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(54) Method and apparatus for providing a codebook for bandwidth extension of an acoustic signal

(57) The invention is directed to a method for providing a codebook spectral envelope for bandwidth extension of an acoustic signal, comprising: providing an upsampled spectral envelope, wherein the up-sampled spectral envelope is restricted to a restricted frequency band with a lower limit frequency and an upper limit frequency; and modifying the spectral envelope to determine the codebook spectral envelope, wherein the magnitude of the codebook spectral envelope outside the frequency band is padded to a predetermined threshold value.

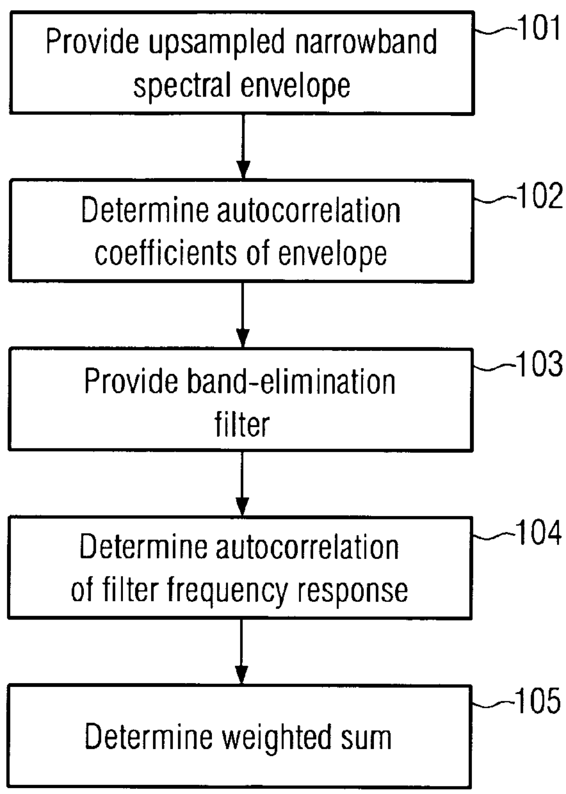

FIG. 1

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Description

[0001] The invention is directed to a method and an apparatus for providing a codebook spectral envelope for bandwidth extension of an acoustic signal, in particular, a speech signal.

[0002] Acoustic signals transmitted via an analog or digital signal path usually suffer from the drawback that the signal path has only a restricted bandwidth such that the transmitted acoustic signal differs considerably from the original signal. For example, in the case of conventional telephone connections, a sampling rate of 8 kHz is used resulting in a maximum signal bandwidth of 4 kHz. Compared to the case of audio CDs, the speech and audio qualities significantly reduce.

[0003] Furthermore, many kinds of transmissions show additional bandwidth restrictions. In the case of an analog telephone connection, only frequencies between 300 Hz and 3.4 kHz are transmitted. As a result, only 3.1 kHz bandwidth is available.

[0004] In the case of speech signals, for example, the lack of high frequencies has the consequence that the intelligibility is reduced. Furthermore, due to missing low frequency components, the speech quality is reduced.

[0005] In principle, the bandwidth of telephone connections could be increased by using broadband or wideband digital coding and decoding methods (so-called broadband codecs). In such a case, however, both the transmitter and the receiver have to support corresponding coding and decoding methods which would require the implementation of a new standard.

[0006] As an alternative, systems for bandwidth extension can be used as described, for example, in P. Jax, Enhancement of Bandwidth Limited Speech Signals: Algorithms and Theoretical Bounds, Dissertation, Aachen, Germany, 2002 or E. Larson, R.M. Aarts, Audio Bandwidth Extension, Wiley, Hoboken, NJ, USA, 2004. These systems are to be implemented on the receiver's side only such that existing telephone connections do not have to be changed. In these systems, the missing frequency components of the input signal with a small bandwidth are estimated and added to the input signal.

[0007] An example of the structure and the corresponding signal flow in such a state of the art bandwidth extension system is illustrated in Figure 11. In general, the missing frequency components are re-synthesized blockwise.

[0008] At block 1101, an incoming or received acoustic signal $x_{tel}(n)$ having a restricted bandwidth is converted to the desired bandwidth by increasing the sampling rate. The variable n denotes the time. In this conversion step, it is the aim to avoid that additional frequency components are generated. This may be achieved by using appropriate anti-aliasing or anti-imaging filtering elements. In order not to amend the transmitted signal, the bandwidth extension is performed only within the missing frequency ranges. Depending on the transmission method, the extension concerns low frequency (for example from 0 to 200 Hz) and/or high frequency (for example from 3,700 Hz to half of the desired sampling rate) ranges.

[0009] At subsequent block 1102, the converted signal x(n) is processed using block extraction and sub-sampling to obtain narrowband signal vectors $\mathbf{x}(n)$.

[0010] In block 1103, a narrowband spectral envelope is extracted from the narrowband signal, the narrowband signal being restricted by the bandwidth restrictions of a telephone channel, for example. Via a non-linear mapping, a corresponding broadband envelope is estimated in block 1105 from the narrowband envelope. The mapping may be based on codebook pairs (see G. Epps, W.H. Holmes, A New Technique for Wideband Enhancement of Coded Narrowband Speech, IEEE Workshop on Speech Coding, Conference Proceedings, Pages 174 - 176, June 1999).

[0011] Furthermore, in block 1104, a broadband or wideband excitation $\mathbf{x}_{exc}(n)$ having a spectrally flat envelope is generated from the narrowband signal. This excitation signal corresponds to the signal which would be recorded directly behind the vocal chords, i.e., the excitation signal contains information about voicing and pitch, but not about form and structures or the spectral shaping in general (see, for example, B. Iser, G. Schmidt, Bandwidth Extension of Telephony Speech, EURASIP Newsletter, Volume 16, Number 2, Pages 2 - 24, June 2005).

[0012] Thus, to retrieve a complete signal, such as a speech signal, the excitation signal has to be weighted with the spectral envelope. For the generation of excitation signals, non-linear characteristics (see U. Kornagel, Spectral Widening of the Excitation Signal for Telephone-Band Speech Enhancement, IWAENC 01, Conference Proceedings, Pages 215 - 218, September 2001) such as two-way rectifying or squaring, for example, may be used. For bandwidth extension, the excitation signal $\mathbf{x}_{exc}(n)$ is spectrally colored using the spectral envelope in block 1105. After that, the spectral ranges used for the extension are extracted using a band-elimination filter in block 1107 resulting in extension signal $\mathbf{x}_{ext}(n)$. The band-elimination filter can be effective, for example, in the range from 200 to 3,700 Hz.

[0013] The signal vectors x(n) of the received signal are passed through a complementary band pass filter in block 1106. Then, the signal components $\mathbf{x}_{ext}(n)$ and $\mathbf{x}_{pass}(n)$ are added to obtain a signal $\mathbf{x}_{tot}(n)$ with extended bandwidth. In block 1108, the different signal vectors are assembled again in a synthesis filter bank performing a block concentration and oversampling to yield the output signal $x_{tot}(n)$ having an extended bandwidth.

[0014] Additional elements might be present in the system, for example, to perform a pre-emphasis and/or a de-emphasis step or to adapt the power of the spectra of the time domain vectors $\mathbf{x}_{tel}(n)$ and $\mathbf{x}_{ext}(n)$. In principle, the signal processing steps may be performed in either the frequency domain using FFT and IFFT or in the time domain.

[0015] Depending on the quality of anti-aliasing or anti-imaging filtering performed after the upsampling in block 1101 (for example, from a sampling rate of 8 kHz to a sampling rate of 11 kHz or 16 kHz), artifacts at the band limits and additional components in the regions outside the restricted frequency band may appear.

[0016] Figure 12 illustrates the case of two spectrograms. In the case of the lower spectrogram, a high quality upsampling has been performed so that outside the restricted frequency band, no additional components appear. In contrast to this, using an upsampling process with poor quality results in a spectrogram as shown in the upper part of Figure 12 where undesirable imaging components are clearly visible.

[0017] However, using an upsampled signal as shown in the upper part of Figure 12 for providing extension signals to a narrowband acoustic signal will lead to mismatches due to the distortions present in the upsampled signal, in particular, as the envelope signals used in the codebooks have been trained on the basis of undistorted input signals.

[0018] Therefore, it is the object underlying the invention to provide a method for providing codebook spectral envelopes with an improved robustness against misclassifications and a method for providing an acoustic signal with extended bandwidth allowing to obtain an output signal with extended bandwidth with improved quality. This problem is solved by a method for providing a codebook spectral envelope according to claim 1 and a method for providing an acoustic signal with extended bandwidth according to claim 8.

[0019] Accordingly, a method for providing a codebook spectral envelope for bandwidth extension of an acoustic signal is provided, comprising:

(a) providing an upsampled spectral envelope, wherein the up-sampled spectral envelope is restricted to a frequency band with a lower limit frequency and an upper limit frequency;

(b) modifying the spectral envelope to determine the codebook spectral envelope, wherein the magnitude of the codebook spectral envelope outside the restricted frequency band is padded to a predetermined threshold value.

[0020] The padded codebook spectral envelope, thus, is equal to or larger than the predetermined threshold outside the restricted frequency band. Surprisingly, it turned out that such a narrowband codebook spectral envelope (i.e. restricted to a restricted frequency band) improves the determination of an adequate codebook envelope during the process of bandwidth extension. In particular, when comparing an upsampled received acoustic signal or its corresponding envelope signal with the codebook envelope signals modified or regularized in the above way, the main focus of the comparison will lie on the signal components within the restricted frequency band so that a best matching codebook envelope may be selected in a more reliable way.

[0021] An envelope may be a signal suitable as envelope signal for an acoustic signal. The envelope signal may be provided based on a predetermined reference acoustic signal. The up-sampled spectral envelope may be provided by providing an envelope signal restricted to the restricted frequency band, i.e. a narrowband envelope, and upsampling said envelope signal. In other words, the upsampling may be performed with respect to the sampling rate of the narrowband envelope signal and/or the underlying narrowband reference acoustic signal.

[0022] The upsampled spectral envelope may be provided in the form of a coefficients vector, in particular, in the form of a LPC coefficients vector. Linear Predictive Coding (LPC) is a particularly advantageous method to determine a spectral envelope based on a reference acoustic signal.

[0023] Step (b) may comprise:

providing a predetermined frequency response of a band-elimination filter, wherein the elimination band corresponds to the restricted frequency band;

determining envelope auto-correlation coefficients of the upsampled spectral envelope;

determining frequency response auto-correlation coefficients of the frequency response;

wherein the codebook spectral envelope is determined using modified auto-correlation coefficients based on a weighted sum of the input signal auto-correlation coefficients and the frequency response auto-correlation coefficients.

[0024] Using auto-correlation coefficients, a spectral envelope can be estimated in an advantageous way. The frequency response of a band-elimination filter allows to modify or regularize the upsampled spectral envelope in a simple way so as to obtain a modified spectral envelope fulfilling the above-mentioned magnitude criterion.

[0025] In particular, the predetermined threshold value may be at least -40 dB, particularly at least -20 dB, particularly at least -15 dB.

[0026] Such a predetermined threshold may be obtained using a predetermined weighting or damping factor for the frequency response auto-correlation coefficients.

[0027] The predetermined frequency response of the band-elimination filter may have an essentially constant magnitude below the lower limit frequency and/or above the upper limit frequency, respectively. Such a constant behavior allows for a straight-forward processing of the frequency response. The constant magnitude below the lower limit frequency and the constant magnitude above the upper limit frequency may be equal but need not be equal.

[0028] The magnitude of the predetermined frequency response of the band-elimination filter may be about -20 dB for frequencies below the lower limit frequency and/or about 0 dB for frequencies above the upper limit frequency. It turned out that such a frequency response is particularly well suited for regularizing the spectral envelope signal.

[0029] The band-elimination filter may be a FIR filter. The frequency response autocorrelation coefficients may be determined based on an inverse Fourier transform of the absolute values squared of the filter coefficients of the band-elimination filter that have been transformed to the frequency domain.

[0030] In the above-described methods, the restricted bandwidth may correspond to the bandwidth of a telephone band. In particular, it may correspond to the bandwidth of an analog telephone band, a GSM telephone band and/or an ISDN telephone band.

[0031] Step (b) may comprise determining LSF coefficients or cepstral coefficients for the codebook spectral envelope. Using Line Spectral Frequency (LSF) coefficients or cepstral coefficients allow for an improved adaptation of the representation of the spectral envelope to particular models of the respective acoustic signal.

[0032] The invention also provides a method for providing an acoustic signal with extended bandwidth, comprising:

providing a first codebook comprising a set of spectral envelopes provided according to the above-mentioned method;

providing a second codebook comprising a set of spectral envelopes, each spectral envelope corresponding to a spectral envelope of the first codebook and having an extended bandwidth compared to the corresponding spectral envelope of the first codebook;

determining a spectral envelope of a received acoustic signal, wherein the received acoustic signal is restricted to a restricted frequency band with a lower limit frequency and an upper limit frequency;

selecting a spectral envelope from the first codebook showing a closest match with the spectral envelope of the received acoustic signal according to a predetermined criterion;

selecting a spectral envelope from the second codebook corresponding to the selected spectral envelope of the first codebook;

providing an extension signal based on the selected spectral envelope of the second codebook for extending the received acoustic signal.

[0033] With this method, both the narrowband codebook spectral envelopes and the spectral envelope of the received acoustic signal undergo a regularization procedure so that the behavior of both envelopes are adapted outside the restricted frequency band to some extent. Due to this, emerging artifacts below and/or above the limit frequencies may be leveled so that their influence when comparing the spectral envelope of the received signal with the codebook envelopes is reduced.

[0034] The frequency band to which the received acoustic signal is restricted may be equal to the frequency band of the upsampled spectral envelope used in the above-described methods. However, the frequency bands need not be the same.

[0035] The spectral envelope of the received acoustic signal may be determined such that the magnitude of the spectral envelope outside the frequency band is padded to a predetermined threshold value. This predetermined threshold value may correspond to the predetermined threshold value used in the above-described method for providing the codebook spectral envelopes.

[0036] In this way, the regularized parts of both the spectral envelopes in the first codebook and the spectral envelope of the received acoustic signal will correspond to a large degree outside the restricted frequency band so that a comparison between the spectral envelope of the received acoustic signal with the elements of the first codebook will concentrate on the region within the restricted frequency band.

[0037] Determining the spectral envelope of the received acoustic signal may comprise:

providing a predetermined frequency response of a band-elimination filter, wherein the elimination band corresponds to the frequency band of the codebook signal;

determining acoustic signal auto-correlation coefficients of the acoustic signal;

determining frequency response auto-correlation coefficients of the frequency response,

wherein the spectral envelope is determined using modified auto-correlation coefficients based on a weighted sum of the acoustic signal auto-correlation coefficients and the frequency response auto-correlation coefficients.

[0038] In this way, an advantageous modification or regularization of the spectral envelope of the received acoustic signal is obtained.

[0039] The predetermined frequency response of the band-elimination filter may have an essentially constant magnitude below the lower limit frequency and above the upper limit frequency, respectively. The magnitude of the predetermined frequency response of the band-elimination filter may be about -20 dB for frequencies below the lower limit and/or about 0 dB for frequencies above the upper limit frequency.

[0040] Determining the spectral envelope of the received acoustic signal may comprise determining LSF coefficients or cepstral coefficients for the codebook spectral envelope.

[0041] The predetermined criterion may be based on a distance measure, in particular, a likelihood ratio distance measure or an Itakuro-Saito distance measure. In this way, it is possible to determine a spectral envelope from the first codebook showing minimal distance to the envelope of the received acoustic signal in a reliable way.

[0042] The step of providing an extension signal may comprise determining an excitation signal corresponding to the received acoustic signal. The excitation signal may be determined such that the product of the selected spectral envelope signal and the excitation signal corresponds to the received acoustic signal.

[0043] In the above methods, determining a broadband excitation signal may be based on prediction error filtering and/or a non-linear characteristic. In this way, suitable excitation signals can be generated. Possible non-linear characteristics are disclosed, for example, in U. Kornagel, *Spectral Widening of the Excitation Signal for Telephone-Band Speech Enhancement.*

[0044] The above described methods for providing an acoustic signal with extended bandwidth may further comprise combining the received acoustic signal and the extension signal by providing a weighted sum of the received acoustic signal and the extension signal. In particular, the extension signal may be restricted to frequencies outside the restricted frequency band. For this purpose, the step of providing the extension signal may comprise a step of band-elimination filtering.

[0045] The invention further provides a computer program product comprising one or more computer-readable media having computer-executable instructions for performing the steps of the above-described methods when run on a computer.

[0046] Furthermore, the invention provides an apparatus for providing a codebook spectral envelope for bandwidth extension of an acoustic signal, comprising a means for providing an upsampled spectral envelope, wherein the upsampled spectral envelope is restricted to a restricted frequency band with a lower limit frequency and an upper limit frequency, and a means for modifying the spectral envelope to determine the codebook spectral envelope, wherein the magnitude of the codebook spectral envelope outside the frequency band is larger than a predetermined threshold value.

[0047] The means of this apparatus may particularly be configured to also perform additional steps as in the above-described methods.

[0048] The invention also provides an apparatus for providing an acoustic signal with extended bandwidth, comprising:

means for providing a first codebook comprising a set of spectral envelopes provided according to the above-described methods;

means for providing a second codebook comprising a set of spectral envelopes, each spectral envelope corresponding to a spectral envelope of the first codebook and having an extended bandwidth compared to the corresponding spectral envelope of the first codebook;

means for determining a spectral envelope of a received acoustic signal, wherein the received acoustic signal is restricted to a restricted frequency band with a lower limit frequency and an upper limit frequency;

means for selecting a spectral envelope from the first codebook showing a closest match with the spectral envelope of the received acoustic signal according to a predetermined criterion;

means for selecting a spectral envelope from the second codebook corresponding to the selected spectral envelope of the first codebook;

means for providing an extension signal based on the selected spectral envelope of the second codebook for extending the received acoustic signal.

[0049] In particular, the means of this apparatus may further be configured to perform steps of the above-described methods. In addition, the means for providing a first codebook may be the apparatus for providing a codebook spectral envelope mentioned before.

[0050] Further embodiments will be described in the following in the context of the accompanying drawings, in which:

Figure 1 shows a flow diagram of a method for providing a codebook spectral envelope;

Figure 2 illustrates an example of a codebook pair;

Figure 3 illustrates an example of a frequency response of a band-elimination filter;

Figure 4 illustrates the frequency response of the auto-correlation corresponding to the filter in Figure 3;

Figure 5 illustrates the auto-correlation coefficients of the frequency response of Figure 4;

Figure 6 illustrates frequency responses of narrowband envelopes;

Figure 7 illustrates a flow diagram of an example of a method for providing an acoustic signal with extended bandwidth;

Figure 8 illustrates a short time spectrum of a speech signal and a corresponding envelope;

Figure 9 illustrates signal spectra and corresponding spectral envelopes;

Figure 10 illustrates spectral envelopes after upsampling;

Figure 11 illustrates the structure of an example of a prior art apparatus for providing an acoustic signal with extended bandwidth; and

Figure 12 illustrates the spectrograms of two speech signals.

[0051] Figure 1 illustrates the flow diagram of an example of a method for providing a codebook spectral envelope for bandwidth extension of an acoustic signal. In a first step 101, an up-sampled narrowband spectral envelope is provided. The upsampled narrowband spectral envelope (or, alternatively, the narrowband spectral envelope prior to upsampling) may be part of a codebook. Such codebooks are used for bandwidth extension of acoustic signals. Usually, codebook pairs are provided, wherein a first codebook comprises a set of narrowband spectral envelopes and the second codebook a set of broadband spectral envelopes. Each broadband spectral envelope in the second codebook corresponds to a narrowband spectral envelope in the first codebook.

[0052] Typical codebook sizes range from 32 to 1,024 envelopes. Codebooks may be created and trained using a larger speech database using the LBG vector quantization algorithm (see, for example, Linde et al, An Algorithm for Vector Quantizer Design, IEEE Transactions on Communications, Volume COM-28, Number 1, Pages 84 - 95, 1980).

[0053] An example of a codebook pair is illustrated in Figure 2. As one can see, the band-limited (narrowband) spectral envelope lies within a restricted frequency band and ranges from approximately 300 to 3,400 Hz. The corresponding broadband envelope further extends to frequencies below and above the limit frequencies of the narrowband envelope.

[0054] In step 102, auto-correlation coefficients of the upsampled spectral envelope are determined using linear predictive coding (LPC):

$$\tilde{\mathbf{r}}_{\mathrm{LPC}}(n) = \left[\tilde{r}_{\mathrm{LPC},0}(n), \tilde{r}_{\mathrm{LPC},1}(n), \ldots \tilde{r}_{\mathrm{LPC},N_{ACF}-1}(n)\right]^{T}$$

with

$$\tilde{r}_{\mathrm{LPC},i}(n) = \frac{1}{N_{\mathrm{Block}} - i - 1} \sum_{k=0}^{N_{\mathrm{Block}}-i-1} s(n+k)s(n+k+i),$$

wherein N_{Block} denotes the length of the extracted signal block, n denotes the current index of the first sampling cycle of the current frame and $s(n)$ the underlying acoustic signal (such as a telephone signal) corresponding to the envelope. It is to be noted that the underlying signal $s(n)$ is a narrowband signal restricted to a particular restricted frequency band (for example, due restrictions of a telephone connection). However, before calculating the auto-correlation coefficients, the signal $s(n)$ has undergone a sampling rate conversion (upsampling) to a desired sampling rate, for example, of 11 kHz or 16 kHz. The parameter N_{ACF} denotes the order of the LPC analysis, wherein

$$N_{\mathrm{Block}} \geq N_{\mathrm{ACF}}.$$

[0055] The above auto-correlation coefficients vector may further be normalized according to

$$\mathbf{r}_{\mathrm{LPC}}(n) = \frac{\tilde{\mathbf{r}}_{\mathrm{LPC}}(n)}{\tilde{r}_{\mathrm{LPC},0}(n)}.$$

[0056] These auto-correlation coefficients may serve for determining corresponding LPC coefficients that may be transformed into LSF coefficients or cepstral coefficients.

[0057] In the following step 103, a band elimination filter is provided in order to modify the upsampled narrowband spectral envelope. As an example, a FIR filter of the order N_{FIR} with the coefficients

$$\mathbf{b} = \left[b_0, b_1, \ldots, b_{N_{\mathrm{FIR}}-1}\right]^{\mathrm{T}}$$

may be used. The FIR filter is chosen such that a predefined modification or regularization frequency response for modifying the narrowband spectral envelope is obtained. In particular, such a frequency response may show a damping of about 20 dB in the frequency range below the lower limit of the narrowband spectral envelope, for example between 0 Hz and 200 Hz. Within the restricted frequency band of the spectral envelope, the filter should show a band-elimination characteristic. Above the upper limit of restricted frequency band, the filter may show a damping of about 0 dB. An example of such a frequency response is shown in Figure 3. Such a suitable frequency response may be obtained using a least squares algorithm.

[0058] In principle, the modification or regularization of the upsampled spectral envelope may be performed in the time domain or in the frequency domain. In the following, as an example, the modification in the frequency domain will be described.

[0059] First of all, the filter coefficients will be transformed using a Discrete Fourier Transform (DFT)

$$\mathbf{B} = \mathrm{F}\{\mathbf{b}\}$$

wherein

$$\mathbf{B} = \left[\mathrm{B}\left(e^{j\frac{2\pi}{N_{\mathrm{DFT}}}0}\right), \mathrm{B}\left(e^{j\frac{2\pi}{N_{\mathrm{DFT}}}1}\right), \ldots, \mathrm{B}\left(e^{j\frac{2\pi}{N_{\mathrm{DFT}}}(N_{\mathrm{DFT}}-1)}\right) \right]^{\mathrm{T}},$$

wherein F{ } denotes the DFT operator.

[0060] As the next step 104 in the flow diagram of Figure 1, auto-correlation coefficients are determined for the regularization filter. For this purpose, an Inverse Discrete Fourier Transform (IDFT) of the absolute values squared of the filter coefficients in the frequency domain is to be performed

$$\mathbf{r} = \mathrm{F}^{-1}\left\{\mathbf{B}_{\mathrm{Q}}\right\},$$

wherein

$$\mathbf{B}_{\mathrm{Q}} = \left[\left|\mathrm{B}\left(e^{j\frac{2\pi}{N_{\mathrm{DFT}}}0}\right)\right|^2, \left|\mathrm{B}\left(e^{j\frac{2\pi}{N_{\mathrm{DFT}}}1}\right)\right|^2, \ldots, \left|\mathrm{B}\left(e^{j\frac{2\pi}{N_{\mathrm{DFT}}}-1}\right)\right|^2 \right]^{\mathrm{T}}$$

and

$$\mathbf{r} = \left[r_0, r_1, \ldots, r_{N_{\mathrm{DFT}}-1}\right]^{\mathrm{T}}.$$

[0061] In these equations, $\mathrm{F}^{-1}\{\ \}$ denotes the Inverse Discrete Fourier Transform.

[0062] The modification vector for the additive regularization

$$\mathbf{r}_{\mathrm{mod}} = \left[r_{\mathrm{mod},0}, r_{\mathrm{mod},1}, \ldots, r_{\mathrm{mod},N_{\mathrm{ACF}}-1}\right]^{\mathrm{T}}$$

of the normalized auto-correlation coefficients may be determined as

$$\mathbf{r}_{\mathrm{mod}} = \mu \frac{\mathbf{W}_{\mathrm{cut}}\mathbf{r}}{r_0},$$

wherein μ is a damping factor for controlling the padding of the spectral envelope and W_{cut} is a $N_{ACF}\mathrm{x}N_{DFT}$ matrix with the structure

$$\mathbf{W}_{\text{cut}} = \begin{bmatrix} w_{1,1} & 0 & \cdots & 0 & 0 & \cdots & 0 \\ 0 & w_{2,2} & \cdots & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & & \vdots \\ 0 & 0 & \cdots & w_{N_{\text{ACF}},N_{\text{ACF}}} & 0 & \cdots & 0 \end{bmatrix}.$$

[0063] As an example, the parameter μ may take the value

$$\mu = 0.0001.$$

[0064] Furthermore,

$$N_{\text{DFT}} \geq N_{\text{ACF}}.$$

[0065] The coefficients of the matrix are

$$w_{i,i} = 1 \text{ for } i \in \{1,\ldots,N_{\text{ACF}}\}.$$

[0066] In the last step 105, the resulting codebook spectral envelope

$$\mathbf{r}_{\text{LPC}} = \frac{\mathbf{r}_{\text{LPC}} + \mathbf{r}_{\text{mod}}}{1 + r_{\text{mod},0}}$$

is determined as a weighted sum of the envelope auto-correlation coefficients and the frequency response auto-correlation coefficients.

[0067] The frequency response of the regularization vector $\mathbf{r}_{\text{mod}}$ corresponding to the frequency response in Figure 3 is shown in Figure 4, the corresponding auto-correlation coefficients are shown in Figure 5 for $N_{\text{ACF}} = 13$.

[0068] When determining the additive regularization in the time domain, the above described determination of the auto-correlation coefficients of the acoustic signal (but now using the frequency response of the band-elimination filter) may be used. For $N_{\text{DFT}} \geq N_{\text{FIR}}$ and $N_{\text{ACF}} \leq N_{\text{DFT}} - N_{\text{FIR}}$, the same results are obtained.

[0069] In Figure 6, the frequency response of a narrowband envelope and the corresponding codebook spectral envelope (being modified using the additive regularization) are shown. As one can see, the codebook spectral envelope does not differ considerably within the restricted frequency band. However, outside the frequency band limits, the magnitude of the codebook spectral envelope is always larger than -10 dB.

[0070] It is to be understood that the steps of the method as illustrated in Figure 1 may also be performed in a different order and/or in parallel. For example, determination of the auto-correlation coefficients of the spectral envelope may take place parallel to or after determination of the auto-correlation coefficients for the filter frequency response.

[0071] In Figure 7, the flow diagram illustrating an example of a method for providing an acoustic signal with extended bandwidth is shown. In a first step 701, a first and a second codebook are provided, wherein the first codebook comprises a set of narrowband spectral envelopes. These narrowband spectral envelopes stem from spectral envelopes of acoustic signals within a restricted frequency band but being modified according to a method as illustrated in Figure 1 and described above. Thus, the spectral envelopes contained in the first codebook have been regularized. The second codebook comprises a set of broadband spectral envelopes, i.e., spectral envelopes corresponding to broadband acoustic signals. In other words, the underlying acoustic signals contain frequency components outside the restricted frequency band; these additional frequency components may be present below and/or above the limits of the restricted frequency band.

[0072] As an example, in Figure 8, a short time spectrum of a narrowband acoustic signal is shown, as well as a corresponding narrowband envelope. It is to be noted that the narrowband spectral envelope shown in this Figure has not yet been regularized according to the present invention.

[0073] In the following step 702, a spectral envelope of the received acoustic signal is determined. To perform this step, the received acoustic signal (which is a narrowband signal, i.e. restricted to a restricted frequency band) has undergone an upsampling to a desired sampling rate, a block extraction and a subsampling so as to be in form of signal vectors. These preliminary processing steps may be performed as in blocks 1101 and 1102 in Figure 11.

[0074] Then, a spectral envelope is determined using Linear Predictive Coding and the auto-correlation method as outlined above in the context of determining the codebook spectral envelopes. However, as in the case of the codebook spectral envelopes, also the spectral envelopes of the acoustic signal are modified using the above-described additive regularization. Also in the case of the acoustic signal, the regularized spectral envelope is obtained as a weighted sum of the envelope auto-correlation coefficients and the frequency response auto-correlation coefficients of the frequency response of a band elimination filter. Preferably, the frequency response of the band elimination filter is the same as in the case of the codebook spectral envelopes. As a result, also in the case of the received acoustic signal, the regularized spectral envelope has been padded to a magnitude of at least -10 dB outside the limits of the restricted frequency range.

[0075] In Figure 9, the short time spectrum of a received acoustic signal is shown. In the same Figure, the signal spectrum resulting from an upsampling with poor quality is depicted showing significant artifacts. The corresponding spectral envelopes for both spectra are shown as well. In particular, above 4 kHz, the spectral envelopes differ considerably from each other.

[0076] In Figure 10, only the envelopes of a narrowband acoustic signal after an upsampling process with high quality and low quality, respectively, are shown. For both spectral envelopes, the corresponding modified envelopes resulting from the above-described regularization process are depicted. In addition, the areas between the modified envelopes are highlighted.

[0077] In the following step 703, a comparison between the regularized spectral envelope of the received acoustic signal and the set of spectral envelopes in the first codebook is performed. Using a distance measure, such as a likelihood ratio distance measure or an Itakuro-Saito distance measure, the spectral envelope from the codebook showing the smallest distance to the envelope of the acoustic signal is selected as the closest matching codebook envelope.

[0078] As one can see in Figure 10, without the regularization, the spectral envelopes of a received acoustic signal might differ considerably outside the restricted frequency band. Although this part of the envelope is of minor importance compared to the frequency components within the restricted frequency band, the components outside the restricted frequency band might lead to a mal-classification if the upsampling process was not optimal. As a consequence, a spectral envelope in the codebook might show an overall smaller distance to the envelope of the received acoustic signal although there is another spectral envelope in the codebook matching the received acoustic signal more closely within the restricted frequency band. This error would result from the deviations outside the restricted frequency band.

[0079] However, due to the regularization, the difference between spectral envelopes resulting from the same underlying acoustic signal but undergoing different upsampling processes is reduced. As a consequence, even in case of an upsampling process with poor quality, the likelihood to select the closest matching codebook spectral envelope (particularly with regard to the portion within the restricted frequency band) is increased.

[0080] With such a regularization of both the codebook spectral envelopes and the spectral envelopes of the received acoustic signal, the method is rendered more independent of the question whether the same restricted frequency band is used during training of the codebook and, later on, during the process of extending of the acoustic signal. This is due to the fact that the steep edges occurring in the signal due to the telephone band path are leveled due to the regularization process. This has also the advantage that the comparison between the envelope of an acoustic signal and the codebook envelope is focused to the region within the frequency band limits.

[0081] The selected spectral envelope may then be used to provide an extension signal for extending the received acoustic signal. For this purpose, an excitation signal corresponding to the received acoustic signal is generated. This broadband excitation signal shows a spectrally flat envelope. It corresponds to a signal which would be recorded directly behind the vocal cords. For the generation of excitation signals, non-linear characteristics (see U. Kornagel, *Spectral Widening of the Excitation Signal for Telephone-Band Speech Enhancement,*) such as two-way rectifying or squaring, for example, may be used.

[0082] Alternatively, determining an excitation signal can be performed in the time sub-band or Fourier domain as well. Examples for this alternative can be found in B. Iser, G. Schmidt, *Bandwidth Extension of Telephony Speech.*

[0083] In a subsequent step, the selected spectral envelope and the excitation signal are used for spectrally coloring the excitation signal. This can be achieved by multiplication in the sub-band or Fourier domain:

[0084] The spectrally colored excitation signal is passed through an adaptive band-elimination filter to extract the spectral regions to be used for bandwidth extension so that an extension signal is obtained. In other words, the band-elimination filter suppresses signal components within the restricted frequency band.

[0085] The extension signal and the received acoustic signal (having passed a band-pass filter, if need be) are then combined to obtain a resulting signal with extended bandwidth.

Claims

1. Method for providing a codebook spectral envelope for bandwidth extension of an acoustic signal, comprising:

    (a) providing an up-sampled spectral envelope, wherein the up-sampled spectral envelope is restricted to a restricted frequency band with a lower limit frequency and an upper limit frequency;
    (b) modifying the spectral envelope to determine the codebook spectral envelope, wherein the magnitude of the codebook spectral envelope outside the restricted frequency band is padded to a predetermined threshold value.

2. Method according to claim 1, wherein the up-sampled spectral envelope is provided in the form of a coefficients vector, in particular, in the form of a LPC coefficients vector.

3. Method according to claim 1 or 2, wherein step (b) comprises:

    providing a predetermined frequency response of a band-elimination filter, wherein the elimination band corresponds to the restricted frequency band;
    determining envelope autocorrelation coefficients of the up-sampled spectral envelope;
    determining frequency response autocorrelation coefficients of the frequency response,
    wherein the codebook spectral envelope is determined using modified autocorrelation coefficients based on a weighted sum of the envelope autocorrelation coefficients and the frequency response autocorrelation coefficients.

4. Method according to claim 3, wherein the predetermined frequency response has an essentially constant magnitude below the lower limit frequency and/or above the upper limit frequency, respectively.

5. Method according to claim 4, wherein the magnitude of the predetermined frequency response is about -20 dB for frequencies below the lower limit frequency and/or about 0 dB for frequencies above the upper limit frequency.

6. Method according to one of the preceding claims, wherein the bandwidth of the restricted frequency band corresponds to the bandwidth of a telephone band.

7. Method according to one of the preceding claims, wherein step (b) comprises determining LSF coefficients or cepstral coefficients for the codebook spectral envelope.

8. Method for providing an acoustic signal with extended bandwidth, comprising:

    providing a first codebook comprising a set of spectral envelopes provided according to the method of one of the preceding claims;
    providing a second codebook comprising a set of spectral envelopes, each spectral envelope corresponding to a spectral envelope of the first codebook and having an extended bandwidth compared to the corresponding spectral envelope of the first codebook;
    determining a spectral envelope of a received acoustic signal, wherein the received acoustic signal is restricted to a restricted frequency band with a lower limit frequency and an upper limit frequency;
    selecting a spectral envelope from the first codebook showing a closest match with the spectral envelope of the received acoustic signal according to a predetermined criterion;
    selecting a spectral envelope from the second codebook corresponding to the selected spectral envelope of the first codebook;
    providing an extension signal based on the selected spectral envelope of the second codebook for extending the received acoustic signal.

9. Method according to claim 8, wherein the spectral envelope of the received acoustic signal is determined such that the magnitude of the spectral envelope outside the frequency band is padded to a predetermined threshold value.

10. Method according to claim 8 or 9, wherein the spectral envelope of the received acoustic signal is determined in the form of a coefficients vector, in particular, in the form of a LPC coefficients vector.

11. Method according to one of the claims 8-10, wherein determining the spectral envelope of the received acoustic signal comprises:

providing a predetermined frequency response of a band-elimination filter, wherein the elimination band corresponds to the frequency band of the codebook signal;
determining acoustic signal autocorrelation coefficients of the acoustic signal;
determining frequency response autocorrelation coefficients of the frequency response,
wherein the spectral envelope is determined using modified autocorrelation coefficients based on a weighted sum of the acoustic signal autocorrelation coefficients and the frequency response autocorrelation coefficients.

12. Method according to claim 11, wherein the predetermined frequency response of the band-elimination filter has an essentially constant magnitude below the lower limit frequency and above the upper limit frequency, respectively.

13. Method according to claim 12, wherein the magnitude of the predetermined frequency response of the band-elimination filter is about -20 dB for frequencies below the lower limit frequency and/or about 0 dB for frequencies above the upper limit frequency.

14. Method according to one of the claims 8-13, wherein determining the spectral envelope of the received acoustic signal comprises determining LSF coefficients or cepstral coefficients for the codebook spectral envelope.

15. Method according to one of the claims 8 - 14, wherein the predetermined criterion is based on a distance measure, in particular, a likelihood ratio distance measure or an Itakuro-Saito distance measure.

16. Method according to one of the claims 8-15, further comprising combining the received acoustic signal and the extension signal by providing a weighted sum of the received acoustic signal and the extension signal.

17. Computer program product comprising one or more computer readable media having computer-executable instructions for performing the steps of the method of one of the preceding claims when run on a computer.

18. Apparatus for providing a codebook spectral envelope for bandwidth extension of an acoustic signal, comprising a means for providing an up-sampled spectral envelope, wherein the up-sampled spectral envelope is restricted to a restricted frequency band with a lower limit frequency and an upper limit frequency, and a means for modifying the spectral envelope to determine the codebook spectral envelope, wherein the magnitude of the codebook spectral envelope outside the restricted frequency band is larger than a predetermined threshold value.

19. Apparatus for providing an acoustic signal with extended bandwidth, comprising:

means for providing a first codebook comprising a set of spectral envelopes provided according to the method of one of the claims 1 - 7;
means for providing a second codebook comprising a set of spectral envelopes, each spectral envelope corresponding to a spectral envelope of the first codebook and having an extended bandwidth compared to the corresponding spectral envelope of the first codebook;
means for determining a spectral envelope of a received acoustic signal, wherein the received acoustic signal is restricted to a restricted frequency band with a lower limit frequency and an upper limit frequency;
means for selecting a spectral envelope from the first codebook showing a closest match with the spectral envelope of the received acoustic signal according to a predetermined criterion;
means for selecting a spectral envelope from the second codebook corresponding to the selected spectral envelope of the first codebook;
means for providing an extension signal based on the selected spectral envelope of the second codebook for extending the received acoustic signal.

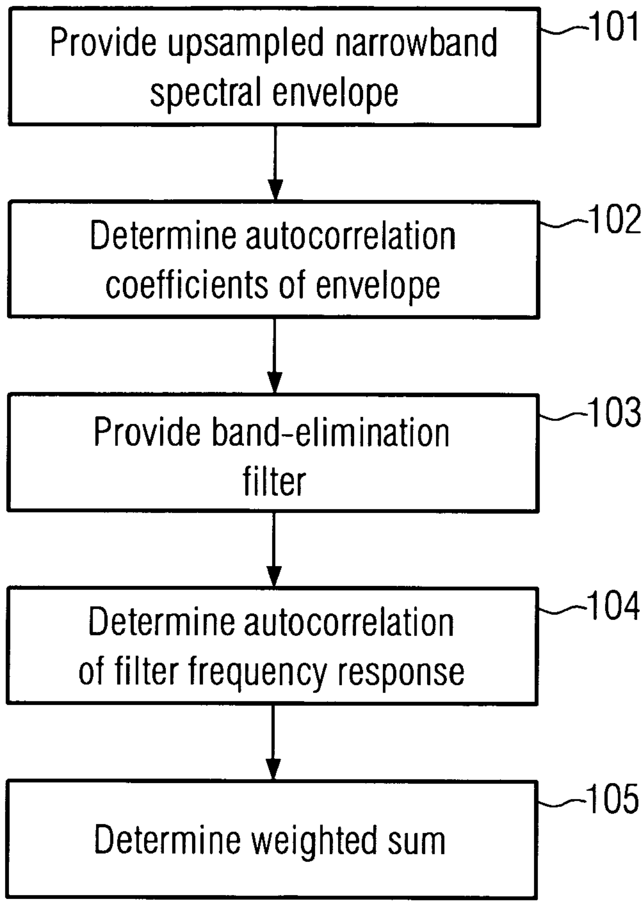

Provide upsampled narrowband spectral envelope
101
Determine autocorrelation coefficients of envelope
102
Provide band-elimination filter
103
Determine autocorrelation of filter frequency response
104
Determine weighted sum
105

FIG. 1

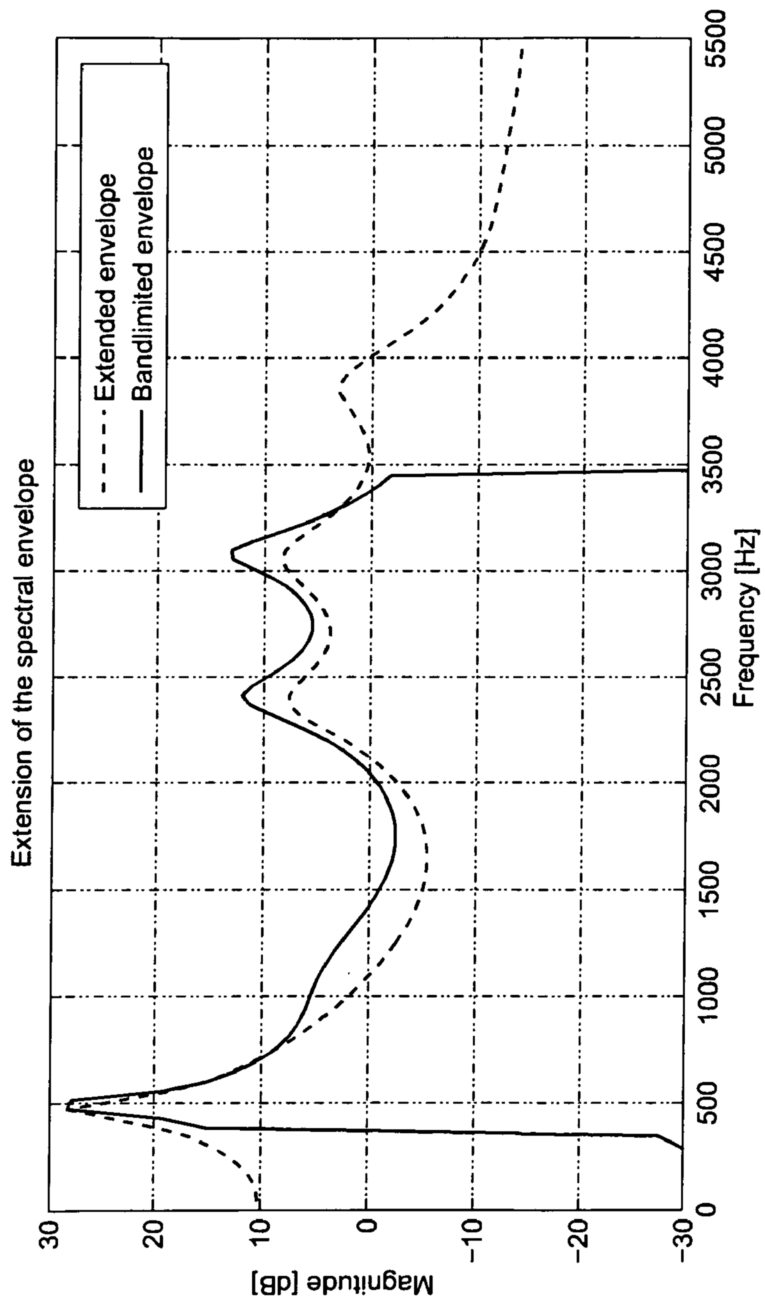

Extension of the spectral envelope
Extended envelope
Bandlimited envelope
Magnitude [dB]
Frequency [Hz]
30
20
10
0
−10
−20
−30
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500

Fig. 2

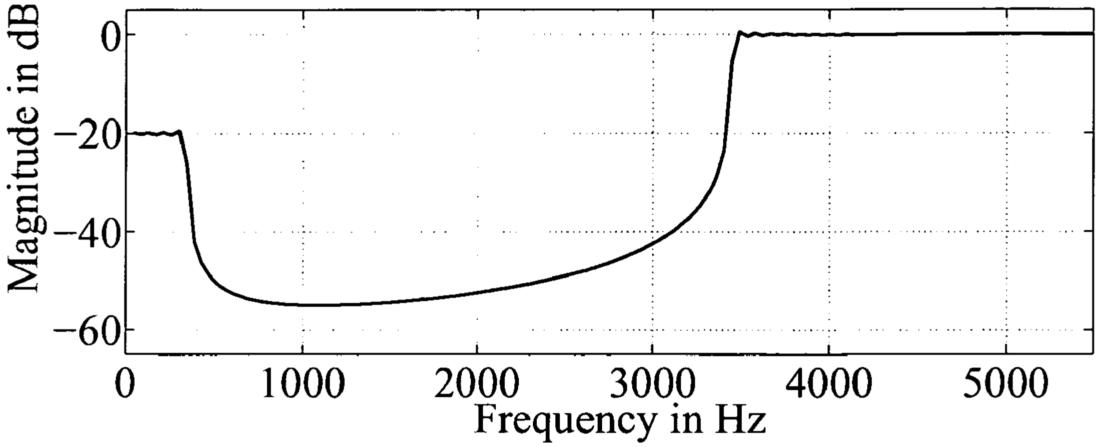

Magnitude in dB
0
−20
−40
−60
0
1000
2000
3000
4000
5000
Frequency in Hz

Fig. 3

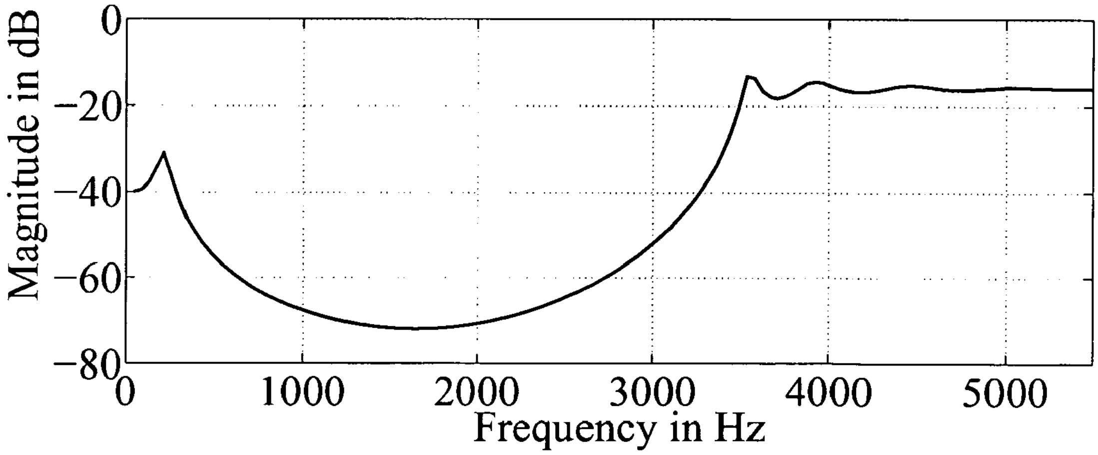

Magnitude in dB
0
−20
−40
−60
−80
0
1000
2000
3000
4000
5000
Frequency in Hz

Fig. 4

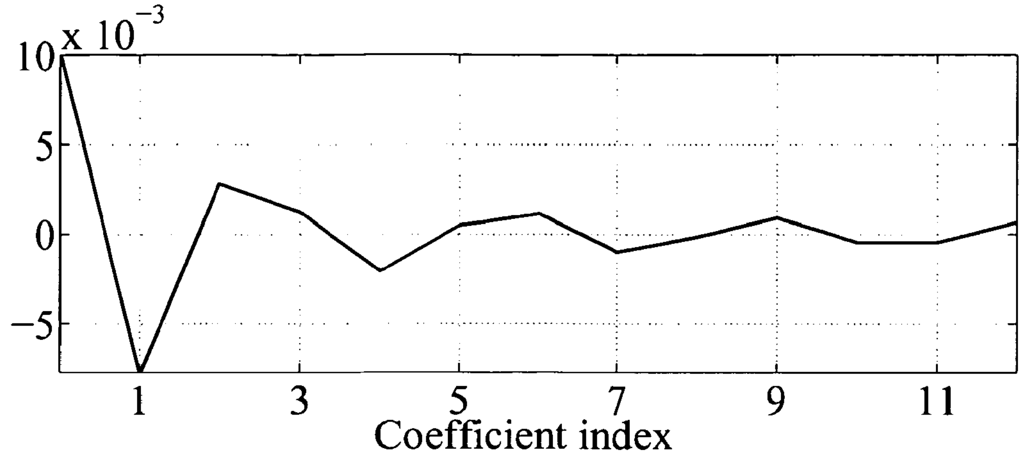

x 10^-3
10
5
0
−5
1
3
5
7
9
11
Coefficient index

Fig. 5

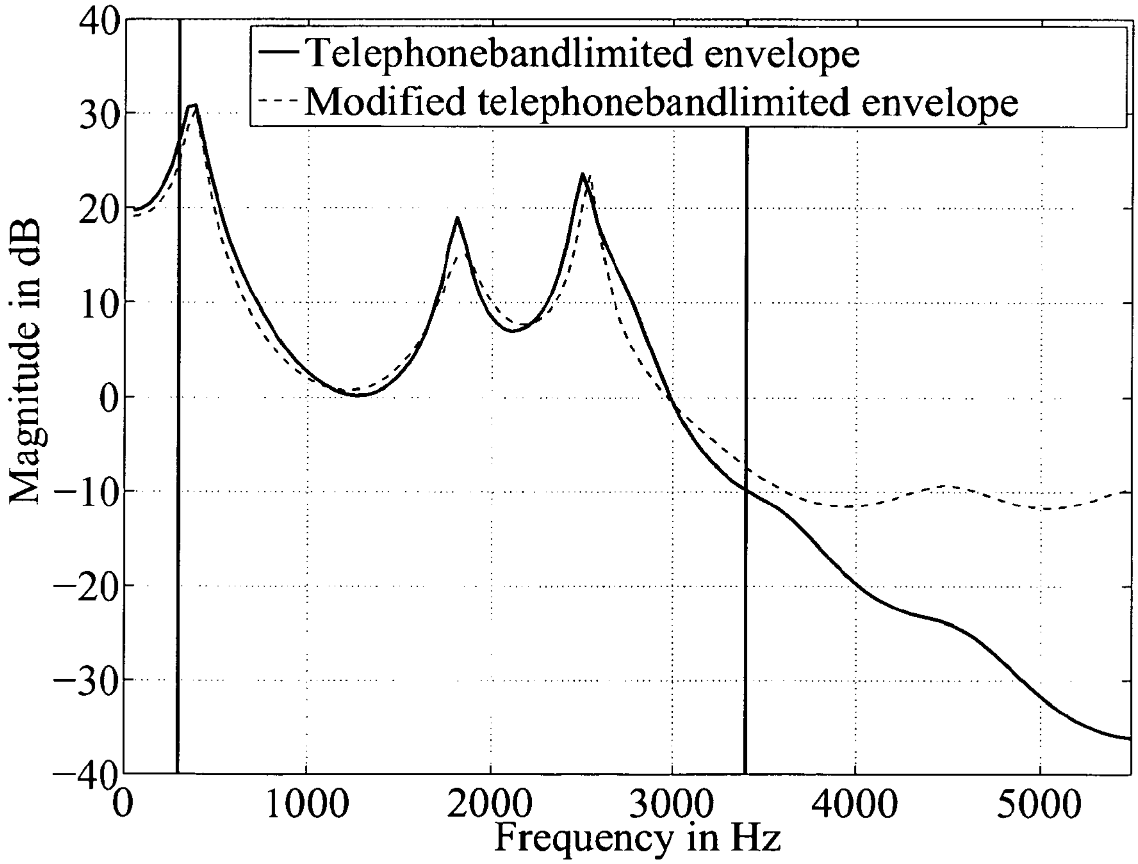

Telephonebandlimited envelope
Modified telephonebandlimited envelope
40
30
20
10
0
−10
−20
−30
−40
Magnitude in dB
0
1000
2000
3000
4000
5000
Frequency in Hz

Fig. 6

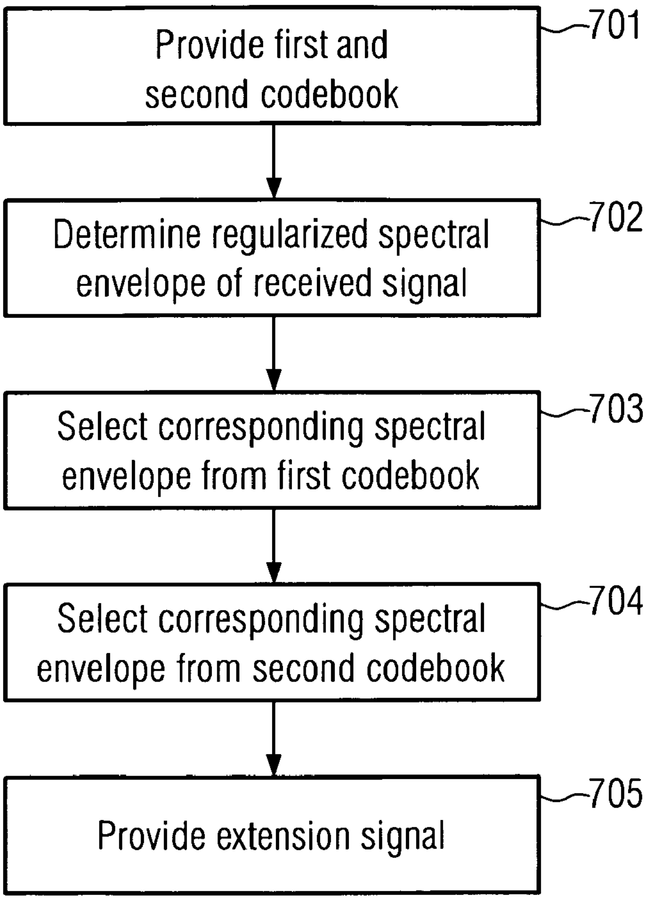

Provide first and second codebook
701
Determine regularized spectral envelope of received signal
702
Select corresponding spectral envelope from first codebook
703
Select corresponding spectral envelope from second codebook
704
Provide extension signal
705

FIG. 7

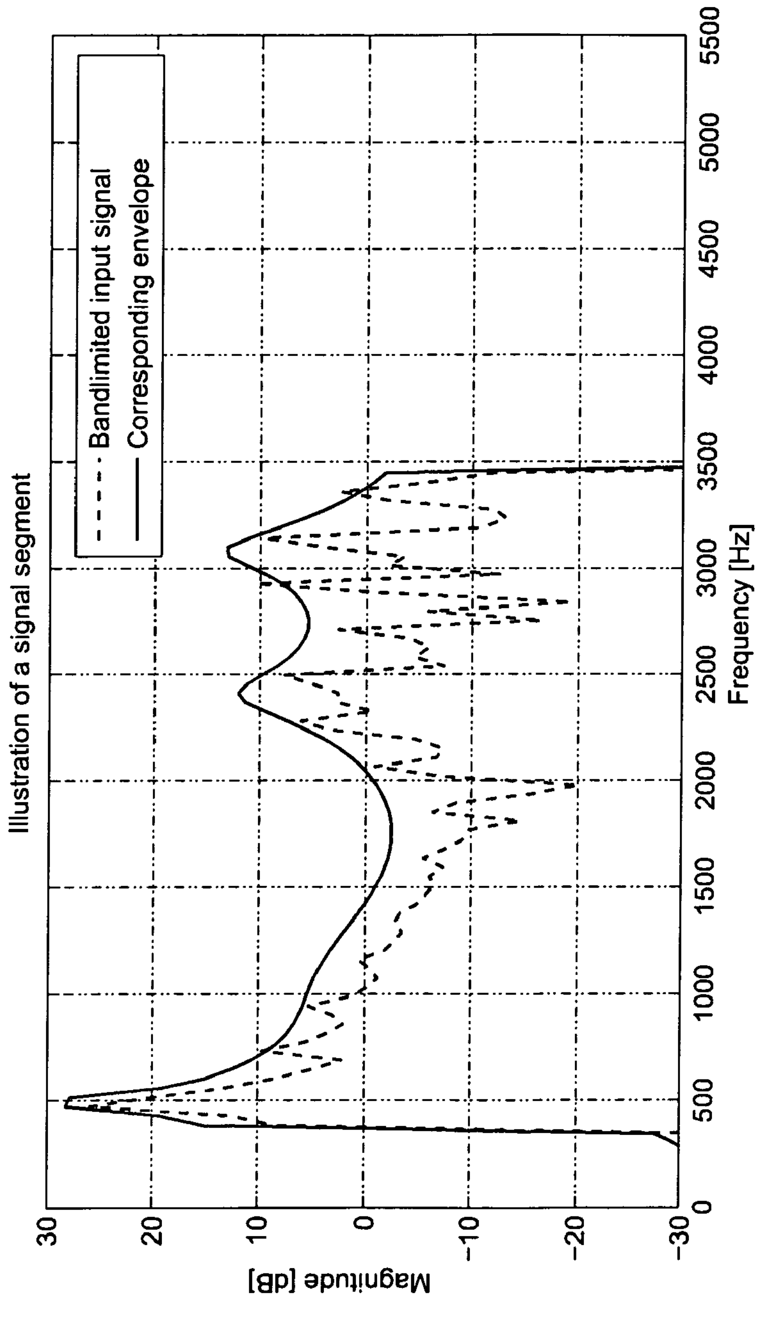
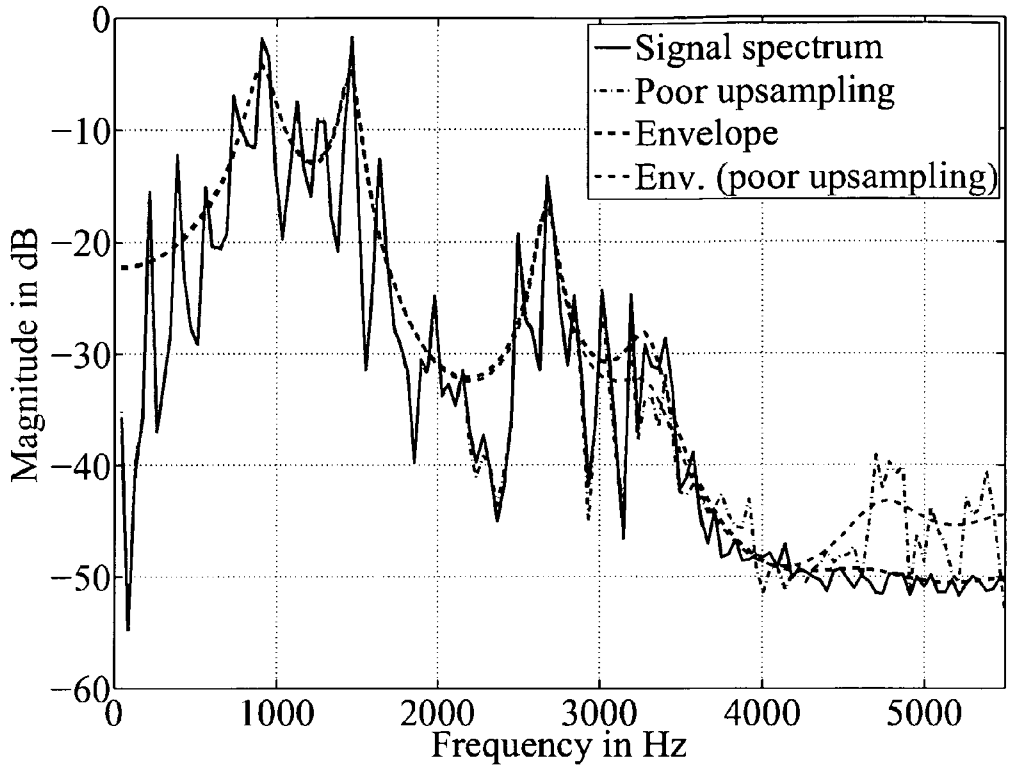


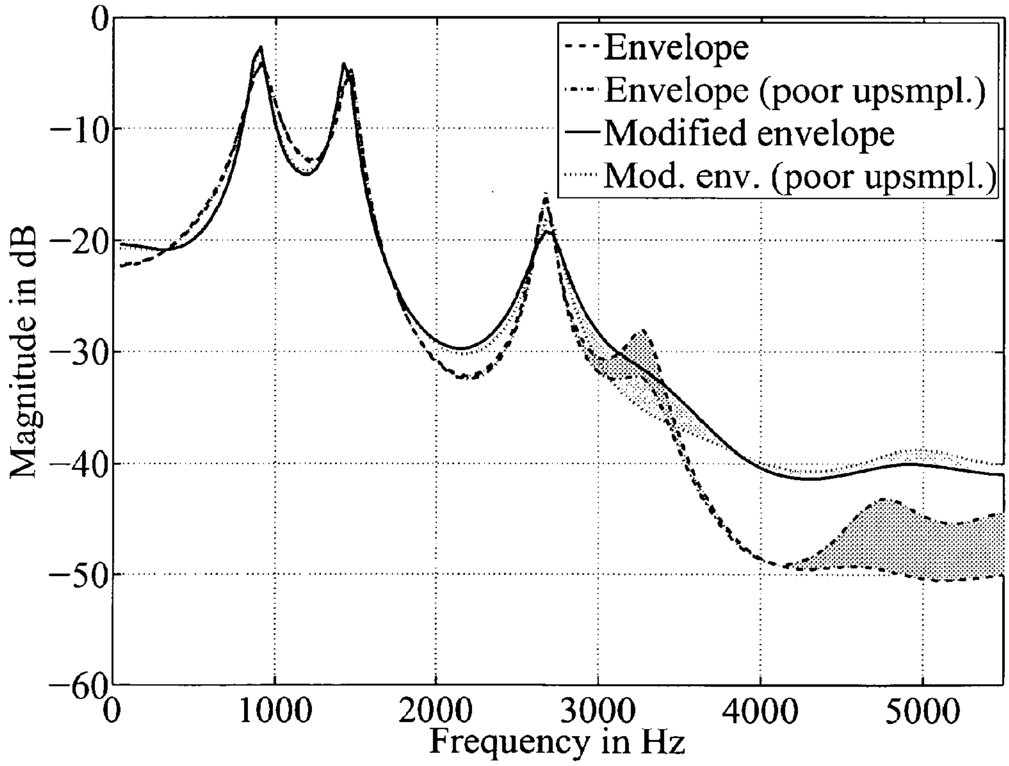
Illustration of a signal segment
Bandlimited input signal
Corresponding envelope
Magnitude [dB]
30
20
10
0
−10
−20
−30
Frequency [Hz]
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500

Fig. 8



Signal spectrum
Poor upsampling
Envelope
Env. (poor upsampling)
Magnitude in dB
Frequency in Hz
0
−10
−20
−30
−40
−50
−60
0
1000
2000
3000
4000
5000

Fig. 9



Envelope
Envelope (poor upsmpl.)
Modified envelope
Mod. env. (poor upsmpl.)
Magnitude in dB
Frequency in Hz
0
−10
−20
−30
−40
−50
−60
0
1000
2000
3000
4000
5000

Fig. 10

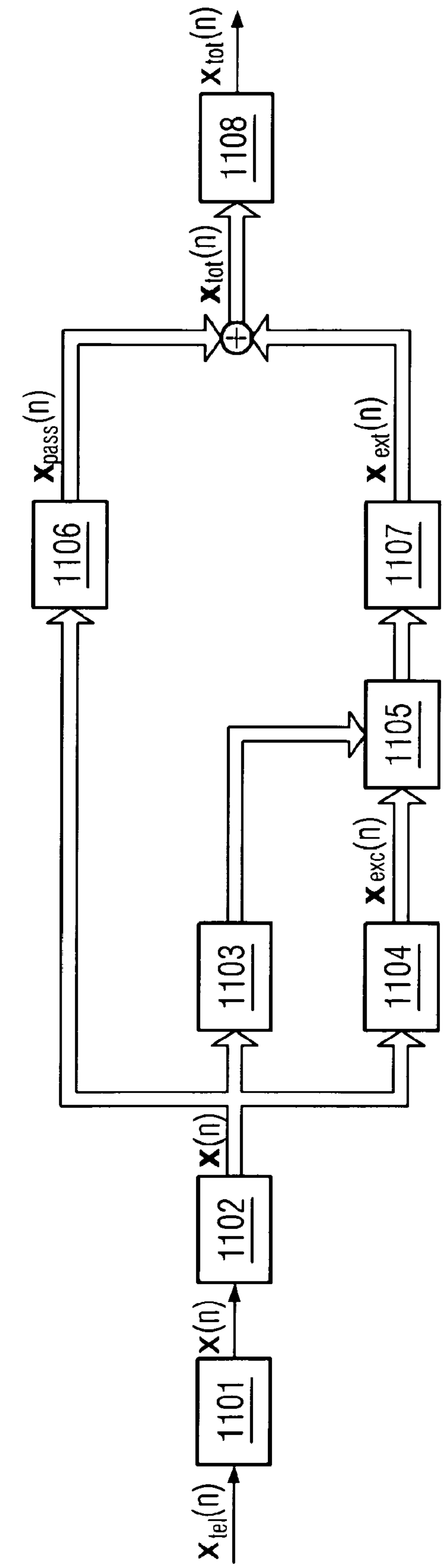

x_tel(n)
1101
x(n)
1102
X(n)
1103
1104
X_exc(n)
1105
1106
1107
X_pass(n)
X_ext(n)
X_tot(n)
1108
x_tot(n)

FIG. 11

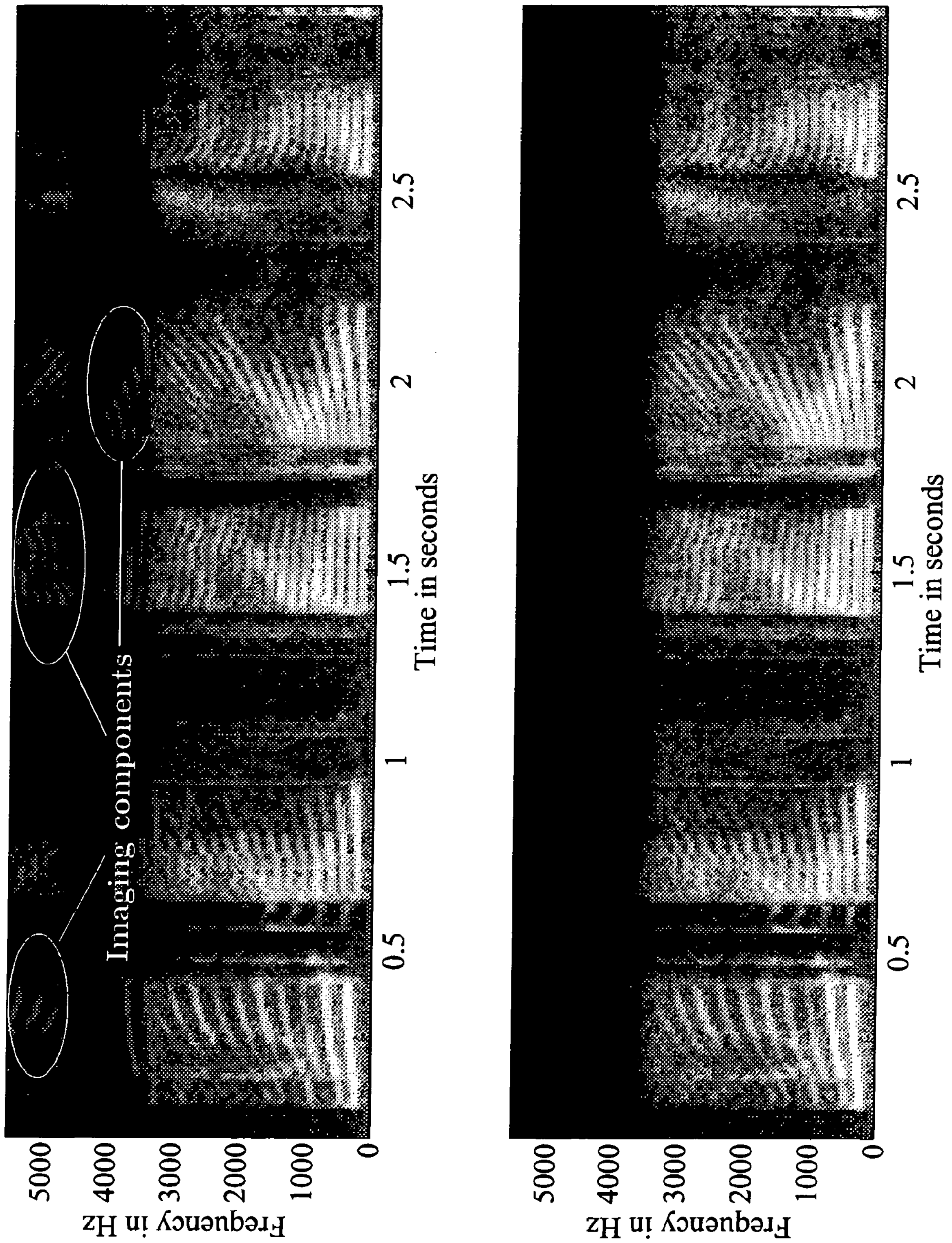

Imaging components
Frequency in Hz
5000
4000
3000
2000
1000
0
0.5
1
1.5
2
2.5
Time in seconds
Frequency in Hz
5000
4000
3000
2000
1000
0
0.5
1
1.5
2
2.5
Time in seconds

Fig. 12

European Patent Office

EUROPEAN SEARCH REPORT

Application Number
EP 07 00 5313

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X Y	EP 1 008 984 A (SONY CORP [JP]) 14 June 2000 (2000-06-14) * abstract * * paragraphs [0015], [0029], [0034], [0055] - [0060], [0072] - [0074] * * figure 4 * -----	1-8, 10-19 9	INV. G10L21/02
X	ISER B ET AL: "BANDWIDTH EXTENSION OF TELEPHONY SPEECH" EURASIP NEWS LETTER,, June 2005 (2005-06), pages 1-148, XP002372006 ISSN: 1687-1421 * page 16, paragraph 4.2.3 * -----	1,8,17, 18	
Y	EP 1 638 083 A (HARMAN BECKER AUTOMOTIVE SYS [DE]) 22 March 2006 (2006-03-22) * abstract * * paragraphs [0008], [0058] - [0060], [0091] * -----	9	
A	WEI-SHOU HSU: "Robust Bandwidth Extension of Narrowband Speech" THESIS. DEPARTMENT OF ELECTRICAL & COMPUTER ENGINEERING, MCGILL UNIVERSITY, November 2004 (2004-11), pages 1-66, XP002430890 Montreal, Canada * pages 39-41, paragraph 4.2 * -----	1-19	TECHNICAL FIELDS SEARCHED (IPC) G10L
A	US 6 539 355 B1 (OMORI ET AL) 25 March 2003 (2003-03-25) * abstract * * column 3, lines 1-8 * * column 8, lines 34-65 * -----	1-19	

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
The Hague	24 April 2007	Santos Luque, Rocio

3

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
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The members are as contained in the European Patent Office EDP file on
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24-04-2007

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP 1008984 A	14-06-2000	CN 1261713 A	02-08-2000
		KR 20000047944 A	25-07-2000
EP 1638083 A	22-03-2006	CA 2518332 A1	17-03-2006
		CN 1750124 A	22-03-2006
		JP 2006085176 A	30-03-2006
		KR 20060051298 A	19-05-2006
		US 2006106619 A1	18-05-2006
US 6539355 B1	25-03-2003	NONE	

EPO FORM P0459

For more details about this annex : see Official Journal of the European Patent Office, No. 12/82

REFERENCES CITED IN THE DESCRIPTION

Non-patent literature cited in the description

- **P. JAX.** Enhancement of Bandwidth Limited Speech Signals: Algorithms and Theoretical Bounds. *Dissertation,* 2002 **[0006]**
- **E. LARSON ; R.M. AARTS.** Audio Bandwidth Extension. Wiley, 2004 **[0006]**
- **G. EPPS ; W.H. HOLMES.** A New Technique for Wideband Enhancement of Coded Narrowband Speech. *IEEE Workshop on Speech Coding,* June 1999, 174-176 **[0010]**
- **B. ISER ; G. SCHMIDT.** Bandwidth Extension of Telephony Speech. *EURASIP Newsletter,* June 2005, vol. 16 (2), 2-24 **[0011]**
- **U. KORNAGEL.** Spectral Widening of the Excitation Signal for Telephone-Band Speech Enhancement. *IWAENC 01, Conference Proceedings,* September 2001, 215-218 **[0012]**
- **LINDE et al.** An Algorithm for Vector Quantizer Design. *IEEE Transactions on Communications,* 1980, vol. COM-28 (1), 84-95 **[0052]**