1BMbrX4yLI9s+el4Ub+DPr/Cng38d
###PmcxVjMunwjeYMcra4mn62tsGnvOgt86k40e8F0z2UJZaSZXy42UwZCxfTUr1ZUH
###3TdUU/2GaoLK6vUE31BP9RvqaaxeTf0bqqk2Vq5mY6lqaoU12rMUN5iZaW13Jmh/
###cftgbAHGcFHA/wGKbPCnDn82Kv8NOAMT776LN3A4XgOTJEjSNmKUEfm4IHNP7bQi
###6veJYRaMh6sJA//w5hlBO7V1vjgexHG5D5nRbf5930pjoHgk87WHP6kVaGD9vnHy
###KS6v9x2V675RBqXp8XcgTJ/H9Qupiv1JKKNOt4DK3laQsw2kAHhYJ+iLP3w2kuX0
###u8aPhOBhyG29P7xNvkX5u5oXA+bh7b//88agsXh/f3cRlMQugxd/ZZdlrAqrdBaA
###SemmFRYUt3oltgmZwgTdYaZQ99UiuvxCzML5nCLUo1XV21VVA326ZVnBJbJZMpYO
###J25tkLrjjMBqtKOGrczWyTZB4oIOhs3+8iVBAtpjNrQUO6Ng/l+x78k9+DyE/+eA
###lkhIE6I87pohkLJKLzIyyqbRNi8OYGXC7Zf07tclUUNmsdG7wSZ1jbIYY1rYhS08
###GN8MLigXC8KSfiwCUwb5JnWse3kDqdgYdnDXuRFwb9ogrwoCJp/P11z04dXK+CvX
###uOQGBLwBNpPNKj2SbYmH6azDCoiZrUJrOMqV3TAv812MoniqA8gLXRk8QLO40vdu
###pkTmBskBwAZ6yJq116DZIpHHUuZTyqCA8PPodE0ki32MfbLy5olLkPkApYmiJVD4
###vH16sn/ayrG5zXBa9LG2YuWM/Wn5j98/P8kpY+5KH6E/MSwI++2j01x/pY9xyXiN
###1Po9Z/WW5T9vU3aE7mHrIOeOfctDkOEG0e/+qPW6k3PE+uWhvDj9Laek1OU/kvyv
###i57s3betk40cLzGafeRsWC8JyPG/7b9q7b/IPUW/CTdLNM1S3yPJzpmL0MxSLeUu
###mqV/xsRUdf9lExPPDeK/MnIBmz6MWhQOINXWv2Pr850/gMCPrrPsY4YZO8edBN2a
###9hdAH4YX0c1wRejarL4ANvwOV4TsW00XgJ/dwGj/hjq0nX4Be01uvBAybv4tgIXB
###jVPg80gB6QDUbn0KDLasxlZVktCDXig/QXkU6gms/K/+odf83JMLM2PzWeJYjtK0
###pcx1NYlYrI84Fi317acRkEJThy6elGuX4uP5+izdzvk4IudBCvAsG3FRUvnlpNKV
###adpMRJ2tm4VKuVIJUj/3O6jIbMCA95JgmSOHs0JeZXVzN3wLJlG8CnBGHTW3ksLd
###dwBQwZwQiOMrWMj3LTBHKnfZm7BUnomQnumNq2BUSfC9lUhGShvcsOKgw54vsMqR
###bX2+rbXelcccW7zyF3O1KA7F3XlmpLEx9f3pU9IVc/knlYqzCeBWr2rEADGy9Iav
###TdMaoYq5WwmeXovcpbJjfN7im0uxSB76qyDtq2rWV9W0r4Ksr2ppXzUyPqgmIthI
###/6hhP0rYY0n6zN1ywG7V3bMb39zCHmaDZy9h/yuru/BaSmKku0JuCoG8p+fj5fg3
###eoaJREMEXosHvyXJV2dqMTuIHemljJG+vHytgNURFmvoV29qxxct3/wf9/x324aS
###ZBNzp/UugLkURVAU9aLw5TxZ3yVyIHyVsL8fH0josilda5HR8eMI/esE4Kz4Xtzw
###8eULh7e7cFTFVs326FNvgGcUlbeImdlzR9LOGOyEYbVwlixLRN+beEnycPC0dKjv
###qCKGelq/YeY33sJVaxfSI9MGHjInYSPJsc2/HstkFSSnXKi49legfiy0VcmLt8rR
###fsyV2SmJk52TEX3ZneW/YNUtfrYgTlDjYoZxdvTBCH0htW2BXs7gLCA6BdiLt1IF
###1TEwDZrPot0EkSYeNcmAx9BXMZcxvFBwiNtxv/6UMZkZH5MsDmNjYea00th0TvIj
###0Zscj3xngRituMcpBinSX8aalmzQTYWrvuDg90T694p6bHOMlI6KYM4SvIJdal/+
###vgq++g/WC7AWX4bzOyewXGIzd40Kv07Ly/XtxVKxer/LupaA+QLLy2H7aP9192T/
###6GUr9zSFnfOveKsLWueXZIGCn7yyQ15HWw1NpMns9SPFeOK+9E0o8lrBQ4TN2KQz
###cQktdYUD3Ee5jMLBRUxG4IcdneXGfOJv13+eRnNK4SJfmxUx3kgOO6U/76UeVXTB
###8u1+17iKUOBX0v11NGJP7JHHjRhckOFQfokZHPcqTGxEYXo3tosdG8k5FUEPJ010
###9VJf5AMOEjFG7BmPzBndz9fhCL7GpTkalFTZ5AQ2QfW51STWo4va81VppRRRwfk8
###HE7w5JWyQ0pjBMdGHmQPb/UZtyT09OV2h2tdRSFZnvwSv1A4YLHjrU7OCBiJdOPa
###C2CYJEXMvFJVctbUaXh1M+hNdTu/qxXSbFByMGc/E3GvpOEee5rZmj+bxElolFE
###vuZispewbiW3QDEA+HwNbfZM3kuTA92aSVhVImvRFxZIFrGySBuTtskCb84ks7FK
###m+kXys1CeJZ8txFJSrNL5tTlJL6lwesZwXmwYtNwSF6xvaOSHB2YK7gnhV6XVELl
###RdNhR6ZACKrERoG79FPkFjpwiHdMI3kx+Q+HnZ2BsEkngXjjbNvwBQ1rfUPMzXnv
###NQg3ZZaqOMYh4xKH8o04IbiyiXjm3OZ0X6SFPdZeAknUWvRtNFIOtE8GFxT8fmug
###w9/DXfZYlHZiWqiyShnxg4ovRbblwfkjzZMG0iSydGlsgr+JueWHjPGehd6lIX4j
###I9A4x4ro95ojNBS2nJmvlTNRzi0DCop5mQfu677cMS+fOVNjSRFiNMU9lEq54gsh
###SV4I+kqQpVGFFR+JM8I/XCkWBxt4X3xcW0uVGxAVoA9osQDhDD7LySPlefVkea6m
```

```

####WwD/IdBl+DcRH0AlD9QNwkYiUvrIekav6cucvOduUXGkYHC8x4BBo35MSqAT8X5N
####/H6jnmQipIp5peage07drbkjIC+eajOA0mgYY0q9T+EUC1cqfW7HaemTTb0D1c4f
####grBUK2CDPGt0jlkzdOfKaPZuRBrXPYoiBWxgcv5xshQyOE8hJy9KSycOu4TqNTH
####VJTJiC2gkkUJgCxLIyybTied2RWjXl30prgGfIrUyeUsbAiV2X9N5zkagOuSbZRo
####OBKK6zLfgN9fiwiJoUmRy8J6dEe+UjNUBD5fR/lrmS0XN9cR4Wk4w/Or4nM4RezH
####mJhVTQ3KSfyi9fzdy27n9Pik1Tl4fdxpdTEICcXvA6Fu8LF7igEvOzBmcyrEXTTE
####AHnz27n29XLMDTqBD/zmr7Vs0l/Db0lrzORj0r+YUeJOKkNTW9q4gsXWofj6Q1/Z
####9/jLvU5LUufdwUGr08HgOn9l8NmH6+F6uB6uh+vhergerofr4Xq4Hq6H6+F6uB6u
####h+tPv/4fhSE5iwAwIAA=

```

A.4. Test vectors

Because of size constraints, the Opus test vectors are not distributed in this draft. They are available from the Opus codec website at <http://opus-codec.org/testvectors/> and will also be made available in IETF meeting proceedings. These test vectors were created specifically to exercise all aspects of the decoder and therefore the audio quality of the decoded output is significantly lower than what Opus can achieve in normal operation.

The SHA1 hash of the files in the test vector package are

1c93c979fcdd3b690e7f026c7d3c0dd7ff18ce26	test1_mono.bit
d081f04726a9b55139169e9102c0e8aefd3bc598	test1_mono.fixed
52ef3919cb33f423ab5ad3d6eaec73c78d59ae47	test1_mono.float
581b0a5dbc1cb624c79e4d881813793d819a43f0	test2_mono.bit
46d4ddc49c0ce80861dcbbcc3264383ebe851bd9	test2_mono.fixed
fc8d3609f7fe22463641b52acf71bda7e97ebc99	test2_mono.float
512965134678ec8a2883796467cd27c9d2e6b2ac	test3_mono.bit
d6401be4d5dc006bb6433c4aa1c4c018ddd4d25c	test3_mono.fixed
d10310d657fde1dd23c1a50c4fb3fad8d8ce8d5f	test3_mono.float
5d3819e5ac37ecfbd6a7ab7142b083279e1815ff	test4_mono.bit
44881c834f03f810fffb2397de3ec850323f49513	test4_mono.fixed
6538684f07dc435aa6877f5cf705936afce3aca9	test4_mono.float
58515e06eee6bfb0981b0d09882e6903b2de3a26	test5_mono.bit
5ae5eb782f911ff7bd1faf2369fd09e88122b356	test5_mono.fixed
120217917cad910d6ea5d6855192210ac88881dd	test5_mono.float
3a8e9c2136daee94f517c0e1bcb79ffee9b094e0	test1_stereo.bit
0016f27e2792ac5651cf9a47abacd0ffc3e3aa6b	test1_stereo.fixed
b63ed7377bd39alebd76e965ff77a32adad837bd	test1_stereo.float
521eb2ale0cc9c31b8b740673307c2d3b10c1900	test2_stereo.bit
3dba673f3ff244fb3930cd712ebf14ab4d51808b	test2_stereo.fixed
8aa4a5c7c2fbd4add2e4d4b76bb0c15c8e3ea8a8	test2_stereo.float
5b50aa6d1c093c77c15e61d6fc466a5ff1f7c423	test3_stereo.bit
165c6b92599ab1319acb8e5637b8123856c102b9	test3_stereo.fixed
e6613f0af12f6faa16f4760b0b1a59a5cb5bfbfd	test3_stereo.float
6bc8f3146fcb96450c901b16c3d464ccdf4d5d96	test4_stereo.bit
01c6f02bc5d10a5a653a89b82f6c5f7807397074	test4_stereo.fixed

20ffcbbf8b0eeaf4ff17ed29d1120b2d23ce50334 test4_stereo.float

Appendix B. Self-Delimiting Framing

To use the internal framing described in Section 3, the decoder must know the total length of the Opus packet, in bytes. This section describes a simple variation of that framing which can be used when the total length of the packet is not known. Nothing in the encoding of the packet itself allows a decoder to distinguish between the regular, undelimited framing and the self-delimiting framing described in this appendix. Which one is used and where must be established by context at the transport layer. It is RECOMMENDED that a transport layer choose exactly one framing scheme, rather than allowing an encoder to signal which one it wants to use.

For example, although a regular Opus stream does not support more than two channels, a multi-channel Opus stream may be formed from several one- and two-channel streams. To pack an Opus packet from each of these streams together in a single packet at the transport layer, one could use the self-delimiting framing for all but the last stream, and then the regular, undelimited framing for the last one. Reverting to the undelimited framing for the last stream saves overhead (because the total size of the transport-layer packet will still be known), and ensures that a "multi-channel" stream which only has a single Opus stream uses the same framing as a regular Opus stream does. This avoids the need for signaling to distinguish these two cases.

The self-delimiting framing is identical to the regular, undelimited framing from Section 3, except that each Opus packet contains one extra length field, encoded using the same one- or two-byte scheme from Section 3.2.1. This extra length immediately precedes the compressed data of the first Opus frame in the packet, and is interpreted in the various modes as follows:

- o Code 0 packets: It is the length of the single Opus frame (see Figure 19).
- o Code 1 packets: It is the length used for both of the Opus frames (see Figure 20).
- o Code 2 packets: It is the length of the second Opus frame (see Figure 21).
- o CBR Code 3 packets: It is the length used for all of the Opus frames (see Figure 22).
- o VBR Code 3 packets: It is the length of the last Opus frame (see Figure 23).

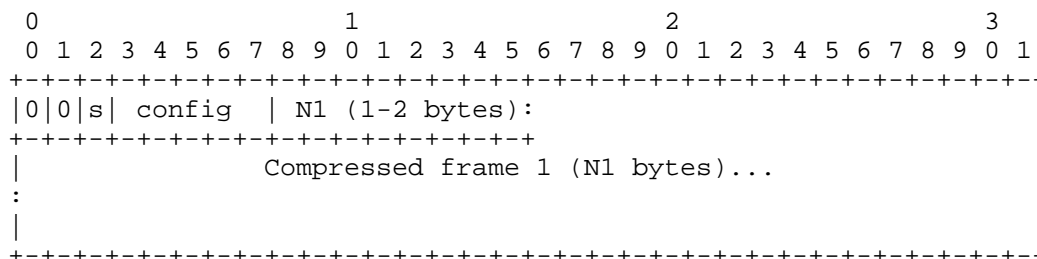


Figure 19: A Self-Delimited Code 0 Packet

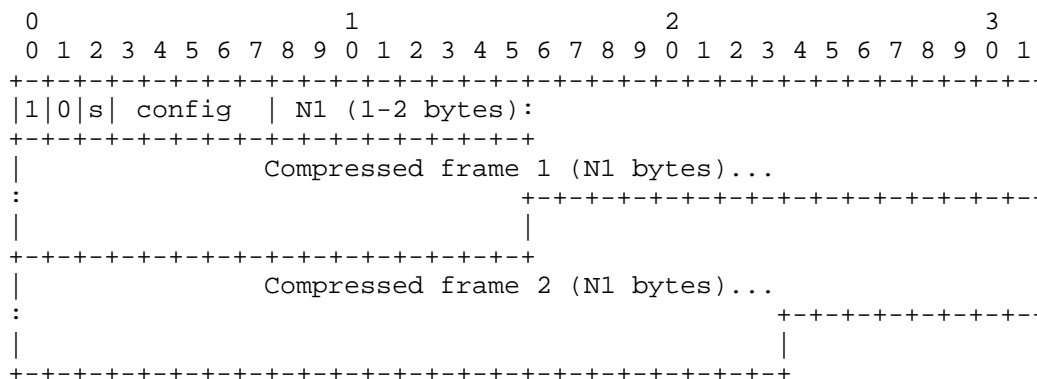


Figure 20: A Self-Delimited Code 1 Packet

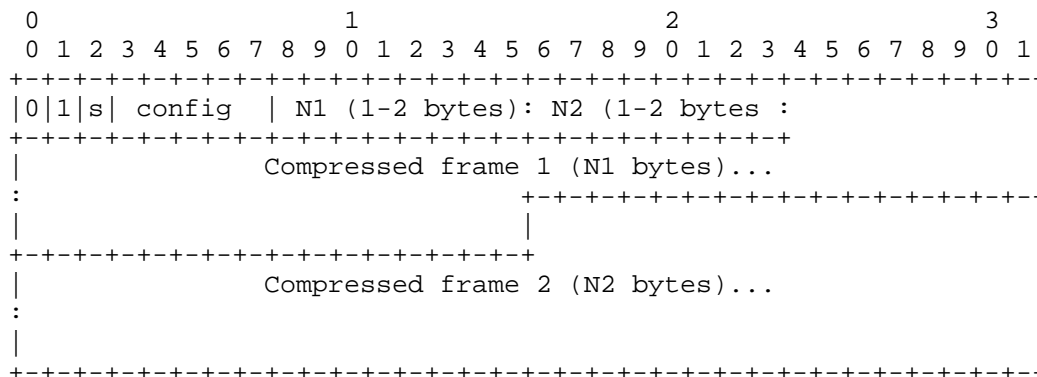


Figure 21: A Self-Delimited Code 2 Packet

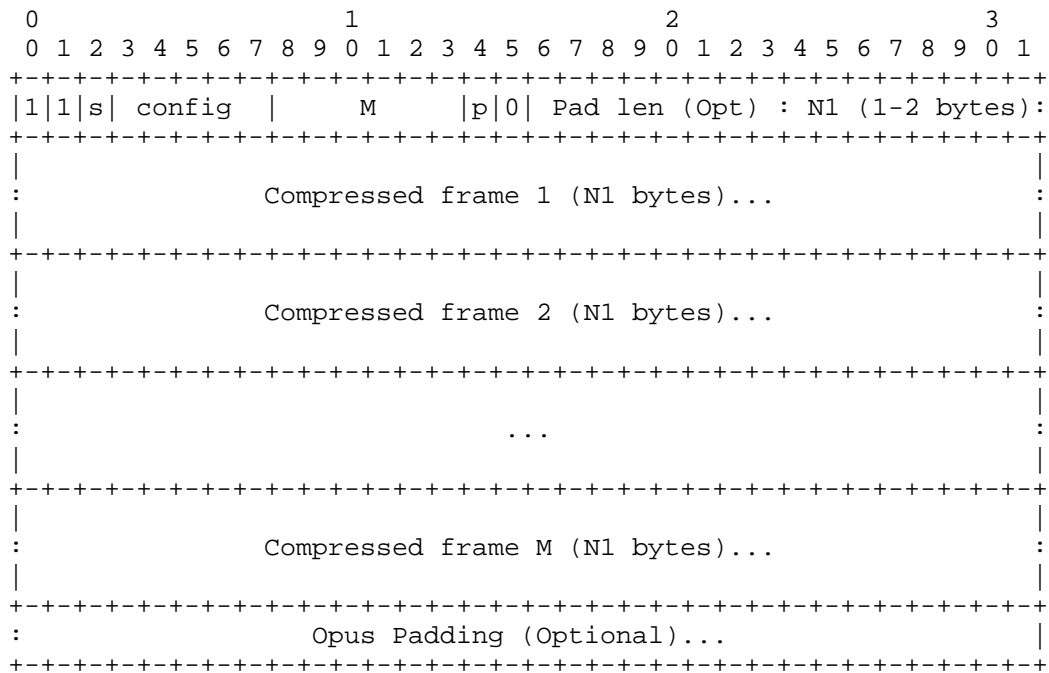


Figure 22: A Self-Delimited CBR Code 3 Packet

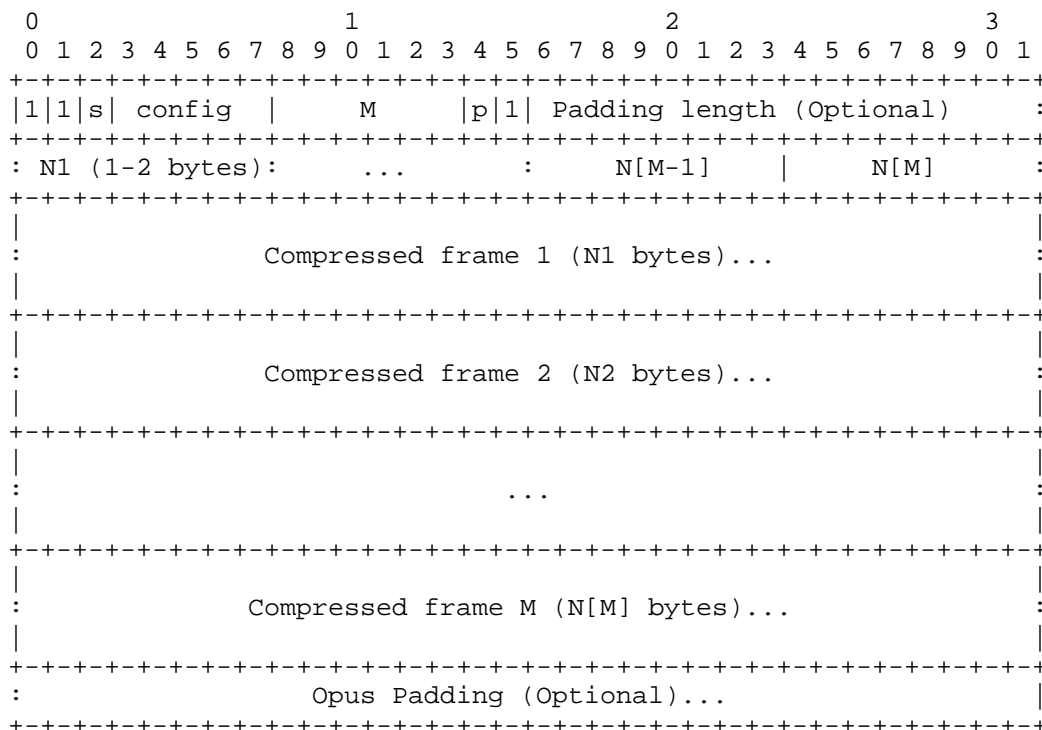


Figure 23: A Self-Delimited VBR Code 3 Packet

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Summary of Opus listening test results
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Abstract

This document describes and examines listening test results obtained for the Opus codec and how they relate to the requirements.

Status of this Memo

This Internet-Draft is submitted in full conformance with the provisions of BCP 78 and BCP 79.

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1. Introduction

This document describes and examines listening test results obtained for the Opus codec. Some of the test results presented are based on older versions of the codec or on older versions of the SILK or CELT components. While they do not necessarily represent the exact quality of the current version, they are nonetheless useful for validating the technology used and as an indication of a lower bound on quality (based on the assumption that the codec has been improved since they were performed).

Throughout this document, all statements about one codec being better than or worse than another codec are based on 95% confidence. When no statistically significant difference can be shown with 95% confidence, then two codecs are said to be "tied".

In addition to the results summarized in this draft, Opus has been subjected to many informal subjective listening tests, as well as objective testing.

2. Opus listening tests on final bit-stream

The following tests were performed on the Opus codec after the bit-stream was finalized.

2.1. Google listening tests

The tests followed the MUSHRA test methodology. Two anchors were used, one lowpass-filtered at 3.5 kHz and one lowpass-filtered at 7.0 kHz. Both trained and untrained listeners participated in the tests. The reference signals were manually normalized to the same subjective levels according to the experimenters' opinion. Experiments with automatic normalization with respect to both level and loudness (in Adobe Audition) did not result in signals having equal subjective loudness. The sample magnitude levels were kept lower than 2^{14} to provide headroom for possible amplification through the codecs. However, the normalization exercise was not repeated with the processed sequences as neither the experimenters nor any of the subjects (which included expert listeners) noticed any significant level differences between the conditions in the tests. The only post-processing performed was to remove noticeable delays in the MP3 files, as one could identify the MP3 samples when switching between conditions when the MP3 had the longer delay. The testing tool Step from ARL was used for tests and all listeners were instructed to carefully listen through the conditions before starting the grading. The results of the tests are available on the testing slides presented at the Prague meeting [Prague-80].

2.1.1. Google narrowband listening test

The test sequences in Test 1 were mono recordings (between 2 and 6 seconds long) of 4 different male and 4 different female speakers sampled at 48 kHz in low background noise. 17 listeners were presented with 6 stimuli according to Table 1 for each test sequence. The corresponding bit rate for the reference is $48000 \text{ (sampling frequency in Hz)} \times 16 \text{ (bits/sample)} = 768 \text{ kbps}$. Since the anchors are low-pass filtered they can also be downsampled for transmission which corresponds to lower bit rates. Three narrowband codecs were compared in this test: Opus NB, the royalty-free iLBC, and the royalty-free Speex. The codecs all have an encoder frame length of 20 ms. Both Opus and Speex had variable rate whereas iLBC operated at a fixed bit rate.

Type	Signal bandwidth	Bitrate
Reference	24 kHz (Fullband)	
Anchor 1	3.5 kHz (Narrowband)	
Anchor 2	7 kHz (Wideband)	
iLBC	4 kHz (Narrowband)	15.2 kbps, CBR
Opus NB	4 kHz (Narrowband)	11 kbps, VBR
Speex NB	3.5 kHz (Narrowband)	11 kbps, VBR

Table 1: Narrowband mono voice: test conditions

The overall results of the narrowband test, i.e., averaged over all listeners for all sequences, are presented in the Prague meeting slides [Prague-80]. The results suggest that Opus at 11 kbps is superior to both iLBC at 15 kbps and Speex at 11 kbps. T-tests performed by Greg Maxwell confirm that there is indeed a statistically significant difference. Note also that Opus has a slightly higher average score than the 3.5 kHz anchor, likely due to the higher bandwidth of Opus.

2.1.2. Google wideband and fullband listening test

The eight test sequences for the previous test were also used in this Test. 16 listeners rated the stimuli listed in Table 2. In this test comparisons were made between four wideband codecs: Opus WB, the royalty-free Speex, the royalty-free ITU-T G.722.1, AMR-WB (ITU-T G.722.2), and two fullband codecs: Opus FB and the royalty-free ITU-T G.719. All six codecs utilize 20 ms encoding frames. Opus used variable bitrate, while other codecs used constant bit rate.

Type	Signal bandwidth	Bitrate
Reference	24 kHz (Fullband)	
Anchor 1	3.5 kHz (Narrowband)	
Anchor 2	7 kHz (Wideband)	
G.722.1	7 kHz (Wideband)	24 kbps, CBR
Speex WB	7 kHz (Wideband)	23.8 kbps, CBR
AMR-WB	7 kHz (Wideband)	19.85 kbps, CBR
Opus WB	8 kHz (Wideband)	19.85 kbps, VBR
G.719	~20 kHz (Fullband)	32 kbps, CBR
Opus FB	~20 kHz (Fullband)	32 kbps, CBR

Table 2: Wideband and fullband mono voice: test conditions

The results from this test are depicted in the Prague meeting slides[Prague-80]. Opus at 32 kbps is almost transparent, although there is a small, but statistically significant, difference from the fullband reference material. Opus at 20 kbps is significantly better than all the other codecs, including AMR-WB and the fullband G.719, and both low-pass anchors.

2.1.3. Google stereo music listening test

The sequences in this test were excerpts from 10 different stereo music files:

- o Rock/RnB (Boz Scaggs)
- o Soft Rock (Steely Dan)
- o Rock (Queen)
- o Jazz (Harry James)
- o Classical (Purcell)
- o Electronica (Matmos)

- o Piano (Moonlight Sonata)
- o Vocals (Suzanne Vega)
- o Glockenspiel
- o Castanets

These sequences were originally recorded at a sampling frequency of 44.1 kHz and were upsampled to 48 kHz prior to processing. Test 3 included comparisons between six codecs (c.f., Table 3): Opus at three rates, G.719, AAC-LC (Nero 1.5.1), and MP3 (Lame 3.98.4). G.719 is a mono codec, so the two channels were each coded independently at 32 kbps. 9 listeners participated in Test 3, and the results are depicted in the Prague meeting slides[Prague-80]. The codecs operated at constant (or comparable) bit rate.

Type	Signal bandwidth	Frame size (ms)	Bitrate
Reference	22 kHz (Fullband)	-	(1536 kbps)
Anchor 1	3.5 kHz (Narrowband)	-	(256 kbps)
Anchor 2	7 kHz (Wideband)	-	(512 kbps)
MP3	16 kHz (Super wideband)	>100	96 kbps, CBR
AAC-LC	~20 kHz (Fullband)	21	64 kbps, CBR (bit reservoir)
G.719	~20 kHz (Fullband)	20	64 kbps (2x32), CBR
Opus FB	~20 kHz (Fullband)	20	64 kbps, constrained VBR
Opus FB	~20 kHz (Fullband)	10	80 kbps, constrained VBR
Opus FB	~20 kHz (Fullband)	5	128 kbps, constrained VBR

Table 3: Stereo music: Test conditions

The results indicate that all codecs had comparable performance, except for G.719, which had a considerably lower score. T-tests by Greg Maxwell verified that the low-delay Opus at 128 kbps had a significantly higher performance and that G.719 had a significantly lower performance than the other four.

2.1.4. Google transcoding test

If two telephone networks of different technology are coupled, frequently speech has to be transcoded: It must be decoded and encoded before it can be forward to the next network. Then, two codecs are cooperating in a row, which is called tandem coding.

In the following tests, Jan Skoglund studied the impact of transcoding if Opus call is forwarded to a cellular phone system. [Skoglund2011]. Two tests were conducted for both narrowband and wideband speech items. The test conditions of the narrow-band tests are given in Table and the respective results in . For the wide-band conditions and results refer to Table and .

Condition	Value
Laboratory	Google
Examiner	Jan Skoglund
Date	August and September 2011
Methodology	ITU-R BS.1534-1 (MUSHRA)
Reference items	Two male and two female speakers from ITU-T P.501. Two male and two female speakers from McGill database. All recorded at 48kHz in a room with low background noise.
Listeners	19 listeners no listeners rejected / trained and untrained English-speaking listeners
Anchor 1	Reference file lowpass-filtered at 3.5 kHz
Anchor 2	Reference file resampled at 8 kHz, with MNRU at 15 dB SNR
Test Condition 1	G.711 at 64 kbps -> Opus NB at 12.2 kbps, variable bit rate
Test Condition 2	G.711 at 64 kbps -> AMR NB at 12.2 kbps, constant bit rate
Test Condition 3	AMR NB at 12.2 kbps -> G.711 at 64 kbps -> Opus NB at 12.2 kbps
Test Condition 4	Opus NB at 12.2 kbps > G.711 at 64 kbps > AMR NB at 12.2 kbps
Test Condition 5	AMR NB at 12.2 kbps -> G.711 at 64 kbps -> AMR NB at 12.2 kbps

Table 4: Narrowband tandem coding: test conditions

Test Item	Subjective MUSHRA score	95% CI
Reference	99.47	0.36
LP3.5	63.49	3.01
G.711->Opus	54.51	2.85
G.711->AMR	54.13	2.67
AMR->G.711->Opus	51.11	2.74
Opus->G.711->AMR	50.95	2.76
AMR->G.711->AMR	47.81	2.95
MNRU	14.94	2.21

Table 5: Tandem narrowband coding: test results

Condition	Value
Laboratory	Google
Examiner	Jan Skoglund
Date	August and September 2011
Methodology	MUSHRA
Reference items	Two male and two female speakers from ITU-T P.501. Two male and two female speakers recorded at Google at 48kHz in a room with low background noise
Listeners	18 listeners after post-screening / no listener rejects / untrained and trained English speaking listeners
Anchor 1	Reference file lowpass-filtered at 3.5 kHz (LP 3.5)
Anchor 2	Reference file lowpass-filtered at 7 kHz (LP 7)
Test Condition 1	Opus WB at 19.85 kbps, variable bit rate (Opus)
Test Condition 2	AMR WB at 19.85 kbps, constant bit rate (AMR WB)
Test Condition 3	AMR WB at 19.85 kbps > Opus WB at 19.85 kbps
Test Condition 4	Opus WB at 19.85 kbps -> AMR WB at 19.85 kbps

Table 6: Tandem wideband coding: test conditions

Test Item	Subjective BS.1587 Score	95% CI
Reference	99.44	0.38
Opus	78.38	2.16
LP7	74.24	2.24
AMR WB	65.26	2.85
AMR WB->Opus	63.97	2.95
Opus->AMR WB	62.83	2.94
LP3.5	37.01	2.95

Table 7: Tandem wideband coding: test results

Under the given statistical confidence, narrowband tandem coding condition using AMR and/or Opus are of similar quality. However, the results have indications that Opus outperforms AMR NB slightly. In any case, narrow band transcoding is worse than a low pass filtering at 3.5kbps.

Opus at 20kbps outperforms AMR WB at a similar coding rate and matches the quality of a 7kHz lowpass filtered signal. Tandem coding with Opus does not reduce the quality of AMR WB encoded speech in the studied conditions.

2.1.5. Google mandarin tests

Modern Standard Chinese - also called Mandarin - is a tonal language that is spoken by about 845 million persons. In past, codecs have been developed without consideration of the unique properties of tonal languages. For the testing of Opus, Jan Skoglund has conducted subjective listening-only tests to verify whether Opus can cope well for Mandarin [Skoglund2011]. Two tests were conducted for both narrow- and wide-band speech items. The test conditions of the narrow-band tests are given in Table and the respective results in . For the wide-band conditions and results refer to Table and Table

Condition	Value
Laboratory	Google
Examiner	Jan Skoglund
Date	August and September 2011
Methodology	ITU-R BS.1534-1 (MUSHRA)
Reference items	Two male and two female speakers from ITU-T P.501. Two male and two female speakers recorded at Google at 48kHz in a room with low background noise.
Listeners	21 listeners after post-screening / no listeners rejected / untrained Mandarin-speaking listeners
Anchor 1	Reference file lowpass-filtered at 3.5 kHz (LP 3.5)
Anchor 2	Reference file resampled at 8 kHz, with MNRU at 15 dB SNR (MNRU)
Test Condition 1	Opus NB at 11 kbps, variable bit rate (Opus 11)
Test Condition 2	Speex NB at 11 kbps, variable bit rate (Speex 11)
Test Condition 3	iLBC at 15.2 kbps, constant bit rate (iLBC 15)

Table 8: Narrowband mandarin: test conditions

Test Item	Subjective BS.1534-1 Score	95% CI
Reference	99.79	0.19
Opus 11	77.90	2.15
iLBC 15	76.76	2.08
LP 3.5	76.25	2.34
Speex 11	63.60	3.30
MNRU	22.83	2.50

Table 9: Mandarin narrowband speech: test results

Condition	Value
Laboratory	Google
Examiner	Jan Skoglund
Date	August and September 2011
Methodology	MUSHRA
Reference items	Two male and two female speakers from ITU-T P.501. Two male and two female speakers recorded at Google at 48kHz in a room with low background noise
Listeners	19 listeners after post-screening / Rejected 3 listeners having score correlation with the total average lower than $R=0.8$.
Anchor 1	Reference file lowpass-filtered at 3.5 kHz (LP 3.5)
Anchor 2	Reference file lowpass-filtered at 7 kHz (LP 7)
Test Condition 1	Opus WB at 19.85 kbps, variable bit rate (Opus 20)
Test Condition 2	Speex WB at 23.8 kbps, constant bit rate (Speex 24)
Test Condition 3	G.722.1 at 24 kbps, constant bit rate (G.722.1 24)
Test Condition 4	Opus FB at 32 kbps, constant bit rate (Opus 32)
Test Condition 5	G.719 at 32 kbps, constant bit rate (G.719 32)

Table 10: Mandarin wideband speech: test conditions

Test Item	Subjective BS.1587 Score	95% CI
Reference	98.95	0.59
Opus 32	98.13	0.72
G.719 32	93.43	1.51
Opus 20	81.59	2.48
LP 7	79.51	2.53
G.722.1 24	72.55	3.06
LP 3.5	54.57	3.44
Speex 24	53.63	4.23

Table 11: Mandarin wideband speech: test results

Under the given confidence intervals, the quality of Opus at 11 kbps equals the quality of iLBC at 15 kbps and the quality after lowpass filtering at 3.5 kHz. Speex at 11 kbps does not perform as well. According to the listening-only tests, Opus at 32 kbps is better than G.719 at 32 kbps. Opus at 20 kbps outperforms G.722.1 and Speex at 24 kbps. If one compares the Mandarin results with those for English (Section 2.1.1 and Section 2.1.2), one can see that are pretty consistent. The only difference is that using English stimuli Opus at 20 kbps outperforms G.719 at 32 kbps. Probably, this is due to the fact that Mandarin speech does not contain as many high frequency-rich consonants such as [s] as English.

2.2. HydrogenAudio stereo music listening test

In March 2011, the HydrogenAudio community conducted a listening test comparing codec performance on stereo audio at 64 kb/s [ha-test]. The Opus codec was compared to the Apple and Nero implementations of HE-AAC, as well as to the Vorbis codec. The test included 30 audio samples, including known "hard to code" samples from previous HydrogenAudio listening tests.

A total of 33 listeners participated in the test, 10 of which provided results for all the audio samples. The results of test showed that Opus out-performed both HE-AAC implementations as well as Vorbis.

2.3. Nokia Interspeech 2011 listening test

In 2011, Anssi Ramo from Nokia submitted [Ramo2011] the results of a second listening test, focusing specifically on the Opus codec, to Interspeech 2011. As in the previous test, the methodology used was a 9-scale ACR MOS test with clean and noisy speech samples.

The results show Opus clearly out-performing both G.722.1C and G.719 on clean speech at 24 kb/s and above, while on noisy speech all codecs and bit-rates above 24 kb/s are very close. It is also found that the Opus hybrid mode at 28 kb/s has quality that is very close to the recent G.718B standard at the same rate. At 20 kb/s, the Opus wideband mode also out-performs AMR-WB, while the situation is reversed for 12 kb/s and below. The only narrowband rate tested is 6 kb/s, which is below what Opus targets and unsurprisingly shows poorer quality than AMR-NB at 5.9 kb/s.M

2.4. Universitaet Tuebingen stereo and binaural tests

Modern teleconferencing system use stereo or spatially rendered speech to enhance the conversation quality. Then, talkers can be identified according to their acoustic locations. Opus allows to encode speech in a stereo mode. In the tests conducted by Christian Hoene[Hoene2011], the performance of Opus coding stereo and binaural speech was studied.

Condition	Value
Laboratory	Univesitaet Tuebingen
Examiner	Christian Hoene and Mansoor Hyder
Date	August 2011
Methodology	ITU-R BS.1534-1 (MUSHRA) using a modified "rateit v0.1" software with German translations.
Reference items	One German female voice recorded in stereo (8s). Two female voices (stereo recording) mixed together (9 s). One moving talker binaural rendered with HTRF and an artificial room impulse response (13 s). Two voices binaural render at two different stationary positions. Acappella Song "Mein Fahrrad" by "Die Prinzen" (10.5s, mono)
Listeners	20 German native speakers. Age between 20 and 59 (avg. 30.55). 9 male and 11 female. All have academic background. Three listeners were rejected because their rating showed a low correlation ($R < 0.8$) to the average ratings.
Anchor	Reference file lowpass-filtered at 3.5 kHz calling "sox in.wav -r48000 -c1 out.wav lowpass 3500"
Test Condition 1	Opus in the SILK mode, 12kbps, stereo, 60ms calling "draft-ietf-codec-opus-07/test_opus 0 48000 2 12000 -cbr -framesize 60 -bandwidth NB"
Test Condition 2	Opus in the SILK mode, 16kbps, stereo, 20ms calling "draft-ietf-codec-opus-07/test_opus 0 48000 2 16000 -cbr -framesize 20 -bandwidth WB"
Test Condition 3	Opus in the HYBRID mode, 32kbps, stereo, 20ms calling "draft-ietf-codec-opus-07/test_opus 0 48000 2 32000 -cbr -framesize 20 -bandwidth FB"
Test Condition 4	Opus in the CELT mode, 64kbps, stereo, 20ms calling "draft-ietf-codec-opus-07/test_opus 1 48000 2 64000 -cbr -framesize 20 -bandwidth FB"
Test Condition 5	AMR-WB+ at 12kbps, 80ms using 26304_ANSI-C_source_code_v6_6_0: Arguments: -rate 12

Test Condition 6	AMR-WB+ at 15.2kbps, 80ms using 26304_ANSI-C_source_code_v6_6_0: Arguments: -rate 16
Test Condition 7	AMR-WB+ at 32kbps, 60ms using 26304_ANSI-C_source_code_v6_6_0: Arguments: -rate 32

Table 12: Stereo and binaural speech coding: test conditions

Test Item	Subjective BS.1534-1 Score	95% CI
Reference	97.36	1.31
Opus 64	95.58	1.76
AMR-WB+ 32	80.11	4.79
Opus 32	55.42	5.96
AMR-WB+ 16	49.69	6.05
LP 3.5	48.35	4.50
Opus 16	39.31	4.80
AMR-WP+ 12	35.40	5.79
Opus 12	16.99	3.49

Table 13: Binaural Speech: Test Results

According to the test results, Opus transmits binaural content well at 64kbps. The other Opus results are not valid anymore as the codec implementation have been updated.

3. Conclusion on the requirements

The requirements call for the Opus codec to be better than Speex and iLBC in narrowband mode, better than Speex and G.722.1 in wideband mode, and better than G.722.1C in super-wideband/fullband mode.

3.1. Comparison to Speex (narrowband)

The Opus codec was compared to Speex in narrowband mode in the Google narrowband test (Section 2.1.1). This test showed that Opus at 11 kb/s was significantly better than Speex at the same rate. In fact, Opus at 11 kb/s was tied with the 3.5 low-pass of the original. Considering the results, we conclude that the Opus codec is better than the Speex codec.

3.2. Comparison to iLBC

The Opus codec was compared to iLBC in the Google narrowband test (Section 2.1.1). This test showed that Opus at 11 kb/s was significantly better than iLBC running at 15 kb/s. Considering the results, we conclude that the Opus codec is better than the iLBC codec.

3.3. Comparison to Speex (wideband)

The Opus codec was compared to Speex in wideband mode in the Google wideband and fullband test (Section 2.1.2). This test showed that Opus at 20 kb/s was significantly better than Speex at 24 kb/s. In fact, Opus at 20 kb/s was better than the 7 kHz low-pass of the original. These results are consistent with an earlier Dynastat test (Appendix A.1) that also concluded that SILK had significantly higher quality than Speex in wideband mode at the same bit-rate. Considering the results, we conclude that the Opus codec is better than the Speex codec for wideband.

3.4. Comparison to G.722.1

In the Google wideband and fullband test (Section 2.1.2), Opus at 20 kb/s was shown to significantly out-perform G.722.1 operating at 24 kb/s. An indirect comparison point also comes from the Nokia Interspeech 2011 listening test (Section 2.3) that shows Opus out-performing AMR-WB at 20 kb/s, while AMR-WB is known to out-perform G.722.1. Considering these results, we conclude that the Opus codec is better than the G.722.1 codec for wideband.

3.5. Comparison to G.722.1C

Opus has been compared to G.722.1C in multiple listening tests. As early as 2008, an old version of the CELT codec (Appendix A.4) using very short frames was found to have higher quality than G.722.1C at 48 kb/s. More recently, the Nokia Interspeech 2011 listening test (Section 2.3) showed that Opus out-performed G.722.1C at 24 kb/s, 32 kb/s, and 48 kb/s. We thus conclude that the Opus codec is better than the G.722.1C codec for superwideband/fullband audio.

3.6. Comparison to AMR-NB

In the Google narrowband test (Section 2.1.1), Opus was shown to out-perform AMR-NB at 12 kb/s. On the other hand, in the Nokia Interspeech 2011 listening test (Section 2.3), AMB-NB was found to have better quality than Opus at 6 kb/s. This indicates that Opus is better than AMR-NB at higher rates and worse at lower rates, which is to be expected given Opus' emphasis on higher quality and higher rates.

3.7. Comparison to AMR-WB

In the Google wideband and fullband test (Section 2.1.2), Opus at 20 kb/s was shown to out-perform AMR-WB at the same rate. This was also confirmed by the Nokia Interspeech 2011 listening test (Section 2.3), with also found AMR-WB to out-perform Opus at 12 kb/s and below. As with AMR-NB, we conclude that Opus is better than AMR-WB at higher rates and worse at lower rates.

4. Security Considerations

No security considerations.

5. IANA Considerations

This document has no actions for IANA.

6. Acknowledgments

The authors would like to thank Anssi Ramo and the HydrogenAudio community, who conducted some of the Opus listening test cited in this draft.

Appendix A. Pre-Opus listening tests

Several listening tests have been performed on the SILK and CELT codecs prior to them being merged as part of the Opus codec.

A.1. SILK Dynastat listening test

The original (pre-Opus) SILK codec was characterized in a Dynastat listening test [SILK-Dynastat]. The test included 32 conditions with 4 male and 4 female talkers. The test signals were wideband speech with and without office background noise at 15 dB SNR. Packet loss was tested at 2, 5, and 10% loss rates. The bitrates ranged from 8.85 kb/s to 64 kb/s. The codecs included in the test were SILK-WB, AMR-WB, Speex-WB and G.722 (which ran at 64 kb/s).

The results showed that for clean speech (1) SILK out-performs AMR-WB at all bit-rates except 8.85 kb/s (which was a tie); (2) SILK out-performs Speex at all bit-rates; and (3) SILK running at 18.25 kb/s and above out-performs G.722 at 64 kbps. For noisy speech, tested at 18.25 kb/s, SILK is tied with AMR-WB, and out-performs Speex. For 2, 5 and 10% packet loss, tested at 18.25 kb/s, SILK out-performs both AMR-WB and Speex in all conditions.

A.2. SILK Deutsche Telekom test

In 2010 Deutsche Telekom published results [Wustenhagen2010] of their evaluation of super-wideband speech and audio codecs. The test included the version of SILK submitted to the IETF. The results showed that for clean speech (item "speechsample") SILK was tied with AMR-WB and G.718, and out-performed Speex. For noisy speech (item "arbeit") SILK out-performed AMR-WB and G.718 at 12 and 24 kb/s, and Speex at all bitrates. At bitrates above 24 kb/s SILK and G.718 were tied.

A.3. SILK Nokia test

In 2010, Anssi Ramo from Nokia presented [Ramo2010] the results of a listening test focusing on open-source codecs at Interspeech 2010. The methodology used was a 9-scale ACR MOS test with clean and noisy speech samples.

It was noted in the test that:

"Especially at around 16 kbit/s or above Silk is better than AMR-WB at comparable bitrates. This is due to the fact that Silk wideband is critically sampled up to 8 kHz instead of ITU- T or 3GPP defined 7 kHz. This added bandwidth (from 7 to 8 kHz) shows up in the results favourable to Silk. It seems that Silk provides quite artifact free

voice quality for the whole 16- 24 kbit/s range with WB signals. At 32 and 40 kbit/s Silk is SWB and competes quite equally against G.718B or G.722.1C although having a slightly narrower bandwidth than the ITU-T standardized codecs."

A.4. CELT 0.3.2 listening test

The first listening tests conducted on CELT version 0.3.2 in 2009 and published in 2010 [valin2010] included AAC-LD (Apple), G.722.1C and MP3 (Lame). Two MUSHRA tests were conducted: a 48 kb/s test and a 64 kb/s test, both at a 44.1 kHz sampling rate. CELT was used with 256-sample frames (5.8 ms). All codecs used constant bit-rate (CBR). The algorithmic delay was 8.7 ms for CELT, 34.8 ms for AAC-LD, 40 ms for G.722.1C and more than 100 ms for MP3.

The 48 kb/s test included two clean speech samples (one male, one female) from the EBU SQAM database, four clean speech files (two male, two female) from the NTT multi-lingual speech database for telephony, and two music samples. In this test, CELT out-performed AAC-LD, G.722.1C and MP3.

The 64 kb/s test included two clean speech samples (one male, one female) from the EBU SQAM database, and six music files. In this test, AAC-LD out-performed CELT, but CELT out-performed both MP3 and G.722.1C (running at its highest rate of 48 kb/s).

A.5. CELT 0.5.0 listening test

Another CELT listening test was conducted in 2009 on version 0.5.0 and presented at EUSIPCO 2009 [valin2009]. In that test, CELT was compared to G.722.1C and to the Fraunhofer Ultra Low-Delay (ULD) codec on 9 audio samples: 2 clean speech samples and 7 music samples. At 64 kb/s with 5.3 ms frames, CELT clearly out-performed G.722.1C running at 48 kb/s with 20 ms frames. Also, at 96 kb/s and equal frame size (2.7 ms), CELT clearly out-performed the ULD codec.

Appendix B. Opus listening tests on non-final bit-stream

The following listening tests were conducted on the Opus codec on versions prior to the bit-stream freeze. While Opus has evolved since these tests were conducted, the results should be considered as a lower bound on the quality of the final codec.

B.1. First hybrid mode test

In July 2010, the Opus codec authors conducted a preliminary MUSHRA listening test to evaluate the quality of the recently created "hybrid" mode combining the SILK and CELT codecs. That test was conducted at 32 kb/s and compared the following codecs:

- o Opus hybrid mode (fullband)
- o G.719 (fullband)
- o CELT (fullband)
- o SILK (wideband)
- o BroadVoice32 (wideband)

The test material consisted of two English speech samples from the EBU SQAM (one male, one female) database and six speech samples (three male, three female) from the NTT multi-lingual speech database for telephony. Although only eight listeners participated to the test, the difference between the Opus hybrid mode and all other codecs was large enough to obtain 95% confidence that the Opus hybrid mode provided better quality than all other codecs tested. This test is of interest because it shows that the hybrid clearly out-performs the codecs that it combines (SILK and CELT). It also out-performs G.719, which is the only fullband interactive codec standardized by the ITU-T. These results were presented [Maastricht-78] at the 78th IETF meeting Maastricht.

B.2. Broadcom stereo music test

In December 2010, Broadcom conducted an ITU-R BS.1116-style subjective listening test comparing different configurations of the CELT-only mode of the IETF Opus codec along with MP3 and AAC-LC. The test included stereo 10 audio samples sampled at 44.1 kHz and distributed as follows:

- o 2 pure speech

- o 2 vocal
- o 2 solo instruments
- o 1 rock-and-roll
- o 1 pop
- o 1 classical orchestra
- o 1 jazz

A total of 17 listeners participated to the test. The results of the test are available on the testing slides presented at the Prague meeting [Prague-80]. Although at the time, Opus was not properly optimised for 44.1 kHz audio, the quality of the Opus codec at 96 kb/s with 22 ms frame was significantly better than MP3 and only slightly worse than AAC-LC. Even in ultra low-delay mode (5.4 ms), Opus still outperformed MP3. The test also confirmed the usefulness of the prefilter/postfilter contribution by Raymond Chen, showing that this contribution significantly improves quality for small frames (long frames were not tested with the prefilter/postfilter disabled).

Appendix C. In-the-field testing

Various versions of Opus (or SILK/CELT components) are currently in use in production in the following applications:

- o Skype: VoIP client used by hundreds of millions of people
- o Steam: Gaming distribution and communications platform with over 30 million users
- o Mumble: Gaming VoIP client with more than 200 thousand users
- o Soundjack: Client for live network music performances
- o Freeswitch: Open-source telephony platform
- o Ekiga: Open-source VoIP client
- o CHNC: Radio station using CELT for its studio-transmitter link

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