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Definition of the Opus Audio Codec
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Abstract

This document defines the Opus codec, designed for interactive speech and audio transmission over the Internet.

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1. Introduction

The Opus codec is a real-time interactive audio codec 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. In general, 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.

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 syntax like "2**n" is used to indicate 2 raised to the power n. 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 lo>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 .

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

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. Internally, the codec always operates at a 48 kHz sampling rate, though it allows input and output of various bandwidths, defined as follows:

Abbreviation	Audio Bandwidth	Sampling 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

These 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.

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 5.2 ms look-ahead for noise shaping estimation (5 ms) and internal resampling (0.2 ms). Like Vorbis and many other modern codecs, SILK is inherently designed for variable-bitrate (VBR) coding, though an encoder can with sufficient effort produce constant-bitrate (CBR) or near-CBR streams.

The MDCT layer is based on the CELT [2] codec [CELT]. It supports sampling 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.

At the decoder, the two decoder outputs are simply added together. To compensate for the different look-aheads 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 lookahead 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.

3. Codec Modes

As described, the two layers can be combined in three possible operating modes:

1. A 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.

A single packet may contain multiple audio frames, however they must share a common set of parameters, including the operating mode, audio bandwidth, frame size, and channel count. A single-byte table-of-contents (TOC) header 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.

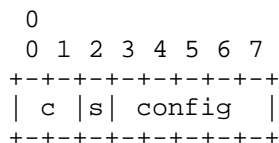


Figure 1: The TOC byte

The top five bits of the TOC byte, labeled "config", encode one of 32 possible configurations of operating mode, audio bandwidth, and frame size. Table 1 lists the parameters for each configuration.

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

Table 1: TOC Byte Configuration Parameters

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

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. It must also obey various additional rules indicated by "MUST", "MUST NOT", etc., in this section. A receiver MUST NOT process packets which violate these rules as normal Opus packets. They are reserved for future applications, such as in-band headers (containing metadata, etc.) or multichannel support.

When a packet contains multiple VBR frames, 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 (DTX or lost packet)
- o 1...251: Size of the frame in bytes
- o 252...255: A second byte is needed. The total size is
(size[1]*4)+size[0]

The maximum representable size is $255 \times 4 + 255 = 1275$ 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 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, it MUST NOT exceed 1275 bytes, to allow for repacketization by gateways, conference bridges, or other software.

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.

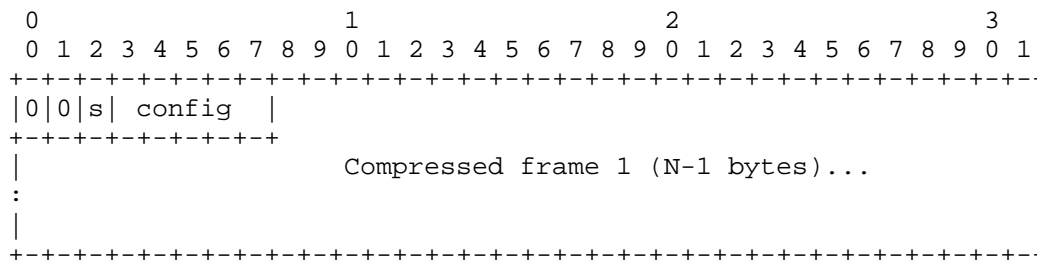


Figure 2: A Code 0 Packet

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.

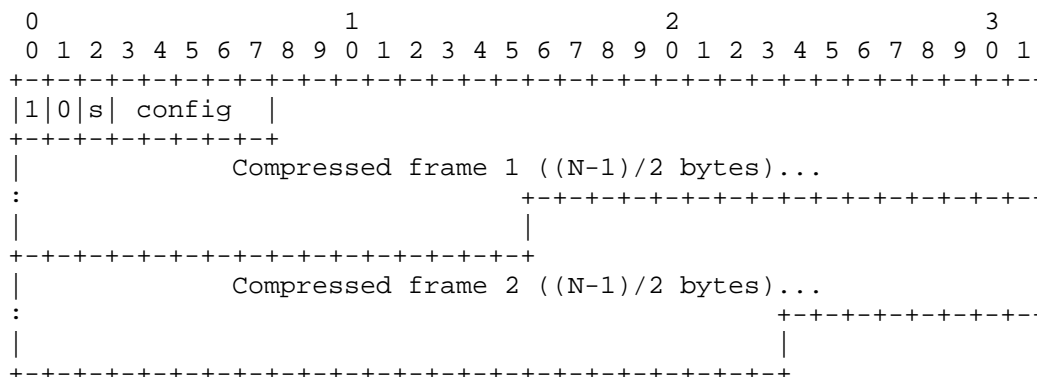


Figure 3: A Code 1 Packet

For code 2 packets, the TOC byte is followed by a one or two byte sequence indicating the the length of the first frame (marked N_1 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. The length of the first frame, N_1 , MUST be no larger than the size of the payload remaining after decoding that length for all code 2 packets.

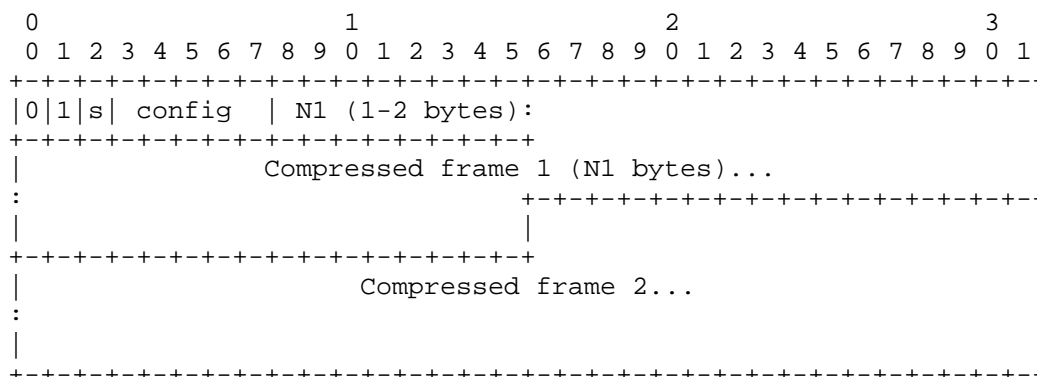


Figure 4: A Code 2 Packet

For code 3 packets, 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 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.

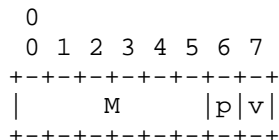


Figure 5: The frame count byte

When 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. The additional padding bytes appear at the end of the packet, and SHOULD be set to zero by the encoder, however the decoder MUST accept any value for the padding bytes. By using code 255 multiple times, it is possible to create a packet of any specific, desired size. Let P be the total amount of padding, including both the trailing padding bytes themselves and the header bytes used to indicate how many there are. Then P MUST be no more than N-2 for CBR packets, or N-M-1 for VBR packets.

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.

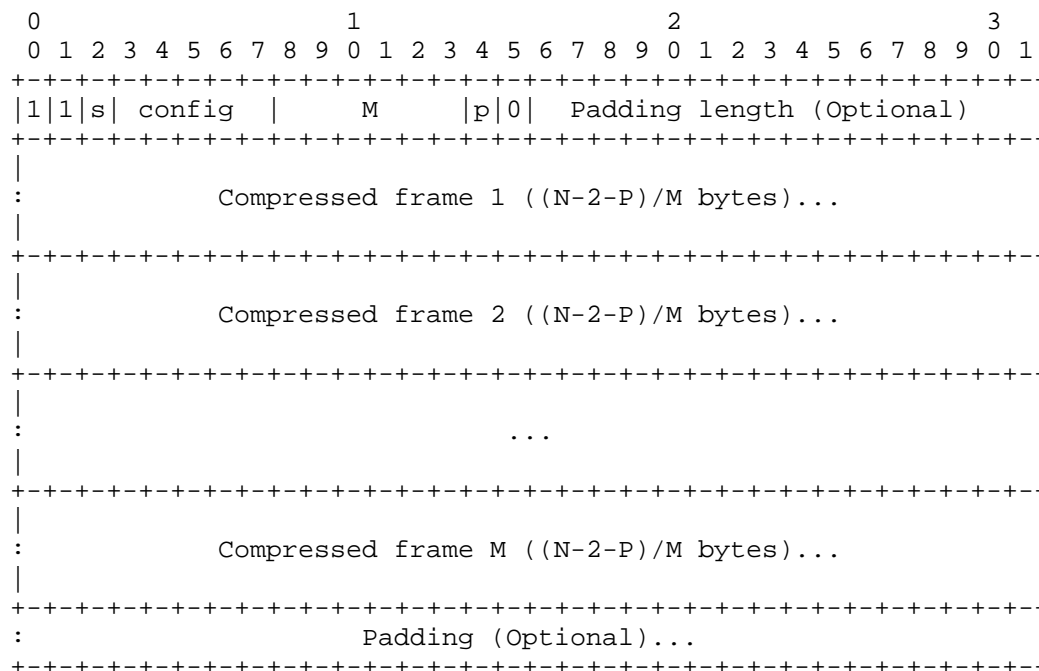


Figure 6: A CBR Code 3 Packet

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 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.

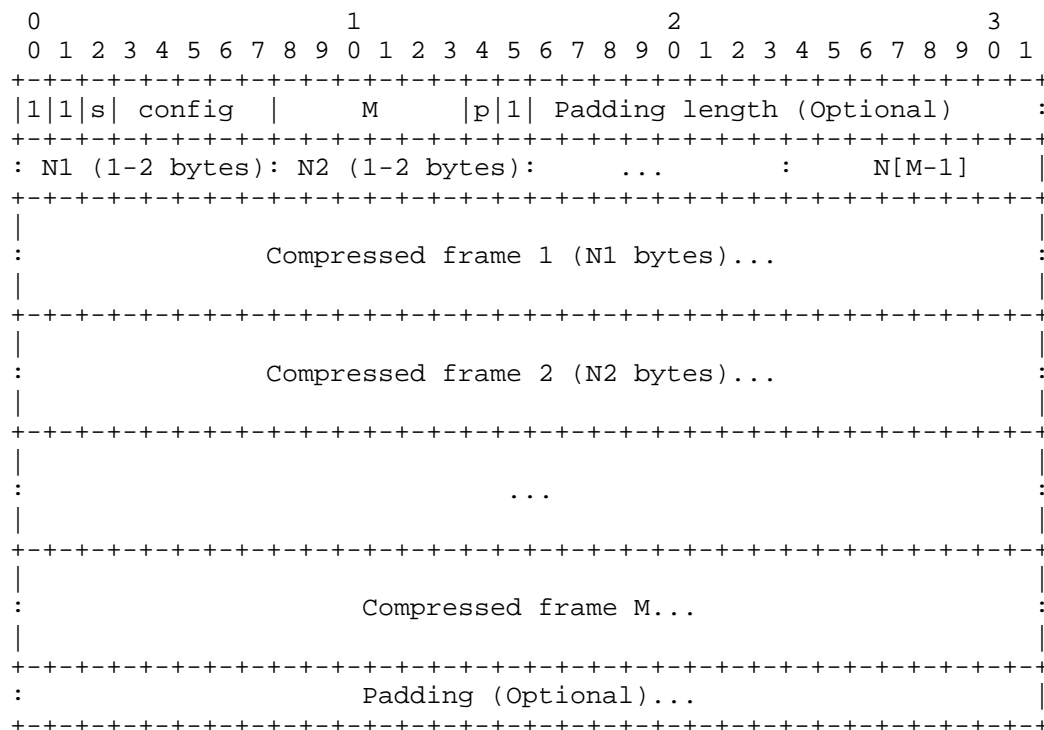
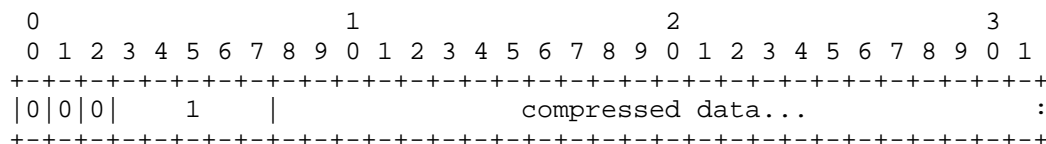


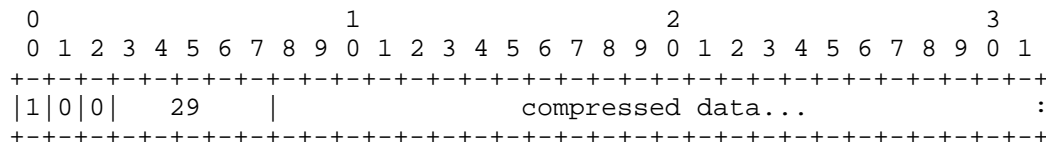
Figure 7: A VBR Code 3 Packet

3.1. 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   |   |   |   |   |   |   |   |
+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+
|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+

```

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

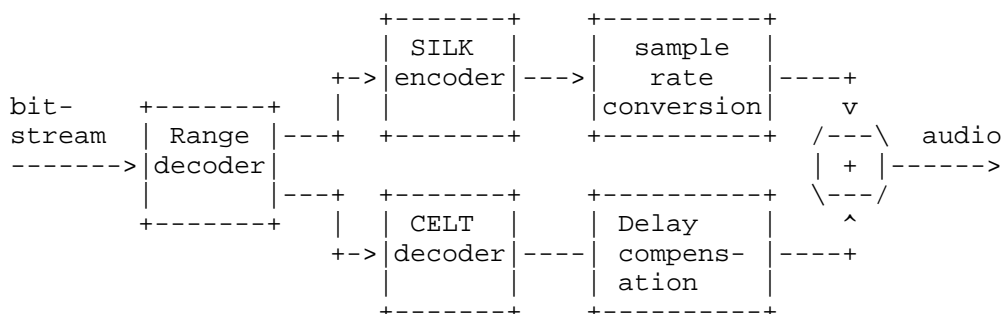
```

      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...   |   |   |   |
+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+

```


4. Opus Decoder

The Opus decoder consists of two main blocks: the SILK decoder and the CELT decoder. 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 as illustrated in the block diagram below. At any given time, one or both of the SILK and CELT decoders may be active.



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. 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.

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. Opus only uses static contexts. They are not adapted to the statistics of the data as it is coded.

The parameters needed to encode or decode a symbol in a given context

are represented by a three-tuple (fl,fh,ft), with $0 \leq fl < fh \leq ft \leq 65535$. The values of this tuple are derived from the probability model for the symbol, represented by traditional `_frequency counts_` (although, since Opus uses static contexts, these are not updated as symbols are decoded). Let $f[i]$ be the frequency of the i -th symbol in a context with n symbols total. Then the three-tuple corresponding to the k -th symbol is given by

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

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 then immediately normalizes the range using the procedure described in Section 4.1.1.1.

4.1.1.1. 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,fh,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 one whose three-tuple (fl,fh,ft) satisfies $fl \leq fs < fh$. It uses this tuple to update val according to $val = val - (rng/ft)*(ft-fh)$. If fl is greater than zero, then the decoder updates rng using $rng = (rng/ft)*(fh-fl)$. Otherwise, it updates rng using $rng = rng - (rng/ft)*(ft-fh)$. After these updates, implemented by `ec_dec_update()` (`entdec.c`), it normalizes the range using the procedure in the next section, and returns the index of the identified symbol.

With this formulation, all the truncation error from using finite precision arithmetic accumulates in symbol 0. This makes the cost of

coding a 0 slightly smaller, on average, than the negative log of its estimated probability 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.

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<<8)`. Then it reads the next 8 bits of input into `sym`, using the remaining bit from the previous input octet as the high bit of `sym`, and the top 7 bits of the next octet as the remaining bits of `sym`. If no more input octets remain, it uses zero bits instead. Then, it sets `val` to `(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 8. 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.

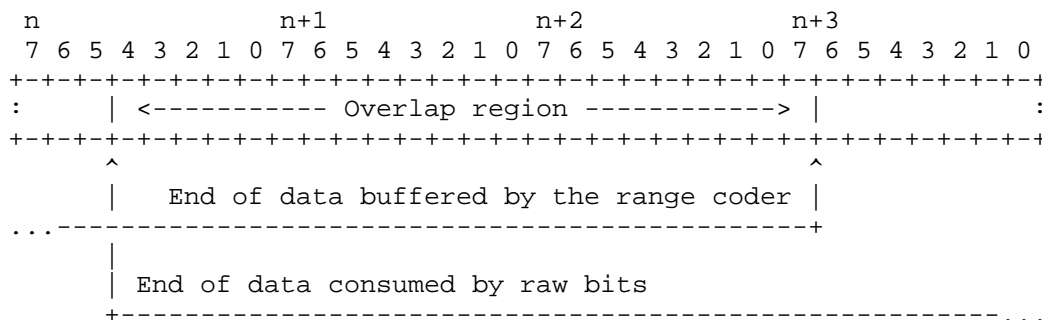


Figure 8: Illustrative example of raw bits overlapping range coder data

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 `fl = 0`, `fh = (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 = (1<<logp)-1`, `fh = 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` for the *k*th symbol in the context, which is equal to `(1<<ftb)-fl` for the (*k*+1)st symbol. `fl` for the 0th symbol is assumed to be 0, and the table is terminated by a value of 0 (where `fh == 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 = (1<<ftb)-icdf[k-1]` (or 0 if `k == 0`), `fh = (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 to be packed in the least significant bit of the last byte, filling up to the most significant bit in the last byte, and 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 $t = \text{ec_decode}((ft-1) \gg (ftb-8) + 1)$, 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 $t = t \ll (ftb-8) | \text{ec_dec_bits}(ftb-8)$. 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 $\text{ceil}(\text{ec_tell_frac}()/8.0)$. 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 symbol that requires a whole number of bits (i.e., $ft/(fh-1)$ is a power of two, including values of ft larger than 2^{*8} with `ec_dec_uint()`), and there are at least p

1/8th bits available, decoding the symbol will never advance the decoder past the end of the frame, i.e., will never `_bust_` the budget. Frames contain a whole number of bits, and the return value of `ec_tell_frac()` will only advance by more than p 1/8th bits in this case if there was a fractional number of bits remaining, and by no more than the fractional part. However, when p is not a whole number of bits, an extra 1/8th bit is required to ensure decoding the symbol will not bust.

The reference implementation keeps track of the total number of whole bits that have been processed by the decoder so far in a 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 = rng >> (l-16)`, so that $32768 \leq r < 65536$, 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 = r * r >> 15`. Then add the 16th bit of `r` to `l` via `l = 2 * l + (r >> 16)`. Finally, if this bit was a 1, reduce `r` by a factor of two via `r = r >> 1`, so that it once again lies in the range $32768 \leq r < 65536$.

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

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 in NB, MB, and WB modes internally. When used in a hybrid frame in SWB or FB mode, the LP layer itself still only runs in WB mode.

Internally, the LP layer of a single Opus frame is composed of either a single 10 ms SILK frame or between one and three 20 ms SILK frames. Each SILK frame is in turn composed of either two or four 5 ms subframes. Optional Low Bit-Rate Redundancy (LBRR) frames, which are reduced-bitrate encodings of previous SILK frames, may appear 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, and from here on this draft will use "SILK frame" to refer to either one and "regular SILK frame" if it needs to draw a distinction between the two.

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.

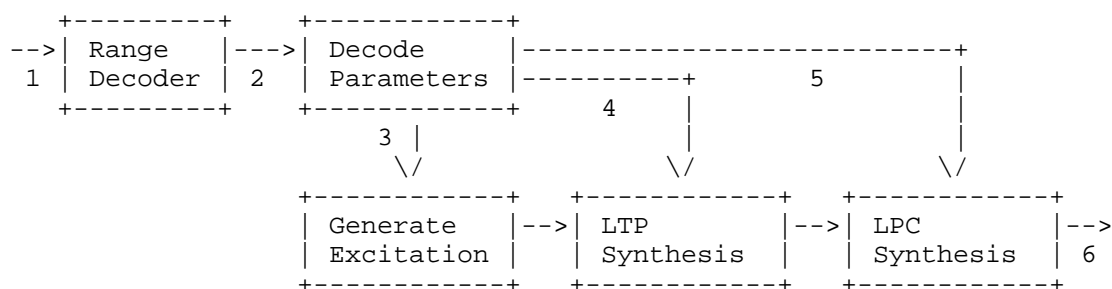
Symbol(s)	PDF	Condition
VAD flags	{1, 1}/2	
LBRR flag	{1, 1}/2	
Per-frame LBRR flags	Section 4.2.3	Section 4.2.3
Frame Type	Section 4.2.4.1	
Gain index	Section 4.2.4.2	

Order of the symbols in the SILK section of the bit-stream.

Table 2

4.2.1. Decoder Modules

An overview of the decoder is given in Figure 9.



- 1: Range encoded bitstream
- 2: Coded parameters
- 3: Pulses and gains
- 4: Pitch lags and LTP coefficients
- 5: LPC coefficients
- 6: Decoded signal

Decoder block diagram.

Figure 9

4.2.1.1. Range Decoder

The range decoder decodes the encoded parameters from the received bitstream. Output from this function includes the pulses and gains for the excitation signal generation, as well as LTP and LSF codebook indices, which are needed for decoding LTP and LPC coefficients needed for LTP and LPC synthesis filtering the excitation signal, respectively.

4.2.1.2. Decode Parameters

Pulses and gains are decoded from the parameters that were decoded by the range decoder.

When a voiced frame is decoded and LTP codebook selection and indices are received, LTP coefficients are decoded using the selected codebook by choosing the vector that corresponds to the given codebook index in that codebook. This is done for each of the four subframes. The LPC coefficients are decoded from the LSF codebook by first adding the chosen LSF vector and the decoded LSF residual signal. The resulting LSF vector is stabilized using the same method that was used in the encoder, see Section 5.2.7.5. The LSF coefficients are then converted to LPC coefficients, and passed on to the LPC synthesis filter.

4.2.1.3. Generate Excitation

The pulses signal is multiplied with the quantization gain to create the excitation signal.

4.2.1.4. LTP Synthesis

For voiced speech, the excitation signal $e(n)$ is input to an LTP synthesis filter that will recreate the long term correlation that was removed in the LTP analysis filter and generate an LPC excitation signal $e_{\text{LPC}}(n)$, according to

$$e_{\text{LPC}}(n) = e(n) + \sum_{i=-d}^d e_{\text{LPC}}(n - L - i) * b_i,$$

using the pitch lag L , and the decoded LTP coefficients b_i . The number of LTP coefficients is 5, and thus $d = 2$. For unvoiced speech, the output signal is simply a copy of the excitation signal,

i.e., $e_{\text{LPC}}(n) = e(n)$.

4.2.1.5. LPC Synthesis

In a similar manner, the short-term correlation that was removed in the LPC analysis filter is recreated in the LPC synthesis filter. The LPC excitation signal $e_{\text{LPC}}(n)$ is filtered using the LTP coefficients a_i , according to

$$y(n) = e_{\text{LPC}}(n) + \sum_{i=1}^{d_{\text{LPC}}} y(n-i) * a_i,$$

where d_{LPC} is the LPC synthesis filter order, and $y(n)$ is the decoded output signal.

4.2.2. Header Bits

The LP layer begins with two to eight header bits, decoded in `silk_Decode()` (`silk_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 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, they can be extracted directly from the upper 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.

4.2.3. LBRR Flags

For Opus frames longer than 20 ms, a set of per-frame LBRR flags is decoded for each channel that has its LBRR flag set. For 40 ms Opus frames the 2-frame LBRR flag PDF from Table 3 is used, and for 60 ms Opus frames the 3-frame LBRR flag PDF is used. 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 3: LBRR Flag PDFs

LBRR frames do not include their own separate VAD flags. An LBRR frame is only meant to be transmitted for active speech, thus all LBRR frames are treated as active.

4.2.4. SILK Frame Contents

Each SILK frame includes a set of side information that encodes the frame type, quantization type and gains, short-term prediction filter coefficients, LSF interpolation weight, long-term prediction filter lags and gains, and a pseudorandom number generator (PRNG) seed. This is followed by the quantized excitation signal.

4.2.4.1. Frame Type

Each SILK frame begins with 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 the value either 0 or 1 and is decoded using the first PDF in Table 4. If the frame is an LBRR frame or a regular SILK frame whose VAD flag was set (an `_active_frame`), then the symbol ranges from 2 to 5, inclusive, and is decoded using the second PDF in Table 4. Table 5 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 4: Frame Type PDFs

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

Table 5: Signal Type and Quantization Offset Type from Frame Type

4.2.4.2. Sub-Frame 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.

For the first LBRR frame, an LBRR frame where the previous LBRR frame was not coded, or the first regular SILK frame in an Opus frame, the first subframe uses an independent coding method. The 3 most significant bits of the quantization gain are decoded using a PDF selected from Table 6 based on the decoded signal type.

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 6: 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 7: PDF for Independent Quantization Gain LSb Coding

For all other subframes (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. The PDF in Table 8 yields a delta gain index between 0 and 40, inclusive.

[illegible]

Table 8: 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:

```
log_gain = min(max(2*gain_index - 16,
                    previous_log_gain + gain_index - 4), 63)
```

`silk_gains_dequant()` (`silk_gain_quant.c`) dequantizes the gain for the `k` th subframe and converts it into a linear Q16 scale factor via

```
gain_Q16[k] = silk_log2lin((0x1D1C71*log_gain>>16) + 2090)
```

The function `silk_log2lin()` (`silk_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. Then, 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

$$(1 < i) + ((-174 * f * (128 - f) > 16) + f) * ((1 < i) > 7) .$$

4.2.4.3. Normalized Line Spectral Frequencies

Normalized Line Spectral Frequencies (LSFs) follow the quantization gains in the bitstream, and represent the Linear Prediction Coefficients (LPCs) for the current SILK frame. Once decoded, they 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 4.2.4.3.3). 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). NB and MB frames use an order-10 predictor, while WB frames use an order-16 predictor, and thus have different sets of tables. The first VQ stage uses a 32-element codebook, coded with one of the PDFs in Table 9, depending on the audio bandwidth and the signal type of the current SILK frame. This yields a single index, `_i1_`, 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 18 and Table 19, 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 9: PDFs for Normalized LSF Index Stage-1 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 10, and the 8 (i...p) for WB frames given in Table 11. Which PDF is used for which coefficient is driven by the index, I_1 , decoded in the first stage. Table 12 lists the letter of the corresponding PDF for each normalized LSF coefficient for NB and MB, and Table 13 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 10: 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 11: 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 12: 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 13: 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 12 or Table 13, and subtracts 4 from the result to given 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 14, 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 14: PDF for Normalized LSF Index Extension Decoding

The decoded indices from both stages are translated back into normalized LSF coefficients in `silk_NLSF_decode()` (`silk_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 15

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 15: Prediction Weights for Normalized LSF Decoding

The prediction is undone using the procedure implemented in `silk_NLSF_residual_dequant()` (`silk_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, `I1`. Table 16 gives the selections for each coefficient for NB and MB, and Table 17 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 16: 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 17: Prediction Weight Selection for WB Normalized LSF Decoding

The spectral distortion introduced by the quantization of each LSF coefficient varies, so the stage-2 residual is weighted accordingly, using the low-complexity weighting 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 18 or Table 19. 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) to avoid computing them when decoding. The reference implementation computes them on the fly in `silk_NLSF_VQ_weights_laroia()` (`silk_NLSF_VQ_weights_laroia.c`) and its caller, to reduce the amount of ROM required.

I1	Codebook									
	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 18: Codebook Vectors for NB/MB Normalized LSF Stage 1 Decoding

I1	Codebook															
	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 19: 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

$$\text{NLSF_Q15}[k] = (\text{cb1_Q8}[k] \ll 7) + (\text{res_Q10}[k] \ll 14) / \text{w_Q9}[k] ,$$

where the division is exact integer division. However, nothing thus far in the reconstruction process, nor in the quantization process in the encoder, 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.

4.2.4.3.1. Normalized LSF Stabilization

The normalized LSF stabilization procedure is implemented in `silk_NLSF_stabilize()` (`silk_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 20 gives the minimum spacings for NB and MB and those for WB, where row k is the minimum allowed value of $\text{NLSF_Q}[k] - \text{NLSF_Q}[k-1]$. 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 20: 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 20. 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:

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

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

After the 20th repetition of the above, 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

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

4.2.4.3.2. Normalized LSF Interpolation

For 20 ms SILK frames, the first half of the frame (i.e., the first two sub-frames) may use normalized LSF coefficients that are interpolated between the decoded LSFs for the previous frame and the current frame. A Q2 interpolation factor follows the LSF coefficient

indices in the bitstream, which is decoded using the PDF in Table 21. This happens in `silk_decode_indices()` (`silk_decode_indices.c`). For the first frame after a decoder reset, 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 21: PDF for Normalized LSF Interpolation Index

Let $n2_Q15[k]$ be the normalized LSF coefficients decoded by the procedure in Section 4.2.4.3, $n0_Q15[k]$ 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()` (`silk_decode_parameters.c`).

4.2.4.3.3. Converting Normalized LSF Coefficients to LPCs

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()` (`silk_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 true the inverse of the cosine function, when deriving the normalized LSF coefficients.

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 approximated cosine, $c_{\text{Q17}}[k]$, is

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

where $\cos_{\text{Q13}}[i]$ is the corresponding entry of Table 22.

	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 22: Q13 Cosine Table for LSF Conversion

Given the list of cosine values, `silk_NLSF2A_find_poly()` (`silk_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 <= 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.

4.2.4.3.4. 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 the largest, breaking ties by using the lower 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()` (`silk_bwexpander_32.c`) performs the bandwidth expansion (again, only when `maxabs_Q12` is greater than 32767) using the following recurrence:

$$\text{a32_Q17}[k] = (\text{a32_Q17}[k] * \text{sc_Q16}[k]) \gg 16$$

$$\text{sc_Q16}[k+1] = (\text{sc_Q16}[0] * \text{sc_Q16}[k] + 32768) \gg 16$$

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 of the coefficients still overflow a 16-bit integer. This saturation is not performed if maxabs_Q12 drops to 32767 or less prior to the 10th round.

4.2.4.3.5. Limiting the Prediction Gain of the LPC Filter

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 `LPC_inverse_pred_gain_QA()` (`silk_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

$$\begin{aligned} rc[k] &= -a[k][k] , \\ a[k-1][n] &= \frac{a[k][n] - a[k][k-n-1]*rc[k]}{1 - rc[k]} . \end{aligned}$$

However, `LPC_inverse_pred_gain_QA()` approximates this using fixed-point arithmetic to guarantee reproducible results across platforms and implementations. It is important to run on the real Q12 coefficients that will be used during reconstruction, because small changes in the coefficients can make a stable filter unstable, but increasing the precision back to Q16 allows more accurate computation of the reflection coefficients. Thus, let

```
a32_Q16[d_LPC-1][n] = ((a32_Q17[n] + 16) >> 5) << 4
```

be the Q16 representation of the Q12 version of the LPC coefficients that will eventually be used. Then for each `k` from `d_LPC-1` down to 0, if `abs(a32_Q16[k][k]) > 65520`, the filter is unstable and the recurrence stops. Otherwise, the row `k-1` of `a32_Q16` is computed from row `k` as

```

rc_Q31[k] = -a32_Q16[k][k] << 15 ,

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

bl[k] = ilog(div_Q30[k]) - 16 ,

inv_Qb1[k] = (1<<29) - 1
             ----- ,
             div_Q30[k] >> (bl[k]+1)

err_Q29[k] = (1<<29)
             - ((div_Q30[k]<<(15-bl[k]))*inv_Qb1[k] >> 16) ,

mul_Q16[k] = ((inv_Qb1[k] << 16)
             + (err_Q29[k]*inv_Qb1[k] >> 13)) >> bl[k] ,

b2[k] = ilog(mul_Q16[k]) - 15 ,

t_Q16[k-1][n] = a32_Q16[k][n]
               - ((a32_Q16[k][k-n-1]*rc_Q31[k] >> 32) << 1) ,

a32_Q16[k-1][n] = ((t_Q16[k-1][n] *
                   (mul_Q16[k] << (16-b2[k]))) >> 32) << b2[k] .

```

Here, $rc_Q30[k]$ are the reflection coefficients. $div_Q30[k]$ is the denominator for each iteration, and $mul_Q16[k]$ is its multiplicative inverse. $inv_Qb1[k]$, which ranges from 16384 to 32767, is a low-precision version of that inverse (with $bl[k]$ fractional bits, where $bl[k]$ ranges from 3 to 14). $err_Q29[k]$ is the residual error, ranging from -32392 to 32763, which is used to improve the accuracy.

$t_Q16[k-1][n]$, $0 \leq n < k$, are the numerators for the next row of coefficients in the recursion, and $a32_Q16[k-1][n]$ is the final version of that row. Every multiply in this procedure except the one used to compute $mul_Q16[k]$ 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 $abs(a32_Q16[k][k]) \leq 65520$ for $0 \leq k < d_LPC$, then the filter is considered stable.

On round i , $1 \leq i \leq 18$, if the filter passes this stability check, then this procedure stops, and the final LPC coefficients to use for reconstruction are

```
a_Q12[k] = (a32_Q17[k] + 16) >> 5 .
```

Otherwise, a round of bandwidth expansion is applied using the same procedure as in Section 4.2.4.3.4, with

$$sc_Q16[0] = 65536 - i*(i+9) .$$

If, after the 18th round, the filter still fails the stability check, then $a_Q12[k]$ is set to 0 for all k .

4.2.4.4. Long-Term Prediction (LTP) Parameters

After the normalized LSF indices and, for 20 ms frames, the LSF interpolation index, voiced frames (see Section 4.2.4.1) include additional Long-Term Prediction (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.

4.2.4.4.1. Pitch Lags

The primary lag index is coded either relative to the primary lag of the prior frame or as an absolute index. Like the quantization gains, the first LBRR frame, an LBRR frame where the previous LBRR frame was not coded, or the first regular SILK frame in an Opus frame all code the pitch lag as an absolute index. When the prior frame was not voiced, this also forces absolute coding.

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 23 and the low part using the codebook corresponding to the current audio bandwidth from Table 24. 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 24, 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 23: 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}/256	8	32	288

Table 24: 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 25. 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 previous frame 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 25: PDF for 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 26 depending on the current frame size and audio bandwidth. Table 27 through Table 30 give the corresponding offsets to apply to the primary pitch lag for each subframe given the decoded codebook index.

Audio Bandwidth	SILK Frame Size	PDF
NB	10 ms	{143, 50, 63}/256
NB	20 ms	{68, 12, 21, 17, 19, 22, 30, 24, 17, 16, 10}/256
MB or WB	10 ms	{91, 46, 39, 19, 14, 12, 8, 7, 6, 5, 5, 4}/256
MB or WB	20 ms	{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}

Table 26: PDFs for Subframe Pitch Contour

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

Table 27: 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 28: 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 29: 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 30: 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()` (`silk_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 24, respectively.

4.2.5. LBRR Frames

LBRR frames, if present, immediately follow the header bits, prior to any regular SILK frames. Each frame whose LBRR flag was set includes a separate set of data for each channel.

4.3. CELT Decoder

The CELT layer is decoded 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 bit-stream.

Table 31

The decoder extracts information from the range-coded bit-stream 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 bit-stream 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: $A(z_l, z_b) = (1 - a \cdot z_l^{-1}) \cdot (1 - z_b^{-1}) / (1 - b \cdot z_b^{-1})$ 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 $a=0$ $b=4915/32768$ 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 bit is 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: 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 bit-stream 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 also 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, 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 process of allocation consists of the following steps: determining the per-band maximum allocation vector, decoding the boosts, decoding the tilt, determining the remaining capacity 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 an shape allocation per-band (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 which 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: bit-stream 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 partially computed form, in order to fit in less memory, as a static table (XXX cache.caps). 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 assign 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 execute on all bands the band boosts have been decoded. This procedure is implemented around line 2352 of celt.c.

At very low rates it's 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 at around 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) then decode the trim value using the inverse CDF {127, 126, 124, 119, 109, 87, 41, 19, 9, 4, 2, 0}.

Stereo parameters

Anti-collapse reservation

The allocation computation first begins by setting up some initial conditions. 'total' is set to the available remaining 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 assure 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 $(LM+2) * 8$. 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 log2 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 excessively an 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 number of channels, the number MDCT bins in the shortest frame size for this mode, the number remaining bands, 2^{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 Decoder

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 that is the nearest to the allocated value (rounding down if exactly half-way between two values), subject to not exceeding 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 codebooks entries can be computed as explained in Section 5.3.5.2. The difference between the number of bits allocated and the number of bits used is accumulated to a _balance_ (initialised to zero) that helps adjusting the allocation for the next bands. One third of the balance is applied to the bit allocation of the each band to help achieving 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. Index Decoding

The codeword is decoded as a uniformly-distributed integer value by decode_pulses() (cwrs.c). The codeword is converted from a unique index in the same way as specified in [PVQ]. The indexing is based

on the calculation of $V(N,K)$ (denoted $N(L,K)$ in [PVQ]), which is the number of possible combinations of K pulses in N samples. 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 pre-computed 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 initialise 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 decoding of the codeword from the index is performed as specified in [PVQ], as implemented in function `decode_pulses()` (`cwrs.c`).

4.3.4.3. Spreading

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

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, then 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 $1/2$. The output is windowed using the same window as the encoder. The IMDCT and windowing are performed by `mdct_backward` (`mdct.c`). If a time-domain pre-emphasis window was applied in the encoder, the (inverse) time-domain de-emphasis window is applied on the IMDCT result.

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 $4 + \text{octave}$ raw bits. The final pitch period is equal to $(16 < \text{octave}) + \text{fine_pitch} - 1$ 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: $1/A(z) = 1 / (1 - \alpha_p z^{-1})$, where $\alpha_p = 0.8500061035$.

4.3.8. Packet Loss Concealment (PLC)

Packet loss concealment (PLC) is an optional decoder-side feature which SHOULD be included when transmitting over an unreliable channel. Because PLC is not part of the bit-stream, there are several possible ways to implement PLC with different complexity/quality trade-offs. The PLC in the reference implementation 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`).

4.4. Mode Switching

Switching between the Opus coding modes requires careful consideration. More specifically, the transitions that cannot be easily handled are the ones where the lower frequencies have to switch between the SILK LP-based model and the CELT transform model. If nothing is done, a glitch will occur for these transitions. On the other hand, switching between the SILK-only modes and the hybrid mode does not require any special treatment.

There are two ways to avoid or reduce glitches during the problematic mode transitions: with, or without side information. Only transitions with side information are normatively specified. For transitions with no side information, it is RECOMMENDED for the decoder to use a concealment technique (e.g. make use of the PLC algorithm) to "fill in" the gap or the discontinuity caused by the mode transition. Note that this concealment MUST NOT be applied when switching between the SILK mode and the hybrid mode or vice versa. Similarly, it MUST NOT be applied when merely changing the bandwidth within the same mode.

4.4.1. Switching Side Information

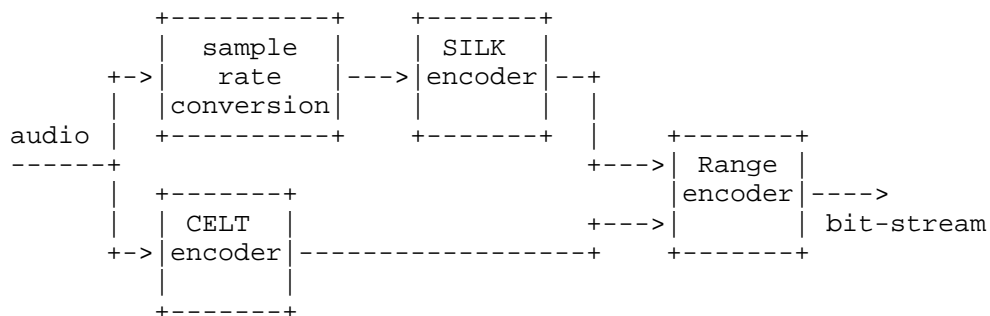
Switching with side information involves transmitting in-band a 5-ms "redundant" CELT frame within the Opus frame. This frame is designed to fill-in the gap or discontinuity without requiring the decoder to conceal it. For transitions from a CELT-only frame to a SILK-only or hybrid frame, the redundant frame is inserted in the frame following the transition (i.e. the SILK-only/hybrid frame). For transitions from a SILK-only/hybrid frame to a CELT-only frame, the redundant frame is inserted in the first frame. For all SILK-only and hybrid frames (not only those involved in a mode transition), a binary symbol of probability 2^{-12} needs to be decoded just after the SILK part of the bit-stream. When the symbol value is 1, then the frame includes an embedded redundant frame. The redundant frame always

starts and ends on byte boundaries. For SILK-only frames, the number of bytes is simply the number of whole remaining bytes. For hybrid frames, the number of bytes is equal to 2, plus a decoded unsigned integer (`ec_dec_uint()`) between 0 and 255. For hybrid frames, the redundant frame is placed at the end of the frame, after the CELT layer of the hybrid frame. The redundant frame is decoded like any other CELT-only frame, with the exception that it does not contain a TOC byte. The bandwidth is instead set to the same bandwidth of the current frame (for mediumband frames, the redundant frame is set to wideband).

For CELT-only to SILK-only/hybrid transitions, the first 2.5 ms of the redundant frame is used as-is for the reconstructed output. The remaining 2.5 ms is overlapped and added (cross-faded using the square of the MDCT power-complementary window) to the decoded SILK/hybrid signal, ensuring a smooth transition. For SILK-only/hybrid to CELT-only transitions, only the second half of the 5-ms decoded redundant frame is used. In that case, only a 2.5-ms cross-fade is applied, still using the power-complementary window.

5. Codec Encoder

Opus encoder block diagram.



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, 231, -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 $(fl, fl+1, 1 \ll ftb)$, 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 the 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`).

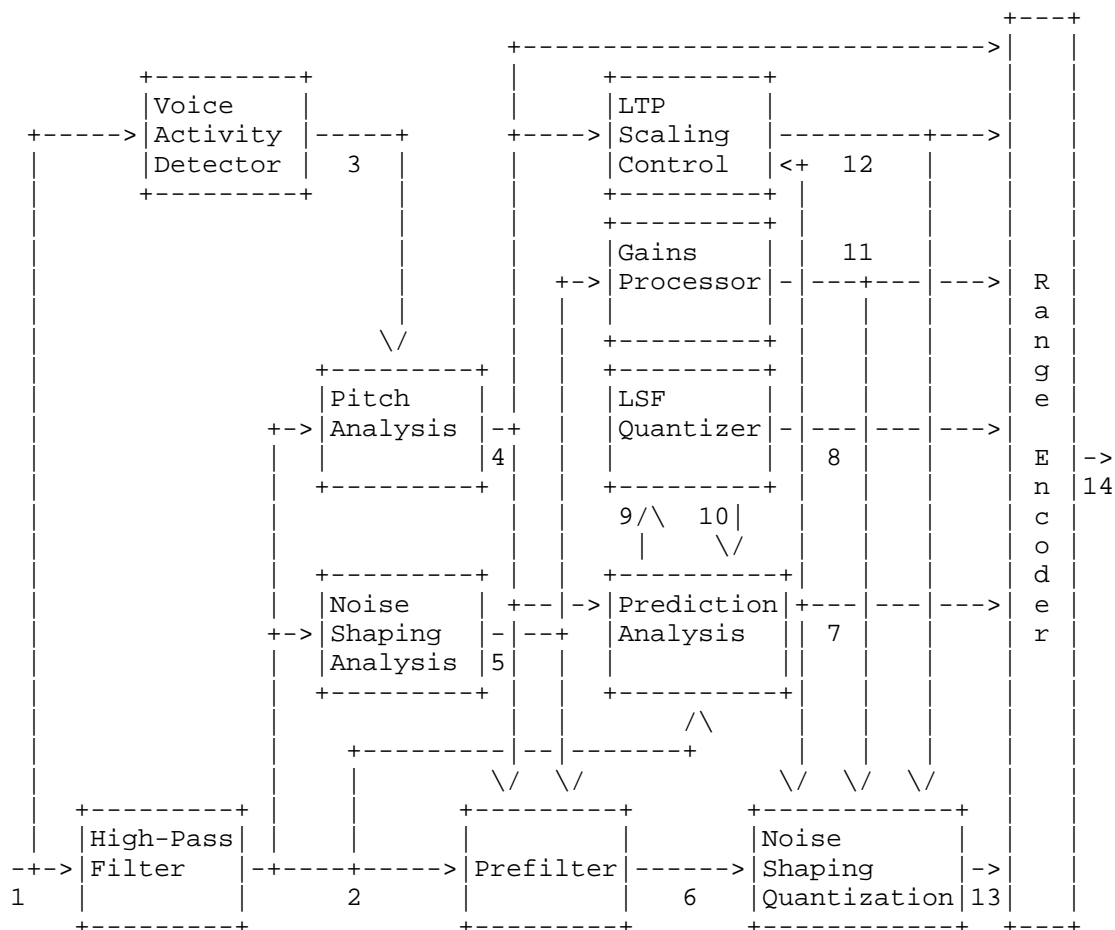
5.1.5. Current Bit Usage

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 the following, we focus on the core encoder and describe its components. For simplicity, we will refer to the core encoder simply as the encoder in the remainder of this document. An overview of the encoder is given in Figure 10.



- ```
1: Input speech signal
2: High passed input signal
```

- 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
- 14: Range encoded bitstream

Encoder block diagram.

Figure 10

#### 5.2.1. Voice Activity Detection

The input signal is processed by a VAD (Voice Activity Detector) to produce a measure of voice activity, and also spectral tilt and signal-to-noise estimates, for each frame. The VAD uses a sequence of half-band filterbanks to split the signal in four subbands: 0 -  $F_s/16$ ,  $F_s/16 - F_s/8$ ,  $F_s/8 - F_s/4$ , and  $F_s/4 - F_s/2$ , where  $F_s$  is the sampling frequency, that is, 8, 12, 16, or 24 kHz. The lowest subband, from 0 -  $F_s/16$  is high-pass filtered with a first-order MA (Moving Average) 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 an SNR (Signal-to-Noise Ratio) 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.

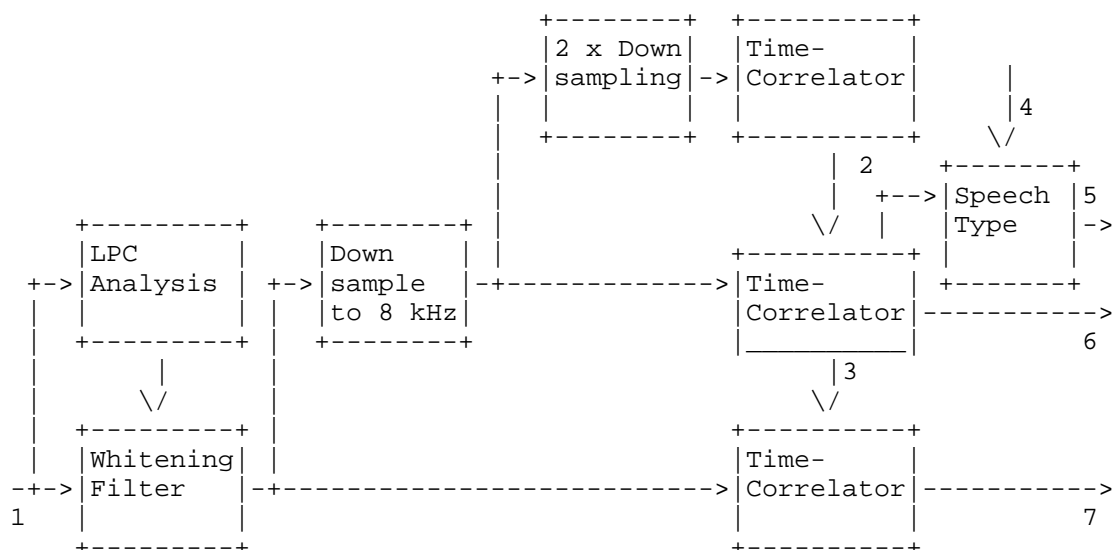
#### 5.2.2. High-Pass Filter

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 ARMA (Auto Regressive Moving Average) filter with a cut-off frequency around 70 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.

#### 5.2.3. Pitch Analysis

The high-passed input signal is processed by the open loop pitch estimator shown in Figure 11.



- 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 11

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 a 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.

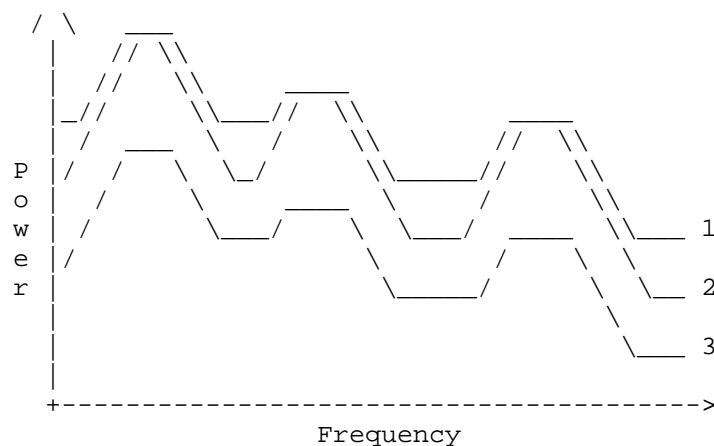
#### 5.2.4. Noise Shaping Analysis

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 fulfil 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 Deemphasizing 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: Deemphasized and level matched spectrum
- 3: Quantization noise spectrum

Noise shaping and spectral de-emphasis illustration.

Figure 12

Figure 12 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 deemphasized 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 deemphasized signal can be described as a filtering operation with a filter

$$H(z) = G * (1 - c\_tilt * z^{-1}) * \frac{W_{ana}(z)}{W_{syn}(z)},$$

having an adjustment gain  $G$ , a first order tilt adjustment filter with tilt coefficient  $c\_tilt$ , and where

$$W_{ana}(z) = (1 - \sum_{k=1}^{16} (a\_ana(k) * z^{-k})) * (1 - z^{-L} \sum_{k=-d}^d b\_ana(k) * z^{-k}),$$

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

$$W_{syn}(z) = (1 - \sum_{k=1}^{16} (a\_syn(k) * z^{-k})) * (1 - z^{-L} \sum_{k=-d}^d b\_syn(k) * z^{-k}).$$

All noise shaping parameters are computed and applied per subframe of 5 milliseconds. First, an LPC analysis is performed on a windowed signal block of 15 milliseconds. The signal block has a look-ahead of 5 milliseconds 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 16 for best quality or 12 in low complexity operation. The quantization gain is found as the square-root of the residual energy from the LPC analysis, multiplied by a value inversely proportional to the coding quality control parameter and the pitch correlation.

Next we find the two sets of short-term noise shaping coefficients

$a_{\text{ana}}(k)$  and  $a_{\text{syn}}(k)$ , 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 origo, using the formulas

$$\begin{aligned} a_{\text{ana}}(k) &= a(k) * g_{\text{ana}}^k, \text{ and} \\ a_{\text{syn}}(k) &= a(k) * g_{\text{syn}}^k, \end{aligned}$$

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

$$\begin{aligned} g_{\text{ana}} &= 0.94 - 0.02 * C, \text{ and} \\ g_{\text{syn}} &= 0.94 + 0.02 * C, \end{aligned}$$

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

$$\begin{aligned} b_{\text{ana}} &= F_{\text{ana}} * [0.25, 0.5, 0.25], \text{ and} \\ b_{\text{syn}} &= F_{\text{syn}} * [0.25, 0.5, 0.25]. \end{aligned}$$

For unvoiced frames these coefficients are set to 0. The multiplication factors  $F_{\text{ana}}$  and  $F_{\text{syn}}$  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  $F_{\text{ana}}$  less than  $F_{\text{syn}}$ , the pitch harmonics are emphasized relative to the valleys in between the harmonics.

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

$$\begin{aligned} c_{\text{tilt}} &= 0.4, \text{ and as} \\ c_{\text{tilt}} &= 0.04 + 0.06 * C \end{aligned}$$

for voiced frames, where  $C$  again is the coding quality control parameter and is between 0 and 1.

The adjustment gain  $G$  serves to correct any level mismatch between original and decoded signal 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.

#### 5.2.5. Prefilter

In the prefilter the input signal is filtered using the spectral valley de-emphasis filter coefficients from the noise shaping analysis, see Section 5.2.4. By applying only the noise shaping analysis filter to the input signal, it provides the input to the noise shaping quantizer.

#### 5.2.6. 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 are described in Section 5.2.6.1 and Section 5.2.6.2, respectively. Inputs to this function include the pre-whitened signal from the pitch estimator, see Section 5.2.3.

##### 5.2.6.1. 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 used to find an LTP residual signal with the simulated output signal as input to obtain better modelling of the output signal. This LTP residual signal is the input to an LPC analysis where the LPCs are estimated using Burgs 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 5.2.7. After quantization, the quantized LSF vector is converted to LPC coefficients and hence by using these quantized coefficients the encoder remains fully synchronized with the decoder. The LTP coefficients are quantized using a method described in Section 5.2.8. The quantized LPC and LTP coefficients are now used to filter the high-pass filtered input signal and measure a residual energy for each of the four subframes.

#### 5.2.6.2. 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 an LTP analysis to be worth-while the cost in terms of complexity and rate. Therefore, the pre-whitened input signal is discarded and instead the high-pass filtered input signal is used for LPC analysis using Burgs method. The resulting LPC coefficients are converted to an LSF vector, quantized as described in the following section and transformed back to obtain quantized LPC coefficients. The quantized LPC coefficients are used to filter the high-pass filtered input signal and measure a residual energy for each of the four subframes.

#### 5.2.7. LSF Quantization

The purpose of quantization in general is to significantly lower the bit rate at the cost of some introduced distortion. A higher rate should always result in lower distortion, and lowering the rate will generally lead to higher distortion. A commonly used but generally sub-optimal approach is to use a quantization method with a constant rate where only the error is minimized when quantizing.

##### 5.2.7.1. Rate-Distortion Optimization

Instead, we minimize an objective function that consists of a weighted sum of rate and distortion, and use a codebook with an associated non-uniform rate table. Thus, we take into account that the probability mass function for selecting the codebook entries are by no means guaranteed to be uniform in our scenario. The advantage of this approach is that it ensures that rarely used codebook vector centroids, which are modelling statistical outliers in the training set can be quantized with a low error but with a relatively high cost

in terms of a high rate. At the same time this approach also provides the advantage that frequently used centroids are modelled with low error and a relatively low rate. This approach will lead to equal or lower distortion than the fixed rate codebook at any given average rate, provided that the data is similar to the data used for training the codebook.

#### 5.2.7.2. Error Mapping

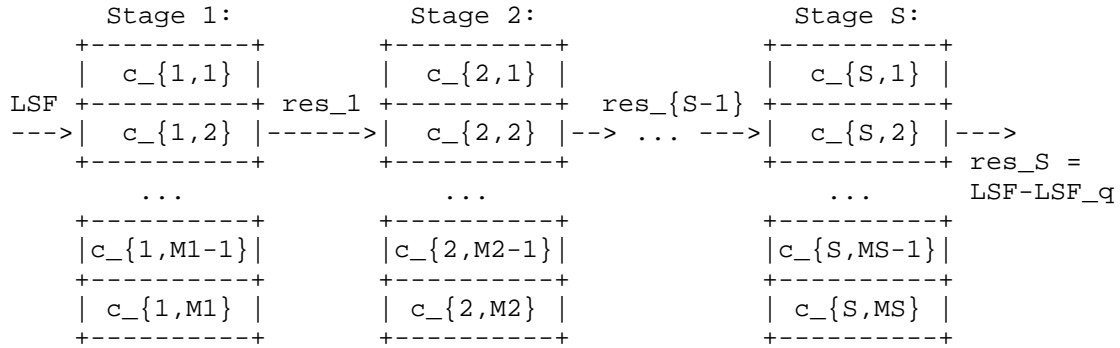
Instead of minimizing the error in the LSF domain, we map the errors to better approximate spectral distortion by applying an individual weight to each element in the error vector. The weight vectors are calculated for each input vector using the Inverse Harmonic Mean Weighting (IHMW) function proposed by Laroia et al., see [laroia-icassp]. Consequently, we solve the following minimization problem, i.e.,

$$\text{LSF\_q} = \underset{c \text{ in } C}{\operatorname{argmin}} \{ (\text{LSF} - c)' * W * (\text{LSF} - c) + \mu * \text{rate} \},$$

where LSF\_q is the quantized vector, LSF is the input vector to be quantized, and c is the quantized LSF vector candidate taken from the set C of all possible outcomes of the codebook.

#### 5.2.7.3. Multi-Stage Vector Codebook

We arrange the codebook in a multiple stage structure to achieve a quantizer that is both memory efficient and highly scalable in terms of computational complexity, see e.g. [sinervo-norsig]. In the first stage the input is the LSF vector to be quantized, and in any other stage  $s > 1$ , the input is the quantization error from the previous stage, see Figure 13.



Multi-Stage LSF Vector Codebook Structure.

Figure 13

By storing total of M codebook vectors, i.e.,

$$M = \sum_{s=1}^S M_s,$$

where  $M_s$  is the number of vectors in stage  $s$ , we obtain a total of

$$T = \prod_{s=1}^S M_s$$

possible combinations for generating the quantized vector. It is for example possible to represent  $2^{*36}$  uniquely combined vectors using only 216 vectors in memory, as done in SILK for voiced speech at all sample frequencies above 8 kHz.

#### 5.2.7.4. Survivor Based Codebook Search

This number of possible combinations is far too high for a full search to be carried out for each frame so for all stages but the last, i.e.,  $s$  smaller than  $S$ , only the best  $\min(L, M_s)$  centroids are carried over to stage  $s+1$ . In each stage the objective function,



i.e., the weighted sum of accumulated bitrate and distortion, is evaluated for each codebook vector entry and the results are sorted. Only the best paths and the corresponding quantization errors are considered in the next stage. In the last stage  $S$  the single best path through the multistage codebook is determined. By varying the maximum number of survivors from each stage to the next  $L$ , the complexity can be adjusted in real-time at the cost of a potential increase when evaluating the objective function for the resulting quantized vector. This approach scales all the way between the two extremes,  $L=1$  being a greedy search, and the desirable but infeasible full search,  $L=T/MS$ . In fact, a performance almost as good as what can be achieved with the infeasible full search can be obtained at a substantially lower complexity by using this approach, see e.g. [leblanc-tsap].

#### 5.2.7.5. LSF Stabilization

If the input is stable, finding the best candidate will usually result in the quantized vector also being stable, but due to the multi-stage approach it could in theory happen that the best quantization candidate is unstable and because of this there is a need to explicitly ensure that the quantized vectors are stable. Therefore we apply a LSF stabilization method which ensures that the LSF parameters are within valid range, increasingly sorted, and have minimum distances between each other and the border values that have been pre-determined as the 0.01 percentile distance values from a large training set.

#### 5.2.7.6. Off-Line Codebook Training

The vectors and rate tables for the multi-stage codebook have been trained by minimizing the average of the objective function for LSF vectors from a large training set.

#### 5.2.8. LTP Quantization

For voiced frames, the prediction analysis described in Section 5.2.6.1 resulted in four sets (one set per subframe) of five LTP coefficients, plus four weighting matrices. Also, 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 give 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 do not fluctuate very fast which causes the  $W_{ltp}$  matrices for different subframes of one frame often to be similar. As a result, one of the three codebooks typically gives good performance for all subframes. 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 and 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.

#### 5.2.9. 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.

#### 5.2.10. Range Encoder

Range encoding is a well known method for entropy coding in which a bitstream sequence is continually updated with every new symbol, based on the probability for that symbol. It is similar to arithmetic coding but rather than being restricted to generating binary output symbols, it can generate symbols in any chosen number base. In SILK all side information is range encoded. Each quantized parameter has its own cumulative density function based on histograms for the quantization indices obtained by running a training database.

##### 5.2.10.1. Bitstream Encoding Details

TBD.

#### 5.3. CELT Encoder

Copy from CELT draft.

##### 5.3.1. Pre-filter

Inverse of the post-filter

##### 5.3.2. Forward MDCT

The MDCT implementation has no special characteristics. The input is a windowed signal (after pre-emphasis) of  $2*N$  samples and the output is  $N$  frequency-domain samples. A `_low-overlap_` window is used to reduce the algorithmic delay. It is derived from a basic (full overlap) window that is the same as the one used in the Vorbis codec:  $W(n)=[\sin(\pi/2*\sin(\pi/2*(n+.5)/L))]^2$ . 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 MDCT is computed in `mdct_forward()` (`mdct.c`), which includes the windowing operation and a scaling of  $2/N$ .

##### 5.3.3. Bands and Normalization

The MDCT output is divided into bands that are designed to match the ear's critical bands for the smallest (2.5ms) frame size. The larger

frame sizes use integer multiplies of the 2.5ms 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 \*non-quantized\* 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.

#### 5.3.4. Energy Envelope Quantization

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 coarse-fine strategy for encoding the energy in the base-2 log domain, as implemented in `quant_bands.c`

##### 5.3.4.1. Coarse energy quantization

The coarse quantization of the energy uses a fixed resolution of 6 dB. To minimize the bitrate, prediction is applied both in time (using the previous frame) and in frequency (using the previous bands). The prediction using the previous frame can be disabled, creating an "intra" frame where the energy is coded without reference to prior frames. An encoder is able to choose the mode used at will based on both loss robustness and efficiency considerations. The 2-D  $z$ -transform of the prediction filter is:  $A(z_l, z_b) = (1 - a * z_l^{-1}) * (1 - z_b^{-1}) / (1 - b * z_b^{-1})$  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  $a=0$   $b=4915/32768$  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. Identical prediction clamping must be implemented in all encoders and decoders. 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 `quant_coarse_energy()` and `quant_coarse_energy()` (`quant_bands.c`). The encoding of the Laplace-distributed values is implemented in `ec_laplace_encode()` (`laplace.c`).

##### 5.3.4.2. Fine energy quantization

After the coarse energy quantization and encoding, the bit allocation is computed (Section 4.3.3) and the number of bits to use for refining the energy quantization is determined for each band. 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`).

If any bits are unused at the end of the encoding process, these bits are used to increase the resolution of the fine energy encoding in some bands. Priority is given to the bands for which the allocation (Section 4.3.3) was rounded down. At the same level of priority, lower bands are encoded first. Refinement bits are added until there is no more room for fine energy or until each band has gained an additional bit of precision or has the maximum fine energy precision. This is implemented in `quant_energy_finalise()` (`quant_bands.c`).

#### 5.3.5. 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 5.3.3 directly. Given a PVQ codevector  $y$ , the unit vector  $X$  is obtained as  $X = y/||y||$ , where  $||.||$  denotes the L2 norm.

##### 5.3.5.1. PVQ Search

The search for the best codevector  $y$  is performed by `alg_quant()` (`qv.c`). There are several possible approaches to the search with a tradeoff between quality and complexity. The method used in the reference implementation computes an initial codeword  $y_1$  by projecting the residual signal  $R = X - p'$  onto the codebook pyramid of  $K-1$  pulses:

$$y_0 = \text{round\_towards\_zero}((K-1) * R / \text{sum}(\text{abs}(R)))$$

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  $R$ :

$$J = -R^T * y / ||y||$$

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 implementors MAY use any other search methods.

#### 5.3.5.2. Index Encoding

The best PVQ codeword is encoded as a uniformly-distributed integer value by `encode_pulses()` (`cwrs.c`). The codeword is converted from a unique index in the same way as specified in [PVQ]. The indexing is based on the calculation of  $V(N,K)$  (denoted  $N(L,K)$  in [PVQ]), which is the number of possible combinations of  $K$  pulses in  $N$  samples.

#### 5.3.6. Stereo support

When encoding a stereo stream, some parameters are shared across the left and right channels, while others are transmitted separately for each channel, or jointly encoded. Only one copy of the flags for the features, transients and pitch (pitch period and filter parameters) are transmitted. The coarse and fine energy parameters are transmitted separately for each channel. Both the coarse energy and fine energy (including the remaining fine bits at the end of the stream) have the left and right bands interleaved in the stream, with the left band encoded first.

The main difference between mono and stereo coding is the PVQ coding of the normalized vectors. In stereo mode, a normalized mid-side (M-S) encoding is used. Let  $L$  and  $R$  be the normalized vector of a certain band for the left and right channels, respectively. The mid and side vectors are computed as  $M=L+R$  and  $S=L-R$  and no longer have unit norm.

From  $M$  and  $S$ , an angular parameter  $\theta = 2/\pi \cdot \text{atan2}(\|S\|, \|M\|)$  is computed. The  $\theta$  parameter is converted to a Q14 fixed-point parameter  $\text{itheta}$ , which is quantized on a scale from 0 to 1 with an interval of  $2^{-\text{qb}}$ , where  $\text{qb}$  is based the number of bits allocated to the band. From here on, the value of  $\text{itheta}$  MUST be treated in a bit-exact manner since both the encoder and decoder rely on it to infer the bit allocation.

Let  $m=M/\|M\|$  and  $s=S/\|S\|$ ;  $m$  and  $s$  are separately encoded with the PVQ encoder described in Section 5.3.5. The number of bits allocated to  $m$  and  $s$  depends on the value of  $\text{itheta}$ .

#### 5.3.7. Synthesis

After all the quantization is completed, the quantized energy is used along with the quantized normalized band data to resynthesize the

MDCT spectrum. The inverse MDCT (Section 4.3.7) and the weighted overlap-add are applied and the signal is stored in the `_synthesis buffer_`. The encoder MAY omit this step of the processing if it does not need the decoded output.

#### 5.3.8. Variable Bitrate (VBR)

Each CELT frame can be encoded in a different number of octets, making it possible to vary the bitrate at will. This property can be used to implement source-controlled variable bitrate (VBR). Support for VBR is OPTIONAL for the encoder, but a decoder MUST be prepared to decode a stream that changes its bitrate dynamically. The method used to vary the bitrate in VBR mode is left to the implementor, as long as each frame can be decoded by the reference decoder.

## 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 in Appendix B compared to the reference implementation.

To complement the Opus specification, the "Opus Custom" codec is defined to handle special sampling 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, 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 later is available, which is available using the `celt_*` function calls in `celt.h`.



## 7. Security Considerations

The codec needs 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 stream 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 such an 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 an implementation avoids them. For such architectures, it is RECOMMENDED that one add very small floating-point offsets to prevent significant numbers of denormalized operations or to configure the hardware to treat denormals as zero (DAZ). No such issue exists for the fixed-point reference implementation.

## 8. IANA Considerations

This document has no actions for IANA.

## 9. Acknowledgments

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[1] <<http://developer.skype.com/silk>>

[2] <<http://www.celt-codec.org/>>

[3] <[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. This implementation can be compiled for either floating-point or fixed-point architectures.

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 package, but it is easy to substitute any other FFT library.

### 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
 's/\\s\\s\\s###/' | base64 -d > opus_source.tar.gz

o tar xzvf opus_source.tar.gz

o cd opus_source

o make
```

### A.2. Development Versions

The current development version of the source code is available in a Git repository [3]. Development snapshots are provided at <http://opus-codec.org/>.

### A.3. Base64-encoded source code

```
###H4sIALXCF04AA+w8a1PbSLbzFf2KnmxtYhsbbEOACYEtYwRox9isbcKk5qa8Qm5jbW
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###/68aT9b/cuPhrd0xengRu8s71dtP87b3cbbP+3YVL9LcXrNJU7zR9I/cU5yfn8P9//
###tje/8+2baUiasCulJtge+cWeTzd6/k2VDD7fzWmV9KzQDGyrqpGcz9+p6dbOTd8iH0
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###b9tz2bRFQIntEq6x7Mm17Zr+HZl4/iyokls7nBLPZ/96ilCbeWN7YlsmIgBCPiVz6s
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###gTYRn4YmsIj4zGvvCw4JGWuuF9oWCDS2gFxABMiSEix9ah8ADnLMe0Z9Tfy6AMdaf
###0RfVjYeAE8vTQLhC9LG3vWYkdb0Iy2ZRMkzjdWzobUt00nSKTLtgRRyqzDaoZnxoAM
###eifDq1ZfJ/D9ot/7YBzrx+ToIxme6QT9Ud84PRuSs17nW08PSKt7DE+7w75xdDns9Q
###faP//ZGgDomzdsqNX9SPRfLvr6YEB6fWKcX3QMqAf4+63u0NAHVWJ0253LY/ByVQIo
###SLc3lDrGuTGEaUPQRCSbBSO9E3Ku99tn8LN1ZHSM4UdG78QYdpHWSa+vtchFqz802p
```

###edVp9cXPYvegOd4MK0jUG70zLO9eMNAuSBJNE/6N0hGZy10h1G8aR32TluDY1eF9jW  
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###0flzAJBslx67x1CsshZaVBJGlosCHty75+jtyCCAAxR40hMbw6uS01ztmMh7o/Q9G  
###Wx/sk05vwARlOdCrQGHYQsKIAQqEwzD36HJgMHkZ3aHe719e4IrLsLlXIBDgsQWgx0  
###yWIAhcKsiml/8ISDWUAZN71Vyd6fC8j6JkkmqhCAYgsfaQSNOAHghwKK1R6+qnHeNU  
###77Z1H00hlitjoJdhmwzg7BRRItmrFtC8ZEvg3QGu+FdjoEXqWmV7SIwT0jr+YCDbYj  
###Js+8AQKsJElj4T4gaNlxJvW7Lk6HF3mMcVjpZ0bPBMDLxBWo5D2LwArDmg/hd4+BLu  
###kKT8Ys1YXP+LWuD8PGahDjJgxcq5Fgg1k/dcUPEKZaE/xoiT2os91okR4M01pTvQFfC  
###h5CSdKXsaLlkiX2gwGx1xzRpeVRZ2qILfKmit7Ti1UA6LJAbcKd09gllGrxqgS1B3D  
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###aRZ1A6ot3DE6LJg3ByhpfmzqMSAQKqKcKvhr8HLgw1zT0egX01nEPo6ENAJRiC4X/t  
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###lofcf7XDuyyVRi7EiQCGewQpz4neTkMUARwPf8lZxxKA91H/EQBnFyNrEYIdjs5+yw  
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```
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###Fy2I8RqPV6XsQ0xdk00u95SvWSnFz2uppZ7rx8blOf4uf4oQSGn08zCuN2KcuOs/xh
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```



```
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###7uy4Si3b9bzjfe/N3unOa/hza/vg8ODsHxyb/YOzI2xuH9rbIkoc7Lw73Dr1Tt6dnh
###x394gMufdncOtgzd7u88AAQ+p+h4p1X29dXhITWK3RHePfz7a00X8tZ5u7wGeW9uH
###e6wp6Onuwenezhl2Sfz2lyfQPaAhIHkIEuxkb+cAf9n7ZQ96tHX6jyqH2t17+w4KwU
###dvd+sNWEldr5ISxoMWcehlwsDw7Lw73XuDeAMluu+2u2cHZ+/OYJCPj3eJ3t290/cw
###vGB9HR53iWZ/efKuu1eFRs62qG0AAgSDAvD79rvuAZHuAFjk9PTdydnB8dEKDPbPQB
###xAcwuq7hKvJ48AEPYKXHV8+g8EjKSgYah6P7/eg/enSFgi2BZSoguE2z1Ti0GLQMcz
###gJR21Tva++nw4Ke9o509/H6McH4+606twKgddLEAAMWGF96CVt9Rx3G0ADOAQ38oTF
###y1UfUO9r2t3fcHiDwvDnzQPeBcQ6Tbec3pDlPskVYyui75fwa j3nAOwvvp7HDP4PJk
###Ou7hFbZnV3+zPlvqEhViRt/B0SEMjrqlka9hhTSIJ8eHFSDMDz/8oFT0KOKD+uJ8fl
###FVrDh2Mbcf32L6EE/9wt4CltMYxTF9R7f+D2YRy jvC44i8SL9ja9AY36RQalHgCtYo
###fGAMwiDXJ2NywM4nIjc6vwhOMZTRbOK3xNk53HQv7wfmqJE9YA4b+edLvYPqJzCtnF
###lUbRIFVeN+RwrnqVe/3YcHo6/pF6t479GrDb9+UOqgn79teRtUW0iNeSNsUc8AzFMK
###GsxxMY16xBWAzgdHPz7yzIMvsps73MLm+Ntq2px/v+b8ezYX3K+54J7NNRY25zfxQt
###EjNde8X3P3JWbrfs0xVlF59IcfVmEwrq15Wake08s14enxu6NdBRsZ+fMHsOd/4C4B
###gPbiB7LwKc0jz7k5T+hGLrQ9UREV0Wqj4RBty9dYcNDgVsgLcX0XeuMnPDgRh/PTQw
###mZQrQCCGxH7yMZ7Xbrf5AX1FiPT/+EXRmDgvdSCC6fqChpJkDHuH5/s/prWpf/yB
###Xy jgMu4HparhZqMPg5Fa/eDHHw6UmCk/2002AnqF5Qe jw3ikVk19ZjzwCvUhkTBSX5
###9BMook/DvFNO+rXRz/3BIr3a4u+EddltTBSh+vieiQSyrrywoJU7z7D7rmFu5Mn9Iu
###6rZ0IsOC6K0pX49PQYUVjC7FLi63PlCYkMkdwsQc9X1BDjqDQc5ldC7SR+CkHHzgeN/
###FNb3JX4Ytp7VUCsKuZDVpBlms4cL78zWK6+Ud3Dc6H4951Io9QdqHmwUgftTf5li/
###NhGfwe jzKXK/on2Xq8EwrnjcJffDD+1IpJE2KoxVqD/n6BrviisslqbChZGwIHrCBuY
###cBSgRIzmBy/sJnKztA7dV8EoQi+DSBSg6Qcmx9zBww5Imqwj4ZkU4kEvtgOs+uauwW
###x9bpmy3vYJA008U6OFyIBKzSXB9KL0zji+SbERVSUp613rhjxJtSwhVBTWVKIr0h
###i6uua jilMxgyQUOYIJ3wBzZH0RGLnxboRYyBtgEYGapQ+r38gNsL9U+09fbngTJbe
###jgahQ5GiUL2jaUCeAph8/fELci6wcMYTPhPZOKbKIQWauxyMKKi40l0lIqxNVTaQyv
###i8fKmS9uN95vAPP6gc+IPIF/cDLXFfNSGzqCu0UzET8YrIM4E5Qnp4u0iKd9EhKXao
###U4/bJOI7y//n9v/+Oo+AOzAPzWU0GCX38vqmzwL/b9AJAt3/67ebQb30/36Pp/T/lv
###7f0v9b+n9L/2/p/y39v/i4/L+YxJr7dFPvg6Ek6Zch80iOfLZB0W5+8IwkgliTdDjP
###vKfAfBKEv5mPVqgVClIA5T1qiXkw9CP562p9PPZFqr7RztZ9CPri4M8dcQs+jQQsn7
###z2VkhUDWDp7Qlmd6zhzIsXWnsnaTWrsEfdDn7F5Geg57ret1VJzVWbrnQJAZ696RTk
###888x0z4oQtK62Z51xQGEM3n4diO/S2b/qL03c5YNyauCpt/lZtOoDwr6xcrC9mBBTa
###9MFghXtLePzwdZESiv5tUMJz15fXmKfcN+LboyYp0006Cwu+HKje4fXLYfCCdQd9i
###ZetyxVzWX0lRaMTwbct9A4MXgoapVMDVis/flXOCusqVExc7rhi/Ou+lpA86hULUaw
```

```
###ggv4yjjvWRhVLVXZGrDOLiRsmblIdla07xiA9VLhSeuwXgdpU1OeMbi9INSFeslz/uU
###oZVUwSoL7XI1Hicxy5WSlr43jhYpMoJbmdcGG077ApIdZLZIIbTDbVhD4QN+T8wMOS
###mDqNU+/0qF4a3YsXBuk3mp1Gr4MpGVRDXtZcGLczlJ72CzKwv009CS6aAZ+13drBJc
###C9+2JSM5WdEIGuWIjsivYXyys8viQz18/zb8+U00C/d2KvaZ26fpFP6kLkFiFWDbe+
###jv0fLs8NPR2Y8rcNdT5zRL26ImvtACACsqXluZcRLT4rAGwt5jTL6oLUlkx+rN+oVu
###3vSSIZgc6WK+ZL/kYGe0xbqEVhg7EJ4Hf1FbKd/rjYm25Agt+TjbElMzo19kMPMzxf
###KcfAEWcbWVtYqLtsT6DAM1+4KHeiWfMNZAKWfyRwa/jPCoZlvpysn6QNpIAcJauS+s
###qyYuoYnXR0B1FldIjFXHmwUccFORsraZqq7Gpncqk9RCqq6b5UIHwmyRaj2KcUnCk/
###Fiy9CRd8vVSdr10JYIFqJSL2tvgejfxZpWHuv2g2txMtdtbdQs/VgLxcU8zJo/WGrw
###VakA5SX6Wdu+Fi5utCPDZNN0qT7zaAelhT18AYn2eCCMXe6sGP6QXKKeZRZ5gpjb5
###sx1DVNFQMC2vTUF1wWVCSMP1+Gp7ucunbQDO52V7qj9WrxuyguHbRMH+FE+2aykXK
###xULJMO4McUPvk2bdrfFgcOolyLQHH1RrDa+eWFXN5E4pNc6Odc0w19Pvfoqe/8YUKV
###c9AL7A/9/x29b5byxe+v+/w1P6/0v/f+n/L/3/pf+/9P+X/n98/qjz30LDksd46hX9
###/LV6+rsR0Hns0GpHzEEQ/OxS5qm83IPhdc4892i4eoSPYyJOhn+TE9w/iHPlmLWAjt
###xcglROVEeZPPLHvC7szFB6ZhtphSev/p6Gilc6he3wU03U0CieiWAQ2LdNo6Ni4eb
###2Gha64e507PWLtx5W/Xk2KTHti3Yhls/izO/fKRM2L4Ou2nB9u8PO9BhNyzYwflhN3
###TYgQW7cX/YTR22b8Fu3h92S4ddt2C37g+7rcH2NizY7fvD7uiwly3YHQ6b3A/cVcDS
###Z6IwqoQL4/Giaxv3PEQoALczjpArURPuL0D9P0iAqp8R2P406iUPkqpqJXYcHpF5YR
###8w91ZlGf89Ahnph5ZANFTb0i8G9GDAQAUfAJoJb0w1VYELP3KkFq0FKoXxOpAyodLD
###mbuge6YnNL3ndMRdw+iJa1LrC4u+mqtjF14/9EVDBlFwmdDXBh1EwdVAXwJ0EAWFvi
###7pdRAFZbsu0HUQBuw4Lrd1EAU1tS6edRADCeL+TFZROLkGY1zT2W7FzXhZXOMgldKc
###5xixZVnPdZD0srzn0/h3WebzHdNoWe7zHbN5WfZDReGh/IcKQRYDcvH3p1IG6EqZuK
###bFfEURXpZA9MTdrpc4w1YKUHTgI2Aq7o2IWYPMXwXr0vndPe6XCR2jvGD2r3TBzP+Q
###e7sM5eZHvRFUT/IrrWXL4Y9OxUxK8BePclctcF5WMLDju62GgyaRwjVGXhr6wOnxv+
###ZCmzoxMVuiFBui20G1+KMD9gFHawXkADlnzfYdDhWL07dn8KkvBUGGKVZrplyq8I1
###LZ5aXF/hotaBb3rtLTauvQU5qsNH0a3FF9/sG3p/FMbf+KKeZgakMQ3Mq17mljhg1C
###pgOg8uuMfn8ACKm3yBYrcXu9XnGrH740DfG4eqRoqMxGau14f6pbsa4hWkfNSonrN
###8nvfTgwkAysIf7yXoP5TXEl8jI7c43RC+XzrRz3/cbq3tftm7/HbyD//UQ+aJRae/2
###hl6s1Gp9X5j7of+EF5/uO7PGfoqRsM+x7f2pbHFDc+CMz3O292N41/fPLkP0HiX8dP
###nhxcSKL9Mah6o/EMw5peVz2eR+MKAZGzLzf4IsI81KAaXAwuefxRrxI/u3xGVxNA5U
###Mp9CQCQXUb92vkOvQwIDMI5x7YfvGKRCHuD9jRC2bdydmbbwAjeHOAleWgbdTjt8sB
###nXEYJwMwVfHUWzKLI0zlyIORsE5Mo4tZ1TjH8ARKTtiJjLHci5Mkmt49eeKveDtDzL
###iBhVPARBlSq0cf4bcfnz+Hf5/hxKohIXvPxtPL5/jnM3gPpXuABfz15EmwQpkxqAP/
###6Tl7Hsln48t49Cy5oj8F5WJJ+yfHIXidu/GcRZ7lZOzzENTQFHWFTiaARD8HU92bxc
###ksxOa8+DbuzSkGDBDJCS0F095zrz+Y0gnU00xJAYtPRSOsySmcUuVLxPr67HkK8iWd
###HKZUn/vPg5VX3ksZtIAMhsrr3/Al8sQIFjD4lYLBtTACJo3xled94CP60XtJazUUYl
###rjqyd4mCf+0auzlJzz/hhlZfydso5iiG/+YTD+8QkH8+OTWu/cPhD8oxePqONk1EUj
###inaLOL4QbPqj93779EntPBr1vwz6syvv5dH272+2f/95+/cu/Le//QqhUGNeWqhC3D
###aKptPx13M6EDP2LubDif6+osDW6PKkxm7KoP3yMnjW+r31ul//Paj/3qz/3q5TO+yw
###P5WacbhJFFBB3XtSQ9lrEt0Nx8DQL8/vYEBEQS1407iZ33jii6hPbaopCB8k7hPl/O
###dL/P0V0amnXDugexX0lCSzFe/Zs2fotqpggojN88UKF9qQ2GGGPL+Kei+aYe8RjJbz9
###vZ0ntf7MPp6ul949++VJbThOgMOAW3qvlGIgEVhuh0nUu8acrFAktU9kqx7eVKnUa3
###69rmJYf/KEGaiIgfRXaDilzDo8cnOG9SVQJpVbiKQPipMGdEfRKOVfwdlRV3/ld+T
###ZzfXj9bGgvW/7tebsP6368123cfAv3W/GXTa5fr/PZ7jk3fdsHv87nRnD310uCTQUt
###Xz/u8T8UcIKwvI4qn+Mh7xl/800+R/7W0e//7+89+vt9ts/rc6TT9ot8r5/x0fygyW
###zn+Y3/ISwM7RT2zGyzeUugTdCYn5YRqj82gwGsxAwCSz6fjOKMFEC0Z6jN1fSodxf5
###pE+G0WT81m+Xe8K4Qs6648HyYZ36ZhEs/CC8fHcOvkWgH4s79NhsD/tGJAV2Gobsb
###xod0P8qkxufJ+DmaDiikI2jy44sLo8DRYXefD8380nlrv4GiQyxufDk53DHeJFfxcB
```

[illegible]

## Appendix B. opus\_compare.c

```
#include <stdio.h>
#include <stdlib.h>
#include <math.h>
#include <string.h>

#define OPUS_PI (3.14159265F)

#define OPUS_MIN(_x,_y) ((_x)<(_y)?(_x):(_y))
#define OPUS_MAX(_x,_y) ((_x)>(_y)?(_x):(_y))
#define OPUS_CLAMP(_a,_b,_c) OPUS_MAX(_a,OPUS_MIN(_b,_c))
#define OPUS_COSF(_x) ((float)cos(_x))
#define OPUS_SINF(_x) ((float)sin(_x))
#define OPUS_SQRTF(_x) ((float)sqrt(_x))
#define OPUS_LOG10F(_x) ((float)log10(_x))

static void *check_alloc(void *_ptr){
 if(_ptr==NULL){
 fprintf(stderr,"Out of memory.\n");
 exit(EXIT_FAILURE);
 }
 return _ptr;
}

static void *opus_malloc(size_t _size){
 return check_alloc(malloc(_size));
}

static void *opus_realloc(void *_ptr,size_t _size){
 return check_alloc(realloc(_ptr,_size));
}

static size_t read_pcm16(float **_samples,FILE *_fin,
 int _nchannels){
 unsigned char buf[1024];
 float *samples;
 size_t nsamples;
 size_t csamples;
 size_t xi;
 size_t nread;
 samples=NULL;
 nsamples=csamples=0;
 for(;;){
 nread=fread(buf,2*_nchannels,1024/(2*_nchannels),_fin);
 if(nread<=0)break;
 }
}
```



```

 if(nsamples+nread>csamples){
 do csamples=csamples<<1|1;
 while(nsamples+nread>csamples);
 samples=(float *)opus_realloc(samples,
 _nchannels*csamples*sizeof(*samples));
 }
 for(xi=0;xi<nread;xi++){
 int ci;
 for(ci=0;ci<_nchannels;ci++){
 int s;
 s=buf[2*(xi*_nchannels+ci)+1]<<8|buf[2*(xi*_nchannels+ci)];
 s=((s&0xFFFF)^0x8000)-0x8000;
 samples[(nsamples+xi)*_nchannels+ci]=s;
 }
 }
 nsamples+=nread;
}
*_samples=(float *)opus_realloc(samples,
 _nchannels*nsamples*sizeof(*samples));
return nsamples;
}

static void band_energy(float *_out,const int *_bands,int _nbands,
 const float *_in,int _nchannels,size_t _nframes,int _window_sz,
 int _step){
 float *window;
 float *x;
 float *c;
 float *s;
 size_t xi;
 int xj;
 window=(float *)opus_malloc(((3+_nchannels)*_window_sz
 *sizeof(*window)));
 c=window+_window_sz;
 s=c+_window_sz;
 x=s+_window_sz;
 for(xj=0;xj<_window_sz;xj++){
 window[xj]=0.5F-0.5F*OPUS_COSF((2*OPUS_PI/(_window_sz-1))*xj);
 }
 for(xj=0;xj<_window_sz;xj++)
 c[xj]=OPUS_COSF((2*OPUS_PI/_window_sz)*xj);
 for(xj=0;xj<_window_sz;xj++)
 s[xj]=OPUS_SINF((2*OPUS_PI/_window_sz)*xj);
 for(xi=0;xi<_nframes;xi++){
 int ci;
 int xk;
 int bi;
 for(ci=0;ci<_nchannels;ci++){

```

```

 for(xk=0;xk<_window_sz;xk++){
 x[ci*_window_sz+xk]=window[xk]
 *_in[(xi*_step+xk)*_nchannels+ci];
 }
 }
 for(bi=xj=0;bi<_nbands;bi++){
 float e2;
 e2=0;
 for(;xj<_bands[bi+1];xj++){
 float p;
 p=0;
 for(ci=0;ci<_nchannels;ci++){
 float re;
 float im;
 int ti;
 ti=0;
 re=im=0;
 for(xk=0;xk<_window_sz;xk++){
 re+=c[ti]*x[ci*_window_sz+xk];
 im-=s[ti]*x[ci*_window_sz+xk];
 ti+=xj;
 if(ti>=_window_sz)ti-=_window_sz;
 }
 p+=OPUS_SQRTF(re*re+im*im);
 }
 p*=(1.0F/_nchannels);
 e2+=p*p;
 }
 _out[xi*_nbands+bi]=e2/(_bands[bi+1]-_bands[bi])+1;
 }
}
free(window);
}

static int cmp_float(const void *_a,const void *_b){
 float a;
 float b;
 a=(const float *)_a;
 b=(const float *)_b;
 return (a>b)-(a<b);
}

#define NBANDS (21)

/*Bands on which we compute the pseudo-NMR (Bark-derived
 CELT bands).*/
static const int BANDS[NBANDS+1]={
 0,2,4,6,8,10,12,14,16,20,24,28,32,40,48,56,68,80,96,120,156,200

```

```
};

/*Per-band NMR threshold.*/
static const float NMR_THRESH[NBANDS]={
85113.804F,72443.596F,61659.5F, 52480.746F,44668.359F,38018.940F,
32359.366F,27542.287F,23442.288F,19952.623F,16982.437F,14454.398F,
12302.688F,10471.285F, 8912.5094F,7585.7758F,6456.5423F,5495.4087F,
4677.3514F,3981.0717F,3388.4416F
};

/*Noise floor.*/
static const float NOISE_FLOOR[NBANDS]={
8.7096359F,7.5857758F,6.6069345F,5.7543994F,5.0118723F,4.3651583F,
3.8018940F,3.3113112F,2.8840315F,2.5118864F,2.1877616F,1.9054607F,
1.6595869F,1.4454398F,1.2589254F,1.0964782F,0.95499259F,0.83176377F,
0.72443596F,0.63095734F,0.54954087F
};

#define TEST_WIN_SIZE (480)
#define TEST_WIN_STEP (TEST_WIN_SIZE>>1)

int main(int _argc,const char **_argv){
 FILE *fin1;
 FILE *fin2;
 float *x;
 float *y;
 float *xb;
 float *eb;
 float *nmr;
 float thresh;
 float mismatch;
 float err;
 float nmr_sum;
 size_t weight;
 size_t xlength;
 size_t ylength;
 size_t nframes;
 size_t xi;
 int bi;
 int nchannels;
 if(_argc<3||_argc>4){
 fprintf(stderr,"Usage: %s [-s] <file1.sw> <file2.sw>\n",
 _argv[0]);
 return EXIT_FAILURE;
 }
 nchannels=1;
 if(strcmp(_argv[1],"-s")==0)nchannels=2;
 fin1=fopen(_argv[nchannels],"rb");
```

```

if(fin1==NULL){
 fprintf(stderr,"Error opening '%s'.\n",_argv[nchannels]);
 return EXIT_FAILURE;
}
fin2=fopen(_argv[nchannels+1],"rb");
if(fin2==NULL){
 fprintf(stderr,"Error opening '%s'.\n",_argv[nchannels+1]);
 fclose(fin1);
 return EXIT_FAILURE;
}
/*Read in the data and allocate scratch space.*/
xlength=read_pcm16(&x,fin1,nchannels);
fclose(fin1);
ylength=read_pcm16(&y,fin2,nchannels);
fclose(fin2);
if(xlength!=ylength){
 fprintf(stderr,"Sample counts do not match (%lu!=%lu).\n",
 (unsigned long)xlength,(unsigned long)ylength);
 return EXIT_FAILURE;
}
if(xlength<TEST_WIN_SIZE){
 fprintf(stderr,"Insufficient sample data (%lu<%i).\n",
 (unsigned long)xlength,TEST_WIN_SIZE);
 return EXIT_FAILURE;
}
nframes=(xlength-TEST_WIN_SIZE+TEST_WIN_STEP)/TEST_WIN_STEP;
xb=(float *)opus_malloc(nframes*NBANDS*sizeof(*xb));
eb=(float *)opus_malloc(nframes*NBANDS*sizeof(*eb));
nmr=(float *)opus_malloc(nframes*NBANDS*sizeof(*nmr));
/*Compute the error signal.*/
for(xi=0;xi<xlength*nchannels;xi++){
 err=x[xi]-y[xi];
 y[xi]=err-OPUS_CLAMP(-1,err,1);
}
/*Compute the per-band spectral energy of the original signal
and the error.*/
band_energy(xb,BANDS,NBANDS,x,nchannels,nframes,
 TEST_WIN_SIZE,TEST_WIN_STEP);
free(x);
band_energy(eb,BANDS,NBANDS,y,nchannels,nframes,
 TEST_WIN_SIZE,TEST_WIN_STEP);
free(y);
nmr_sum=0;
for(xi=0;xi<nframes;xi++){
 /*Frequency masking (low to high): 10 dB/Bark slope.*/
 for(bi=1;bi<NBANDS;bi++){
 xb[xi*NBANDS+bi]+=0.1F*xb[xi*NBANDS+bi-1];
 }
 /*Frequency masking (high to low): 15 dB/Bark slope.*/

```

```

 for(bi=NBANDS-1;bi-->0;)
 xb[xi*NBANDS+bi]+=0.03F*xb[xi*NBANDS+bi+1];
 if(xi>0){
 /*Temporal masking: 5 dB/5ms slope.*/
 for(bi=0;bi<NBANDS;bi++){
 xb[xi*NBANDS+bi]+=0.3F*xb[(xi-1)*NBANDS+bi];
 }
 /*Compute NMR.*/
 for(bi=0;bi<NBANDS;bi++){
 nmr[xi*NBANDS+bi]=xb[xi*NBANDS+bi]/eb[xi*NBANDS+bi];
 nmr_sum+=10*OPUS_LOG10F(nmr[xi*NBANDS+bi]);
 }
 }
 /*Find the 90th percentile of the errors.*/
 memcpy(xb,eb,nframes*NBANDS*sizeof(*xb));
 qsort(xb,nframes*NBANDS,sizeof(*xb),cmp_float);
 thresh=xb[(9*nframes*NBANDS+5)/10];
 free(xb);
 /*Compute the mismatch.*/
 mismatch=0;
 weight=0;
 for(xi=0;xi<nframes;xi++){
 for(bi=0;bi<NBANDS;bi++){
 if(eb[xi*NBANDS+bi]>thresh){
 mismatch+=NMR_THRESH[bi]/nmr[xi*NBANDS+bi];
 weight++;
 }
 }
 }
 free(nmr);
 free(eb);
 printf("Average pseudo-NMR: %3.2f dB\n",nmr_sum/(nframes*NBANDS));
 if(weight<=0){
 err=-100;
 printf("Mismatch level: below noise floor\n");
 }
 else{
 err=10*OPUS_LOG10F(mismatch/weight);
 printf("Weighted mismatch: %3.2f dB\n",err);
 }
 printf("\n");
 if(err<0){
 printf("***Decoder PASSES test (mismatch < 0 dB)\n");
 return EXIT_SUCCESS;
 }
 printf("***Decoder FAILS test (mismatch >= 0 dB)\n");
 return EXIT_FAILURE;
}

```

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