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(54)

Stereo multiplex-signal transmission with one single sideband modulation of the stereo-difference signal for frequency modulated broadcast system

(57) To increase the signal to noise ratio of a frequency-demodulated stereo audio signal the stereo-multiplex signal at the transmitter side is modified so that the information of the stereo-difference signal is carried in only one sideband of the amplitude modulated stereo-difference signal, preferably in the lower sideband. Therefore, receivers which generate the stereo-difference signal on basis of only the lower sideband produce

a higher signal to noise ratio of the frequency demodulated stereo audio signal than conventional FM-stereo receivers, because the noise bandwidth is reduced and in case only the lower sideband carries the information of the stereo-difference signal also the noise power spectral density is reduced. Conventional FM-stereo-receivers reproduce the modified stereo-multiplex signal without increase or decrease in quality.

Figure 2:

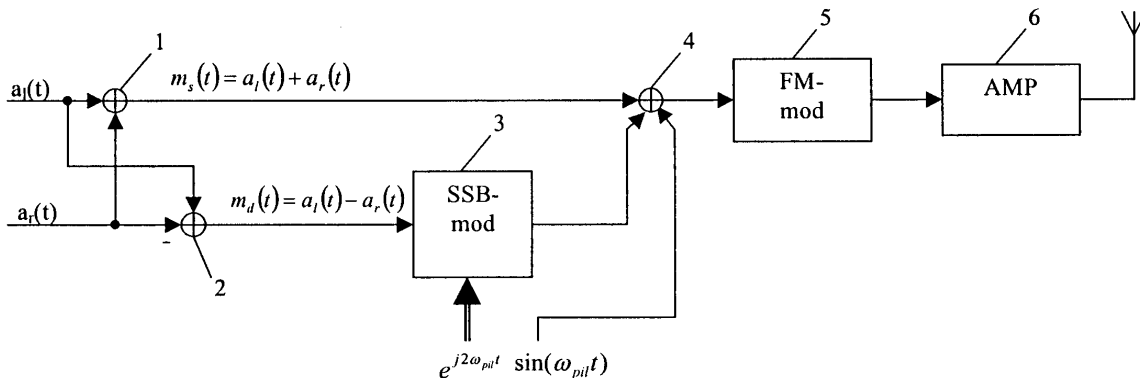
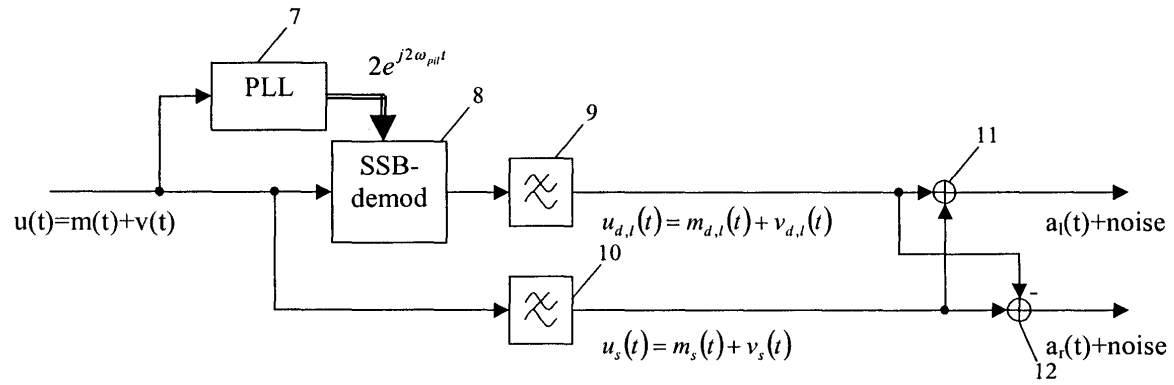


Figure 3:



Description

[0001] The present invention relates to the transmission of a stereo signal and in particular to an improvement of the signal to noise ratio of the receiver output signal.

[0002] In fm-broadcasting a stereo-multiplex signal is frequency modulated. The stereo-multiplex signal consists of a stereo-sum signal and a stereo-difference signal. The stereo-difference signal is amplitude modulated with suppressed carrier. To allow a coherent amplitude demodulation of the stereo-difference signal at the receiver, a pilot carrier with half the AM-carrier frequency is added to the stereo-multiplex signal.

[0003] The stereo-sum signal and the stereo-difference signal are defined by

$$m_s(t) = a_l(t) + a_r(t)$$

$$m_d(t) = a_l(t) - a_r(t)$$

[0004] The stereo-multiplex signal is defined by

$$m_{\text{stmux}}(t) = m_s(t) + \sin(2\omega_{\text{pil}}t) \cdot m_d(t) + A_{\text{pil}} \cdot \sin(\omega_{\text{pil}}t)$$

[0005] The stereo-multiplex signal is frequency modulated:

$$S_{\text{FM}}(t) = A_{\text{FM}} \cos \left(\omega_c(t) + \Delta\omega \int_{-\infty}^t m_{\text{stmux}}(\tau) d\tau \right)$$

with

ω_c : carrier frequency

$\Delta\omega$: frequency deviation

[0006] At the receiver side the frequency modulated stereo-multiplex signal is frequency demodulated and stereo-demultiplexed to calculate the left and right audio signal.

[0007] For the stereo demultiplexing, the stereo demultiplexer needs to recover the 2nd harmonic of the pilot carrier. Therefore, a PLL locks to the pilot carrier and generates the 2nd harmonic of the pilot carrier. The 2nd harmonic that is locked in phase to the pilot carrier is needed for the coherent amplitude demodulation of the stereo-difference signal.

[0008] Fig. 5 shows the basic functionality of a state of the art stereo-demultiplexer. For the sake of simplicity the noise $n_b(t)$ added to the frequency modulated stereo-multiplex signal $S_{\text{FM}}(t)$ on the transmitter side, the receiver side and within the transmission channel is shown to be added to the frequency modulated stereo-multiplex signal $S_{\text{FM}}(t)$ by way of an adder 13 just before the frequency demodulator 14 of the stereo-demultiplexer shown in Fig. 5. Therefore, the frequency demodulator 14 outputs a stereo-multiplex signal $u(t)$ that consists of the stereo-multiplex signal $m_{\text{stmux}}(t)$ as generated on the transmitter side and additionally an added noise component $v(t)$ that is the frequency demodulated noise signal $n_b(t)$. On basis of this stereo-multiplex signal $u(t)$ a PLL-circuit 7 generates the 2nd harmonic of the pilot carrier, i. e. a signal that is in phase to the pilot carrier with twice the frequency of the pilot carrier, which is needed for the coherent amplitude demodulation of the stereo-multiplex signal $u(t)$ to gain the stereo-difference signal $u_d(t)$. This coherent amplitude demodulation is performed by way of a demodulator 15 which receives the stereo-multiplex signal $u(t)$ at its first input and the 2nd harmonic of the pilot carrier at its second input. The output signal of the demodulator 15 is input to a filter 9 which outputs the stereo-difference signal $u_d(t)$ that consists of the stereo-difference signal $m_d(t)$ generated at the transmitter side plus an additional noise component $v_d(t)$. A stereo-sum signal $u_s(t)$ comprising the stereo-sum signal $m_s(t)$ plus an additional noise component $v_s(t)$ is generated by a lowpass filtering of the stereo-multiplex signal $u(t)$ with a lowpass filter 10 that receives the output signal of the frequency demodulator 14. The left audio signal is calculated by an addition of the stereo-sum signal $u_s(t)$ and the stereo-difference signal $u_d(t)$ with an adder 11. The right audio signal $r(t)$ is calculated by a subtraction of the stereo-difference signal $u_d(t)$ from the stereo-

sum signal $u_s(t)$ with a subtracter 12. The left output channel consists of the left audio signal $l(t)$ and a noise component $v_d(t) + v_s(t)$ and the right audio channel consists of the right audio signal $r(t)$ and a noise component $v_s(t) - v_d(t)$.

[0009] Therefore, without consideration of the noise $n_b(t)$ introduced in the transmission chain, the stereo-sum signal $m_s(t)$ is generated by a lowpass filtering of the stereo-multiplex signal and the stereo-difference signal is generated by a coherent amplitude demodulation of the amplitude modulated stereo-difference signal. The left and right audio signals $l(t)$ and $r(t)$ are calculated by addition and subtraction of the stereo-sum signal and the stereo-difference signal:

$$r(t) = m_s(t) - m_d(t) = (a_l(t) + a_r(t)) - (a_l(t) - a_r(t)) = 2a_r(t)$$

$$l(t) = m_s(t) + m_d(t) = (a_l(t) + a_r(t)) + (a_l(t) - a_r(t)) = 2a_l(t)$$

[0010] Fig. 6 shows the spectrum of the stereo-multiplex signal consisting of

- the spectrum $M_s(j\omega)$ of the stereo-sum signal $m_s(t)$,
- the pilot carrier,
- the spectrum $M_{d,l}(j\omega)$ of the lower sideband of the amplitude modulated single sideband signal $m_{d,l}(t)$, and
- the spectrum $M_{d,u}(j\omega)$ of the upper sideband of the amplitude modulated single sideband signal $m_{d,u}(t)$.

[0011] For the calculation of the noise of the frequency demodulated signal the noise at the input of the frequency demodulator is assumed to be zero mean Gaussian noise. Fig. 7 shows the assumed power spectral density of the noise $n_b(t)$ at the input of the frequency demodulator. The power spectral density $S_{n_b}(j\omega)$ equals to $N_0/2$ from frequencies $-\omega_c - B_n$ to $-\omega_c + B_n$ and from frequencies $\omega_c - B_n$ to $\omega_c + B_n$. With N_0 being the value of the power spectral density of the noise, ω_c being the fm carrier frequency and B_n being the noise bandwidth. It is shown in Kammeyer, Nachricht-tenubertragung, ISBN 3-519-16142-7 that the power spectral density of the noise $v(t)$ of the frequency demodulated signal can be calculated to:

$$S_{vv}(j\omega) \approx \left(\frac{\omega}{A_{FM}} \right)^2 N_0$$

[0012] The frequency demodulation performed by the demodulator applies quadratic shaping of the input noise spectrum. Fig. 8 depicts the power spectral density (PSD) $S_{vv}(j\omega)$ of the demodulator output at high carrier to noise ratios (CNRs). It can be seen that $S_{vv}(j\omega)$ over the frequency ω has the shape of a parabola.

[0013] Comparing the graphs shown in Figs. 6 and 8, the signal to noise ratio of the frequency demodulated stereo audio signal at the receiver output can be estimated. It is the object underlying the present invention to improve this signal to noise ratio.

[0014] Therefore, to solve this object, the present invention provides a new method to generate a frequency modulated stereo-multiplex signal which is defined in independent claim 1, a stereo-multiplexer adapted to operate according to the method defined in independent claim 1 according to independent claim 3, a frequency-modulated stereo-multiplex signal which is backward compatible according to independent claim 5, a method to demultiplex such a frequency modulated stereo multiplex signal according to independent claim 7 and a stereo demultiplexer adapted to operate according to the demultiplexing method according to the present invention according to independent claim 9. Preferred embodiments thereof are respectively defined in the respective following dependent claim.

[0015] The present invention results from the finding that the stereo-multiplex signal described above in connection with the state of the art itself is no optimal solution in terms of the audio output noise of the receiver.

[0016] The variance of the noise $\sigma_{v_d}^2$ in the amplitude demodulated stereo-difference signal is depending on the noise bandwidth and the PSD $S_{v_d v_d}(j\omega)$ of the amplitude modulated stereo-difference signal. By minimizing the noise bandwidth, the variance of the noise $\sigma_{v_d}^2$ in the amplitude demodulated stereo-difference signal can be decreased. Therefore, according to the present invention, the noise bandwidth of the stereo-difference signal is minimized by replacing the amplitude modulation of the stereo-difference signal $m_d(t)$ with a single sideband amplitude modulation of the stereo-difference signal $m_d(t)$.

[0017] Due to the quadratic shape of the PSD of the frequency demodulator output noise $S_{vv}(j\omega)$, as shown in Fig. 8, the PSD of the noise in the lower sideband of the SSB-demodulated stereo-difference signal $S_{v_d, l v_d, l}(j\omega)$ is lower than the PSD of the noise in the upper sideband $S_{v_d, u v_d, u}(j\omega)$. Therefore, according to a preferred embodiment of the present invention, the lower sideband is chosen for the SSB amplitude modulation of the stereo-difference signal at the transmitter side.

[0018] Therewith, the present invention ensures a backward compatibility while improving the signal to noise ratio of the receiver audio output signal. This backward compatibility ensures that existing FM-receivers are not disturbed, but that receivers according to the present invention have an improved signal to noise ratio of the audio signal.

[0019] As will be shown in the following, the gain in signal to noise ratio of the stereo-difference signal is about 5.05 dB.

[0020] The changes at the transmitter side are limited to changes of the stereo-multiplexer so that existing transmitters can be changed to operate according to the present invention very simple and inexpensive.

[0021] The present invention and its preferred embodiment will now be described, by way of example only, with reference to the accompanying drawings of which:

Fig. 1 shows the spectrum of the stereo-multiplex signal according to a preferred embodiment of the present invention;

Fig. 2 shows a stereo-multiplexer and transmitter stage according to the present invention;

Fig. 3 shows a stereo-demultiplexer according to the present invention;

Fig. 4a shows the power spectral density of the stereo-difference signal demodulated according to the present invention and conventionally demodulated;

Fig. 4b shows the gain of the noise-power spectral density of the stereo-difference signal demodulated according to the present invention against the noise-power spectral density of the stereo-difference signal conventionally demodulated;

Fig. 5 shows the basic functionality of a stereo-demultiplexer according to the prior art;

Fig. 6 shows the spectrum of a state-of-the-art stereo-multiplex signal;

Fig. 7 shows the assumed power spectral density of the noise at the input of the frequency demodulator; and

Fig. 8 shows the power spectral density of the noise at the frequency demodulator output.

[0022] In case of amplitude modulation of the conventional stereo-difference signal both sideband signals carry the same information

$$m_{d,u}(t) = m_{d,l}(t) = \frac{m_d(t)}{2}$$

[0023] According to a preferred embodiment of the present invention which is described in the following, on the other hand, only the lower sideband of the stereo-difference signal contains information, namely the whole information of the stereo-difference signal, and the upper sideband of the stereo-difference signal carries no information. Therefore,

$$m_{d,l}(t) = m_d(t)$$

$$m_{d,u}(t) = m_d(t) - m_{d,l}(t) = 0$$

[0024] Fig. 1 shows the spectrum of the optimized stereo-multiplex signal consisting of

- the spectrum $M_s(j\omega)$ of the stereo-sum signal $m_s(t)$,
- the pilot carrier,
- the spectrum $M_{d,l}(j\omega)$ of the lower sideband of the amplitude modulated single sideband signal $m_{d,l}(t)$ that contains all information of the stereo-difference signal $m_{d,l}(t)$,
- the spectrum $M_{d,u}(j\omega)$ of the upper sideband of the amplitude modulated single sideband signal $m_{d,u}(t)$ that contains no information.

[0025] A comparison of Figs. 1 and 6 shows that the spectrum $M_s(j\omega)$ of the stereo-sum signal $m_s(t)$ remained unchanged, but that the spectrum $M_{d,l}(j\omega)$ of the lower sideband of the amplitude modulated single sideband signal $m_{d,l}(t)$ according to the present invention has twice the amplitude than the spectrum $M_{d,l}(j\omega)$ of the lower sideband of the amplitude modulated single sideband signal $m_{d,l}(t)$ according to the prior art, whereas the spectrum $M_{d,u}(j\omega)$ of the upper sideband of the amplitude modulated single sideband signal $m_{d,u}(t)$ according to the present invention remains zero over all frequencies.

[0026] Fig. 2 shows a stereo-transmitter which comprises a stereo-multiplexer stage as input stage and a FM-modulation and amplifying stage as output stage. The incoming signal of the left channel is respectively input to a first input of an adder 1 which receives the first summand and the first input of a subtractor 2 which receives the minuent. The

input signal of the right channel is input to respective second inputs of the adder 1 and subtractor 2 which respectively receive the second summand and the subtrahend. The adder 1 outputs a sum-signal which consists of the signal of the left channel plus the signal of the right channel. The subtractor 2 outputs a difference-signal which consists of the signal of the left channel minus the signal of the right channel. The output signal of the subtractor 2 is input to a single sideband amplitude modulator 3 which performs a lower sideband amplitude modulation of the input stereo-difference signal according to the preferred embodiment of the present invention. The output signals of the single sideband amplitude modulator 3 and the adder 1 are input to the inputs of an adder 4 which produces the stereo-multiplex signal, consisting of the stereo-sum signal and the single sideband amplitude modulated stereo-difference signal. Additionally, the pilot carrier is added to the stereo-multiplex signal. These elements 1 to 4 build the stereo-multiplexing stage. The output signal of the adder 4 is input to a FM-modulator 5 whereafter an amplification 6 is performed before the resulting signal is transmitted via an aerial.

[0027] According to the preferred embodiment of the present invention only the lower sideband of the SSB-demodulated stereo-difference signal contains information:

$$u_{d,l}(t) = m_d(t) + v_{d,l}(t)$$

$$u_{d,u}(t) = v_{d,u}(t)$$

[0028] Therefore, only the lower sideband of the stereo-difference signal needs to be demodulated within the receiver.

[0029] The block diagram of Fig. 3 shows a stereo-demultiplexer according to the present invention that demodulates only the lower sideband $u_{d,l}(t)$ of the stereo-difference signal $u_d(t)$ to gather the information of the stereo-difference signal. In the stereo-demultiplexer according to the present invention the stereo-sum signal $u_s(t)$ is generated identical to the stereo-sum signal $u_s(t)$ shown in Fig. 5, i. e. by a lowpass filtering of the stereo-multiplex signal $u(t)$ with a lowpass filter 10. According to the present invention, the coherent amplitude demodulation of the amplitude modulated stereo-difference signal is performed with a single sideband demodulator 8 that receives the stereo-multiplex signal $u(t)$ and at a second input the complex signal $2(\cos(2\omega_{pil}) + j \cdot \sin(2\omega_{pil}))$ from the PLL circuit 7. The single sideband demodulator 8 comprises digital filters and generates the single sideband signal which passes a lowpass filter 9 to become the lower sideband signal $u_{d,l}(t)$. Thereafter, the generation of the left and right audio channels is performed similar to the state-of-the-art stereo-demultiplexer shown in Fig. 5, namely the output signal for the left channel is gained by a summation of the stereo-sum signal output by the lowpass filter 10 and the stereo-difference signal output by the filter 9 with an adder 11 and the audio signal for the right channel is gained by a subtraction of the stereo-difference signal output by the filter 9 of the stereo-sum signal output by the lowpass filter 10 with a subtracter 12. Both audio output signals respectively comprise a noise component.

[0030] The noise-PSD of the stereo-difference signal is the same as the PSD of the lower sideband signal $u_{d,l}(t)$:

$$S_{v_{d,l} v_{d,l}}(j\omega) = \begin{cases} N_0 \left(\frac{2\omega_{pil} - |\omega|}{A_{fm}} \right)^2 & \text{for } |\omega| \leq B_{nf} \\ 0 & \text{for } |\omega| > B_{nf} \end{cases}$$

with A_{fm} being the amplitude of the audio signal and B_{nf} being the bandwidth of the audio signal.

[0031] Fig. 4a) depicts the noise-PSD of the conventionally demodulated stereo-difference signal as a dashed line and the noise-PSD of the SSB-demodulated stereo-difference signal according to the present invention as a solid line. Fig. 4b) depicts the gain of the noise-PSD of the SSB modulated/demodulated stereo-difference signal against noise-PSD of the conventionally demodulated stereo-difference signal. It can be seen that the gain in SNR of the stereo-difference signal with $\frac{B_{nf}}{2\pi} = 15$ kHz and $\frac{\omega_{pil}}{2\pi} = 19$ kHz equals to 5.05 dB:

$$\begin{aligned}
\frac{\sigma_{m_{stmux}}^2}{\sigma_{v_{d,l}}^2} &= \frac{\sigma_{v_d}^2}{\sigma_{v_{d,l}}^2} = \frac{\frac{1}{\pi} \int_0^{B_{nf}} S_{v_d} v_d(j\omega) d\omega}{\frac{1}{\pi} \int_0^{B_{nf}} S_{v_{d,l}} v_{d,l}(j\omega) d\omega} = \frac{\frac{N_0}{\pi A_{fm0}^2} \int_0^{B_{nf}} (2\omega_{pil} - \omega)^2 + (2\omega_{pil} + \omega)^2 d\omega}{\frac{N_0}{\pi A_{fm0}^2} \int_0^{B_{nf}} (2\omega_{pil} - \omega)^2 d\omega} \\
&= \frac{8\omega_{pil}^2 B_{nf} + \frac{2}{3} B_{nf}^3}{4\omega_{pil}^2 B_{nf} - 2\omega_{pil} B_{nf}^2 + \frac{1}{3} B_{nf}^3} = 3.2 \equiv 5.05 \text{ dB}
\end{aligned}$$

Claims

1. Method to generate a frequency modulated stereo-multiplex signal ($S_{FM}(t)$), **characterized by** a single sideband amplitude modulation of the stereo-difference signal ($m_d(t)$).
2. Method according to claim 1, **characterized in that** a lower sideband amplitude modulation is performed.
3. Stereo multiplexer, **characterized by** one single sideband modulator (3) to modulate the stereo-difference signal ($m_d(t)$).
4. Stereo multiplexer according to claim 3, **characterized in that** said single sideband modulator (3) generates a modulated stereo-difference signal ($m_{d,l}(t)$) consisting only of the lower sideband of the stereo-difference signal ($m_{d,l}(t)$).
5. Frequency modulated stereo-multiplex signal ($S_{FM}(t)$), **characterized in that** the information of the stereo-difference signal ($m_d(t)$) is carried in only one sideband of the amplitude modulated stereo difference signal.
6. Frequency modulated stereo-multiplex signal ($S_{FM}(t)$) according to claim 5, **characterized in that** the information of the stereo-difference signal ($m_d(t)$) is carried in the lower sideband of the stereo difference signal ($m_{d,l}(t)$).
7. Method to demultiplex a frequency modulated stereo-multiplex signal ($S_{FM}(t)$) according to claim 5 or 6, **characterized in that** the information of the stereo-difference signal ($m_d(t)$) is gathered by a single sideband demodulation of the stereo-multiplex signal ($m(t)$).
8. Method according to claims 6 and 7, **characterized in that** the single sideband demodulation is performed on the lower sideband of the stereo-difference signal ($m_{d,l}(t)$).
9. Stereo demultiplexer, **characterized by** a single sideband demodulator (8) to generate the stereo-difference signal ($m_d(t)$).
10. Stereo multiplexer according to claim 9, **characterized in that** said single sideband modulator (8) demodulates only the lower sideband of the stereo-difference signal ($m_{d,l}(t)$) to generate the stereo-difference signal ($m_d(t)$).

Figure 1:

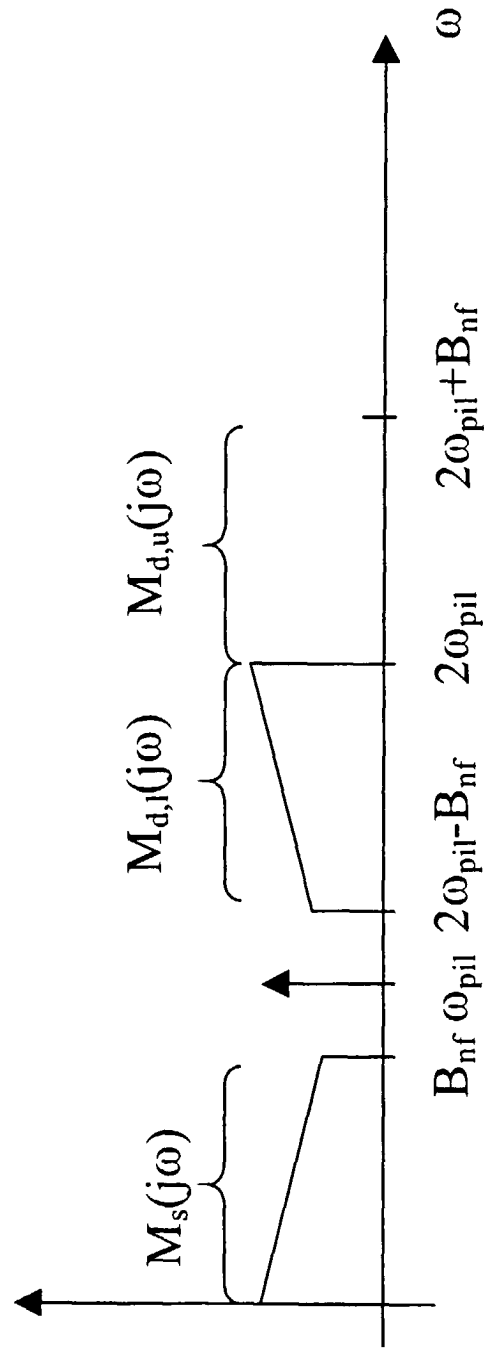


Figure 2:

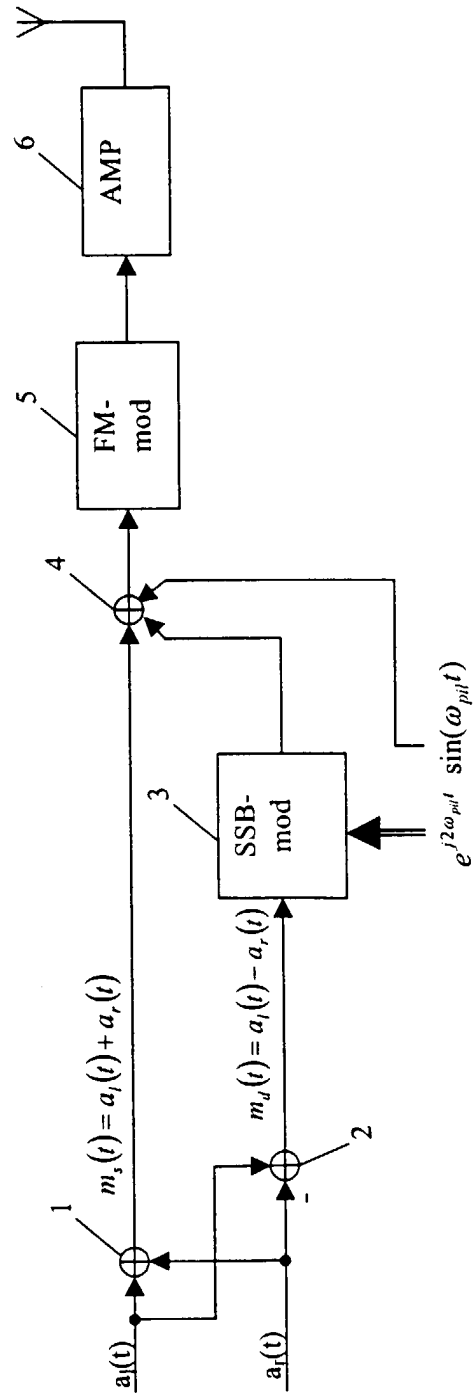


Figure 3:

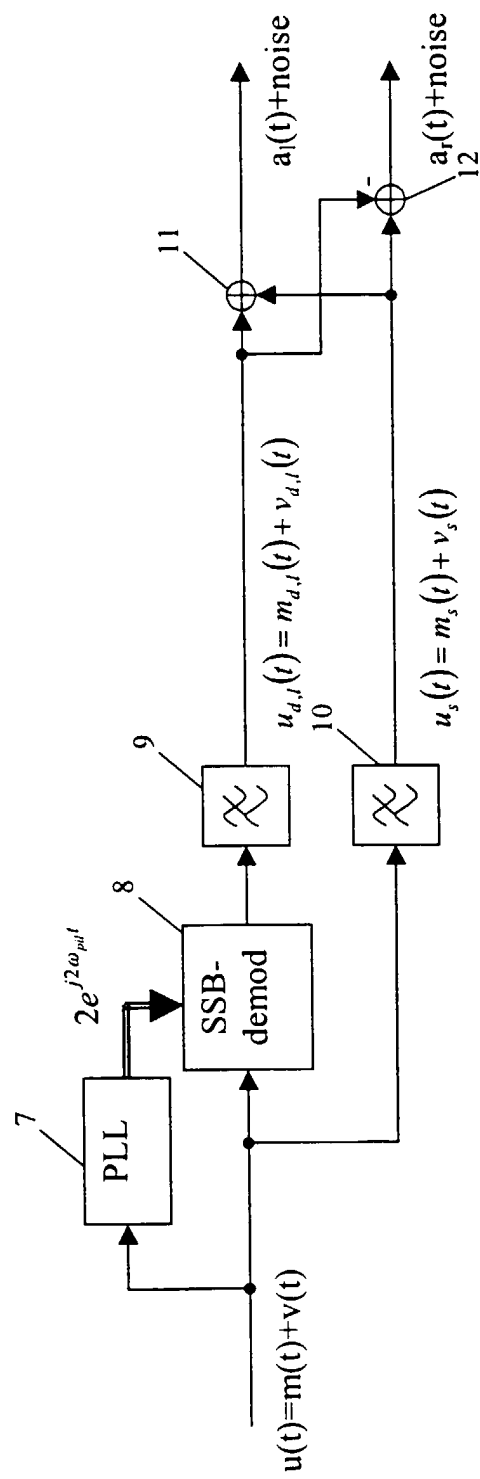


Figure 4:

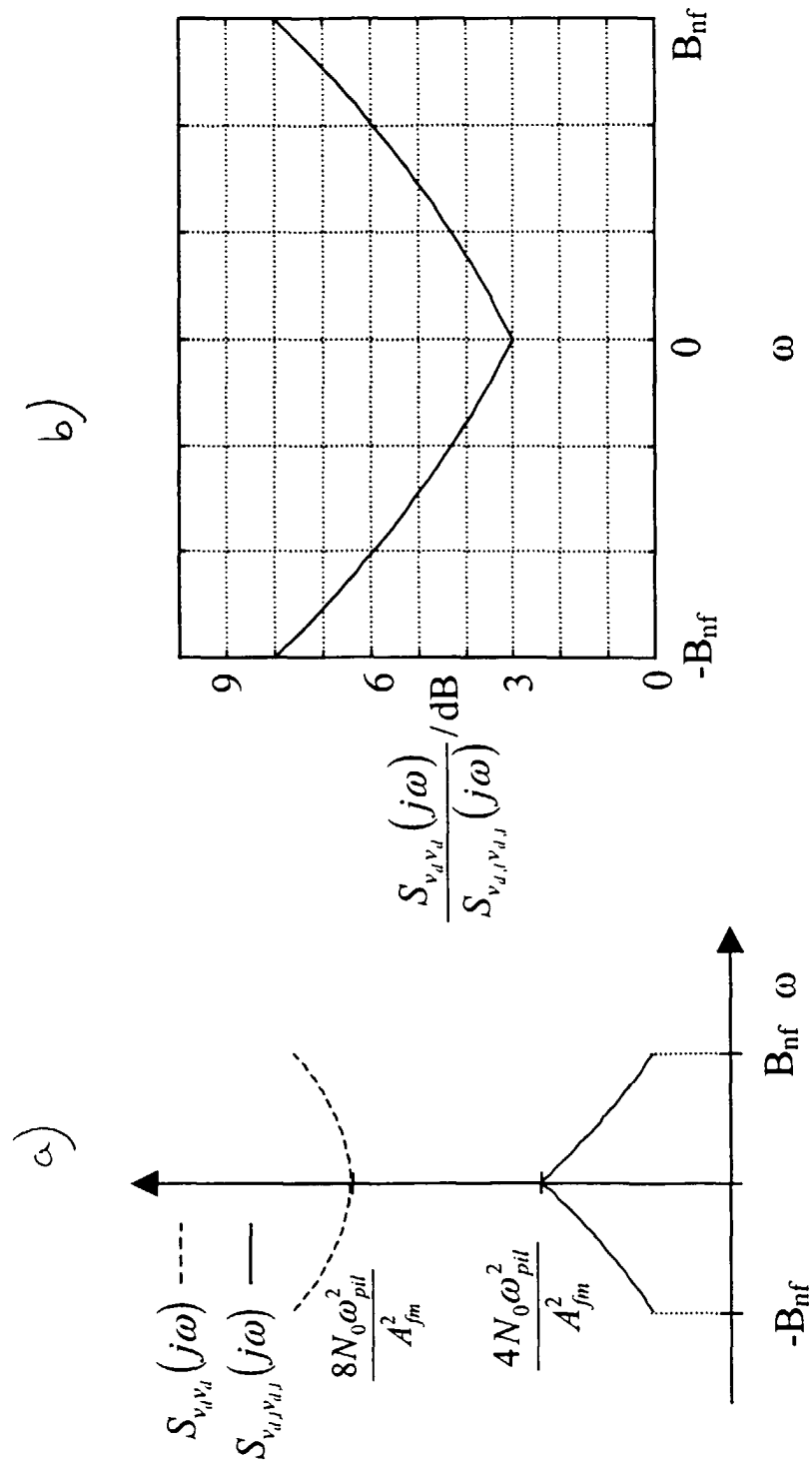


Figure 5:

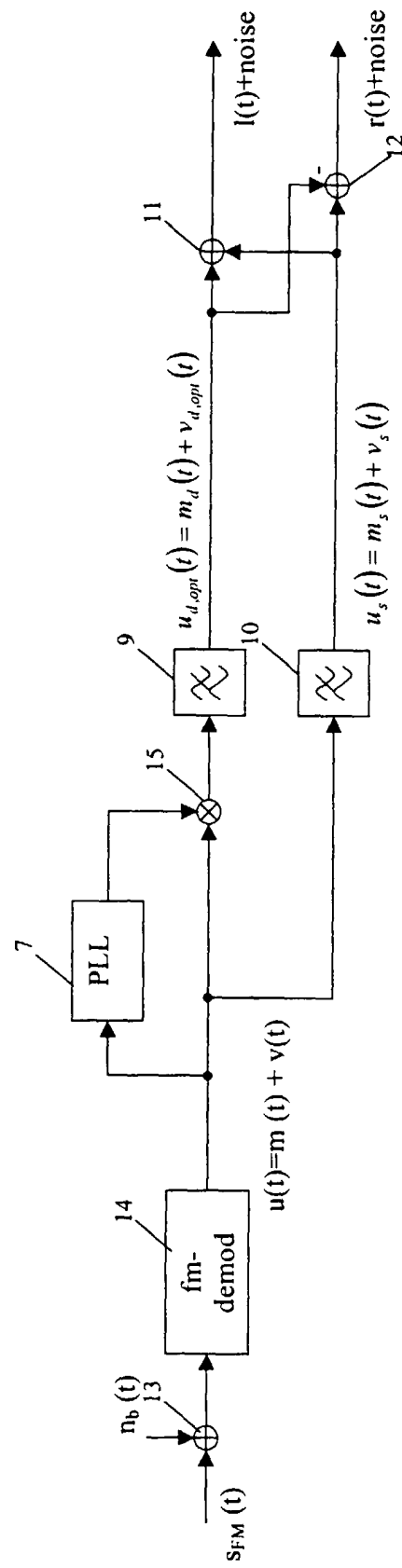


Figure 6:

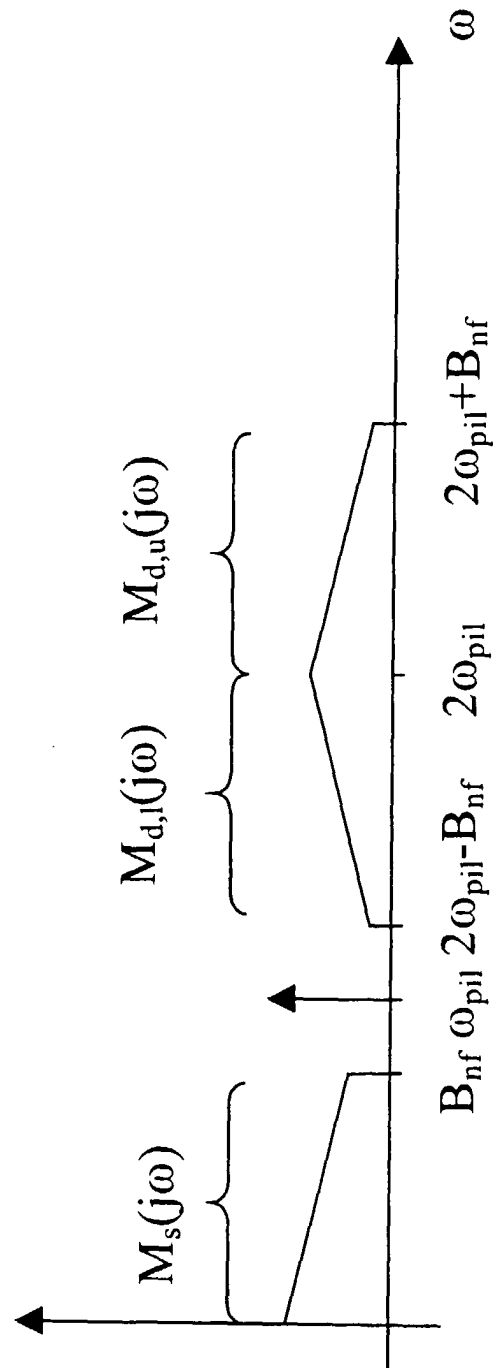


Figure 7:

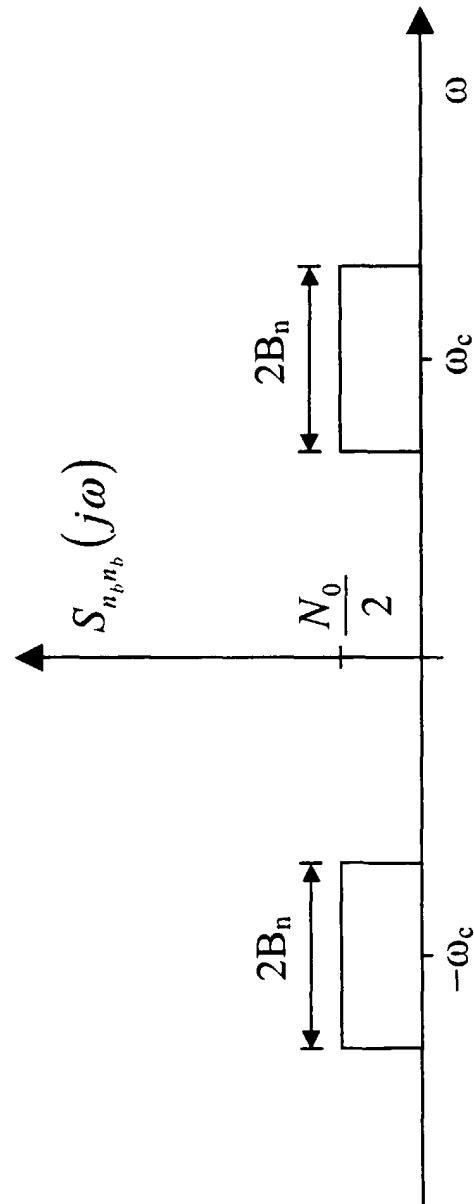
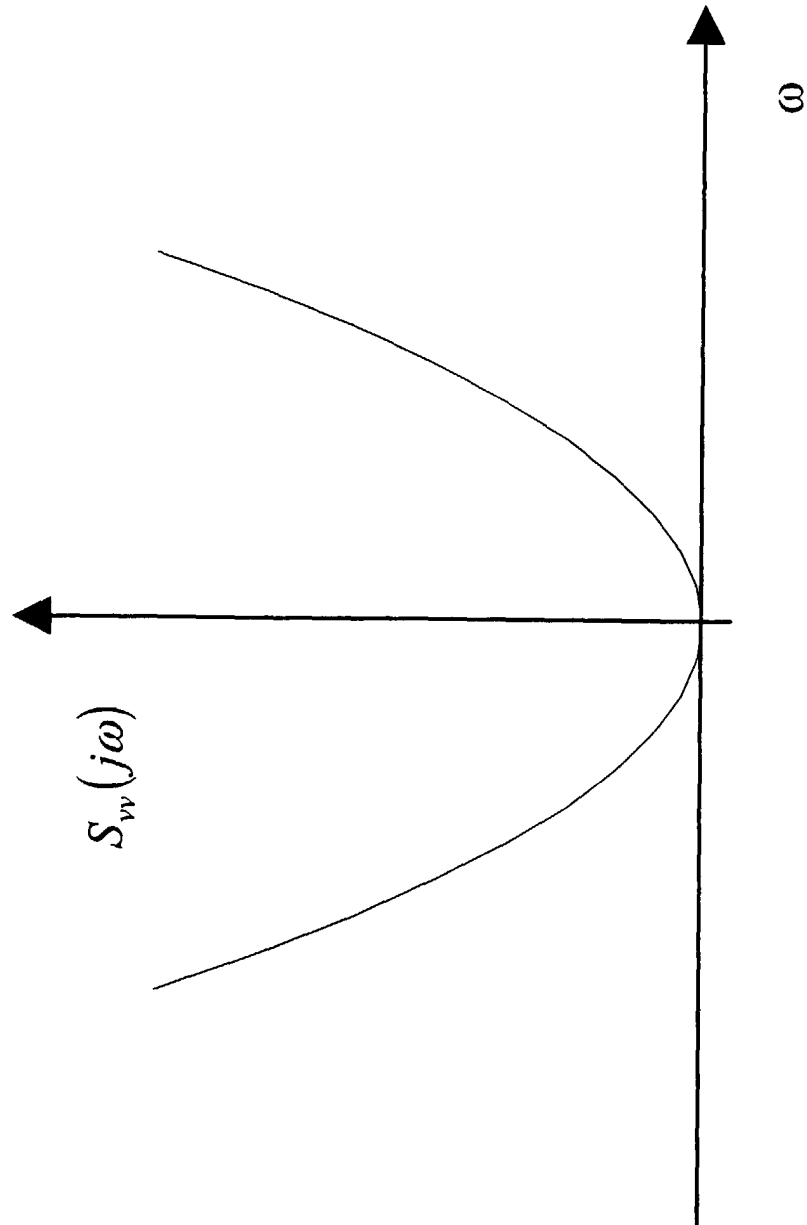


Figure 8:





European Patent
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EUROPEAN SEARCH REPORT

Application Number
EP 99 11 4353

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.7)
X	US 4 771 464 A (KADIN JEFFREY B ET AL) 13 September 1988 (1988-09-13) * abstract * * column 16, line 11 - line 19 * * figure 2 *	1-10	H04H5/00
X	US 3 883 700 A (BAUER BENJAMIN B ET AL) 13 May 1975 (1975-05-13) * abstract * * claims 1,2 * * figure ALL *	1-10	
A	US 5 077 616 A (KLUTH HANS-JUERGEN) 31 December 1991 (1991-12-31) * abstract * * column 1, line 49 - column 3, line 2 * * figure 2 *	1-10	
The present search report has been drawn up for all claims			TECHNICAL FIELDS SEARCHED (Int.Cl.7)
			H04H
Place of search THE HAGUE		Date of completion of the search 16 December 1999	Examiner Simon, V
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EP 99 11 4353

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16-12-1999

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