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Measuring the Quality of an Internet Interactive Audio Codec  
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## Abstract

The quality of a codec has to be measured by multiple parameters such as audio quality, speech quality, algorithmic efficiency, latency, coding rates and their respective tradeoffs. During standardization, codecs are tested and evaluated multiple times to ensure a high quality outcome.

As the upcoming Internet codec is likely to have unique features, there is a need to develop new quality testing procedures to measure these features. Thus, this draft reviews existing methods on how to measure a codec's qualities, proposes a couple of new methods, and gives suggestions which may be used for testing the Internet Interactive Audio Codec (IIAC).

This document is work in progress.

## Conventions used in this document

In this document, equations are written in Latex syntax. An equation starts with a dollar sign and ends with a dollar sign. The text in between is an equation following the notation of Latex Version 2e. In the PDF version of this document, as a courtesy to its readers, all Latex equations are already rendered.

## Table of Contents

Conventions used in this document .....	2
1. Introduction .....	4
2. Optimization Goal .....	6
3. Measuring Speech and Audio Quality .....	7
3.1. Formal Subjective Tests .....	7
3.1.1. ITU-R Recommendation BS.1116-1 .....	7
3.1.2. ITU-R Recommendation BS.1534-1 (MUSHRA) .....	8
3.1.3. ITU-T Recommendation P.800 .....	8
3.1.4. ITU-T Recommendation P.805 .....	8
3.1.5. ITU-T Recommendation P.880 .....	9
3.1.6. Formal Methods Used for Codec Testing at the ITU ...	9
3.2. Informal Subjective Tests .....	9
3.3. Interview and Survey Tests .....	9
3.4. Web-based Testing .....	10
3.5. Call Length and Conversational Quality .....	10
3.6. Field Studies .....	12
3.7. Objective Tests.....	13
3.7.1. ITU-R Recommendation BS.1387-1 .....	14
3.7.2. ITU-T Recommendation P.862 .....	14
3.7.3. ITU-T Draft P.OLQA .....	15

4. Measuring Complexity .....	15
4.1. ITU-T Approaches to Measuring Algorithmic Efficiency ...	15
4.2. Software Profiling .....	17
4.3. Cycle Accurate Simulation .....	18
4.4. Typical run time environments .....	19
5. Measuring Latency .....	19
5.1. ITU-T Recommendation G.114 .....	20
5.2. Discussion .....	20
6. Measuring Bit and Frame Rates .....	21
7. Codec Testing Procedures Used by Other SDOs .....	22
7.1. ITU-T Recommendation P.830 .....	22
7.2. Testing procedure for the ITU-T G.719 .....	24
8. Transmission Channel .....	25
8.1. ITU-T G.1050: Network Model for Evaluating Multimedia Transmission Performance over IP (11/2007) .....	26
8.2. Draft G.1050 / TIA-921B .....	27
8.3. Delay and Throughput Distributions on the Global Internet	27
8.4. Transmission Variability on the Internet .....	30
8.5. The Effects of Transport Protocols .....	30
8.6. The Effect of Jitter Buffers and FEC .....	33
8.7. Discussion .....	33
9. Usage Scenarios .....	34
9.1. Point-to-point Calls (VoIP) .....	34
9.2. High Quality Interactive Audio Transmissions (AoIP) ....	35
9.3. High Quality Teleconferencing .....	35
9.4. Interconnecting to Legacy PSTN and VoIP (Convergence) ..	36
9.5. Music streaming.....	36
9.6. Ensemble Performances over a Network .....	36
9.7. Push-to-talk like Services (PTT) .....	37
9.8. Discussion .....	38
10. Recommendations for Testing the IIAC .....	38
10.1. During Codec Development .....	38
10.2. Characterization Phase .....	39
10.2.1. Methodology .....	39
10.2.2. Material .....	39
10.2.3. Listening Laboratory .....	40
10.2.4. Degradation Factors .....	40
10.3. Application Developers .....	41
10.4. Codec Implementers .....	42
10.5. End Users .....	42
11. Security Considerations .....	42
12. IANA Considerations.....	42
13. References .....	43
13.1. Normative References .....	43
13.2. Informative References .....	43
14. Acknowledgments .....	48

## 1. Introduction

The IETF Working Group CODEC is standardizing an Internet Interactive Audio and Speech Codec (IIAC). If the codec shall be of high quality it is important to measure the codec's quality throughout the entire process of development, standardization, and usage. Thus, this document supports the standardizing process by providing an overview of quality metrics, quality assessment procedures, and other quality control issues and gives suggestions on how to test the IIAC.

Quality must be measured by the following stakeholders and in the following phases of the codec's development:

- o Codec developers must decide on different algorithms or parameter sets during the development and enhancement of a codec. These might also include the selection among multiple codec candidates that implement different algorithms; however the WG Codec base its work on a common consensus not on a competitive selection of one of multiple codec contributions. Thus, measuring the quality of codecs to select one might not be required. Besides selection, one is obliged to debug the codec software. To find errors and bugs - and programming mistakes are present in any complex software - the developer has to test this software by conducting quality measurements.
- o Typically the codec standardization includes a qualification phase that measures the performance of a codec and verifies whether it confirms to predefined quality requirements. In the qualification phase, it becomes obvious whether the codec development and standardization has been successful. Again, in the process of rigorous testing during qualification phase, algorithmic weaknesses and bugs in the implementation may be found. Still, in complex software such as the IIAC, correctness cannot be proved or guaranteed.

- o Users of the codec need to know how well the codec is performing while manufactures need to decide whether to include the IIAC in their products. Quality measures play an important role in this decision process. Also, the numerous quality measurement results of the quality help developers of the VoIP system to dimension or tune their system to take optimal advantage of a codec. For example, during network planning, operators can predict the amount of bandwidth needed for high quality voice calls. An adaptive VoIP application needs to know which quality is achieved with a different codec parameters set to be able to make an optimal selection of the codec parameters under varying network conditions.  
As suggested in [50] an RTP payload specification for an IIAC codec should include a rate control. Similar to the performance of the codec, the rate control unit has a big impact on the overall quality of experience. Thus, it should be tested well too.
- o Software implementers need to verify whether their particular codec implementation that might be optimized on a specific platform confirms to the standard's reference implementation. This is particularly important as some intellectual property rights might only be granted, if the codec conforms to the standard.  
As the IIAC must not to be bit conform, which would allow simple comparisons of correctness, other means of conformance testing must be applied.  
In addition, the standard conformance and interoperability of multiple implementations must be checked.  
Last but not least, implementers may implement optimized concealment algorithms, jitter buffers or other algorithms. Those algorithms have to be tested, too.
- o Since the success of MP3, end users do acknowledge the existence of a high quality codec. It would make sense to use the IIAC in a brand marketing campaign (such as "Intel inside"). A quality comparison between IIAC and other codecs might be part of the marketing. Online testing with user participation might also raise the awareness level.

All those stakeholders might have different requirements regarding the codec's quality testing procedures. Thus, this document tries to identify those requirements and shows which of the existing quality measurement procedures can be applied to fulfill those specific demands efficiently.

In the following section we describe a primary optimization goal: Quality of Experience (QoE). Next, we briefly list the most common methods of how to perform subjective evaluations on speech and audio quality. In Section 4, 5, and 6, we discuss on how to measure complexity, latency, and bit- and frame rates. Section 7 describes how other SDOs have measured the quality of their codecs. As compared IIAC to previous standardized codecs, the IIAC is likely to have different unique requirements and thus needs newly developed quality testing procedures. To achieve this, in Section 8 we describe the properties of Internet transmission paths. Section 9 summarizes the usage scenarios, for which the codec is going to be used and finally, in Section 10, we recommend procedures on how to test the IIAC.

## 2. Optimization Goal

The aim of the Codec WG is to produce a codec of high quality. However, how can quality be measured? The measurement of the features of a codec can be based on many different criteria. Those include complexity, memory consumption, audio quality, speech quality, and others. But in the end, it's the users' opinions that really count since they are the customers. Thus, one important - if not the most important quality measure of the IIAC - shall be the Quality of Experience (QoE).

The ITU-T Standards ITU-T P.10/G.100 [22] defines the term "Quality of Experience" as "the overall acceptability of an application or service, as perceived subjectively by the end-user." The ITU-T document G.RQAM [21] extends this definition by noting that "quality of experience includes the complete end-to-end system effects (client, terminal, network, services infrastructure, etc.)" and that the "overall acceptability may be influenced by user expectations and context".

These definitions already give guidelines on how to judge the quality of the IIAC:

- o The acceptability and the subjective quality impression of endusers have to be measured (Section 3).
- o The IIAC codec has to be tested as part of an entire telecommunication system. It must be carefully considered whether to measure the codec's performance just in a stand-alone setup or to evaluate it as part of the overall system (Section 8).

- o The environments and contexts of particular communication scenarios have to be considered and controlled because they have an impact on the human rating behavior and on quality expectations and requirements (Section 9).

### 3. Measuring Speech and Audio Quality

The perceived quality of a service can be measured by various means. If humans are interrogated, those quality tests are called subjective. If the tests are conducted by instrumental means (such as an algorithm) they are called objective. Subjective tests are divided up into formal and informal tests. Formal tests follow strictly defined procedures and methods and typically include a large number of subjects. Informal tests are less precise because they are conducted in an uncontrolled manner.

#### 3.1. Formal Subjective Tests

Formal subjective tests must follow a well-defined procedure. Otherwise the results of multiple tests cannot be mutually compared and are not repeatable. Most subjective testing procedures have been standardized by the ITU. If applied to coding testing, the testing procedures follow the same pattern [26]:

"Performing subjective evaluations of digital codecs proceeds via a number of steps:

- o Preparation of source speech materials, including recording of talkers;
- o Selection of experimental parameters to exercise the features of the codec that are of interest;
- o Design of the experiment;
- o Selection of a test procedure and conduct of the experiment;
- o Analysis of results."

The ITU has standardized different formal subjective tests to measure the quality of speech and audio transmission, which are described in the following.

##### 3.1.1. ITU-R Recommendation BS.1116-1

The ITU-R BS.1116-1 standard [14] is good for audio items with small degradations (stimuli) and uses a continuous scale from

imperceptible (5.0) to very annoying (1.0). It is a double blind triple-stimulus with a hidden reference testing method and must be done twice for the degraded sample and the hidden reference. In a 30 minutes session, 10-15 sample items can be judged. Overall, about 20 subjects shall rate the items. Testing shall take place with loudspeakers in a controlled environment or with headphones in a quiet room.

#### 3.1.2. ITU-R Recommendation BS.1534-1 (MUSHRA)

The ITU-R BS.1534-1 standard [16] defines a method for the subjective assessment of intermediate quality levels. Multiple audio stimuli are compared at the same time. Maximal 12 but preferably only 8 stimuli plus a hidden one with Hidden Reference and an anchor are compared and judged. MUSHRA uses a continuous quality scale (CQS) ranging from 0 to 100 divided into five equal intervals ("bad" to "excellent"). In 30 minutes, about 42 stimuli can be tested. Again, 20 test subjects shall rate the items with either headphones or loudspeakers.

The standard recommends using as lower anchor a low-pass filtered version with a bandwidth limit of 3.5 kHz. Additional anchors are recommended, especially if specific distortions are to be tested.

#### 3.1.3. ITU-T Recommendation P.800

The ITU-T P.800 defines multiple testing procedures to assess the speech quality of telephone connections. The most important procedure is called listening-only speech quality of telephone connections. Listeners rate short groups of unrelated sentences. The listeners are taken from the normal telephone-using population (no experts). They use a typical sending system (e.g. a local telephone) that may follow "modified IRS" frequency characteristics. The results is the listening-quality scale, which is an absolute category scale (ACS) ranging from excellent=5 to bad=1. Listeners can judge about 54 stimuli within 30 minutes.

Other tests described in P.800 measure listening-effort, loudness-preference scale, conversation opinion and difficulty, delectability, degradation, or minimal differences.

#### 3.1.4. ITU-T Recommendation P.805

The P.805 standard [24] extends P.800 and defines precisely how to measure conversational quality. Subjects have to do conversation tests to evaluate the communication quality of a connected. Expert, experienced or untrained (naive) subjects have to do these tests



collaboratively in soundproof cabinets. Typically, 6 transmission conditions can be tested within 30 minutes. Depending on the required precision, these tests have to be made 20 to 40 times.

#### 3.1.5. ITU-T Recommendation P.880

To measure time-variable distortion, a continuous evaluation of speech quality has been defined in P.880 [31]. Subjects have to assess transmitted speech quality consisting of long speech sequences with quality/time fluctuations. The quality is rated on a continuous scale ranging from Excellent=5 to Bad=1 is dynamically changed over the time while the stimuli are played. Stimuli have a length of between 45 seconds and 3 minutes.

#### 3.1.6. Formal Methods Used for Codec Testing at the ITU

In the last year, new narrow and wideband codecs have been tested using ITU-T P.800 (and ITU-T P.830). For the ITU-T G.719 standard, which supports besides speech content also audio, the ITU-R BS.1116-1 testing method has been applied during the selection of potential codec candidates. During the qualification phase, the method that was used was the ITU-P BS.1584-1. For the ITU-T G.718 codec, the Absolute Category Rating (ACR) following ITU-T P.800 has been applied.

#### 3.2. Informal Subjective Tests

Besides formal tests, informal subjective tests following less stringent conditions might be taken to judge the quality of stimuli. However, informal tests cannot be easily verified and lack the reliability, accuracy and precision of formal tests. Informal tests are needed if the available number of subjects who are able to conduct the tests is low, or if time or money is limited.

#### 3.3. Interview and Survey Tests

In ITU-T P.800 [23] and [9] interview and survey tests are described. In P.800, it says that "if the rather large amount of effort needed is available and the importance of the study warrants it, transmission quality can be determined by 'service observations'."

These service observations are based on statistical surveys common in social science and marketing research. Typically, the questions asked in a survey are structured.

In addition, according to [23]: "To maintain a high degree of precision a total of at least 100 interviews per condition is required. A disadvantage of the service-observation method for many purposes is that little control is possible over the detailed characteristics of the telephone connections being tested."

### 3.4. Web-based Testing

If the large-wide scale proliferation of the Internet, researchers suggested testing the speech or audio quality on web sites via web site visitors [43]. A current web site that compares multiple audio codecs has been setup at SoundExpert.org [42]. On this web site, a user can download an audio item that consists of a reference item and a degraded item. Then, the user must identify the reference and rate the ODG of the degraded item. The tests are single-blind as the user does not know which codec he is currently rating.

One can anticipate that the visitors of web sites will use similar equipment for testing of audio samples and for conducting VoIP calls. Thus, web site testing can be made realistic in a way that considers the impact of (typically used) loudspeakers and headphones.

However, currently used web sites lack a proper identification of outliers. Thus, all ratings of all users are considered despite the fact that they might be (deliberately) faked or that subjects might not be able to hear well the acoustic difference. Thus, one can expect that web based ratings will show a high degree of variation and that many more tests are needed to achieve the same confidence that is gained within formal tests. A profound scientific study on the quality of web based audio rating has not yet been published. Thus, any statements on the validity of web based rating are premature.

### 3.5. Call Length and Conversational Quality

In the ETSI technical report document ETR-250 [6], a model is presented that discusses various impairments caused in narrow band telephone systems. The ETSI model describes the combinatorial effect of all those impairments. The ETSI model later became the famous E-Model described in ITU-T G.107. Both the ETSI- and the E-Model calculate the R factor that ranges from 0 (bad) to 100 (excellent conversational quality).

Based on the R factor, the users' reaction to the voice transmission quality of a connection can be predicted. For example, Section 8.3 describes the effect that users terminate the call if the quality is

bad. More precisely, they summarize it as users who "(i) terminate their calls unusually early, (ii) re-dial or even (iii) actually complain to the network operator".

In the ETSI model, the percentage of users "terminating calls early", TME, is given as

$$TME = 100 \cdot \operatorname{erf}\left(\frac{36-R}{16}\right) \%$$

with  $\operatorname{erf}(X)$  being the sigmoid shaped Gaussian error function and  $R$  the R Factor of the E-Model (Figure 1). This relation is based on results from "AT&T Long toll" interviews as cited in [2].

These findings have been confirmed by Holub et al. [12] who have studied the correlation between call length and narrow band speech quality. Birke et al. [1] have also studied the duration of phone calls which show a duration varying with day time and day of the week and also may be affected by pricing schemata.

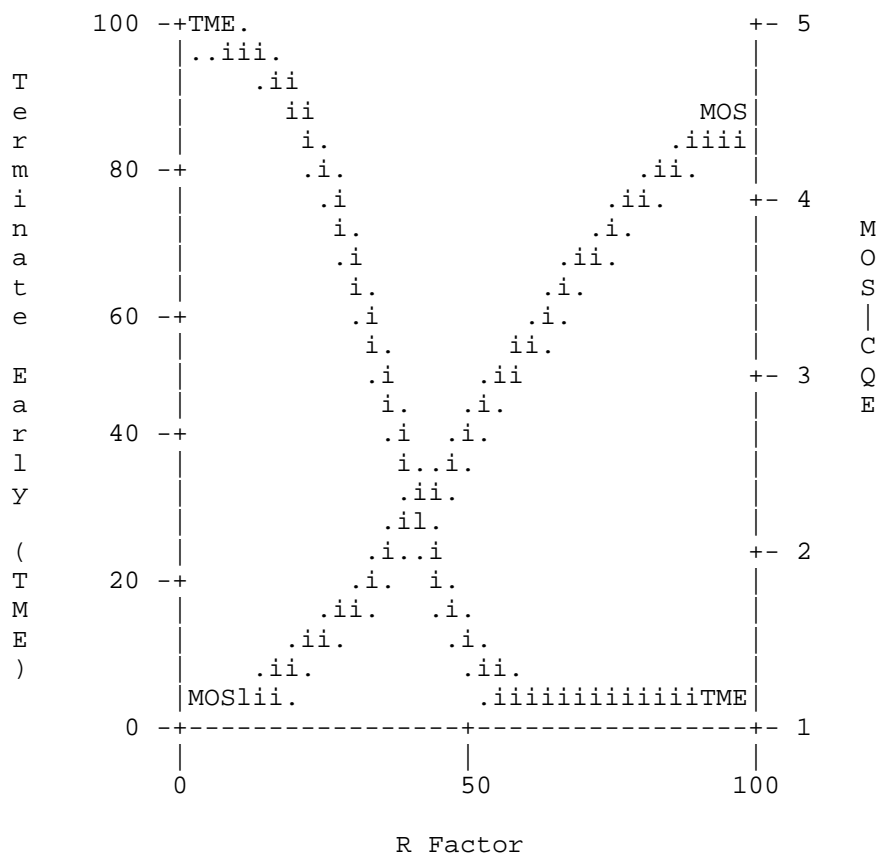


Figure 1 - Relation between calls terminating early, the R Factor, and the speech quality given in (MOS-CQE)

Whereas bad quality is related to short calls, it remains unproven whether better quality (>4 MOS) results in longer phone calls. There are two factors which might have an opposite effect on the call length. On the one hand, if the quality is superb, the talkers might be more willing to talk because of the pleasure of talking, on the other hand they might fulfill their conversational tasks faster because of the great quality. Thus, depending on the context, good speech quality might result either in longer or shorter calls.

### 3.6. Field Studies

Field studies can be conducted if usage data on calls are collected. Field studies are useful to monitor real user behavior and to collect data about the actual conversational context.

Because of highly varying conditions, the precision of those measurements is high and many tests have to be done to get significantly different measurement values. Also, the tests are not repeatable because the conditions are changing with time.

For example, Skype has done quality tests in a deployed VoIP system in the field with its users as testers [47]. The subjective tests are done in the following manner.

- o Download of test vectors to VoIP clients. Typically, this can be done with an automated software update.
- o Delivery changing VoIP configurations (such as the used codecs) so that different calls are subjected to different configurations. The selection of configurations can be done randomly, alternating in time or based on other criteria.
- o Collecting feedback from the users. For example, the following parameters can be monitored or recorded:
  - o The call length and other call specific parameters
  - o A user's quality voting (e.g. MOS-ACR) after the call
  - o Other feedback of the user (e.g. via support channels)

The field tests have the benefit of being conducted under real conditions with the real users. However, they have some drawbacks. First, the experimental conditions cannot be controlled well. Second, the tests are only valid for the current situations and do not allow predictions for other use cases. Third, the statistical significance might be largely questionable if confidence intervals are overlapping.

The costs for running the tests are low because the users are doing the tests for free. However, the operator might lose users after a user experienced a test case causing bad quality.

### 3.7. Objective Tests

Objective tests, also called instrumental tests, try to predict the human rating behavior with mathematical models and algorithms. They also calculate quality ratings for a given set of audio items. Naturally, they are not rating as precisely as their human counterparts, whom they try to simulate. However, the results are repeatable and less costly than formal subjective testing campaigns. Instrumental methods have a limited precision. That means that their

quality ratings do not perfectly match the results of formal listening-only tests. Typically, the correlation between formal results and instrumental calculations are compared using a correlation function. The resulting metric is given as R ranging from 0 (no correlation) to 1 (perfect match).

Over the last years, several objective evaluation algorithms have been developed and standardized. We describe them briefly in the following.

#### 3.7.1. ITU-R Recommendation BS.1387-1

The ITU developed an algorithm that is called Perceptual Evaluation of Audio Quality (PEAQ). It was published in the document ITU-R BS.1387 called Method for objective measurements of perceived audio quality in 1998 [15]. PEAQ is intended to predict the quality rating of low-bit-rate coded audio signals. Two different versions of PEAQ are provided: a basic version with lower computational complexity and an advanced version with higher computational complexity.

PEAQ calculates a quality grading called "Objective Difference Grade" (ODG) ranging from 0 to -4. Typically, it shows a prediction quality of between  $R=0.85$  and  $0.97$  when compared to subjective testing results. The ITU-T Study Group 12 assumes that PEAQ can detect audible differences between two implementations of the same codec [5].

#### 3.7.2. ITU-T Recommendation P.862

The ITU-T PESQ algorithm [27] is intended to judge distortions caused by narrow band speech codecs and other kind of channel and transmission errors. These include also variable delays, filtering and short localized distortions such as those caused by frame loss concealment. For a large number of conditions, the validity and precision of PESQ has been proven. For untested distortions, prior subjective tests must be conducted to verify whether PESQ judges these kinds of distortions precisely. Also, it is recommended to use PESQ for 3.1 kHz (narrow-band) handset telephony and narrow-band speech codecs only. For wide-band operations, a modified filter has to be applied prior to the tests.

Furthermore, the ITU-T Recommendation P.862.1 [28] describes how to transfer the PESQ's raw scores, which range from  $-0.5$  to  $4.5$ , to MOS-LQO values similar to those gathered from ACR ratings. Then, as it has been shown, the correlation between a large corpus of testing samplings shows a correlation of  $R=0.879$  (instead of  $R=0.876$ ) between subjective and MOS-LQO (respective PESQ raw) ratings. The

ITU-T Recommendation P.862.2 [29] modifies the PESQ algorithm slightly to support wideband operations. And finally, the ITU-T Recommendation P.862.3 [30] gives detailed hints and recommendations on how and when to use the PESQ algorithms.

### 3.7.3. ITU-T Draft P.OLQA

The soon-to-be standardized algorithm P.OLQA [40] extends PESQ and will be able to rate narrow to super-wideband speech and the effect of time-varying speech playout. Later distortions are common in modern VoIP systems which stretch and shrink the speech playout during voice activity to adapt it to the delay process of the network.

## 4. Measuring Complexity

Besides audio and speech quality, the complexity of a codec is of prime importance. Knowing the algorithmic efficiency is important because:

- . the complexity has an impact on power consumption and system costs
- . the hardware can be selected to fit pre-known complexity requirements and
- . different codec proposals can be compared if they show similar performances in other aspects.

Before any complexity comparisons can be made, one has to agree on an objective, precise, reliable, and repeatable metric on how to measure the algorithmic efficiency. In the following, we list three different approaches.

### 4.1. ITU-T Approaches to Measuring Algorithmic Efficiency

Over the last 17 years, the ITU-T Study Group 16 measured the complexity of codecs using a library called ITU-T Basic Operators and described in ITU-T G.191 [19], which counts the kind and number of operations and the amount of memory used. The latest version of the standard supports both fix-point operations of different widths and floating operations. Each operation can be counted automatically and weighted accordingly. The following source code is an [edited] excerpt from the source file baseop32.h:

```

/* Prototypes for basic arithmetic operators */

/* Short add,          1 */
Word16 add (Word16 var1, Word16 var2);

/* Short sub,          1 */
Word16 sub (Word16 var1, Word16 var2);

/* Short abs,          1 */
Word16 abs_s (Word16 var1);

/* Short shift left,   1 */
Word16 shl (Word16 var1, Word16 var2);

/* Short shift right,  1 */
Word16 shr (Word16 var1, Word16 var2);

...

/* Short division,     18 */
Word16 div_s (Word16 var1, Word16 var2);

/* Long norm,          1 */
Word16 norm_l (Word32 L_var1);

```

In the upcoming ITU-T G.GSAD standard another approach has been used as shown in the following code example. For each operation, WMPOS functions have been added, which count the number of operations. If the efficiency of an algorithm has to be measured, the program is started and the operations are counted for a known input length.

```

for (i=0; i<NUM_BAND; i++)
{
#ifdef WMOPS_FX
    move32();move32();
    move32();move32();
#endif
    state_fx->band_enrg_long_fx[i] = 30;
    state_fx->band_enrg_fx[i] = 30;
    state_fx->band_enrg_bgd_fx[i] = 30;
    state_fx->min_band_enrg_fx[i] = 30;
}

```



#### 4.2. Software Profiling

The previously described methods are well-established procedures on how to measure computational complexity. Still, they have some drawbacks:

- o Existing algorithms must be modified manually to include instructions that count arithmetic operations. In complex codecs, this may take substantial time.
- o The CPU model is simple as it does not consider memory access (e.g. cache), parallel executions, or other kinds of optimization that are done in modern microprocessors and compilers. Thus, the number of instructions might not correlate to the actual execution time on modern CPUs.

Thus, instead of counting instructions manually, run times of the codec can be measured on a real system. In software engineering, this is called profiling. The Wikipedia article on profiling [54] explains profiling as follows:

"In software engineering, program profiling, software profiling or simply profiling, a form of dynamic program analysis (as opposed to static code analysis), is the investigation of a program's behavior using information gathered as the program executes. The usual purpose of this analysis is to determine which sections of a program to optimize - to increase its overall speed, decrease its memory requirement or sometimes both.

- o A (code) profiler is a performance analysis tool that, most commonly, measures only the frequency and duration of function calls, but there are other specific types of profilers (e.g. memory profilers) in addition to more comprehensive profilers, capable of gathering extensive performance data
- o An instruction set simulator which is also - by necessity - a profiler, can measure the totality of a program's behaviour from invocation to termination."

Thus, a typical profiler such as the GNU gprof can be used to measure and understand the complexity of a codec implementation. This is precisely the case because it is used on modern computers. However, the execution times depend on the CPU architecture, the PC in general, the OS and parallel running programs.

To ensure repeatable results, the execution environment (i.e. the computer) must be standardized. Otherwise the results of run times cannot be verified by other parties as the results may differ if done under slightly changed conditions.

#### 4.3. Cycle Accurate Simulation

If reliable and repeatable results are needed, another similar approach can be chosen. Instead of run times, CPU clock cycles on a virtual reference system can be measured. Quoting Wikipedia again [52]:

"A Cycle Accurate Simulator (CAS) is a computer program that simulates a microarchitecture cycle-accurate. In contrast an instruction set simulator simulates an Instruction Set Architecture usually faster but not cycle-accurate to a specific implementation of this architecture."

With a cycle accurate simulator, the execution times are precise and repeatable for the system that is being studied. If two parties make measurements using different real computers, they still get the same results if they use the same CAS.

A cycle accurate simulator is slower than the real CPU by a factor of about 100. Also, it might have a measurement error as compared to the simulated, real CPU because the CPU is typically not perfectly modeled.

If an x86-64 architecture shall be simulated, the open-source Cycle accurate simulator called PTLsim can be considered [55]. PTLsim simulates a Pentium IV. On their website, the authors of PTLsim write:

"PTLsim is a cycle accurate x86 microprocessor simulator and virtual machine for the x86 and x86-64 instruction sets. PTLsim models a modern superscalar out of order x86-64 compatible processor core at a configurable level of detail ranging from full-speed native execution on the host CPU all the way down to RTL level models of all key pipeline structures."

Another cycle accurate simulator called FaCSIM simulated the ARM9E-S processor core and ARM926EJ-S memory subsystem [36]. It is also available as open-source. Texas Instruments also provides a CAS for its C64x+ digital signal processor [44].

To have a metric that is independent of a particular architecture, the results of cycle accurate simulators could be combined.

#### 4.4. Typical run time environments

The IIAC codec will run on various different platforms with quite diverse properties. After discussions on the WG mailing list, a few typical run time environments have been identified.

Three of the run time environments are end devices (aka phones). The first one is a PC, either stationary or a portable, having a >2 GHz PCU, >2 GByte of RAM, and a hard disk for permanent storage. Typically, a Windows, MacOS or Linux operating system is running on a PC. The second one is a SmartPhone, for example with an ARM11 500 MHz CPU, 192 Mbyte RAM and 256 MByte Flashrom. An example is the HTC Dream Smart phone equipped with Qualcomm MSM7201A chip. Various operating systems are found on those devices such as Symbian, Android, and iOS. The last ones are high end stationary VoIP phones with for example a 275-MHz MIPS32 CPU (with 400 DMIPS) with a 125-MHz (250 MIPS) ZSP DSP with dual-MAC. They both have more than 1 Mbyte RAM and FlashRom. An exemplary Chip is the BCM1103 [3].

Besides phones, VoIP gateways are frequently needed for conferencing or transcoding to legacy VoIP or PSTN. In this case, two different platforms have been identified. The first one is based on standard PC server platforms. It consists, for example, of an Intel six core Xeon 54XX or 55XX, two 1 GB NIC, 12 GByte RAM, hard disks, and a Linux operating system. Thus, a server can serve from 400 to 10000 calls depending on conference mode, codecs used, and ability of user pre-encoded audio [46]. On the other hand, high density, highly optimized voice gateways use a special purpose hardware platform like for example, TNETV3020 chips consisting of six TI C64x+ DSPs with 5.5 MB internal RAM. If they run with a Telogy conference engine, they might serve about 1300 AMR or 3000 G.711 calls per chip [45].

#### 5. Measuring Latency

Latency is a measure of time delay experienced in a system. Latency can be measured as one-way delay or as round-trip time. The latter one is the one-way latency from a source to destination plus the one-way latency back from destination to source. Latency can be measured at multiple positions, at the network layer or at higher layers [53].

As we aim to increase the Quality of Experience, the mouth-to-ear delay is of importance because it directly correlates with perceptual quality [17]. More precisely, the acoustic round-trip time shall be a means of optimization when studying interactive and conversational application scenarios.

### 5.1. ITU-T Recommendation G.114

The G.114 standard [45] gives guidelines on how to estimate one-way transmission delays. It describes how the delay introduced by the codec is generated. Because most of the encoders do a processing of frames, the duration of a frame (named "frame size") is the foremost contributor to the overall algorithmic delay. Citing [18]:

"In addition, many coders also look into the succeeding frame to improve compression efficiency. The length of this advance look is known as the look-ahead time of the coder. The time required to process an input frame is assumed to be the same as the frame length since efficient use of processor resources will be accomplished when an encoder/decoder pair (or multiple encoder/decoder pairs operating in parallel on multiple input streams) fully uses the available processing power (evenly distributed in the time domain). Thus, the delay through an encoder/decoder pair is normally assumed to be:"

$2 \times \text{frameSize} + \text{lookAhead}$

In addition, if the link speeds are low, the serialization delay might contribute significantly to the codec delay.

Also, if IP transmissions are used and multiple frames are concatenated in one IP packet, further delay is added. Then, "the minimum delay attributable to codec-related processing in IP-based systems with multiple frames per packet is:"

$(N+1) \times \text{frameSize} + \text{lookAhead}$

"where N is the number of frames in each packet."

### 5.2. Discussion

Extensive discussion on the WG mailing list led to the insight that the afore mentioned ITU delay model overestimates the delay introduced by the codec. In the last decade, two developments led to slightly other conditions.

First, the processing power of CPU increased significantly (see Section 4.4). Nowadays, even stand-alone VoIPs have CPUs with a speed of 300 MHz. They are capable of doing the encoding and decoding faster than real time. Thus, also the delay introduced by processing is not at 100% anymore but significantly lower. For example, it might be just 10% or less.

Second, even if the CPUs are fully loaded, especially if also other tasks such as a video conference or other calls need to be processed, advantaged scheduling algorithms allow for a timely encoding and decoding. For example, a staggered processing schedule can be used to reduce processing delays [45].

Thus, the impact of processing delay is reduced significantly in most of the cases.

Moreover, besides a look-ahead time, the decoder might also contribute to the algorithmic delay e.g. if decoded and concealed periods shall be mixed well.

## 6. Measuring Bit and Frame Rates

For decades, there was a quest to achieve high quality while keeping the coding rate low. Coding rate, sometimes called multimedia bit rate, is the bit rate that an encoder produces as its output stream. In cases of variable rate encoding, the coding bit rate differs over time. Thus, one has to describe the coding rate statistically. For example, minimal, mean, and maximal coding rates need to be measured.

A second parameter is the frame rate as the encoder produces frames at a given rate. Again, in case of discontinuous transmission modes (DTX), the frame rate can vary and a statistical description is required.

Both coding and frame rate influence network related bit rates. For example, the physical layer gross bit rate is the total number of physically transferred bits per second over a communication link, including useful data as well as protocol overhead [51]. It depends on the access technology, the packet rate, and packet sizes. The physical layer net bit rate is measured in a similar way but excludes the physical layer protocol overhead. The network throughput is the maximal throughput of a communication link of an access network. Finally, the goodput or data transfer rate refers to the net bit rate delivered to an application excluding all protocol headers and data link layer retransmissions, etc. Typically, to avoid packet losses or queuing delay, the goodput shall be equally large as the coding rate.

The relation between goodput and the physical layer gross bit rate is not trivial. First of all, the goodput is measured end-to-end. The end-to-end path can consist of multiple physical links, each having a different overhead. Second, the overhead of physical layers may vary with time and load, depending for example on link

utilization and link quality. Third, packets may be tunneled through the network and additional headers (such as IPsec) might be added. Fourth, IP header compression might be applied (as in LTE networks) and the overhead might be reduced. Overall, many information about the network connection must be collected to predict what the relation between physical layer gross bit rate and a given coding and frame rate is going to be. Applications, which have only a limited view of the network, can hardly know the precise relation.

For example, the DCCP TFRC-SP transport protocol simply estimates a header size on data packets of 36 bytes (20 bytes for the IPv4 header and 16 bytes for the DCCP-Data header with 48-bit sequence numbers) [7][8]. Thus, [11] suggested a typical scenario in which one encoded frame is transmitted with the RTP, UDP, IPv4 and IEEE 802.3 protocols and thus each packet contains packet headers having 12 bytes, 8 bytes, 20 bytes and 18 bytes respectively. The gross bit rate calculates as

$$r_{\text{gross}} = r_{\text{coding}} + \text{overhead} \cdot \text{framerate}$$

where  $r_{\text{coding}}$  is the coding rate of the encoding,  $\text{framerate}$  is the frame rate of the codec,  $\text{overhead}$  is the number of bits for protocol headers in each packet (typically  $58 \cdot 8 = 464$ ), and the  $r_{\text{gross}}$  is the rate used on physical mediums.

## 7. Codec Testing Procedures Used by Other SDOs

To ensure quality, each newly standardized codec is rigorously tested. ITU-T Study Group 12 and 16 have developed very good and mature procedures on how to test codecs. The ITU-T Study Group 12 has described the testing procedures of narrow- and wide-band codecs in the ITU-T P.830 standard.

### 7.1. ITU-T Recommendation P.830

The ITU-T P.830 recommendation describes methods and procedures for conducting subjective performance evaluations of digital speech codecs. It recommends for most applications the Absolute Category Rating (ACR) method using the Listening Quality scale. The process of judging the quality of a speech codec consists of five steps, which are described in the following.

Step 1: Preparation of Source Speech Materials Including Recording of Talkers. When testing a narrow band codec, the recommendation suggests to use a bandwidth filter before applying sample items to a codec. This bandwidth filter is called modified Intermediate Reference System (IRS) and limits the frequency band to the range

between 300 and 3400 Hz. In addition, the recommendation states that "if a wideband system (100-7000 Hz) is to be used for audio-conferencing, then the sending end should conform to IEC Publication 581.7."

It also says that "speech material should consist of simple, short, meaningful sentences." The sentences shall be understandable to a broad audience and sample items should consist of two or three sentences, each of them having a duration of between 2 and 3 seconds. Sample items should not contain noise or reverberations longer than 500 ms. The recommendation also makes suggestions on the loudness of the signal: "A typical nominal value for mean active speech level (measured according to Recommendation P.56) is -20 dBm0, corresponding to approximately -26 dBov"

Step 2: Selection of Experimental Parameters to Exercise the Features of the Codec That Are of Interest. Various parameters shall be tested. Those include

- o Codec Conditions

- o Speech input levels ("input levels of 14, 26 and 38 dB below the overload point of the codec")
- o Listening levels ("levels should lie 10 dB to either side of the preferred listening level")
- o Talkers
  - . Different talkers ("a minimum of two male and two female talkers")
  - . Multiple talkers ("multiple simultaneous voice input signals")
- o Errors ("randomly distributed bit errors" or burst-errors)
- o Bitrates ("The codec must be tested at all the bit rates")
- o Transcodings ("Asynchronous tandeming", "Synchronous tandeming", and "Interoperability with other speech coding standards")
- o Mismatch (sender and receiver operate in different modes)
- o Environmental noise (sending) ("30 dB for room noise" and "10 dB and 20 dB for vehicular noise")

- o Network information signals ("signaling tones, conforming to Recommendation Q.35, should be tested subjectively, and the minimum should be proceed to dial tone, called subscriber ringing tone, called subscriber engaged tone, equipment engaged tone, [and] number unobtainable tone.")
- o Music ("to ensure that the music is of reasonable quality")
- o Reference conditions ("for making meaningful comparisons")
  - o Direct (no coding, only input and output filtering)
  - o Modulated Noise Reference Unit (MNRU)
  - o Signal-to-Noise Ratio (SNR) (for comparison purposes)
  - o Reference codecs

Step 3: Design of the Experiment. The considerations described in B.3/P.80 apply here. Typically, it is not possible to test each combination of parameters. Thus, recommendation P.830 states that "it is recommended that a minimum set of experiments be conducted, which, although they would not cover every combination, would result in sufficient data to make sensible decisions. [...] Extreme caution should be used when comparing systems with widely differing degradations, e.g. digital codecs, frequency division multiplex systems, vocoders, etc., even within the same test."

Step 4: Selection of a Test Procedure and Conduct of the Experiment. Here, the considerations as in B.4/P.80 apply. However, a modified IRS at the receiver shall be used (narrow band) or an IEC Publication 581.7 filter (wideband). Also, "Gaussian noise equivalent to -68 dBmp should be added at the input to the receiving system to reduce noise contrast effects at the onset of speech utterances."

Step 5: Analysis of Results. Again, the considerations detailed in B.4.7/P.80 apply. The arithmetic mean (over subjects) is to be calculated for each condition at each listening level.

## 7.2. Testing procedure for the ITU-T G.719

Recently, the ITU-T has standardized the audio and speech codec ITU-T G.719. The G.719 has similar properties as the anticipated IIAC, thus the optimization and characterization of the G.719 is of particular interest.



In the following, we will describe the "Quality Assessment Test Plan" in TD 322 and 323 [33][35]. The ITU Study Group 16 used ITU-R BS.1116 to tests sample items. Audio sample items were sampled at 48 kHz mixed down to mono. Speech sample items contain one sentence with a duration of 4 s, mixed content had a duration of 5-6 s and music a duration of between 10 and 15 s. The beginning and ending of the samples were smoothed. Also, a filter was applied to limit the nominal bandwidth of the input signal to the range of 20 to 20000 Hz. As for the mixed content, advertisements, film trailers and news (including a jingle) have been selected. For music items, classical and modern styles of music have been selected. Besides the codec under test, test stimuli degraded with LAMP MP3 and G722 were added to the tests. Some test stimuli have been modified to include reverberations or an interfering talker and office noise. Some tests were done studying the effect of a frame erasure rate of 3% having random loss patterns. All listening labs used different sample items and attention paid to not use the same material twice.

Listening labs were required to provide the results of 24 experienced listeners excluding those listeners, who did not passed a pre- and post-screening. The experienced listeners should "neither have a background in technical implementations of the equipment under test nor do they have detailed knowledge of the influence of these implementations on subjective quality".

During the tests, "circum aural headphones - open back for example: STAX Signature SR-404 or Sennheiser HD-600) on both ears (diotic presentation)" were used. The listening levels were -26 dB relative to OVL.

Some results of the listening tests are given in TD 341 R1 [34]. In those tests, they also compared the subjective ratings that were made following BS.1116 with the objective ratings of ITU-R BS.1387-1. The correlation between objective and subjective ratings was below  $R=0.9$ .

## 8. Transmission Channel

Between speech encoder and decoder lies a transmission channel that effects the transmission. For cellular or wireless phones, the typical transmission channel is assumed to be equal to the wireless link(s). This typically means, that a circuit switch link is assumed (e.g., in GSM, UMTS, DECT). The bandwidth is typically constant in DECT and GSM or variable in a given range depending on the quality of the wireless transmission (UMTS). Bit errors do occur but they don't be equally distributed if unequal bit error correction is applied (UMTS).

In the case of the IIAC codec, the transmission channel is the internet. More precisely, it is the packet transmission over the Internet, plus the transport protocol (e.g. UDP, TCP, DCCP), plus potentially Forward Error Correction, and plus dejittering buffers.

Also, the transmission channel is reactive. It changes its properties depending on how much data is transmitted. For example, parallel TCP flows reduce their transmission bandwidth in the presence of an unresponsive UDP stream.

Overall, one can say that the transmission channel "Internet" is difficult to understand. Thus, in this chapter, we try to shed light on the question of what types of transmission channels a codec has to cope with.

#### 8.1. ITU-T G.1050: Network Model for Evaluating Multimedia Transmission Performance over IP (11/2007)

The current ITU-T G.1050 standard [20] describes layer 3 packet transmission models that can be used to evaluate IP applications. The models are of statistical nature. They consider networks architectures, types of access links, QoS controlled edge routing, MTU size, networks faults, link failures, route flapping, reordered packets, packet loss, one-way delay, variable deploys and background traffics.

G.1050 is a network model consisting of three parts, LAN a, LAN b, and an interconnection core. Both LANs can have different rates and occupancy and can be of different types. LAN and core are connected via access technologies, which might vary in data rate, occupancy and MTU size.

The core is characterized by route flapping, link failures, one-way delay, jitter, packet loss and reordered packets. Route flaps are repeatedly changed in a transmission path because of alternating routing tables. These routing updates cause incremental changes in the transmission delays. A link failure is a period of consecutive packet loss. Packet losses can be bursty having a high loss rate during bursts and having otherwise a lower loss rate otherwise. Delays are modeled via multiple different jitter models supporting delay spikes, random jitter and filtered random jitters.

The standard recommends three profiles, named "Well-managed IP network", "Partially-managed IP network", and "Unmanaged IP Network, Internet", which differ in their connection qualities.

Limitations to these models are the missing cross-correlation between packet delays and packet loss events, the lack of responsiveness to the tests application flow, and the lack of link qualities that vary with time.

#### 8.2. Draft G.1050 / TIA-921B

Currently, an enhancement to ITU-T G.1050 (11/2007) is being developed (e.g. [13])). It does not use a statistical model but takes advantage of the NS/2 simulator. Thus, most of the above mentioned limitations have been overcome.

Despite that, even the new model does not yet give an answer to the question of which distributions of typical Internet connection qualities can be expected.

#### 8.3. Delay and Throughput Distributions on the Global Internet

In general, it is not precisely known how the qualities of end-to-end connections are distributed. It is also unclear whether the anticipated IIAC Codec will be used globally or whether its area of usage will be somehow restricted.

Despite the fact, that the codec has to be optimized for an unknown Internet, the following scientific publications give an estimate on how different Internet end-to-end paths might behave. One recent example is on studies about the residential broadband Internet access traffic of a major European ISP [37].

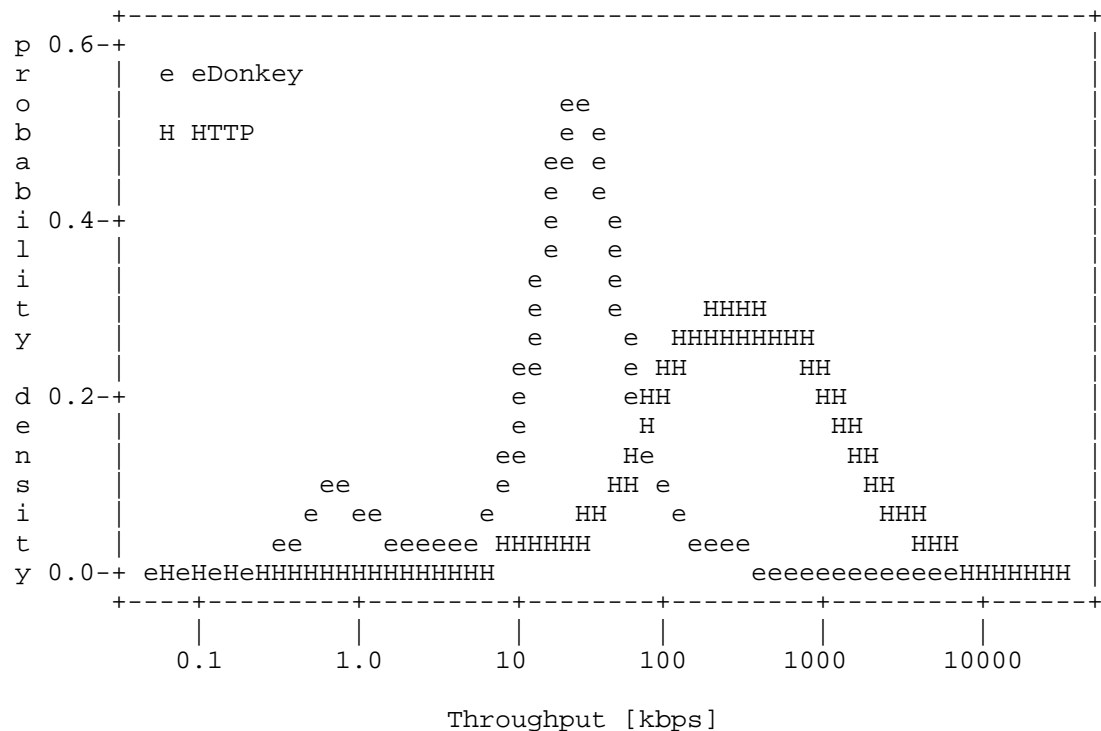


Figure 2 Achieved throughput of flows measured for eDonkey and HTTP applications [37]

Figure 2 displays the throughput distribution of TCP connections for eDonkey peer-to-peer and HTTP applications. It only considers single flow with a length of more than 50 Kbyte. But typically, a web browser uses two to three TCP connections at the same time and an eDonkey client about 10. Still, the throughput of a single HTTP flow is in about an order faster than the of eDonkey flow. In [37], the authors assume this is due to the fact that peer-to-peer connections fill the uplink and that HTTP is used at the faster downlink.

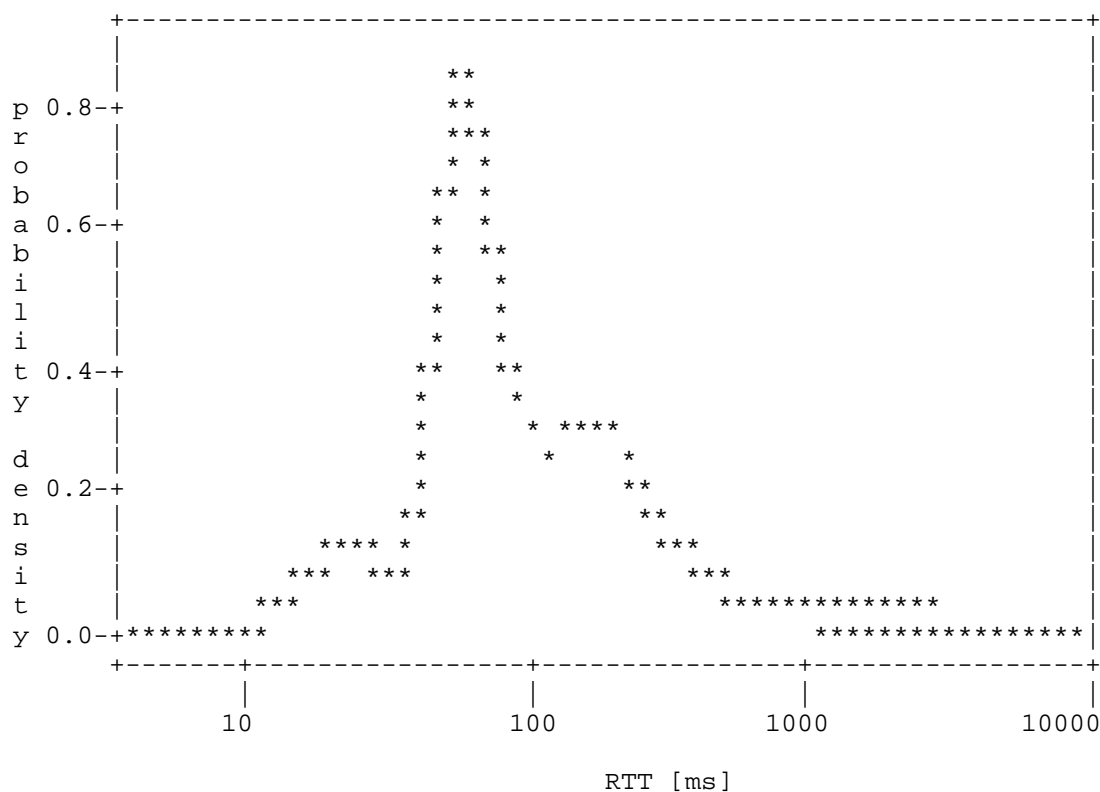


Figure 3 TCP roundtrip times [36]

Figure 3 displays TCP roundtrip times including both access and backbone network. Both graphs can be seen as an indication for the assumption that an application, even in modern Internet access networks, might be subjected to a wide variability of throughput ranging from a few kbits/s up to 10 Gbit/s and TCP round trip times from 5ms up to one of several seconds.

Albeit these results are only valid for TCP, similar results should be expected for RTP over UDP - with a small advantage because UDP flows are not always responsive.

As a summary, a codec for the Internet should be able to work under these widely varying transmission conditions and should be tested against a wide distribution of expected throughputs.

#### 8.4. Transmission Variability on the Internet

Besides effects such as route flapping or link failures modeled in G.1050 [20], the Internet experience in short-time scales sharp changes sharply in bandwidth utilization. For example, [49] and [38] showed that variability of Internet traffic comes in form of spike like traffic increments. Similarly, [32] studied why the Internet is bursty in time scales of between 100 and to 1000 milliseconds.

In the light of these results, one can assume that the IIAC's transmission conditions will vary in similar time scales. More precisely, it will be subjected to

- . variability due to bursty traffic having a duration of between 100 and 1000 milliseconds,
- . interruptions due to temporal link failures every minute to every hour that might have a temporal interruption from 64 ms to several seconds [20], and
- . route flap events every minute to every hour that have a delay of between 2 and 128 ms [20].

#### 8.5. The Effects of Transport Protocols

Realtime multimedia is not always transported over RTP and UDP. Sometimes it makes sense to use a different transport protocol or an additional rate adaptation. The reasons for that are manifold.

- . If a scalable codec shall be supported, RTCP-based feedback information can be utilized to implement a rate control mechanisms [41]. However, RTCP-based feedback suffers from the drawback that RTCP messages are allowed only every 5 s. Thus, implementing a fast responding mechanism is not possible.
- . In the presence of restricted firewalls, VoIP can sometimes only be transmitted over TCP. In those cases, the transmission scheduling is not given by the codec but by TCP. TCP algorithms typically don't have a smooth sending rate but frequently send packets in bursts and change the amount of packets sent every round trip time (Figure 4). More precisely, TCP causes the sending schedule to behave in the following way:
  - . During the Slow Start phase (for example at the beginning of a TCP connection) the transmission rate increases exponentially.

- . If a TCP segment is not acknowledged after about four RTTs, the TCP sending rate starts at one packet per RTT again.
- . During congestion avoidance, the sending rate increases steadily by one segment per RTT.
- . If a congestion event is then detected, the sending rate is reduced by 50%.

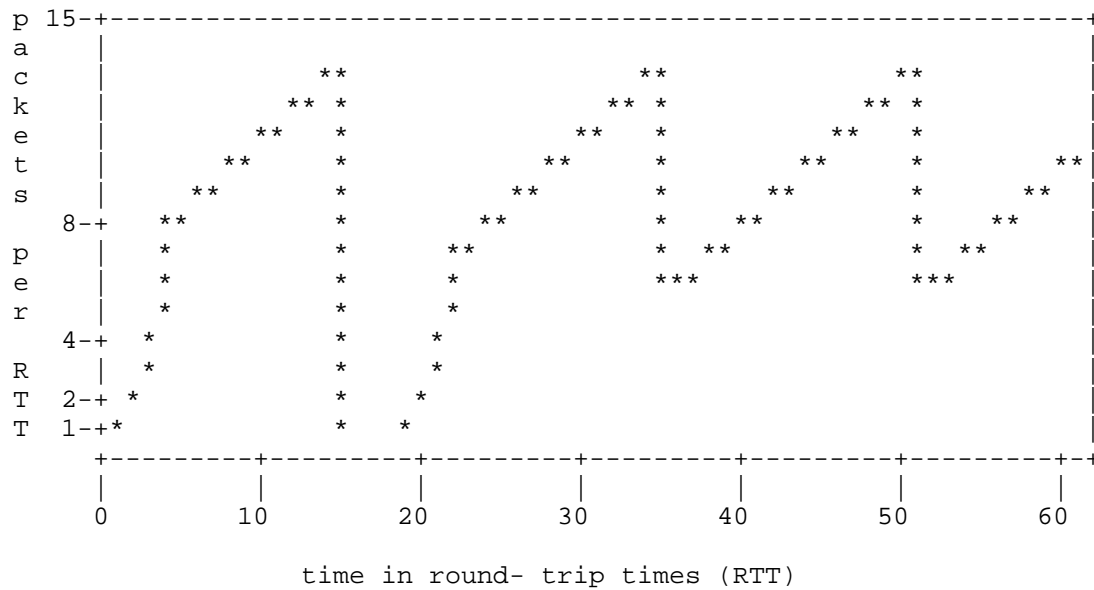


Figure 4 Sending rate of a standard TCP over time

- . The DCCP transport protocol supports multiple congestion control protocols and gives means to support TCP friendliness without retransmission. Thus, it is suitable for real time multimedia transmissions. DCCP supports a TCP emulation, which shows a similar rate over time as TCP, and the TFRC congestion control, which changes its rate in a smoother way (Figure 5). Besides TFRC, which is intended to transmit packets of maximal size (aka MTU), TFRC-SP is optimized for flows with variable packet sizes such as VoIP. With TFRC-SP, smaller packets can be transmitted at a faster pace than it is the case for larger packets because they contribute less to the gross bandwidth consumption. The TFRC protocol might provide a lower bandwidth and a lower QoE as UDP or TCP, unless if not proper optimizations are taken (see [48]). Also, it is suggested to limit the rate control to 100 packets per second. This limit might be too low for an IIAC.

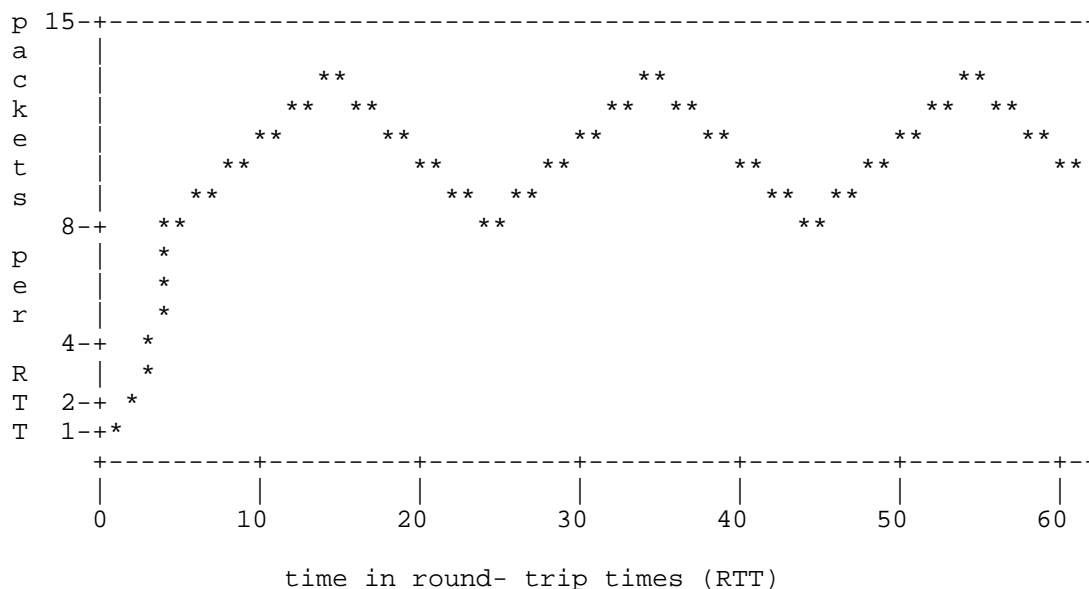


Figure 5 Sending rate of the TFRC protocol

In general, the transport protocol has a clear influence on the transmission conditions. Coding rates need to be adapted by sharply and smoothly to changed bandwidth estimations. Changes of the bandwidth estimation may occur every RTT. Also, in cases of a TCP timeout, the transmission is halted and the decoding must be stalled.



### 8.6. The Effect of Jitter Buffers and FEC

Both jitter buffers trade frame losses against delay. In cases of a jitter buffer, frames are delayed before playout. This helps in cases of lately arriving frames that would otherwise be ignored and would have to be concealed. Jitter buffers are adaptive and are changing dynamically to the current loss process on the Internet.

Forward Error Correction helps to cope with isolated losses as redundant speech frames are transmitted in the following packets. In the presence of loss, FEC increases the delay because the receiver has to wait for the following packets. Both delay and packet losses are important contributors to the overall Quality of Experience [2].

Since the delay process on the Internet often comes in the form of a gamma distribution, thus a statistical monitor of past delays helps to predict the size of future jitter. Then, if the playout schedule does not match the predicted loss process, playout can be accelerated or slowed down.

However, due to the reasons described in Section 8.4 not all increments in transmission time might be predictable. This has a profound effect on the jitter buffer as it actually cannot predict well, whether a frame is lost or whether it is going to be delayed. If a frame is scheduled for playout but has not been received, the jitter buffer has to consider two cases. First, the frame is lost and has to be concealed. This typically means that the audio signal needs to be extrapolated or interpolated to conceal the gap due to a lost frame. Second, the frame is delayed and shall be played out at a later point in time. Then, the resulting gap in playout must be concealed by extrapolating the previous audio signal.

These issues have an effect on testing the concealment algorithm of the codec. The same concealment function must be tested against time gap concealment and loss concealment.

### 8.7. Discussion

Judging a codec performance using a realistic model of a transmission channel is difficult. Good models of IP transmission channels are available. However, before a codec can be tested against those channels, further building blocks such as the transport protocol, the jitter buffer, and FEC should be known - at least roughly.

Alternatively, a codec can be tested only against of packet loss patterns only without considering any rate adaption or playout

rescheduling. But then again, the codec should be additionally tested for those impairments, which occur due to the dynamics of the Internet. These include

- o slowing down and speeding up the playout in cases of moderate rescheduling of playout times,
- o stalling and resuming the playout in cases of temporal link outages,
- o moderately reducing and increasing bit and frame rates during contention periods, and
- o sharply reducing (in case of congestion) and fast increasing (during connection establishment) of bit and frame rates.
- o Time gap and loss concealment.
- o Speeding up and slowing down the playout speed.

## 9. Usage Scenarios

Quality of Experience is the service quality perceived subjectively by end-users (refer to Section 2) and as ITU-T document G.RQAM [21] states "overall acceptability may be influenced by user expectations and context". Thus, in this section we describe the usage scenarios, in which the IIAC codec will probably be used, and the expectations users have in those communication contexts. We list seven main scenarios and describe their quality requirements.

### 9.1. Point-to-point Calls (VoIP)

The classic scenario is that of the phone usage to which we will refer in this document as Voice over IP (VoIP). Human speech is transmitted interactively between two Internet hosts. Typically, besides speech some background noise is present, too.

The quality of a telephone call is traditionally judged by subjective tests such as those described in [24]. The ACR scale used in MOS-LQS sometimes might not be very suitable for high quality calls, then - for example - the MUSHRA [16] rating can be applied.

A telephone call is considered good if it has a maximal mouth-to-ear delay of 150 ms [17] and a speech quality of MOS-LQS 4 or above. However, interhuman communication is still possible if the mouth-to-ear delay is much larger.

The effect of delay jitter might not be very well notable in case of speech. Thus, playout rescheduling can happen often take place.

In many cases, phone calls are made between mobile devices such as mobile phones and cellular phone. In these cases, energy consumption is crucial and both complexity and transmission rate may be reduced to save resources.

### 9.2. High Quality Interactive Audio Transmissions (AoIP)

In this scenario we consider a telephone call having a very good audio quality at modest acoustic one-way latencies ranging from 50 and 150 ms [17], so that music can be listened to over the telephone while two persons are talking interactively.

While delay expectations might be similar to those of classic telephony, the audio quality must meet similar standards as those of consumer Hifi equipment like MP3 and CD players, iPods, etc.

If music is played, playout rescheduling events may be heard easily be heard as the rhythm changes. Only a few studies such as [10] have been made to examine the effect of time varying delays on service quality. In general, it can be assumed that the requirements regarding constancies of playout schedules are higher than in case of speech because human beings can notice rhythmic changes easily. Thus, in the presence of music, frequent playout rescheduling shall be avoided.

### 9.3. High Quality Teleconferencing

Also, for today's teleconferencing and videoconferencing systems there is a strong and increasing demand for audio coding providing the full human auditory bandwidth of 20 Hz to 20 kHz. This rising demand for high quality audio is due to the following reasons:

- o Conferencing systems are increasingly used for more elaborated presentations, often including music and sound effects which occupy a wider audio bandwidth than that of speech. For example, Web conferences such as WebEx, GoToMeeting, Adobe Acrobat Connect are based on an IP based transmission.
- o The new "Telepresence" video conferencing systems, providing the user with High Definition video and audio quality, create the experience of being in the same room by introducing high quality media delivery (such as from Cisco).

- o The emerging Digital Living Rooms are to be interconnected and might require a constant high quality acoustic transmission at high qualities.
- o Spatial audio teleconference solutions increase the quality because they take advantage of the cocktail-party effect. By taking advantage of 3D audio, participants can be identified by their location in a virtual acoustic environment and multiple talkers can be distinguished from each other. However, these systems require stereo audio, if the spatial audio is rendered for headphones.

#### 9.4. Interconnecting to Legacy PSTN and VoIP (Convergence)

This scenario does not include the use case of using a VoIP-PSTN gateway to connect to legacy telephone systems. In those cases, the gateway would make an audio conversion from broadband Internet voice to the frugal 1930's 3.1 kHz audio bandwidth.

The quality requirements in this scenario are low because legacy PSTN typically uses narrow-band voice. Also, in those cases one might expect the codec negotiation might decide on a common codec both for PSTN and VoIP in order to avoid transcoding.

However, the complexity requirements might be stringent because central media gateways must scale to a high number of users. In this context, hardware costs are an important criterion and the codec has to operate efficient.

#### 9.5. Music streaming

Music streaming typically does not require low delays. However, in special cases such as live events and in the presence of alternative transmission technologies, low-delay streaming may be demanded.

Examples are important sport events, which are streamed both on terrestrial, (analogue) and low delay broadcast networks and on IP-based distribution networks. The latter ones becomes aware (such as when a footballer scores) more lately than the ones their neighbors using terrestrial technology.

#### 9.6. Ensemble Performances over a Network

In some usage scenarios, users want to act simultaneously and not just interactively. For example, if persons sing in a chorus, if musicians jam, or if e-sportsmen play computer games in a team together they need to communicate acoustically.

In this scenario, the latency requirements are much harder than for interactive usages. For example, if two musicians are placed more than 10 meters apart, they can hardly stay synchronized. Empirical studies [10] have shown that if ensembles play over networks, the optimal acoustic latency is at around 11.5 ms with a targeted range from 10 to 25 ms.

Also, the users demand very high audio quality, very low delay and very few events of playout rescheduling.

#### 9.7. Push-to-talk like Services (PTT)

In spite of the development of broadband access (xDSL), a lot of users do only have service access via PSTN modems or mobile links. Also, on these links the available bandwidth might be shared among multiple flows and is subjected to congestion. Then, even low coding rates of about 8 kbps are too high.

If transmission capacity hardly exists, one can still degrade the quality of a telephone call to something like a push-to-talk (PTT) like service having very high latencies. Technically, this scenario takes advantage of bandwidth gains due to disruptive transmission (DTX) modes and very large packets containing multiple speech frames causing a very low packetization overhead.

The quality requirements of a push-to-talk like service have hardly been studied. The OMA lists as a requirement of a Push-to-talk over cellular service a transmission delay of 1.6 s and a MOS values of above 3.0 that typically should be kept [39]. However, as long as an understandable transmission of speech is possible, the delay can be even higher. For example, [39] allows a delay of typically up to 4 s for the first talk-burst. Also, [39] describes a maximum duration of speaking. If a participant speaking reaches the time limit, the participant's righttospeak shall be automatically revoked.

If the quality of a telephone call is very low, then instead of listening-only speech quality the degree of understandability can be chosen as performance metric. For example, objective tests of the understandability use automatic speech recognition (ASR) systems and measure the amount of correctly detected words.

In any case, the participant shall be informed about the quality of connection, the presence of high delays, the half-duplex style of communication, and its (limited) righttospeak. For example this can be achieved by a simulated talker echo.

## 9.8. Discussion

The requirements of the usage scenarios are summarized in the following table.

Scenario	Sound Quality			Latency			Complexity	
	low	avg.	hifi	10ms	150ms	high	low	high
VoIP	X				X		X	X
AoIP		X	X		X			X
Conference		X			X			X
Convergence	X				X		X	X
Streaming		X	X			X		X
Performances			X	X				X
Push-To-Talk	X					X	X	X

Figure 6 Different requirements for different usage scenarios

## 10. Recommendations for Testing the IIAC

The IETF IIAC differs substantially from a classic narrow and wideband codec. Thus, the previously applied codec testing procedures such as ITU P.830 cannot be entirely adopted. Instead, one must check carefully, which of the procedures are used without changes, which procedures are used with minor changes and which procedures are dropped or replaced.

In Section 1 we listed five groups of stakeholders, which have different requirements and demands on how to test the quality of an IIAC. In the following, we recommend testing procedures for those stakeholders.

### 10.1. During Codec Development

The codec development is an innovative process. In general, innovation and research in general benefits from openness and discussion between experts. Thus, format restrictions on how to test the codec might hinder the codec development because innovation may also take place in testing procedures. Instead, many experts both in codec development and codec usage shall be able to participate. If this is the case, they contribute with their expertise, identify weaknesses, and discuss potential codec enhancements. During innovation, openness in participation and discussion is very fruitful and leads to good results.

Based on the ongoing experience, codec developers know best on how to tests their codecs. Typically, those tests include informal

testing, semiformal testing, and expert interviews. They are intended to find weaknesses in the codec, to identify artifacts or distortions, and to achieve algorithmic progress.

## 10.2. Characterization Phase

The characterization phase is intended to study the features, the quality tradeoff and the properties of a codec under standardization. It is intended to be an objective measure of the codec's quality to convince third parties of the quality properties of the standardized codec. In order to achieve this aim, a formal testing procedure has to be established.

In general, we recommend to base the procedure of the characterization phase on procedures that are similar to those that were used for the G.719 standardization (Section 7.2 and especially [35]). In the following, we describe the suggested testing procedure in the characterization phase.

### 10.2.1. Methodology

The testing of sound quality can be done using the MUSHRA tests with eight samples and three anchors. One anchor is the known reference, the second one is a hidden reference, and the third one the hidden anchor. It is suggested to use a bandwidth filtered signal with at low-pass filter at 3.5 kHz. However, because a will range of qualities are to be tested ranging from Hifi down to toll quality, it is beneficial to add a further low quality anchor such as a 3.5 kHz bandwidth sample distorted by modulated noise (MNRU) [25], for example with MNRU of a strength of  $Q=25$  dB that corresponds to a MOS value of 1.79 [4].

### 10.2.2. Material

Reference samples should be 48 kHz sampled, stereo channel material. The nominal bandwidth of the reference samples shall be limited to the range of 20 to 20000 Hz. Three different kinds of contents shall be tested: speech, music and mixed content.

Speech samples shall include different languages including English and tonal languages. The speech samples shall be recorded in a quiet environment without background noise or reverberations. The speech samples shall contain one meaningful sentence having a length of about 4 s.

Music samples shall contain a wide variety of music styles including classical music, pop, jazz, and single instruments. The length of

samples shall be of between 10 and 15 s. A smoothing of 100 ms both at the beginning and at the end shall be conducted, if required.

Mixed content may contain advertisements, film trailers, news with jingles and other mixtures of speech, music and noises. The length may be at about 5-6 s.

#### 10.2.3. Listening Laboratory

Multiple independent laboratories shall conduct the listening tests. They are responsible for generating or selecting reference samples as well as for the pre and post screening of subjects. In the end, the results of about 24 experienced listeners shall be published (in addition to the samples).

The tests must be conducted in a quiet listening environment at about NC25 (approximate 35 dBA). For example, an ISOBOOTH room can be used.

It is recommended to use a high quality D/A, such as Benchmark DAC, Metric Halo ULN-2, Apogee MiniDAC. High quality headphone amplifiers and playback level calibration shall be used. Playback levels might be measured via Etymotic in-ear microphones. Also, high quality headphones (e.g. AKG 240DF, Sennheiser HD600) are advisable.

#### 10.2.4. Degradation Factors

The IIAC is likely to be highly configurable. However, due to time limits, only a few parameter sets can be tested subjectively. Thus, we recommend to do subjective studies with

- o different bit rates (from low to high, 5 tests)
- o different frame rates (from low to high, 2 tests)
- o different loss pattern (G.1050 profile A, B, and C at low rate with speech content and at high rate with music content. The influence of jitter, delay, and link failures shall be ignored. In total, this would be 6 tests)
- o different sample contents
  - o Speech, speech+reverberations, and speech+noise+reverberations at low and medium rates (3 tests).
  - o The speech sample must be tested in different languages (English, Chinese, ...) and with male/female voices (6 tests)



- o Mixed content and music shall be tested at medium and high rates (about 10 tests).
- o A low complexity mode, DTX and the FEC mode shall be tested at low rates because they are typically used on constraint devices (3 tests)
- o Abrupt changes in bit and frame rates (reduction by half, exponential start, 2 tests)
- o Smooth changes of bit and frame rates (incrementing or decreasing the codec's gross rate by 1.5 kbyte every 100ms, 2 tests)
- o Stall and continue operations (20, 200, and 1000 ms, 3 tests)
- o Accelerated and slowed down playout (+- 10% for speech at low rates)
- o Reference codecs such as LAME MP3, G.719, and AMR each at two coding rate (6 tests)

Already, these are 48 different tests that need to be conducted.

In addition, for intermediate values objective tests shall be run using PEAQ (for music) and P.OLQA (for speech). The intermediate results shall be mapped on the MUSHRA scale with a quadratic regression because PEAQ and P.OLQA are using an ODG and MOS scale respectively.

### 10.3. Application Developers

Application developers can take advantage of the results of the qualification phase. They may use the results to develop a quality model, which describes the expected quality of the codec at a given parameter set (refer to [11] for an example).

In addition, they can test their system using the draft G.1050 simulation model, which is especially useful for optimizing rate control, dejittering buffers and concealment algorithms. Different systems may be tested with quality models, subjective listening tests, conversational listening tests, or with objective measures such as POLQA.

Also, field tests may be conducted to test the effect of a real network on the VoIP application.

#### 10.4. Codec Implementers

To tests the conformance of a codec, codec implementers can use objective tools like PEAQ or P.OLQA to see, whether the newly implemented codec performs in a way that is similar to the performance of the reference implementation. These tests shall be done for many different parameter sets.

#### 10.5. End Users

End user may be included in the qualification tests. The intentions of these tests are two-fold. First, the awareness of the end-user shall be increased. Second, querying users may be a cost effective way of conducting listening-only tests.

However, before the rating results of end users can be considered for further usage, one need to compare between formal and web-based testing results to see, to what extent they differ from each other.

#### 11. Security Considerations

The results of the quality tests shall be convincing. Thus, special care has to be taken to make the tests precise, accurate, repeatable and trustworthy.

Some testing houses may have a conflict of interest between accurate quality ratings and promotion of own codecs. Thus, a high degree of openness shall be enforced that requires all of the testing material and results to be published. This way, others may verify the results of testing houses. In addition, some stimuli shall be tested by all the testing houses to compare their quality of rating.

Moreover, hidden anchors may help to identify subjects, which rate the quality of samples less precisely.

#### 12. IANA Considerations

This document has no actions for IANA.

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Guidelines for the Codec Development Within the IETF  
draft-ietf-codec-guidelines-02

Abstract

This document provides general guidelines for work on developing and specifying a codec within the IETF. These guidelines cover the development process, evaluation, requirements conformance, and intellectual property issues.

Status of this Memo

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

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## Table of Contents

1. Introduction . . . . .	3
2. Development Process . . . . .	4
3. Evaluation, Testing, and Characterization . . . . .	7
4. Specifying the Codec . . . . .	8
5. Intellectual Property . . . . .	10
6. Relationship with Other SDOs . . . . .	13
7. Security Considerations . . . . .	15
8. IANA Considerations . . . . .	16
9. Acknowledgments . . . . .	17
10. References . . . . .	18
10.1. Normative References . . . . .	18
10.2. Informative References . . . . .	18
Authors' Addresses . . . . .	19

## 1. Introduction

This document describes a suggested process for work at the IETF on standardization of a codec that is optimized for use in interactive Internet applications and that can be widely implemented and easily distributed among application developers, service operators, and end users.

## 2. Development Process

The process outlined here is intended to make the work on a codec within the IETF transparent, predictable, and well organized. Such work might involve development of a completely new codec, adaptation of an existing codec to meet the requirements of the working group, or integration between two or more existing codecs that results in an improved codec combining the best aspects of each. To enable such procedural transparency, the contributor of an existing codec must be willing to cede change control to the IETF and should have sufficient knowledge of the codec to assist in the work of adapting it or applying some of its technology to the development or improvement of other codecs. Furthermore, contributors need to be aware that any codec that results from work within the IETF is likely to be different from any existing codec that was contributed to the Internet Standards Process.

Work on codec development is expected to proceed as follows:

1. IETF participants will identify the requirements to be met by an Internet codec, in the form of an Internet-Draft.
2. Interested parties are encouraged to make contributions proposing existing or new codecs, or elements thereof, to the codec WG as long as these contributions are within the scope of the WG. Ideally, these contributions should be in the form of Internet Drafts, although other forms of contributions are also possible, as discussed in [PROCESS].
3. Given the importance of IPR to the activities of the working group, any IPR disclosures must be made in a timely way. Contributors are required, as described in [IPR], to disclose any known IPR, both first and third party. Timely disclosures are particularly important, since those disclosures may be material to the decision process of the working group.
4. As contributions are received and discussed within the working group, the group should gain a clearer understanding of what is achievable within the design space. As a result, the authors of the requirements document should iteratively clarify and improve their document to reflect the emerging working group consensus. This is likely to involve collaboration with IETF working groups in other areas, such as collaboration with working groups in the Transport area to identify important aspects of packet transmission over the Internet and to understand the degree of rate adaptation desirable, and with working groups in the RAI area to ensure that information about and negotiation of the codec can be easily represented at the signaling layer. In

parallel with this work, interested parties should evaluate the contributions at a higher level to see which requirements might be met by each codec.

5. Once a sufficient number of proposals has been received, the interested parties will identify the strengths, weaknesses, and innovative aspects of the contributed codecs. This step will consider not only the codecs as a whole, but also key features of the individual algorithms (predictors, quantizers, transforms, etc.).
6. Interested parties are encouraged to collaborate together and combine the best ideas from the various codec contributions into a consolidated codec definition, representing the merging of some of the contributions. Through this iterative process, the number of proposals will reduce and consensus will generally form around one of them. At that point, the working group should adopt that document as a working group item, forming a baseline codec.
7. IETF participants should then attempt to iteratively add to or improve each component of the baseline codec reference implementation, where by "component" we mean individual algorithms such as predictors, transforms, quantizers, and entropy coders. The participants should proceed by trying new designs, applying ideas from the contributed codecs, evaluating "proof of concept" ideas, and using their expertise in codec development to improve the baseline codec. Any aspect of the baseline codec might be changed (even the fundamental principles of the codec) or the participants might start over entirely by scrapping the baseline codec and designing a completely new one. The overriding goal shall be to design a codec that will meet the requirements defined in the requirements document. Given the IETF's open standards process, any interested party will be able to contribute to this work, whether or not they submitted an Internet-Draft for one of the contributed codecs. The codec itself should be normatively specified with code in an Internet-Draft.
8. In parallel with work on the codec reference implementation, developers and other interested parties should perform evaluation of the codec as described under Section 3, IETF participants should define (within the AVT Working Group) the codec's payload format for use with the Real-time Transport Protocol [RTP]. Ideally, application developers should test the codec by implementing it in code and deploying it in actual Internet applications. Unfortunately, developers will frequently wait until RFC or until a stable bitstream is guaranteed before deployment. As such, this is a nice-to-have and not a

requirement for this process. Lab implementations are certainly encouraged.

9. As the developed codec stabilizes and the group feels no more changes are needed, the testing done to date is taken, along with any additional testing required to give confidence that the codec meets the requirements, and those test results form the final characterization of the codec. The process of testing is described under Section Section 3.



### 3. Evaluation, Testing, and Characterization

Lab evaluation of the codec being developed should happen throughout the development process because it will help ensure that progress is being made toward fulfillment of the requirements. There are many ways in which continuous evaluation can be performed. For minor, uncontroversial changes to the codec it should usually be sufficient to use objective measurements (e.g., PESQ, PEAQ, and SegSNR) validated by informal subjective evaluation. For more complex changes (e.g., when psychoacoustic aspects are involved) or for controversial issues, internal testing should be performed. An example of internal testing would be to have individual participants rate the decoded samples using one of the established testing methodologies, such as ITU-R BS.1534 (MUSHRA).

Throughout the process, it will be important to make use of the Internet community at large for real-world distributed testing. This will enable many different people with different equipment and use cases to test the codec and report any problems they experience. In the same way, third-party developers will be encouraged to integrate the codec into their software (with a warning about the bit-stream not being final) and provide feedback on its performance in real-world use cases.

Characterization of the final codec must be based on the reference implementation only (and not on any "private implementation"). This can be performed by independent testing labs or, if this is not possible, using the testing labs of the organizations that contribute to the Internet Standards Process. Packet loss robustness should be evaluated using actual loss patterns collected from use over the Internet, rather than theoretical models. The goals of the characterization phase are to:

- o ensure that the requirements have been fulfilled
- o guide the IESG in its evaluation of the resulting work
- o assist application developers in understanding whether the codec is suitable for a particular application

The exact methodology for the characterization phase can be determined the working group. Because the IETF does not have testing resources of its own, it has to rely on the resources of its participants. For this reason, even if the group agrees that a particular test is important, if no one volunteers to do it, or if volunteers do not complete it in a timely fashion, then that test should be discarded. This ensures that only important tests be done, and in particular those tests which are important to participants.

#### 4. Specifying the Codec

Specifying a codec requires careful consideration around what is required vs. what is left to the implementation. The following text provides suggestions for consideration by the working group:

1. Any codec specified by the IETF must include source code for a normative software implementation, documented in an Internet Draft destined for standards track RFC. This implementation will be used to verify conformance of an implementation. Although a text description of the algorithm should be provided, its use should be limited to helping the reader in understanding the source code. Should the description contradict the source code, the latter shall take precedence. For convenience, the source code may be provided in compressed form, with base64 encoding.
2. Because of the size and complexity of most codecs, it is possible that even after publishing the RFC, bugs will be found in the reference implementation, or differences between the implementation and the text description. An errata of the RFC should be maintained, along with a public software repository containing the current reference implementation.
3. It is the intention of the group to allow the greatest possible choice of freedom in implementing the specification. Accordingly, the number of binding RFC2119 keywords will be the minimum that still allows interoperable implementations. In practice this generally means that only the decoder needs to be normative, so that the encoder can improve over time. This also enables different trade-offs between quality and complexity.
4. To reduce the risk of bias towards certain CPU/DSP architectures, ideally the decoder specification should not require "bit-exact" conformance with the reference implementation. In that case, the output of a decoder implementation should only be "close enough" to the output of the reference decoder and a comparison tool should be provided along with the codec to verify objectively that the output of a decoder is likely to be perceptually indistinguishable from that of the reference decoder. An implementation may still wish to produce an output that is bit-exact with the reference implementation to simplify the testing procedure.
5. To ensure freedom of implementation, decoder-side only error concealment does not need to be specified, although the reference implementation should include the same PLC algorithm as used in the testing phase. Is it up to the working group to decide whether minimum requirements on PLC quality will be required for

compliance with the specification. Obviously, any information signaled in the bitstream intended to aid PLC needs to be specified.

6. An encoder implementation should not be required to make use of all the "features" (tools) in the bit-stream definition. However, the codec specification may require that an encoder implementation be able to generate any possible bit-rate. Unless a particular "profile" is defined in the specification, the decoder must be able to decode all features of the bit-stream. The decoder must also be able to handle any combination of bits, even combinations that cannot be generated by the reference encoder. It is recommended that the decoder specification shall define how the decoder should react to "impossible" packets (e.g. reject, consider as valid). However, an encoder must never generate such packets that do not conform to the bit-stream definition.
7. Compressed test vectors should be provided as a means to verify conformance with the decoder specification. These test vectors should be designed to exercise as much of the decoder code as possible.
8. While the exact encoder will not be specified, it is recommended to specify objective measurement targets for an encoder, below which use of a particular encoder implementation is not recommended. For example, one such specification could be: "the use of an encoder whose PESQ MOS is better than 0.1 below the reference encoder in the following conditions is not recommended".

## 5. Intellectual Property

Producing an unencumbered codec is desirable for the following reasons:

- o It is the experience of a wide variety of application developers and service providers that encumbrances such as licensing and royalties make it difficult to implement, deploy, and distribute multimedia applications for use by the Internet community.
- o It is beneficial to have low-cost options whenever possible, because innovation - the hallmark of the Internet - is hampered when small development teams cannot deploy an application because of usage-based licensing fees and royalties.
- o Many market segments are moving away from selling hard-coded hardware devices and toward freely distributing end-user software; this is true of numerous large application providers and even telcos themselves.
- o Compatibility with the licensing of typical open source applications implies the need to avoid encumbrances, including even the requirement to obtain a license for implementation, deployment, or use (even if the license does not require the payment of a fee).

Therefore, a codec that can be widely implemented and easily distributed among application developers, service operators, and end users is preferred. Many existing codecs that might fulfill some or most of the technical attributes listed above are encumbered in various ways. For example, patent holders might require that those wishing to implement the codec in software, deploy the codec in a service, or distribute the codec in software or hardware need to request a license, enter into a business agreement, pay licensing fees or royalties, or adhere to other special conditions or restrictions. Because such encumbrances have made it difficult to widely implement and easily distribute high-quality codecs across the entire Internet community, the working group prefers unencumbered technologies in a way that is consistent with BCP 78 and BCP 79. In particular, the working group shall heed the preference stated in BCP 79: "In general, IETF working groups prefer technologies with no known IPR claims or, for technologies with claims against them, an offer of royalty-free licensing." Although this preference cannot guarantee that the working group will produce an unencumbered codec, the working group shall follow BCP 79, and adhere to the spirit of BCP 79. The working group cannot explicitly rule out the possibility of adopting encumbered technologies; however, the working group will try to avoid encumbered technologies that require royalties or other

encumbrances that would prevent such technologies from being easy to redistribute and use.

When considering license terms for technologies with IPR claims against them, some members of the working group have expressed their preference for license terms which:

- o are available to all, worldwide, whether or not they are working group participants
- o extend to all essential claims owned or controlled by the licensor
- o do not require payment of royalties, fees or other consideration
- o do not require licensees to adhere to restrictions on usage (though, licenses which apply only to implementation of the standard are acceptable)
- o do not otherwise impede the ability of the codec to be implemented in open-source software projects

The following guidelines will help to maximize the odds that the codec will be unencumbered:

1. In accordance with BCP 79 [IPR], contributed codecs should preferably use technologies with no known IPR claims or technologies with an offer of royalty-free (RF) licensing.
2. As described in BCP 79, the working group should use technologies that are perceived by the participants to be safer with regard to IPR issues.
3. Contributors must disclose IPR as specified in BCP 79.
4. In cases where no RF license can be obtained regarding a patent, BCP 79 suggests that the working group consider alternative algorithms or methods, even if they result in lower quality, higher complexity, or otherwise less desirable characteristics.
5. In accordance with BCP 78 [TRUST], the source code for the reference implementation must be made available under a BSD-style license (or whatever license is defined as acceptable by the IETF Trust when the Internet-Draft defining the reference implementation is published).

Many IPR licenses specify that a license is granted only for technologies which are adopted by the IETF as a standard. While reasonable, this has the unintended side-effect of discouraging

implementation prior to RFC status. Real-world implementation is beneficial for evaluation of the codec. As such, entities making IPR license statements are encouraged to use wording which permits early implementation and deployment.

IETF participants should be aware that, given the way patents work in most countries, the resulting codec can never be guaranteed to be free of patent claims because some patents may not be known to the contributors, some patent applications may not be disclosed at the time the codec is developed, and only courts of law can determine the validity and breadth of patent claims. However, these observations are no different within the Internet Standards Process than they are for standardization of codecs within other SDOs (or development of codecs outside the context of any SDO), and furthermore are no different for codecs than for other technologies worked on within the IETF. In all these cases, the best approach is to minimize the risk of unknowingly incurring encumbrance on existing patents. Despite these precautions, participants need to understand that, practically speaking, it is nearly impossible to guarantee that implementers will not incur encumbrance on existing patents.

## 6. Relationship with Other SDOs

It is understood that other SDOs are also involved in the codec development and standardization, including but not necessarily limited to:

- o The Telecommunication Standardization Sector (ITU-T) of the International Telecommunication Union (ITU), in particular Study Group 16
- o The Moving Picture Experts Group (MPEG) of the International Organization for Standardization and International Electrotechnical Commission (ISO/IEC)
- o The European Telecommunications Standards Institute (ETSI)
- o The 3rd Generation Partnership Project (3GPP)
- o The 3rd Generation Partnership Project 2 (3GPP2)

It is important to ensure that such work does not constitute uncoordinated protocol development, of the kind described in [UNCOORD] in the following principle:

[T]he IAB considers an essential principle of the protocol development process that only one SDO maintains design authority for a given protocol, with that SDO having ultimate authority over the allocation of protocol parameter code-points; defining the intended semantics, interpretation, and actions associated with those code-points.

The work envisioned by this guidelines document is not uncoordinated in the sense described in the foregoing quote, since the intention of this process is that two possible outcomes might occur:

1. The IETF adopts an existing codec, and specifies that it is the "anointed" IETF Internet codec. In such a case, codec ownership lies entirely with the SDO which produced the codec, and not with the IETF, OR
2. The IETF produces a new codec. Even if this codec uses concepts, algorithms, codepoints, or even source code from a codec produced by another SDO, the IETF codec is a specification unto itself and under complete control of the IETF. Any changes or enhancements made by the original SDO to the codecs whose components the IETF used are not applicable to the IETF codec. Such changes would be incorporated as a consequence of a revision or extension of the IETF RFC.

Although there is already sufficient codec expertise available among IETF participants to complete the envisioned work, additional contributions are welcome within the framework of the Internet Standards Process, in the following ways:

- o Individuals who are technical contributors to codec work within other SDOs can participate directly in codec work within the IETF.
- o Other SDOs can contribute their expertise (e.g., codec characterization and evaluation techniques) and thus facilitate the testing of a codec produced by the IETF.
- o Any SDO can provide input to IETF work through liaison statements.

However, it is important to note that final responsibility for the development process and the resulting codec will remain with the IETF as governed by BCP 9 [PROCESS].

Finally, there is precedent for the contribution of codecs developed elsewhere to the ITU-T (e.g., AMR Wideband was standardized originally within 3GPP). This is a model to explore as the IETF coordinates further with the ITU-T in accordance with the collaboration guidelines defined in [COLLAB].



## 7. Security Considerations

The procedural guidelines for codec development do not have security considerations. However, the resulting codec needs to take appropriate security considerations into account, for example as outlined in [DOS] and [SECGUIDE].

## 8. IANA Considerations

This document has no actions for IANA.

## 9. Acknowledgments

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Definition of the Opus Audio Codec  
draft-ietf-codec-opus-07

Abstract

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

Status of this Memo

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

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## Table of Contents

1.	Introduction . . . . .	4
1.1.	Notation and Conventions . . . . .	5
1.1.1.	min(x,y) . . . . .	5
1.1.2.	max(x,y) . . . . .	5
1.1.3.	clamp(lo,x,hi) . . . . .	5
1.1.4.	sign(x) . . . . .	5
1.1.5.	log2(f) . . . . .	6
1.1.6.	ilog(n) . . . . .	6
2.	Opus Codec Overview . . . . .	7
3.	Codec Modes . . . . .	9
3.1.	Examples . . . . .	15
4.	Opus Decoder . . . . .	17
4.1.	Range Decoder . . . . .	17
4.1.1.	Decoding Symbols . . . . .	18
4.1.2.	Alternate Decoding Methods . . . . .	20
4.1.3.	Decoding Raw Bits . . . . .	21
4.1.4.	Decoding Uniformly Distributed Integers . . . . .	21
4.1.5.	Current Bit Usage . . . . .	22
4.2.	SILK Decoder . . . . .	24
4.2.1.	Decoder Modules . . . . .	25
4.2.2.	Header Bits . . . . .	27
4.2.3.	LBRR Flags . . . . .	27
4.2.4.	SILK Frame Contents . . . . .	28
4.2.5.	LBRR Frames . . . . .	61
4.3.	CELT Decoder . . . . .	61
4.3.1.	Transient Decoding . . . . .	63
4.3.2.	Energy Envelope Decoding . . . . .	63
4.3.3.	Bit allocation . . . . .	64
4.3.4.	Shape Decoder . . . . .	69
4.3.5.	Anti-collapse processing . . . . .	70
4.3.6.	Denormalization . . . . .	70
4.3.7.	Inverse MDCT . . . . .	71
4.3.8.	Packet Loss Concealment (PLC) . . . . .	72
4.4.	Mode Switching . . . . .	72
4.4.1.	Switching Side Information . . . . .	72
5.	Codec Encoder . . . . .	74
5.1.	Range Coder . . . . .	74
5.1.1.	Encoding Symbols . . . . .	74
5.1.2.	Encoding Raw Bits . . . . .	75
5.1.3.	Encoding Uniformly Distributed Integers . . . . .	76
5.1.4.	Finalizing the Stream . . . . .	76
5.1.5.	Current Bit Usage . . . . .	76
5.2.	SILK Encoder . . . . .	77
5.2.1.	Voice Activity Detection . . . . .	78
5.2.2.	High-Pass Filter . . . . .	79
5.2.3.	Pitch Analysis . . . . .	79



5.2.4.	Noise Shaping Analysis . . . . .	81
5.2.5.	Prefilter . . . . .	85
5.2.6.	Prediction Analysis . . . . .	85
5.2.7.	LSF Quantization . . . . .	86
5.2.8.	LTP Quantization . . . . .	89
5.2.9.	Noise Shaping Quantizer . . . . .	90
5.2.10.	Range Encoder . . . . .	91
5.3.	CELT Encoder . . . . .	91
5.3.1.	Pre-filter . . . . .	91
5.3.2.	Forward MDCT . . . . .	91
5.3.3.	Bands and Normalization . . . . .	91
5.3.4.	Energy Envelope Quantization . . . . .	92
5.3.5.	Spherical Vector Quantization . . . . .	93
5.3.6.	Stereo support . . . . .	94
5.3.7.	Synthesis . . . . .	94
5.3.8.	Variable Bitrate (VBR) . . . . .	95
6.	Conformance . . . . .	96
7.	Security Considerations . . . . .	97
8.	IANA Considerations . . . . .	98
9.	Acknowledgments . . . . .	99
10.	Informative References . . . . .	100
	Appendix A. Reference Implementation . . . . .	102
	A.1. Extracting the source . . . . .	102
	A.2. Development Versions . . . . .	102
	A.3. Base64-encoded source code . . . . .	102
	Appendix B. opus_compare.c . . . . .	248
	Authors' Addresses . . . . .	254

## 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<sub>n</sub>", 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)

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

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  $n$ .

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

Examples:

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

## 2. Opus Codec Overview

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

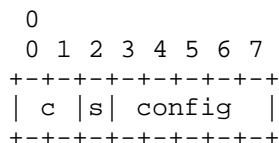


Figure 1: The TOC byte

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.

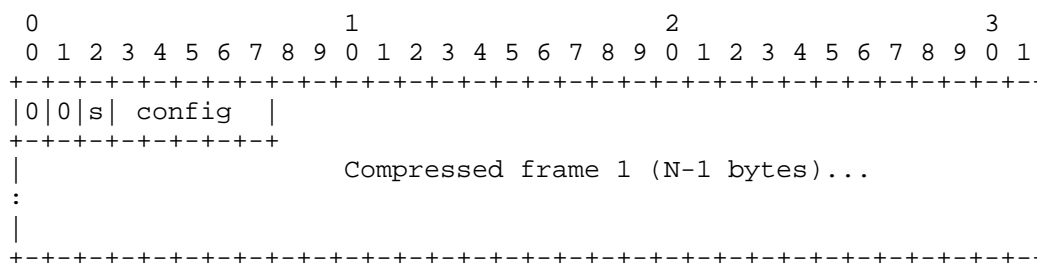


Figure 2: A Code 0 Packet

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.

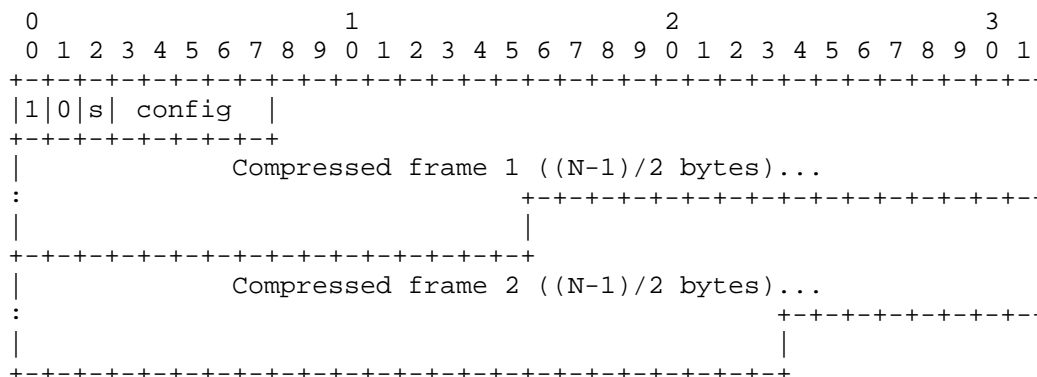


Figure 3: A Code 1 Packet

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.

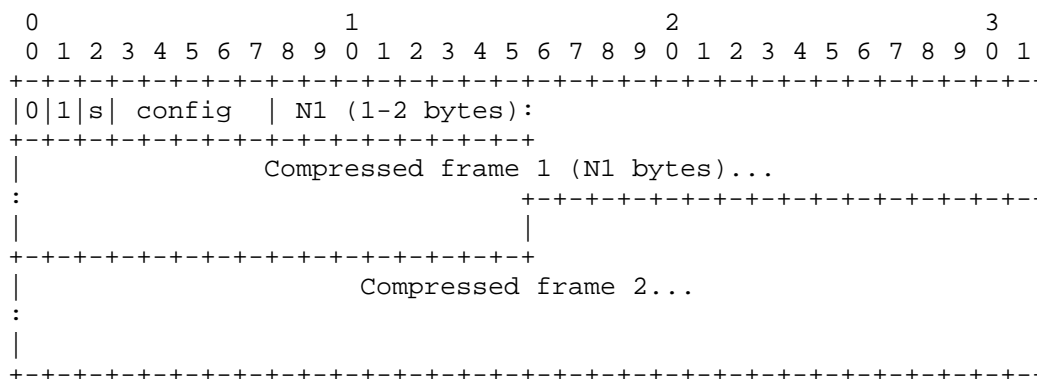


Figure 4: A Code 2 Packet

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.

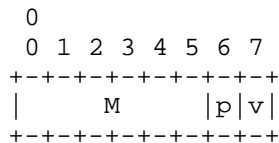


Figure 5: The frame count byte

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.

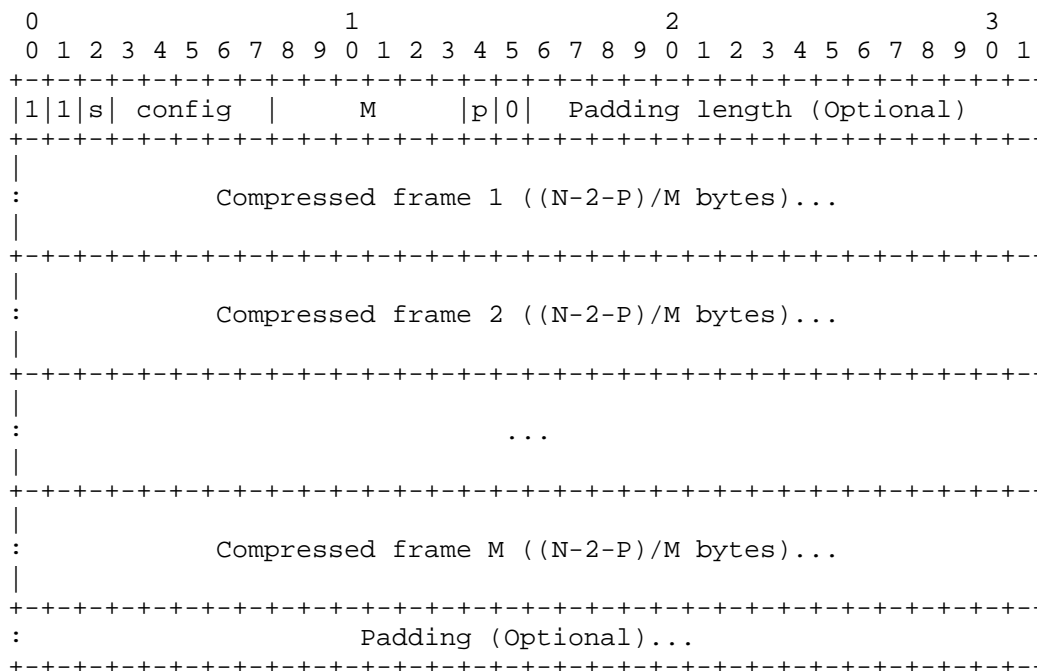


Figure 6: A CBR Code 3 Packet

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.

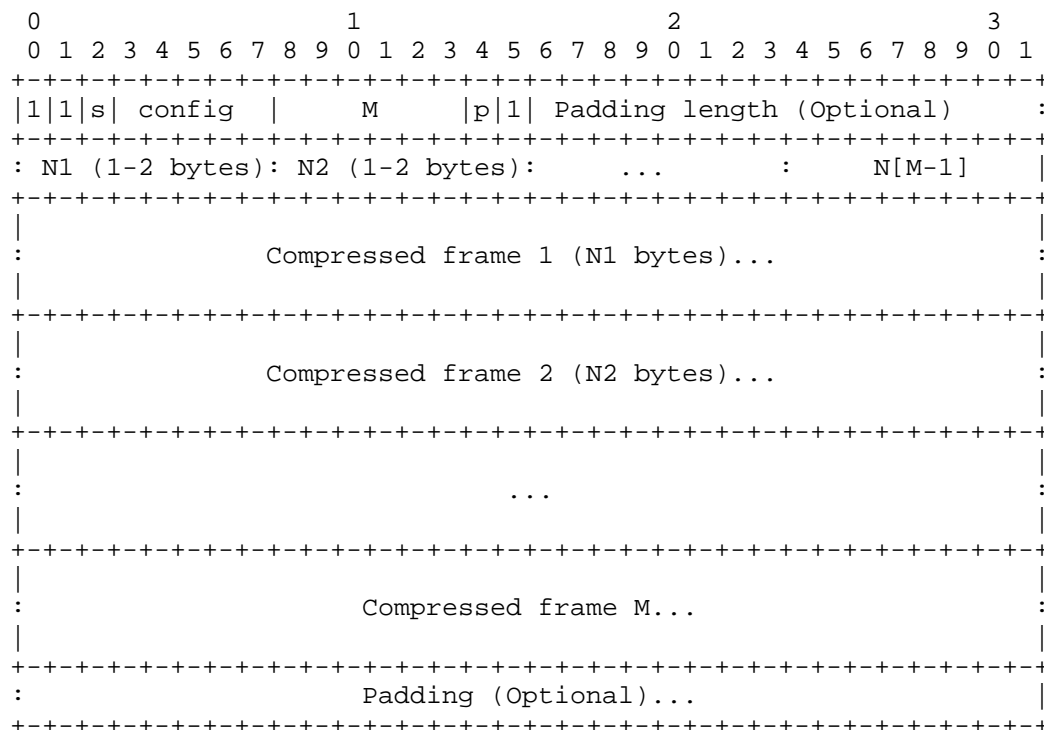
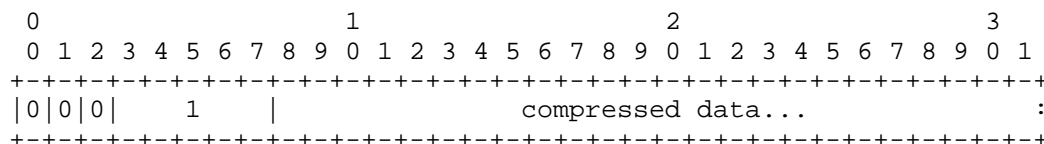


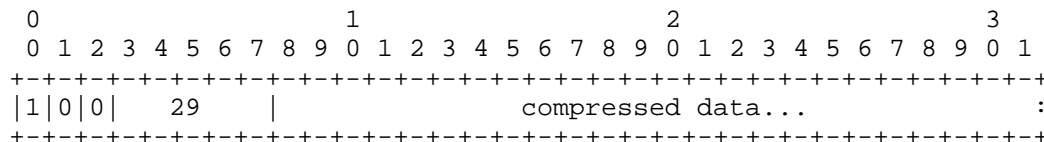
Figure 7: A VBR Code 3 Packet

### 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   |   |   |   |   |   |   |   |
+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+
|                                     compressed data...           :
+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+

```

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

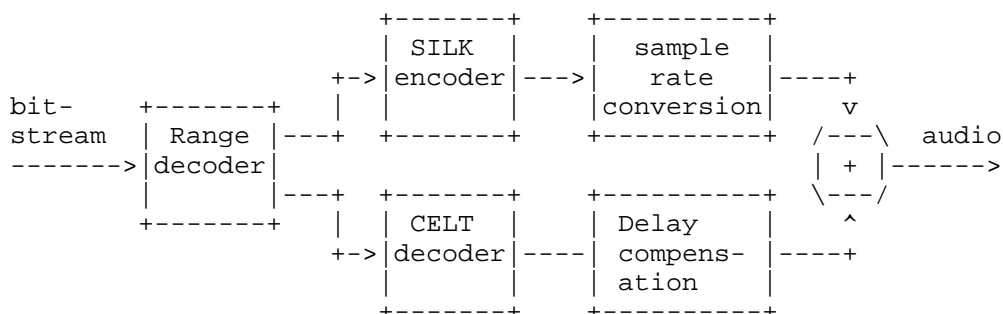
```

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

```

#### 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.

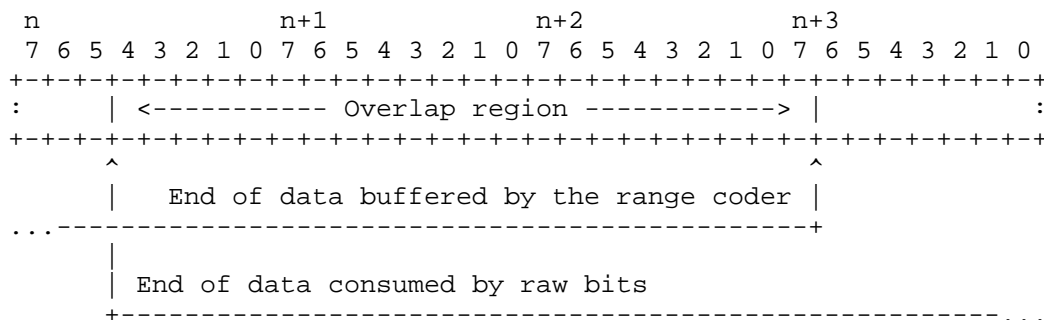


Figure 8: Illustrative example of raw bits overlapping range coder data

#### 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.

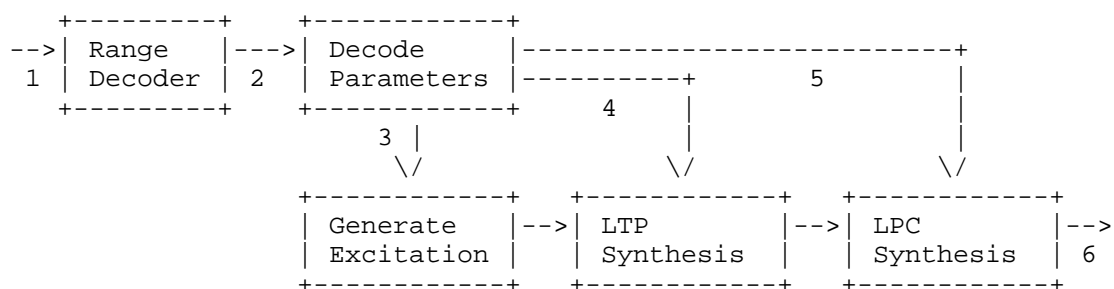
Symbol(s)	PDF	Condition
VAD flags	$\{1, 1\}/2$	
LBRR flag	$\{1, 1\}/2$	
Per-frame LBRR flags	Section 4.2.3	Section 4.2.3
Frame Type	Section 4.2.4.1	
Gain index	Section 4.2.4.2	

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  $d_{\text{LPC}}$  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<<i) + (((-174*f*(128-f)>>16)+f)>>7)*(1<<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  $\pi$  (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  $NLSF\_Q[k] - NLSF\_Q[k-1]$ . For the purposes of computing this spacing for the first and last coefficient, `NLSF_Q15[-1]` is taken to be 0, and `NLSF_Q15[d_LPC]` is taken to be 32768.

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

Table 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:

$$\begin{aligned} \text{min\_center\_Q15} &= (\text{NDeltaMin}[i] \gg 1) + \frac{\sum_{k=0}^{i-1} \text{NDeltaMin}[k]}{i} \\ \text{max\_center\_Q15} &= 32768 - (\text{NDeltaMin}[i] \gg 1) - \frac{\sum_{k=i+1}^{d\_LPC} \text{NDeltaMin}[k]}{d\_LPC - i} \\ \text{center\_freq\_Q15} &= \text{clamp}(\text{min\_center\_Q15}[i], \\ &\quad (\text{NLSF\_Q15}[i-1] + \text{NLSF\_Q15}[i] + 1) \gg 1, \\ &\quad \text{max\_center\_Q15}[i]) \\ \text{NLSF\_Q15}[i-1] &= \text{center\_freq\_Q15} - (\text{NDeltaMin\_Q15}[i] \gg 1) \\ \text{NLSF\_Q15}[i] &= \text{NLSF\_Q15}[i-1] + \text{NDeltaMin\_Q15}[i] . \end{aligned}$$

Then the procedure repeats again, until it has 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  $\pi$  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] =  $\frac{(1<<29) - 1}{div\_Q30[k] \gg (bl[k]+1)}$  ,

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 ≤ 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]) ≤ 65520 for 0 ≤ k < d\_LPC, then the filter is considered stable.

On round i, 1 ≤ i ≤ 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  $\text{lag\_high}$  is the high part,  $\text{lag\_low}$  is the low part, and  $\text{lag\_scale}$  and  $\text{lag\_min}$  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

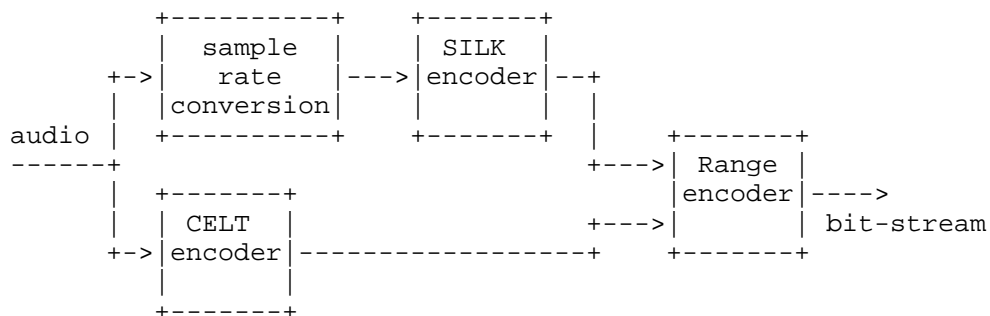
Switching with side information involves transmitting in-band a 5-ms "redundant" CELT frame within the Opus frame. This frame is designed to fill-in the gap or discontinuity without requiring the decoder to conceal it. For transitions from a CELT-only frame to a SILK-only or hybrid frame, the redundant 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  $(fl, fl+1, 1 < ftb)$ , 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`).

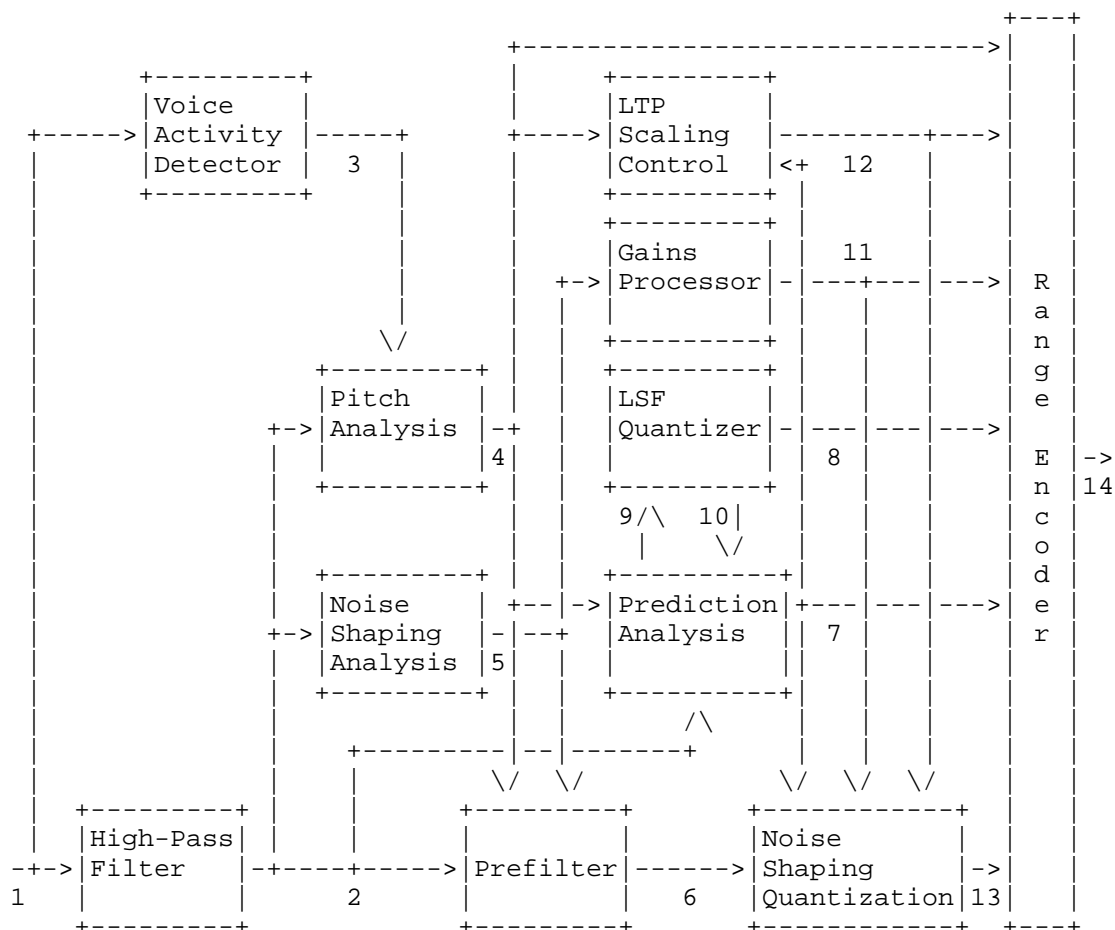
#### 5.1.5. Current Bit Usage

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.

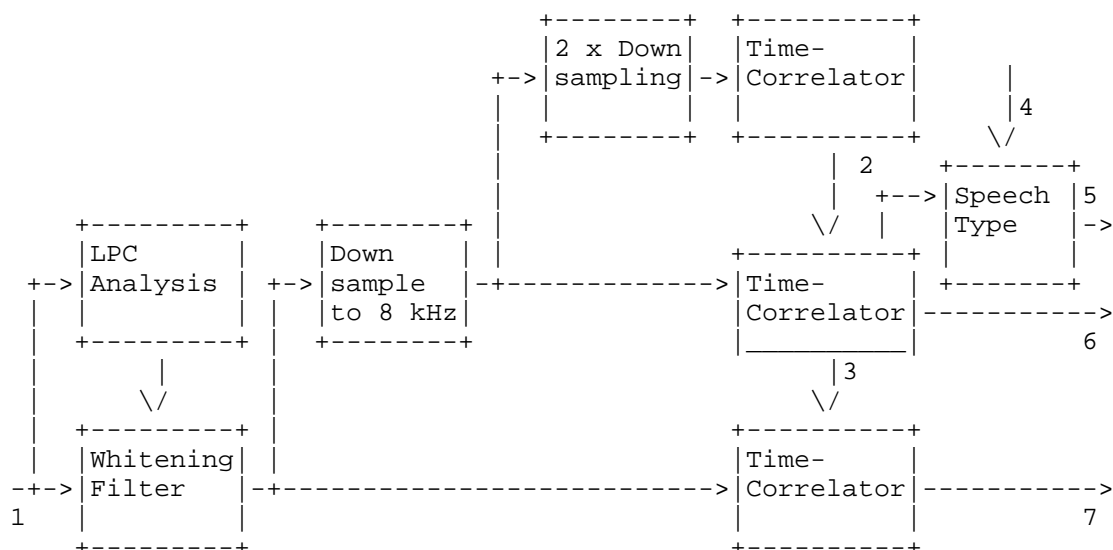
#### 5.2.2. High-Pass Filter

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.

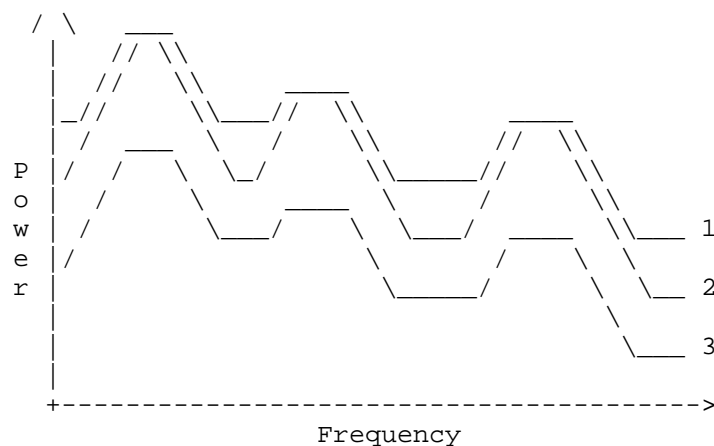
#### 5.2.4. Noise Shaping Analysis

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

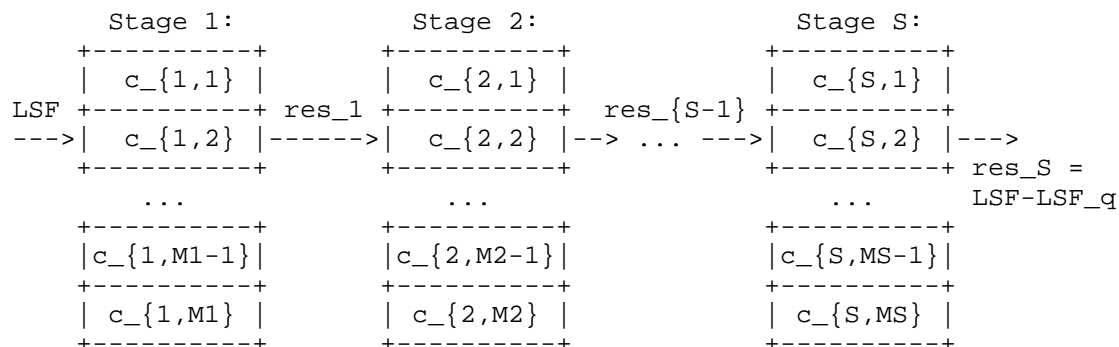
Instead of minimizing the error in the LSF domain, we map the errors to better approximate spectral distortion by applying an individual weight to each element in the error vector. The weight vectors are calculated for each input vector using the Inverse Harmonic Mean Weighting (IHMW) function proposed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

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

where  $\text{LSF}_q$  is the quantized vector,  $\text{LSF}$  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 to 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  $||\cdot||$  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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```

###edVp9cXPYvegOd4MK0jUG70zLO9eMNAuSBJNE/6N0hGZy10h1G8aR32TluDY1eF9jW  
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###FVrDh2Mbcf32L6EE/9wt4CltMYxTF9R7f+D2YRyJvC44i8SL9ja9AY36RQalHgCtYo  
###fGAMwiDXJ2NywM4nIjc6vwhOMZTRbOK3xNk53HQv7wfmqJE9YA4b+edLvYPqJzCtnF  
###lUbRIFVeN+RwrnqVe/3YcHo6/pF6t479GrDb9+UOqgn79teRtUW0iNeSNsUc8AzFMK  
###GsxxMYl6xBWAzgdHPz7yzIMvsps73MLm+Ntq2px/v+b8ezYX3K+54J7NNRY25zfxQt  
###EjNde8X3P3JWbrfs0xVlF59IcfVmEwrq15Wake08s14enxu6NdBRsZ+fMHsOd/4C4B  
###gPbiB7LwKc0jz7k5T+hGLrQ9UREV0Wqj4RBty9dYcNDgVsgLcX0XeuMnPDgRh/PTQw  
###mZQrQCCGxH7yMZ7Xbrf5AXlFiPT/+EXRmDgvdSCC6fqChpJkDHuH5/s/prWpf/yB  
###XyJgMu4HparhZqMPg5Fa/eDHHw6UmCk/2002AnqF5Qejw3ikVkl9ZjzwCvUhkTBSX5  
###9BMook/DvFNO+rXRz/3BIr3a4u+EddltTBSh+vieiQSyrrywoJU7z7D7rmFu5Mn9Iu  
###6rZ0IsOC6K0pX49PQYUVjC7FLi63PlCYkMkdwsQc9XlBDjqDQc5ldC7SR+CkHHzgeN/  
###FNb3JX4Ytp7VUCsKuZDVpBlms4cL78zWK6+Ud3Dc6H4951Io9QdqHmwUgfqtTf5li/  
###NhGfweJzKXK/on2Xq8EwrnjcJffDD+lIpJE2KoxVqD/n6BrviSSLqbChZGwIHrCBuY  
###cBSgRIzmBy/sJnKztA7dV8EoQi+DSBSg6Qcmx9zBww5Imqwj4ZkU4kEvtgOs+uauwW  
###x9bpmy3vYJA008U6OFyIBKzSXB9KL0zji+SbERVSUp6l3rhjxJtSwhVBTWVKIr0h  
###i6uuaJilMxgyQJUOYIJ3wBzZH0RGLnxboRYyBtgEYGapQ+r38gNsL9U+09fbngTJbe  
###JgahQ5GiUL2jaUCeAph8/fELci6wcMYTPhPZOKbKIQWauxyMKKi40l0lIqxNVTaQyv  
###i8fKmS9uN95vAPP6gc+IPIF/cDLXFfNSGzqCu0UzET8YrIM4E5Qnp4u0iKd9EhKXao  
###U4/bJOI7y//n9v/+Oo+AOzAPzWU0GCX38vqmzwL/b9AJAt3/67ebQb30/36Pp/T/lv  
###7f0v9b+n9L/2/p/y39v/i4/L+YxJr7dFPvg6Ek6Zch8OiOfLZB0W5+8IwkgliTdDjP  
###vKfAfBKEv5mPVqgVClIA5TlqiXkw9CP562p9PPZFqr7RztZ9CPri4M8dcQs+jQQsn7  
###z2VkhUDWDp7Qlmd6zhzIsXWnsnaTWrsEfdDn7F5Geg57ret1VJzVWbrnQJAZ696RTk  
###888x0z4oQtK62Z51xQGEM3n4diO/S2b/qL03c5YNyauCpt/lZtOoDwr6xcrC9mBBTa  
###9MFGHxTLePZwdZESiv5tUMJz15fXmKfcN+LboyYp0006Cwu+HKje4fXLYfCCDCQd9i  
###ZetyxVzWXOlRaMTwbct9A4MXgoapVMDVis/flXOCusqVExc7rhi/Ou+lpA86hULUaw

```
###ggv4yjjvWRhVLVXZGrDoliRsmblIdla07xiA9VLhSeuwXgdpU1OeMbi9INSFeslz/uU
###oZVUwSoL7XI1Hicxy5WSlr43jhYpMoJbmdcGG077ApIdZLZI1bTDbVhD4QN+T8wMOS
###mDqNU+/0qF4a3YsXBuk3mp1Gr4MpGVRDXtZCGLczlJ72CzKwv009CS6aAZ+13drBJc
###C9+2JSM5WdEIGuWIjsivYXyys8viQz18/zb8+U00C/d2KvaZ26fpFP6kLkFiFWDbe+
###jv0fLs8NPR2Y8rcNdT5zRL26ImvtACACsqXluZcRLT4rAGwt5jTL6oLU1kx+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
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###2Gha64e507PWLtx5W/Xk2KTHti3Yhls/izO/fKRM2L4Ou2nB9u8PO9BhNyzYwflhN3
###TYgQW7cX/YTR22b8Fu3h92S4ddt2C37g+7rcH2NizY7fvD7uiwly3YHQ6b3A/cVcDS
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###mbuge6YnNL3ndMRdw+iJa1LrC4u+mqjtfL4/9EVDBlFwmdDXBh1EwdVAXwJ0EAWFvi
###7pdRAFZbsu0HUQBuw4Lrd1EAU1tS6edRADCeL+TFZROLkGY1zT2W7FzXhZXOMgldKc
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###bFfEURXpZA9MTdrpc4w1YKUHTgI2Aq7o2IWYPMXwXr0vndPe6XCR2jvGD2r3TBzP+Q
###e7sM5eZHvRFUT/IrrWXL4Y9OxUxK8BePclctcF5WMLDju62GgyaRwJVGXhr6wOnxv+
###ZCmzoxMVuiFBui20G1+KMD9gFHawXkADlnzfYdDhWL07dn8KkvBUGGKVZrplyq8I1
###LZ5aXF/hotaBb3rtLTauvQU5qsNH0a3FF9/sG3p/FMbf+KKeZgakMQ3Mq17mljhg1C
###pgOg8uuMfn8ACKm3yBYrcXu9XnGrH740DfG4eqRoqMxGau14f6pbsa4hWkfNSonrN
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###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/7Woe//7+89+vt9ts/rc6TT9ot8r5/x0fygyW
###zn+Y3/ISwM7RT2zGyzeUugTdCYn5YRqj82gwGsxAWCSz6fjOKMFEC0Z6jN1fSodxf5
###pE+G0WT81m+Xe8K4Qs6648HyYZ36ZhEs/CC8fHcOvkWgH4Ls79NhsD/tGJAV2Gobsb
###xod0P8qkxufJ+DmaDiikI2jy44sLo8DRYXefD8380nlrv4GiQyxufDk53DHeJFfxcB
```



## 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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Summary of Opus listening test results  
draft-valin-codec-results-00

Abstract

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

Status of this Memo

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

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## Table of Contents

|                                                              |    |
|--------------------------------------------------------------|----|
| 1. Introduction . . . . .                                    | 3  |
| 2. Pre-Opus listening tests . . . . .                        | 4  |
| 2.1. SILK Dynastat listening test . . . . .                  | 4  |
| 2.2. SILK Deutsche Telekom test . . . . .                    | 4  |
| 2.3. SILK Nokia test . . . . .                               | 4  |
| 2.4. CELT 0.3.2 listening test . . . . .                     | 5  |
| 2.5. CELT 0.5.0 listening test . . . . .                     | 5  |
| 3. Opus listening tests on non-final bit-stream . . . . .    | 6  |
| 3.1. First hybrid mode test . . . . .                        | 6  |
| 3.2. Broadcom stereo music test . . . . .                    | 6  |
| 4. Opus listening tests on final bit-stream . . . . .        | 8  |
| 4.1. Google listening tests . . . . .                        | 8  |
| 4.1.1. Google narrowband listening test . . . . .            | 8  |
| 4.1.2. Google wideband and fullband listening test . . . . . | 9  |
| 4.1.3. Google stereo music listening test . . . . .          | 10 |
| 4.2. HydrogenAudio stereo music listening test . . . . .     | 12 |
| 4.3. Nokia Interspeech 2011 listening test . . . . .         | 12 |
| 5. In-the-field testing . . . . .                            | 13 |
| 6. Conclusion on the requirements . . . . .                  | 14 |
| 6.1. Comparison to Speex (narrowband) . . . . .              | 14 |
| 6.2. Comparison to iLBC . . . . .                            | 14 |
| 6.3. Comparison to Speex (wideband) . . . . .                | 14 |
| 6.4. Comparison to G.722.1 . . . . .                         | 14 |
| 6.5. Comparison to G.722.1C . . . . .                        | 15 |
| 6.6. Comparison to AMR-NB . . . . .                          | 15 |
| 6.7. Comparison to AMR-WB . . . . .                          | 15 |
| 7. Security Considerations . . . . .                         | 16 |
| 8. IANA Considerations . . . . .                             | 17 |
| 9. Acknowledgments . . . . .                                 | 18 |
| 10. Informative References . . . . .                         | 19 |
| Authors' Addresses . . . . .                                 | 20 |

## 1. Introduction

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

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

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



## 2. Pre-Opus listening tests

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

### 2.1. SILK Dynastat listening test

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

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

### 2.2. SILK Deutsche Telekom test

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

### 2.3. SILK Nokia test

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

It was noted in the test that:

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

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

#### 2.4. CELT 0.3.2 listening test

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

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

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

#### 2.5. CELT 0.5.0 listening test

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

### 3. Opus listening tests on non-final bit-stream

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

#### 3.1. First hybrid mode test

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

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

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

#### 3.2. Broadcom stereo music test

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

- o 2 pure speech

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

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

#### 4. Opus listening tests on final bit-stream

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

##### 4.1. Google listening tests

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

##### 4.1.1. Google narrowband listening test

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

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

Test 1 stimuli

Table 1

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

#### 4.1.2. Google wideband and fullband listening test

The eight test sequences for Test 1 were also used in Test 2. 16 listeners rated the stimuli listed in Table 2. In this test comparisons were made between four wideband codecs: Opus WB, the royalty-free Speex, the royalty-free ITU-T G.722.1, AMR-WB (ITU-T G.722.2), and two fullband codecs: Opus FB and the royalty-free ITU-T G.719. All six codecs utilize 20 ms encoding frames. Opus used variable bitrate, while other codecs used constant bit rate.

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

Test 2 stimuli

Table 2

The results from Test 2 are depicted in the Prague meeting slides [Prague-80]. Opus at 32 kbps is almost transparent, although there is a small, but statistically significant, difference from the fullband reference material. Opus at 20 kbps is significantly better than all the other codecs, including AMR-WB and the fullband G.719, and both low-pass anchors.

#### 4.1.3. Google stereo music listening test

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

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

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

These sequences were originally recorded at a sampling frequency of 44.1 kHz and were upsampled to 48 kHz prior to processing. Test 3 included comparisons between six codecs (c.f., Table 3): Opus at three rates, G.719, AAC-LC [9] (Nero 1.5.1 [10]), and MP3 [11,12] (Lame 3.98.4 [13]). G.719 is a mono codec, so the two channels were each coded independently at 32 kbps. 9 listeners participated in Test 3, and the results are depicted in the Prague meeting slides [Prague-80]. The codecs operated at constant (or comparable) bit rate.

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



|         |                       |         |                              |
|---------|-----------------------|---------|------------------------------|
| Opus FB | ~20 kHz<br>(Fullband) | 5       | 128 kbps,<br>constrained VBR |
| +-----+ | +-----+               | +-----+ | +-----+                      |

Test 3 stimuli

Table 3

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

#### 4.2. HydrogenAudio stereo music listening test

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

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

#### 4.3. Nokia Interspeech 2011 listening test

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

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

## 5. In-the-field testing

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

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

## 6. Conclusion on the requirements

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

### 6.1. Comparison to Speex (narrowband)

The Opus codec was compared to Speex in narrowband mode in the Google narrowband test (Section 4.1.1). This test showed that Opus at 11 kb/s was significantly better than Speex at the same rate. In fact, Opus at 11 kb/s was tied with the 3.5 low-pass of the original. Considering the results, we conclude that the Opus codec is better than the Speex codec.

### 6.2. Comparison to iLBC

The Opus codec was compared to iLBC in the Google narrowband test (Section 4.1.1). This test showed that Opus at 11 kb/s was significantly better than iLBC running at 15 kb/s. Considering the results, we conclude that the Opus codec is better than the iLBC codec.

### 6.3. Comparison to Speex (wideband)

The Opus codec was compared to Speex in wideband mode in the Google wideband and fullband test (Section 4.1.2). This test showed that Opus at 20 kb/s was significantly better than Speex at 24 kb/s. In fact, Opus at 20 kb/s was better than the 7 kHz low-pass of the original. These results are consistent with an earlier Dynastat test (Section 2.1) that also concluded that SILK had significantly higher quality than Speex in wideband mode at the same bit-rate. Considering the results, we conclude that the Opus codec is better than the Speex codec for wideband.

### 6.4. Comparison to G.722.1

In the Google wideband and fullband test (Section 4.1.2), Opus at 20 kb/s was shown to significantly out-perform G.722.1 operating at 24 kb/s. An indirect comparison point also comes from the Nokia Interspeech 2011 listening test (Section 4.3) that shows Opus out-performing AMR-WB at 20 kb/s, while AMR-WB is known to out-perform G.722.1. Considering these results, we conclude that the Opus codec is better than the G.722.1 codec for wideband.

#### 6.5. Comparison to G.722.1C

Opus has been compared to G.722.1C in multiple listening tests. As early as 2008, an old version of the CELT codec (Section 2.4) using very short frames was found to have higher quality than G.722.1C at 48 kb/s. More recently, the Nokia Interspeech 2011 listening test (Section 4.3) showed that Opus out-performed G.722.1C at 24 kb/s, 32 kb/s, and 48 kb/s. We thus conclude that the Opus codec is better than the G.722.1C codec for superwideband/fullband audio.

#### 6.6. Comparison to AMR-NB

In the Google narrowband test (Section 4.1.1), Opus was shown to out-perform AMR-NB at 12 kb/s. On the other hand, in the Nokia Interspeech 2011 listening test (Section 4.3), AMB-NB was found to have better quality than Opus at 6 kb/s. This indicates that Opus is better than AMR-NB at higher rates and worse at lower rates, which is to be expected given Opus' emphasis on higher quality and higher rates.

#### 6.7. Comparison to AMR-WB

In the Google wideband and fullband test (Section 4.1.2), Opus at 20 kb/s was shown to out-perform AMR-WB at the same rate. This was also confirmed by the Nokia Interspeech 2011 listening test (Section 4.3), with also found AMR-WB to out-perform Opus at 12 kb/s and below. As with AMR-NB, we conclude that Opus is better than AMR-WB at higher rates and worse at lower rates.

## 7. Security Considerations

No security considerations.

## 8. IANA Considerations

This document has no actions for IANA.

## 9. Acknowledgments

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

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