

Speex: A Free Codec For Free Speech

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Abstract—The Speex project has been started in 2002 to address the need for a free, open-source speech codec. Speex is based on the Code Excited Linear Prediction (CELP) algorithm and, unlike the previously existing Vorbis codec, is optimised for transmitting speech for low latency communication over an unreliable packet network. This paper presents an overview of Speex, the technology involved in it and how it can be used in applications. The most recent developments in Speex, such as the fixed-point port, acoustic echo cancellation and noise suppression are also addressed.

I. INTRODUCTION

When I started implementing Speex in 2002, there was no good free codec that could be used for speech communication. The situation was greatly harming the development of voice over IP (VoIP) on Linux and other free operating systems. Unlike the Vorbis¹ codec that already existed at that time, the Speex codec is optimised for speech and is designed for low latency communication over an unreliable packet network.

Speex is based on the popular Code Excited Linear Prediction (CELP) algorithm but because of patent restrictions, some techniques like the use of algebraic codes (ACELP) could not be used. Nevertheless, Speex is able to achieve a quality comparable to proprietary codecs at the same bitrate, while supporting features not found in other speech codecs. These features include variable bitrate, which makes better use of the bits when encoding to a file, and embedded coding, which provides an easy way to interface wideband (16 kHz) channels with legacy narrowband (8 kHz) telephony equipment.

Speex is now evolving into a complete toolkit for voice over IP (VoIP) development, including algorithms for noise cancellation, acoustic echo cancellation and adaptive jitter buffering. This allows a developer without any signal processing knowledge to implement a VoIP client. In the mean time, Speex is being ported to architectures without a floating-point unit, allowing Speex to be used

in embedded devices equipped with a fixed-point CPU or DSP.

The paper is organised as follows. Section II presents overview of Speex. Then, an explanation of the underlying coding algorithm (CELP) is provided in Section III. Section IV provides information and tips about using the Speex library in applications. Finally, Section V discusses recent developments in Speex and Section VI concludes this paper.

II. OVERVIEW

The Speex project was stated in February 2002 because there was a need for a speech codec that was open-source and free from software patents. These are essential conditions for being used by any open-source software. At that time, the only options for compressing speech were the G.711 codec (also known as μ -law and A-law) and the open-source implementation of the aging GSM-FR codec², although the patent status of the latter is unclear. The Vorbis codec was also available for general audio compression, but it was not really suitable for speech.

Unlike many other speech codecs, Speex is not targeted at cell phones but rather at voice over IP (VoIP) and file-based compression. Because any codec suitable for VoIP is also suitable for file-based compression, only the VoIP requirements are taken into account. Version 1.0 was released in March 2003 and the bitstream has been frozen since that time, which means that all versions since then are compatible with version 1.0.

A. Design Decisions

The use of Speex for VoIP imposes the following requirements:

- The frame size and algorithmic delay must be small
- Both the encoder and decoder must run in real-time with limited resources

¹<http://www.vorbis.com/>

²<http://kbs.cs.tu-berlin.de/~jutta/toast.html>

- The effect of lost packets during transmission must be minimised
- The codec must support both narrowband and wideband
- Multiple bit-rates and quality settings must be supported to take into account different connection speeds
- Good compression must be achieved while avoiding known speech coding patents

The CELP algorithm [1] was chosen because of its proven track record from low bitrates (e.g. DoD CELP at 4.8 kbps) to high bitrates (e.g. G.728 LD-CELP at 16 kbps) and because the patents on the base algorithm have now expired. Unfortunately, newer variants such as the use of arithmetic codebooks in ACELP could not be used in Speex because of patent issues. It was decided to encode in chunks of 20 ms (frame size) and only use 10 ms of additional buffering (look-ahead).

Because Speex is designed for VoIP instead of cell phones (like many other speech codecs) it must be robust to lost packets, but not to corrupted ones – UDP/RTP packets either arrive unaltered or they don't arrive at all. For this reason, we have chosen to restrict the amount of inter-frame dependency to pitch prediction only, without incurring the overhead of coding frames independently as done in the iLBC [2] codec.

As much as we would like it to be true, Speex is not the most technologically advanced speech codec available and it was never meant to be. The original goal was to achieve the same quality as state-of-the-art codecs with comparable or slightly higher bit-rate and this goal has been achieved.

Speex also has the following features, some of which are not found in other speech codecs:

- Integration of narrowband and wideband using an embedded bit-stream
- Wide range of bit-rates available (from 2 kbps to 44 kbps)
- Dynamic bit-rate switching and Variable Bit-Rate (VBR)
- Voice Activity Detection (VAD, integrated with VBR)
- Variable complexity
- Ultra-wideband mode at 32 kHz
- Intensity stereo encoding option

B. Legal Status

One of the most frequently asked question about Speex is: “But how can you be sure it is not patented?”. The short answer is that we don't know for sure. The

longer answer is that first, we (Xiph.Org, me) obviously did not patent Speex. During development, we were careful not to use techniques known to be patented and we searched through the USPTO database to see if anything we were doing was covered.

That being said, we cannot offer any absolute warranty regarding patents. No company does that, simply because of the mess the patent system is. Even if you pay for a codec, you cannot have the guaranty that nobody else owns a (previously unknown) patent on that codec. Even if someone comes forward and claims to have a patent on a certain piece of software, it takes years of legal procedures to sort out. This has been happening recently with the JPEG standard, which has always been thought to be free of patents. It is not yet clear what will happen in this particular case. Sadly, this is how things are when it comes to patents – at least in the United States because every country has different patent laws, which makes the matter even more complicated.

In any program written that is longer than "Hello World" (and even that!), there might be a patent issue, generally a trivial patent (e.g. 1-click shopping) nobody thought about. There are probably patents out there claiming rights on "using a computer for doing useful things" or something like that. What this means for Speex is that we did our best to avoid known patents and minimise the risk. This is about the best that can be done when writing software at the moment, regardless of whether the software is Free or proprietary.

III. SPEEX AND CELP

Speex is based on CELP, which stands for Code Excited Linear Prediction. The CELP technique is based on three ideas:

- 1) Using a linear prediction (LP) model to model the vocal tract;
- 2) Using of an adaptive and a fixed codebook as the input (excitation) of the LP model;
- 3) Performing a search in closed-loop in a “perceptually weighted domain”.

The description of the Speex encoder and decoder in this section has been greatly simplified for clarity purposes. Nonetheless, speech processing knowledge is required to understand some parts.

A. Source-Filter Speech Model

Before going into Speex and CELP in details, let us introduce the source-filter model of speech. This model assumes that the vocal cords are the source of spectrally flat sound (the “excitation signal”), and that the vocal

tract acts as a filter to spectrally shape the various sounds of speech. While still an approximation, the model is widely used in speech coding because of its simplicity. Its use is also the reason why most speech codecs (Speex included) perform badly on music signals.

The different phonemes can be distinguished by their excitation (source) and spectral shape (filter). Voiced sounds (e.g. vowels) have an excitation signal that is periodic and that can be approximated by an impulse train in the time domain or by regularly-spaced harmonics in the frequency domain. On the other hand, fricatives (such as the “s”, “sh” and “f” sounds) have an excitation signal that is similar to white Gaussian noise. So called “voice fricatives” (such as “z” and “v”) have excitation signal composed of an harmonic part and a noisy part.

B. Speex Decoder

Before exploring the complex encoding process of Speex we introduce the Speex decoder here. For the sake of simplicity only the narrowband decoder is presented. Figure 1 describes a generic CELP decoder. The excitation is produced by summing the contributions from an adaptive (*aka* pitch) codebook and a fixed (*aka* innovation) codebook:

$$e[n] = e_a[n] + e_f[n] \quad (1)$$

where $e_a[n]$ is the adaptive codebook contribution and $e_f[n]$ is the fixed codebook contribution.

The filter that shapes the excitation has an all-pole (infinite impulse response) model of the form $1/A(z)$, where $A(z)$ is called the prediction filter and is obtained using linear prediction (Levinson-Durbin algorithm). An all-pole filter is used because it is a good representation of the human vocal tract and because it is easy to compute.

In Speex, frames are 20 ms long, which is 160 samples for narrowband. Furthermore, each frame is divided into 4 sub-frames of 40 samples that are encoded sequentially. In most modes, only the synthesis filter and the global excitation gain (see below) is encoded on a frame basis, the other parameters are encoded on a sub-frame basis.

Speex includes three main differences compared to most recent CELP codecs. First, while most recent CELP codecs make use of fractional pitch estimation [3] with a single gain, Speex uses an integer to encode the pitch period, but uses a 3-tap predictor [4] (3 gains). The adaptive codebook contribution can thus be expressed as:

$$e_a[n] = g_0 e[n-T-1] + g_1 e[n-T] + g_2 e[n-T+1] \quad (2)$$

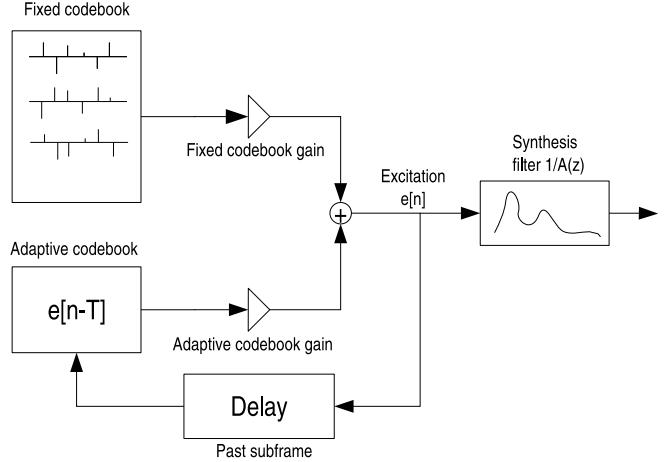


Fig. 1. A generic CELP decoder.

where g_0 , g_1 and g_2 are the pitch gains and are jointly quantised (VQ).

Many current CELP codecs use moving average (MA) prediction to encode the fixed codebook gain. This provides slightly better coding at the expense of introducing some extra dependency with past frames. Speex encodes the fixed codebook gain as a global excitation gain for the frame as well as a set of sub-frame gain corrections.

Speex uses sub-vector quantisation of the innovation (fixed codebook) signal. Unfortunately, this is not a very efficient quantisation method, but it was the best that could be used given patent restrictions. Each sub-frame is divided into sub-vectors of length ranging between 5 and 20 samples. Each sub-vector is chosen from a bitrate-dependent codebook and all sub-vectors are then concatenated. As an example, the 3.95 kbps mode uses a sub-vector size of 20 samples with 32 entries in the codebook (5 bits). This means that the innovation is encoded with 10 bits per sub-frame, or 2000 bps. On the other hand, the 18.2 kbps mode uses a sub-vector size of 5 samples with 256 entries in the codebook (8 bits), so the innovation uses 64 bits per sub-frame, or 12800 bps.

C. Speex Encoder

The main principle behind CELP is called Analysis-by-Synthesis (AbS) and means that the encoding (analysis) is performed by perceptually optimising the decoded (synthesis) signal in a closed loop. In theory, the best CELP stream would be produced by trying all possible bit combinations and selecting the one that produces the best-sounding decoded signal. This is obviously not possible in practice for two reasons: the required

complexity is beyond any currently available hardware and the “best sounding” selection criterion implies a human listener.

In order to achieve real-time encoding using limited computing resources, the CELP optimisation is broken down into smaller, more manageable, sequential searches using a simple perceptual weighting function. In the case of Speex, the optimisation is performed in four steps

- 1) Linear prediction analysis is used to determine the synthesis filter, which is converted to Line Spectral Pair (LSP) coefficients and vector-quantised.
- 2) The adaptive codebook entry and gain are jointly searched for the best pitch-gain combination using AbS.
- 3) The fixed codebook gain is determined in an “open-loop” manner only the energy of the excitation signal.
- 4) The fixed codebook is searched for the best entry using AbS.

Optimisation for steps 2) and 4) are performed in the so called “perceptually weighted domain”, meaning that we try to minimise the perceptual difference with the original (as opposed to simply maximising the signal-to-noise ratio). In order to do that, the following weighting filter is applied on the input signal:

$$W(z) = \frac{A(z/\gamma_1)}{A(z/\gamma_2)} \quad (3)$$

where $A(z)$ is the linear prediction filter and γ_1 and γ_2 control the shape of the filter by moving the poles and zeros toward the centre of the z -transform unit circle (Speex uses $\gamma_1 = 0.9$ and $\gamma_2 = 0.6$). The filter defined in 3 is in fact a very, very rough approximation for what is known as the “masking curve” in audio codecs such as Vorbis. The overall effect of the weighting filter $W(z)$ is that the encoder is allowed to introduce more noise at frequencies where the power level is high and less noise at frequencies where the power level is low.

D. Wideband CELP (aka SB-CELP)

The wideband mode in Speex differs from most wideband speech codecs as it separates the signal into two sub-bands (SB-CELP). The lower band is encoded using the narrowband encode. This has the advantage of making it easy to interoperate with “legacy” systems (e.g. PSTN) operating in narrowband. The high-band is encoded using a CELP encoder similar to the narrowband encoder with the difference that only a fixed codebook is used, with no adaptive codebook. The high-band information is encoded after then narrowband

(low-band) data, so simply discarding the last part of a wideband frame produces a valid narrowband frame. Alternatively, a wideband decoder is able to identify that the high-band information is missing and thus is able to decode a narrowband frame.

One particularity of the wideband mode made possible by the SB-CELP scheme is that for low-bitrate, only the spectral shape (envelope) of the high-band is encoded. The high-band excitation is obtained simply by “folding” the narrowband excitation. The technique is similar to the low bit-rate encoding of the high frequencies described in [5].

IV. IMPLEMENTING SPEEX SUPPORT

Unlike most speech codecs, Speex supports several sampling rates and several bit-rates for each sampling rate. The thing one must determine before choosing a codec (or in this case, which mode of the codec) is:

- What is the bandwidth available?
- What is the quality requirement?
- What is the latency requirement?

When designing a Voice over IP application, the first aspect one must consider is the fact that the combination of IP, UDP and RTP incurs an overhead of 40 bytes per packet transmitted. When transmitting one packet every 20 ms as is commonly done, the overhead is equal to 16 kbps! Considering that, it is obvious that in most situations, there is little incentive to use very low bit-rate.

A. Choosing the Right Mode

The first choice one must make when using Speex is the sampling rate used. For new applications, it is recommended to use wideband (16 kHz sampling rate) audio whenever possible. Wideband speech sounds much clearer than narrowband speech and is also easier to understand. In many case, for example when implementing a VoIP application, it is a good idea to also support narrowband – either directly or through the wideband encoder/decoder. In this context, narrowband is useful for both compatibility reasons (with clients that may not support wideband) and because at very low bit-rates (<10 kbps), it sometimes provides better quality than wideband.

Once the sampling rate is chosen, one must decide on the bitrate. It is generally recommended to use constant bitrate (CBR) in voice over IP applications because of the fixed channel (especially if using a modem) capacity. On the other hand, VBR is usually more efficient for file compression, because bits can be allocated where

needed. When calculating for a target bit-rate, it is important to also consider the overhead. The VoIP overhead when using RTP and one frame per packet is 16 kbps, so when using a 56 kbps modem, this leaves very little bandwidth for the codec itself. For file encoding in Ogg, the overhead is approximately 1 byte per frame, so it is usually not problematic. For very low bit-rates, the *-nframes* option to *speexenc* can be useful as it packs multiple frames in an Ogg packet.

B. Libspeex API Overview

The reference implementation of Speex uses a C API. Only an overview of the codec API is provided here. When using Speex, one must first create an instance of an encoder and/or a decoder. If more than one channel is used, then an instance is required for each channel (Speex is not stateless).

In order to encode speech using Speex, the following header must be included:

```
#include <speex/speex.h>
```

Then, a Speex bit-packing struct and a encoder state are necessary:

```
SpeexBits bits;
void *enc;
```

These are initialized by:

```
speex_bits_init(&bits);
enc = speex_encoder_init(&speex_nb_mode);
```

For wideband coding, *speex_nb_mode* will be replaced by *speex_wb_mode*. In most cases, you will need to know the frame size used by the mode you are using. The value can be obtained in the *frame_size* variable using:

```
speex_encoder_ctl(enc,
    SPEEX_GET_FRAME_SIZE,&frame_size);
```

In practice, *frame_size* will correspond to 20 ms when using 8, 16, or 32 kHz sampling rate.

Once the initialization is complete, frames can be encoded using:

```
speex_bits_reset(&bits);
speex_encode_int(enc_state, input_frame,
    &bits);
nbBytes = speex_bits_write(&bits, byte_ptr,
    MAX_NB_BYTES);
```

where *input_frame* is a (*int16_t **) pointing to the beginning of a speech frame, *byte_ptr* is a (*char **) where the encoded frame will be written, *MAX_NB_BYTES* is the maximum number of bytes that can be written to *byte_ptr* without causing an overflow and *nbBytes* is the number of bytes actually written to *byte_ptr* (the encoded size in bytes). Before calling *speex_bits_write*, it is possible to find the number of bytes that need to be written by calling *speex_bits_nbytes(&bits)*, which returns a number of bytes.

After you're done with the encoding, all resources can be freed using:

```
speex_bits_destroy(&bits);
speex_encoder_destroy(enc_state);
```

The decoder API can be used in a similar manner. For more details, refer the Speex manual³.

C. Common Layer 8 Problems

There are problems that frequently arise when implementing support for Speex. While some of them are due to programming errors, most are by sending or receiving the wrong signals. The most important aspect for the input signal is the amplitude. Speex can encode any signal in the [-32768, 32767] range. However, it is best to make use of the full dynamic range without being too close to saturation because that could cause the decoded speech to saturate even if the encoded speech does not. In practice, it is best to scale the input signal so the maximum amplitude is between 5000 and 20000.

Another important characteristics of the signals is the frequency content. DC offsets should be avoided at all cost as it causes the Speex encoder to produce bad sounding files (DC is never needed for audio). A DC offsets is sometimes caused by a cheap soundcard and means that the signal is not centred around the zero (zero-mean). In the most simple case, a DC offset can easily be removed using a notch filter of the form:

$$N(z) = \frac{1 - z^{-1}}{1 - \alpha z^{-1}} \quad (4)$$

where a value of $\alpha = 0.98$ is usually appropriate for both narrowband and wideband. The filter described in (4) can be implemented as:

```
#define ALPHA .98f
static float mem=0;
for (i=0;i<frame_size;i++)
{
mem = ALPHA*mem + (1-ALPHA)*input[i];
output[i] = output[i] - mem;
}
```

While the effect is less obvious, sometimes excessive amount of low frequencies can cause sub-optimal encoding with Speex. As a general rule, narrowband audio should be high-pass filtered at 300 Hz and wideband audio should be filtered at 50 Hz. It is one of the planned features for Speex to do the filtering automatically, this has not been done yet (as of November 2005).

³<http://www.speex.org/docs.html>

V. RECENT DEVELOPMENTS

Improvements to Speex have continued since the Speex bitstream was frozen with the release of version 1.0. These improvements are included in the 1.1.x unstable branch, which will lead to version 1.2. These are improvements to the actual implementation as well as extra features outside of the codec itself. It should be emphasised that the bitstream of version 1.2 will be exactly the same as for version 1.0.

A. Fixed-Point Port

Since November 2003 (version 1.1.1), work has been going on to convert Speex to fixed-point. This effort has been pushing Speex into embedded devices.

While the port is not yet complete (as of November 2005), a large part of the code has now been converted. Because the fixed-point code is implemented using arithmetic operator abstraction (macros), using Speex on a fixed-point architecture is as simple as configuring with the `-enable-fixed-point` option or defining the `FIXED_POINT` macro. As of November 2005, the status of the different components of Speex regarding fixed-point are as follows:

- Narrowband: Completely converted for all constant bit-rates ranging from 3.95 kbps to 18.2 kbps (inclusively). Other bit-rate and narrowband options have only a few float operations left (float emulation is realistic)
- Wideband: Mostly converted to fixed-point, but some float operations are left (float emulation is realistic on a fast chip).
- Preprocessor: Not converted to fixed-point yet.
- Echo canceller: Fixed-point port planned in the near future.

Using the fixed-point port, Speex is known to run on the following fixed-point architectures:

- Blackfin (μ Clinux)
Speex now includes architecture-dependent optimisations for the Analog Devices Inc. Blackfin DSP. It is possible to develop with Speex on Blackfin using μ Clinux⁴, GCC and Linphone⁵ on the GPL-licensed STAMP board⁶.
- ARM (Linux, Symbian)
Speex includes architecture-dependent optimisations for the ARM v4 and ARM v5E architectures.

⁴<http://blackfin.uclinux.org/>

⁵<http://www.linphone.org/>

⁶<http://blackfin.uclinux.org/projects/stamp/>

The GCC compiler can be used to compile Speex on ARM.

- TI C55x, C54x, C6x.

Speex has been adapted to the “non-conventional” architecture of these TI DSP families. There are unfortunately no architecture-dependent optimisations yet and (to the author’s knowledge) no Free compiler available.

Other fixed-point architectures may also be able to run Speex simply by enabling fixed-point compilation.

B. Preprocessor

A preprocessor module was introduced early in the 1.1.x branch. It is still under development, but many developers have already used it successfully. The pre-processor is designed to be used on the audio *before* running the encoder and provides three functionalities:

- noise suppression (denoiser)
- automatic gain control (AGC)
- voice activity detection (VAD)

The denoiser can be used to reduce the amount of background noise present in the input signal. This provides higher quality speech whether or not the denoised signal is encoded with Speex (or at all). However, when using the denoised signal with the codec, there is an additional benefit. Speech codecs in general (Speex included) tend to perform poorly on noisy input and tend to amplify the noise. The denoiser greatly reduces this effect.

Automatic gain control (AGC) is a feature that deals with the fact that the recording volume may vary by a large amount between different hardware and software setups. The AGC provides a way to adjust a signal to a reference volume. This is useful for voice over IP because it removes the need for manual adjustment of the microphone gain. A secondary advantage is that by setting the microphone gain to a conservative (low) level, it is easier to avoid clipping.

The voice activity detector (VAD) provided by the preprocessor is more advanced than the one directly provided in the codec. Unfortunately, it cannot directly be used by the encoder yet.

C. Acoustic Echo Cancellation

The Speex library now includes an echo cancellation algorithm suitable for Acoustic Echo Cancellation (AEC). AEC is especially useful in applications (VoIP or others) where one records from a microphone while speakers are being used. Speex uses an implementation of the multidelay block frequency (MDF) algorithm [6].

Again, the algorithm is still under development, but has already been successfully used in some applications.

Echo cancellation algorithms are generally very dependent on the quality and characteristics of the processed signals. The Speex AEC is no exception and there are several things that may prevent the echo canceller from working properly, some of which are non-obvious to people with no signal processing background. While it is always possible to encounter a bug in the Speex AEC, there are many other options that should be considered before.

First, using a different soundcard to do the capture and playback will not work, regardless of what some people think. The only exception to that is if the two cards can be made to have their sampling clock “locked” on the same source. However, this feature is only supported on professional soundcards.

The delay between the record and playback signals must be minimal. Any signal played has to “appear” on the playback (far end) signal slightly before the echo canceller “sees” it in the near end signal. However, excessive delay means that part of the filter length is wasted. In the worst-case situation, the delay is such that it is longer than the filter length, in which case, no echo can be cancelled.

When it comes to echo tail length (filter length), longer is not necessarily better. The longer the tail length, the longer it takes for the filter to adapt. Of course, a tail length that is too short will not cancel enough echo, but the most common problem seen is that people set a very long tail length and then wonder why no echo is being cancelled (or why adaptation is very slow).

Non-linear distortion cannot (by definition) be modelled by the linear adaptive filter used in the echo canceller and thus cannot be cancelled. It is thus best to use good audio hardware and avoid saturation/clipping at all cost. Also, the AEC should be the first algorithm to process the microphone signal and the last algorithm to see the speaker (far end) signal. A common mistake when implementing echo cancellation is to use noise suppression or automatic gain control before the AEC. Any processing, especially if it is non-linear, should occur only after the echo cancellation algorithm.

VI. CONCLUSION

In this paper, the origin and design goals of the Speex speech codec were presented. Also, a description of the CELP algorithm and its implementation in Speex was given. Some guidelines for programming with libspeex and choosing the right encoding options were provided

in order to help developers make better use of Speex in applications.

Even though the bitstream itself has been frozen for more than two years, work on Speex is continuing. Recent improvements focus on bringing support for fixed-point CPU and DSP architectures as well as providing additional functionality, such as echo cancellation and noise suppression, that are useful for VoIP applications.

RESOURCES

Speex: <http://www.speex.org>

Speex mailing list: speex-dev@xiph.org

Xiph.Org Foundation: <http://www.xiph.org>

APPLICATION SUPPORT

Speex is supported in the following applications⁷:

- OpenH323 (<http://www.openh323.org/>): Free implementation of the H323 protocol
- Linphone (<http://www.linphone.org/>): SIP-based VoIP application, one of the first application to support Speex
- Gnomemeeting (<http://www.gnomemeeting.org/>): VoIP application based on OpenH323 (with SIP support coming)
- Sweep (<http://www.metadecks.org/software/sweep/>): Sound editor
- Asterisk (<http://www.asteriskpbx.org/>): PBX Software
- Annodex (<http://www.annodex.net/>): Open standard for annotating media
- Ogg DirectShow (<http://www.illiminable.com/ogg/>): Windows DirectShow filters for Speex, Vorbis, FLAC and Theora
- JSpeex (<http://jspeex.sourceforge.net/>): Java port of Speex
- Libfishsound (<http://www.annodex.net/software/libfishsound/>): Simple library for encoding and decoding Ogg audio files
- GStreamer (<http://gstreamer.freedesktop.org/>): Multimedia framework library
- MPlayer (<http://www.mplayerhq.hu/>): Media player
- Xine (<http://xinehq.de/>): Media player
- VLC (<http://www.videolan.org/vlc/>): Media player and streaming server
- SIP Express Media Server (<http://www.iptel.org/sems/>): Extensible media server for voice services

⁷Only open-source software is listed here, in no particular order. This is not a complete list.

REFERENCES

- [1] M. Schroeder and B. Atal, "Code-excited linear prediction(celp): High-quality speech at very low bit rates," in *Proceedings IEEE International Conference on Acoustics, Speech and Signal Processing*, pp. 937–940, 1984.
- [2] S. Andersen, W. Kleijn, R. Hagen, J. Linden, M. Murthi, and J. Skoglund, "iLBC-a linear predictive coder with robustness to packet losses," in *Proc. IEEE Speech Coding Workshop*, pp. 23–25, 2002.
- [3] P. Kroon and B. Atal, "Pitch predictors with high temporal resolution," in *Proceedings IEEE International Conference on Acoustics, Speech and Signal Processing*, pp. 661–664, 1990.
- [4] J.-H. Chen, "Toll-quality 16 kb/s celp speech coding with very low complexity," in *Proceedings IEEE International Conference on Acoustics, Speech and Signal Processing*, pp. 9–12, 1995.
- [5] J.-M. Valin and R. Lefebvre, "Bandwidth extension of narrow-band speech for low bit-rate wideband coding," in *Proceedings IEEE Speech Coding Workshop*, pp. 130–132, 2000.
- [6] J.-S. Soo and K. Pang, "Multidelay block frequency domain adaptive filter," vol. 38, no. 2, pp. 373–376, 1990.