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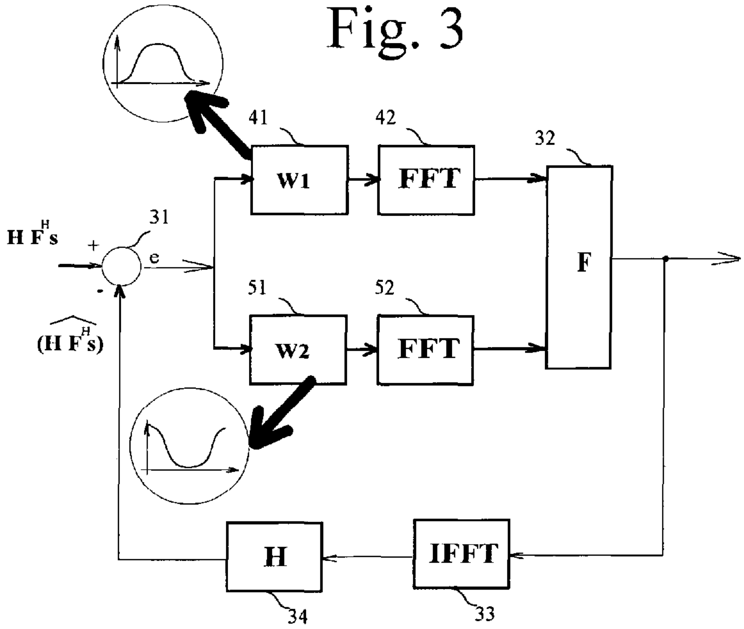
(54) **Title**: SYSTEM AND METHOD FOR OFDM RECEPTION IN THE PRESENCE OF DOPPLER EFFECT BASED ON TIME DOMAIN WINDOWING

Fig. 3



(57) **Abstract**: An OFDM receiver for processing a OFDM received signal to perform OFDM reception in presence of Doppler, comprising: - at least two parallel processing chains, comprising each: - a time domain windowing (41, 51) for processing a OFDM block, said processing consisting in the multiplication, element by element of said OFDM block, by a set of predetermined coefficient, - a DFT block (42, 52) (such as FFT) for demodulating said windowed OFDM symbol into the frequency domain equivalent, characterized in that the windowings of said at least two parallel processing chains have complementary profile so as to avoid any loss of information throughout the OFDM sample. The invention also provides a process to be used in a OFDM receiver.

WO 2010/102829 A1

SYSTEM AND METHOD FOR OFDM RECEPTION IN THE PRESENCE OF DOPPLER EFFECT BASED ON TIME DOMAIN WINDOWING

Technical field

The invention relates to the field of wireless digital communications and more particularly to a process for processing a OFDM received signal to perform OFDM reception in presence of Doppler, based on a time domain windowing.

Background Art

Digital wireless communications are being widely used throughout the world particularly with the latest development of the Orthogonal Frequency Division Multiplex (OFDM systems) and the latest evolution, namely the so-called Long Term Evolution (LTE), DVB-H, WiFi 802.11 and WiMax 802.16 systems. It is well-known by one skilled in the art that OFDM communication systems performances are severely impaired by the rising of inter-carrier interference (ICI) effect in the presence of time-varying propagation channels. Those circumstances occur in mobile cellular OFDM communication systems as those envisaged in above mentioned standards.

It is well-known that classical OFDM low-complexity detection techniques are severely impaired when the user equipment (UE) moves at high velocity. Those conditions result in fast time-varying propagation channels and high Doppler spread which in turn yields to significant ICI. The so increased ICI prevents classical OFDM receiver schemes from reliably detecting the desired signal. Hence more advanced receiver equalization techniques are required to mitigate the effect of the ICI.

It is well-known from the literature that a solution to the above ICI mitigation-equalization optimization problem is readily found if the receiver could afford to support the complexity involved by a full matrix inversion. In existing telecommunication systems, such a full channel matrix inversion operation cannot be supported by a practical mobile receiver.

Hence several approaches have been introduced to reduce the complexity of the above optimization problem. To this end the use of time-domain windowing of the OFDM symbol has been shown to limit the span of inter-carrier interference and allow for frequency-domain iterative detection exploiting the voluntarily-generated banded nature of the new channel matrix.

Figure 1 illustrates the general principle of a prior art technique using one time domain windowing. One sees that, in the transmitter part of the OFDM system, the frequency domain signal s is being converted in the time domain by means of a inverse Fourier Transform block 11 before being serialized by a parallel to serial block 12 and transmitted through a propagation channel represented by block H. In the receiver, a time domain windowing is applied on the signal received from the antenna before the serial to parallel conversion by a block 15 and the Fourier transform by block 16. Time domain windowing is based on the multiplication of the samples of one Block by coefficients embodying a window. Such operation has the effect of controlling the inter-carrier interference (ICI), i.e. the interference among different subcarriers, and causes the limitation of the span of the matrix $\mathbf{FWHF}^{\mathbf{H}}$ between the transmitted sequence s and the received signal r .

$$\mathbf{r} = \mathbf{F}\ \mathbf{W}\mathbf{H}\ \ \mathbf{F}^{\mathrm{H}}\mathbf{s}$$

The result is that equalization is facilitated on such span limited matrix.

However this known technique has a serious drawback in that the time domain window results in loss of energy of the received signal due to the suppression of some samples of the received signal.

Figure 2 shows the equivalent model of that prior art technique consisting of the time domain windowing block 21, the Fast Fourrier transform block 22, and then followed by a Decision Feedback Equalizer embodied by a forward filter 23, adder-subtractor 24 and a backward filter 25 arranged in a feedback loop. The loss of information resulting from the time domain windowing has the result of jeopardizing the convergence of the equalizing process.

Such technique shows unsatisfactory when the Doppler effects is increased because of the loss of information resulting from the time domain windowing being performed.

Such is the technical problem to solve by the present invention.

Summary of the invention

It is an objective of the present invention to provide a OFDM receiver which yields optimal detection performance for the desired signal by means of complexity-effective inter-carrier interference (ICI) cancellation.

It is a further object of the present invention to provide a OFDM receiver which includes time domain windowing and providers fast convergence of the equalization process.

It is still another object of the invention to provide a process which is adapted to carry out an OFDM receiver, such as, for instance, a LTE communication system.

These and other objects of the invention are carried out by means of a OFDM receiver for processing a OFDM received signal to perform OFDM reception in presence of Doppler which comprises at least two parallel processing chains, each comprising:

- a time domain windowing for processing a OFDM block, said processing consisting in the multiplication, element by element of said OFDM block, by a set of predetermined coefficient,

- a DFT block such as FFT for demodulating said windowed OFDM symbol into the frequency domain equivalent,

Because of the complementary profiles of the at least two windowing operations applied in the time domain , the processing of the signal received from the communication system can be done without loss of data, what guarantees the use of the maximum energy of the received signal.

In one embodiment, the OFDM receiver includes a linear multipath equalizer and detector which receives the output of the parallel processing chains and outputs an estimated sequence of transmitted data.

In one embodiment, the receiver includes a feedback loop comprising a Inverse Fourier Transfer block and a block corresponding to the estimated channel H of the propagation channel. A cancellation loop is arranged in the time domain field, based on a subtractor (31) subtracting the output of the feedback loop to the received signal before it is passed to the at least two windowing paths.

This cancellation loop performed at the time domain level, allows fast convergence of the equalization process.

In practical circumstances, as a particular embodiment , the OFDM receiver comprising only two parallel time domain windowing having complementary profiles is shown to provide nearly optimal performances at limited complexity.

In particular, this allows to reduce the complexity of the receiver (of the order $N x \log_2 N$) which is significant less than the complexity (NxN) resulting from a full NxN matrix inversion.

In one embodiment, the inear multipath equalizer and detector includes a multipath Decision Feedback Equalization (DFE).

Alternatively, the linear multipath equalizer and detector include a multipath MMSE equalizer.

In one embodiment, the linear multipath equalizer and detector includes channel code detection such as Turbo or Viterbi decoding means for decoding the data before it is passed to the feedback loop.

The invention also provides a method for processing a OFDM received signal to perform OFDM reception in the presence of Doppler spread, comprising the following steps:

- subtracting the received signal in the time domain with the output of a feedback loop comprising a IFFT block and a channel estimate (H) block;
- inputting the output of said subtractor to at least two parallel processing chains, comprising each:
    - a time domain windowing (41, 51) step for processing a OFDM block, said processing consisting in the multiplication, element by element of said OFDM block, by a set of predetermined coefficient,
    - a DFT step (42, 52) (such as FFT) for demodulating said windowed OFDM symbol into the frequency domain equivalent, the windowings of said at least two parallel processing chains have complementary profile so as to avoid any loss of information throughout the OFDM sample.
- applying a linear multipath equalization and detection process for the purpose of generating an estimate of the transmitted sequence to be forwarded to said feedback loop..

The invention is suitable for the realization of mobile receivers for LTE , DVB-H, Wifi 802.11 and WiMax 802.16.

Description of the drawings

Other features of one or more embodiments of the invention will best be understood by reference to the following detailed description when read in conjunction with the accompanying drawings.

Figure 1 illustrates the general principle of a prior art technique using one time domain windowing.

Figure 2 shows the equivalent model of the prior art technique.

Figure 3 illustrates one embodiment of a OFDM receiver in accordance with the present invention based on two parallel time domain windowing.

Figure 4 shows the equivalent Basis Expansion Model of the transmitter and of the propagation channel to give the time domain received signal.

Figure 5 shows the classical OFDM Matched filter receiver operating on several branches corresponding to several time-domain windowing.

Figure 6 shows the improved OFDM receiver to perform Inter Carrier Interference cancellation operating on several time-domain windowing branches

Figure 7 shows the implementation of an iterative receiver in frequency-domain based on the improved OFDM receiver performing ICI cancellation in open format.

Figure 8 shows the implementation of an iterative receiver in time-domain based on the improved OFDM receiver performing ICI cancellation in open format.

Figures 9 – 12 show the result of simulations of the present invention in four particular situations.

Description of the preferred embodiments

The invention is suitable for any OFDM receiver, and more particularly to a LTE-A product, such as complying with the 3GPP standard specification.

Figure 3 shows the general architecture of one embodiment of OFDM receiver.

The signal received from the antenna is

$$\mathbf{H}\,\mathbf{F}^{\mathrm{H}}\,\mathbf{s}$$

with s being the transmitted frequency domain sequence, F^H being the inverse Fourrier Transform applied in the transmitter and H being the propagation channel.

The invention comprises a feedback loop arranged in the time domain level, based on a subtractor 31 having a first input receiving the Hx F^H s signal from the antenna and a second input receiving the output of a feedback loop of blocks 33 (Inverse Fast Fourrier Transform) and 34 (Channel estimate H).

In addition to subtractor 31, the receiver comprises at least a first and a second path comprising each a time domain windowing block associated with its own Discrete Fourier Transform or DFT (or FFT). One key point of the present invention resides in the fact that the different time domain windowing are arranged in such a way as to prevent any loss of information in the received signal. For that purpose, the windowings are chosen so as to provide complementary profiles.

For the sake of clarity , figure 3 only illustrates two windowing process, respectively based on a first windowing block W1 41 embodying a first concave profile (represented in the figure) and a second windowing block W2 51 emboyding a second convex profile (illustrated in the figure).

It can be seen that the two profiles being illustrated in the figure result in the fact that no samples in the OFDM block is being lost and the two different paths, respectively based on blocks 41-42 and 51-52 provide a full and comprehensive information, without any loss to a Block 32.

Block 32 embodies a linear multi-path equalizer and estimation block which may use any conventional equalization technique, such as a Decision Feedback Equalization (DFE) , Minimum.Mean.Square Error (MMSE) Equalizer. The point is that block 32 receives information from at least two parallel processing paths or channels (resp. 41-42 and 51-52).

Alternatively, Block 32 may include a detector based on turbo code decoding as well as some preconditioning algorithms in order to facilitate convergence of the equalizing and detection process.

In any case, it can be seen that the general architecture of the receiver which is based on at least two complementary windowing profiles significantly facilitates the equalizing process because it avoids loss of information in the receiver.

The receiver further comprises, in order to complete the feedback loop, a inverse Fourier Transform block IFFT 33 followed by a block 34 which comprises the estimate of the channel H. Estimation of the channel in block 34 is performed by means of conventional techniques based on the use of pilot signals as known by a skilled man.

It can therefore be seen that the invention provides an adaptive feedback loop which is surprisingly arranged in the time domain level which is quite novel. Such feedback loop has the drawback of requiring two FFT blocks (resp. 42 and 52) and one IFFT (33), but has the significant advantage of facilitating the equalizing process due to the avoidance of the loss of any information due to the time domain windowings performed.

This results in the possibility of properly processing the Doppler effect without requiring a significant amount of digital processing resources. For instance, implementing a full NxN matrix inversion would lead to a complexity of the order of N^2 while, with the invention , the complexity remains reasonable since it is only proportional to Nxlog2.

This low complexity is achieved without the loss of any information, which could not be prevented with the known prior art technique based on one single time domain windowing and a feedback loop located within the frequency domain only.

. Figures 4-9 illustrates the application of the principle of the invention to P parallel paths, each associated with a given time domain window.

Figure 4 shows the equivalent model of the OFDM transmitter and the time-varying propagation channel plus noise cascade HxF^Hxs+z in a Basis Expansion Model form. In fact the cascade of HxF^H can be equivalently written as the sum of the combination of several branches each comprising the cascade of a diagonal matrix D_p, an inverse Fourier trasform F^H and a basis function corresponding to the diagonal matrix B_p. Moreover the basis function B_p can be seen as an equivalent transmitter windowing operation.

D_0, D_1 ,.... D_{P-1} represent the channel coefficients for each basis function B_0, B_1 ,.... B_{P-1}. z represents the additive noise, s the tranmsitted sequence and r the received signal.

Figure 5 shows the classical Matched Filter (MF) OFDM receiver in its Basis Expansion Model form. This receiver is one possible arrangement for estimating the $\hat{s}_{MF}$ from the received signal r. This figure shows how the equivalent transmitter model of figure 4 is exploited in the receiver structure, the classical Matched Filter in this case. $B^H{}_0$, $B^H{}_1$,.... $B^H{}_{P-1}$ represent the conjugate transpose diagonal matrix of the basis function B_0, B_1 ,.... B_{P-1} at the transmitter of figure 4. $B^H{}_0$, $B^H{}_1$,.... $B^H{}_{P-1}$ are exactly equivalent to the time-domain windowing operations W1 and W2 of Figure 2 where only two basis are only showed (Hence W1= B^H_0 and W2= B^H_1). D^H_0, D^H_1 ,.... D^H_{P-1} represent the conjugate transpose channel coefficients for each basis function B_0, B_1 ,.... B_{P-1} r is the received signal and $\hat{s}_{MF}$ is the estimated sequence according to the Matched Filter criterium.

Figure 6 shows the equivalent model providing the estimation of $\hat{s}_{P\text{-}MMSE}$ in the case of a P multipath time domain windowing corresponding to the Basis Expansion Model as in previous figure but for an improved detection technique based on MMSE equalization and able to cancel Inter Carrier Interference. Again, B^H_0, B^H_1 ,.... B^H_{P-1} represent the conjugate transpose diagonal matrix of the basis function B_0, B_1 ,.... B_{P-1} at the transmitter of figure 4 and D^H_0, D^H_1 ,.... D^H_{P-1} represent the conjugate transpose channel coefficients for each basis function B_0, B_1 ,.... B_{P-1}. G denotes the ICI cancelling MMSE filter and $\hat{s}_{P\text{-}MMSE}$ the estimated transmitted sequence.

Figure 7 shows the implementation of an iterative receiver in its open form exploiting the Basis Expansion Model of the channel and the multi-windowing approach based on Matched Filtering. The blocks U is exactly equivalent to the multi-branch representation given in figure 5. Therefore U= $D_0xF^HxB_0$+ $D_1xF^HxB_1$+.. $D_{P-1}xF^HxB_{P-1}$. U^H is its transpose conjugate, i.e. U^H= $D^H_0xFxB^H_0$+ $D^H_1xFxB^H_1$+.. $D^H_{P-1}xFxB^H_{P-1}$. σ^2 represents the knowledge of the noise variance or an estimate if available. w(0) ..w(K) represent some combining weighting factors used to retrieve the final trasnmitted sequence estimate $\hat{s}$.

Figure 8 shows the implementation of an iterative receiver in its open form exploiting the Basis Expansion Model of the channel and the multi-windowing approach based on MMSE filtering. The blocks U denotes again the multi-branch representation given in figure 5. Therefore U= $D_0xF^HxB_0$+ $D_1xF^HxB_1$+.. $D_{P-1}xF^HxB_{P-1}$. Q denotes a partial matched filter operation, more precisely Q= [FxB^H_0; $D^H_1xFxB^H_1$;... ;FxB^H_{P-1}]. w(0)...w(K) represent some combining weighting factors used to retrieve the final trasnmitted sequence estimate $\hat{s}$

Considering now figures 9-12, there is provided the results of simulation allowing the comparison with the proposed architecture and the prior art methods with respect to the uncoded Bit Error Rate (BER) for a Quadrature Phase Shift Keying (QPSK) modulation.

For the sake of clarity, the following references are used for all figures :

Reference 101 (P-MMSE-PIC MMSE-comb.) shows the Bit Error Rate (BER) in the case of an iterative OFDM receiver exactly as described in figure 8 where the combining weights are chosen according to an MMSE criterium..

Reference 102 (P-MMSE-PIC simple comb.) shows the BER in the case of n iterative OFDM receiver exactly as described in figure 8 where the combining weights are all equal to one and referred as “simple combining”.

Reference 103 (MF-HD-PIC) shows the BER in the case of an iterative OFDM receiver exactly as described in figure 7 where the combining weights are substituted by hard-decisions, i.e. the sign of the intermediate decoded signals are only retained..

Reference 104 (MF-PE-Muller) shows the BER in the case of an iterative OFDM receiver exactly as described in figure 7 where the combining weights are computed according to the Mueller Polynomial Expansion formula..

Reference 105 shows the Block Error Rate in the case of the use of the full-MMSE method which, as known by the skilled man, provides the best results.

Reference 106 (ZFinvApproxMat1) shows the BER in the situation to a receiver that iteratively approximates the inverse of the frequency-domain channel matrix $FxHxF^H$ according to Mc Laurin expansion. This BER performance is used as a reference of alternative feasible iterative technique known to the man skilled in the art....

Reference 107 (ZfinvApproxMat2) shows the BER in the situation of to a receiver that iteratively approximates the inverse of the frequency-domain channel matrix $FxHxF^H$ according to Newton expansion formula. This BER performance is used as a reference of alternative feasible iterative technique known to the man skilled in the art....

It can be seen that the invention proposes a general framework for an OFDM receiver where a BEM is adopted to allow effective preconditioning for fast-converging iterative ICI cancellation algorithms, in both time and frequency domains, which provide nearly optimal performances for the desired signal detection with limited complexity. The particular structure of the proposed algorithms lends itself to a modular and scalable architecture implementation where complexity can be further reduced at the expense of minor performance losses.

The following advantages have been discovered:

Nearly optimal performances with linearly bounded complexity

Fast-converging iterative interference cancellation algorithms thanks to suited use of BEM based preconditioning

Modular recursive algorithms structure for modular and scalable architecture implementation

Architecture ready for BEM based channel estimation

The use of the proposed architectures shows that:

1.Windowing techniques are re-interpreted and generalized under the framework of the Basis Expansion Modeling (BEM) of the time-varying channel.

2.The general framework provided by the BEM allows effective preconditioning for fast-converging iterative ICI cancellation algorithms, in both time and frequency domains, which provide nearly optimal performances for the desired signal detection

3.The newly introduced pre-conditioned iterative interference cancellation algorithms have limited bounded complexity (linear with the OFDM block size)

4.From a practical implementation viewpoint, the newly introduced pre-conditioned iterative interference cancellation algorithms recursive structure lends itself to a modular and flexible architecture where complexity can be even more significantly reduced at the expense of minor performance losses

5.The BEM general framework along with the preconditioned fast-converging iterative ICI cancellation, provides also means for low complexity accurate channel estimation resulting in even better desired signal detection performances

6.The proposed algorithms can be used in combination with channel decoding, in particular with turbo decoding for fast converging so-called turbo-equalization (shown to perform close to the perfect-interference-cancellation bound)

7.The invention provides a general framework to consistently describe and compare most known receiver techniques. Analytical and numerical results will be provided to this end.

Claims

1. OFDM receiver for processing a OFDM received signal to perform OFDM reception in presence of Doppler, characterized in that it comprises:

- at least two parallel processing chains, comprising each:
  - a time domain windowing (41, 51) for processing a OFDM block, said processing consisting in the multiplication, element by element of said OFDM block, by a set of predetermined coefficient,
  - a DFT block (42, 52) (such as FFT) for demodulating said windowed OFDM symbol into the frequency domain equivalent,

  the windowings of said at least two parallel processing chains have complementary profile so as to avoid any loss of information throughout the OFDM sample.

2. OFDM receiver according to claim 1 characterized in that it further includes a linear multipath equalizer and detector (32) receiving the output of said parallel processing chains and outputting an estimation of the sequence of transmitted data, and that it further includes:

- a subtractor (31) having a first input receiving the received signal, a second input receiving the output signal from a feedback loop (33, 34) and having an output for providing data to the input of said at least two parallel processing chains;
- a feedback loop comprising:
  - a Inverse Fourier Transfer block (33) embodying an Inverse Fourier transfer corresponding to the IFFT used in the transmitter;
  - a block (34) corresponding to the estimated channel H of the propagation channel;

3. OFDM receiver according to claim 1 characterized in that it comprises two parallel time domain windowing having complementary profiles.

4. OFDM receiver according to anyone of claims 1 to 3 characterized in that said linear multipath equalizer and detector (32) includes a multipath Decision Feedback Equalization (DFE).

5. OFDM receiver according to anyone of claims 1 to 3 characterized in that said linear multipath equalizer and detector (32) includes a multipath MMSE equalizer.

6. OFDM receiver according to anyone of claims 1 to 3 characterized in that said linear multipath equalizer and detector (32) includes turbo code detection means for decoding the data before it is passed to the feedback loop (33, 34).

7. OFDM receiver according to anyone of the preceding claims characterized in that it is used for a Long Term Evolution (LTE) Terminal Equipment.

8. OFDM receiver according to anyone of the preceding claims characterized in that it is used for a mobile telephone.

9. OFDM mobile terminal receiver adapted for existing telecommunication standards such as the 3GPP Long Term Evolution (LTE), DVB-H, WiFi 802.11 and WiMax 802.16 systems including:

- at least two parallel processing chains, each comprising:
  - a time domain windowing (41, 51) for processing a OFDM block, said processing consisting in the multiplication, element by element of said OFDM block, by a set of predetermined coefficient,
  - a DFT block (42, 52) (such as FFT) for demodulating said windowed OFDM symbol into the frequency domain equivalent,

  the windowing of said at least first and second chains have complementary profile so as to avoid any loss of information throughout the OFDM sample.

10. Mobile terminal receiver according to claim 9 characterized in that it further includes a linear multipath equalizer and detector (32) receiving the output of said parallel processing chains and outputting an estimation of the sequence of transmitted data,

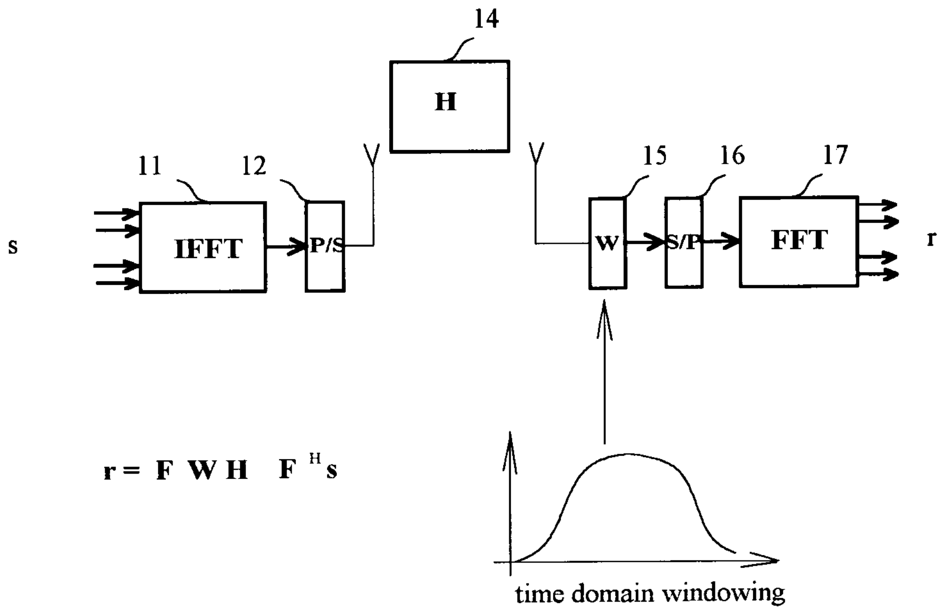
and that it further includes:

- a subtractor (31) having a first input receiving the received signal, a second input receiving the output signal from a feedback loop (33, 34) and having an output for providing data to the input of said at least two parallel processing chains;

- a feedback loop comprising:
  - a Inverse Fourier Transfer block (33) embodying an Inverse Fourier transfer corresponding to the IFFT used in the transmitter;
  - a block (34) corresponding to the estimated channel H of the propagation channel;

11. Process for processing a OFDM received signal to perform OFDM reception in presence of Doppler, comprising the following steps:

- subtracting the received signal in the time domain with the output of a feedback loop comprising a IFFT block and a channel estimate (H) block;
- inputting the output of said subtractor to at least two parallel processing chains, comprising each:
  - a time domain windowing (41, 51) step for processing a OFDM block, said processing consisting in the multiplication, element by element of said OFDM block, by a set of predetermined coefficient,
  - a DFT step (42, 52) (such as FFT) for demodulating said windowed OFDM symbol into the frequency domain equivalent, the windowings of said at least two parallel processing chains have complementary profile so as to avoid any loss of information throughout the OFDM sample.
- applying a linear multipath equalization and detection process for the purpose of generating an estimate of the transmitted sequence to be forwarded to said feedback loop.


14
H
11
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s
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time domain windowing

Fig. 1

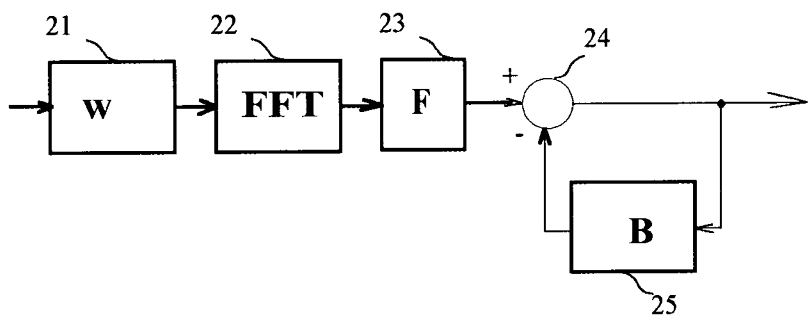
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Fig. 2

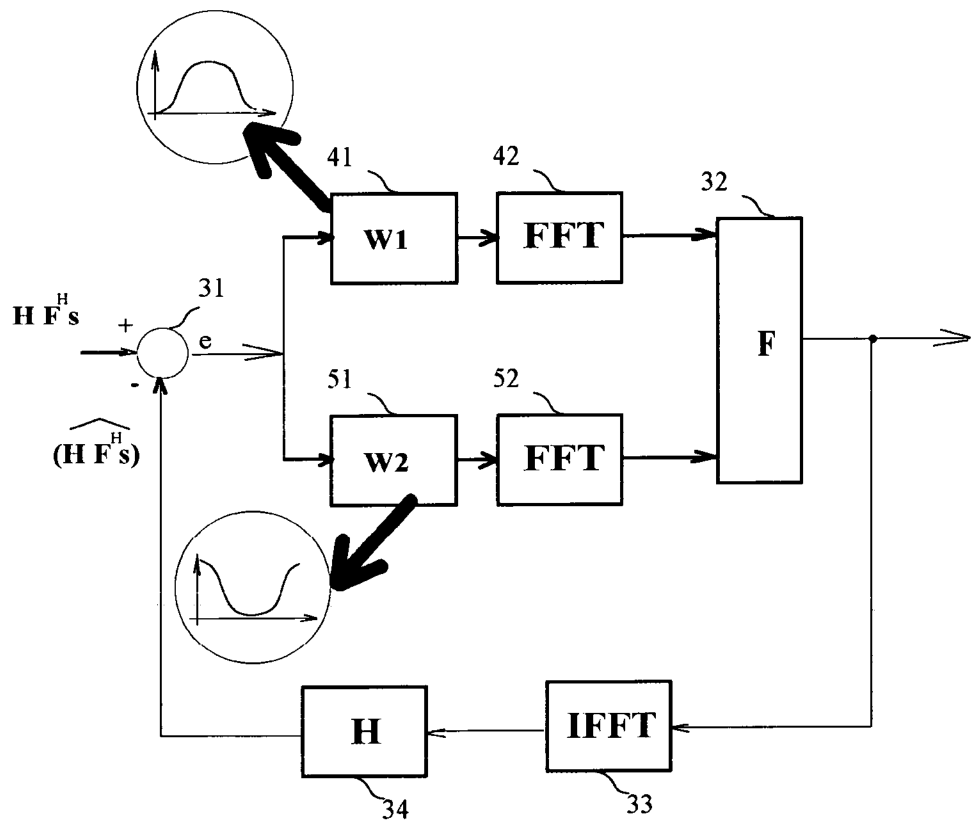


Fig. 3

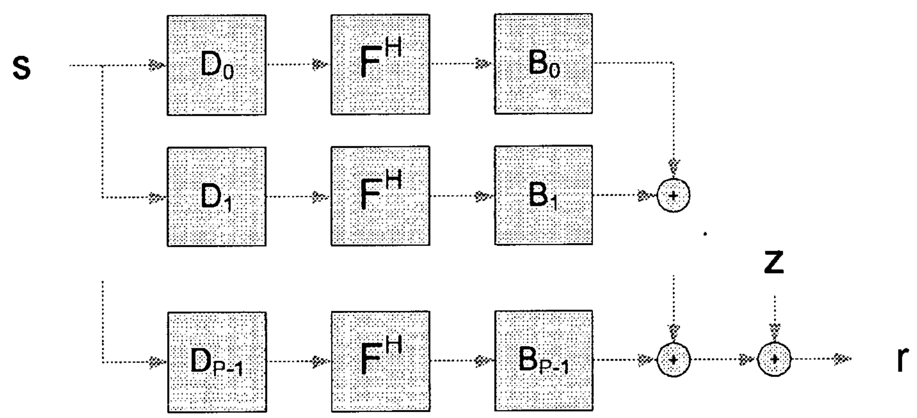


Fig. 4

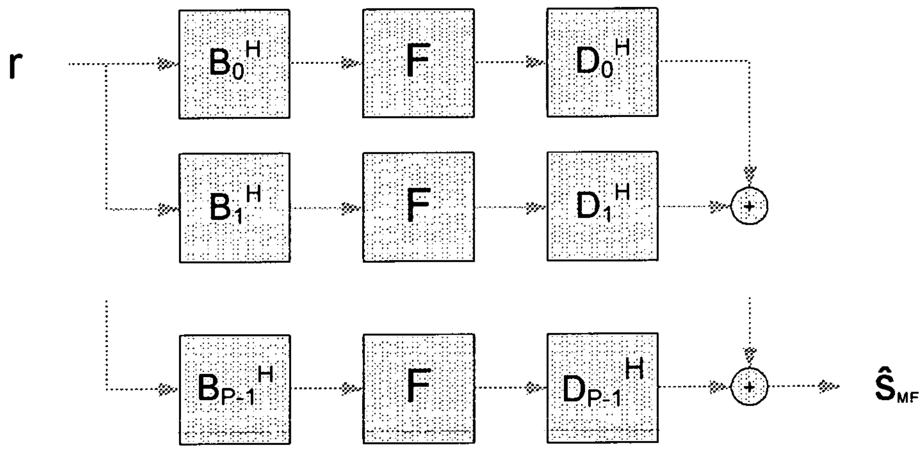


Fig. 5

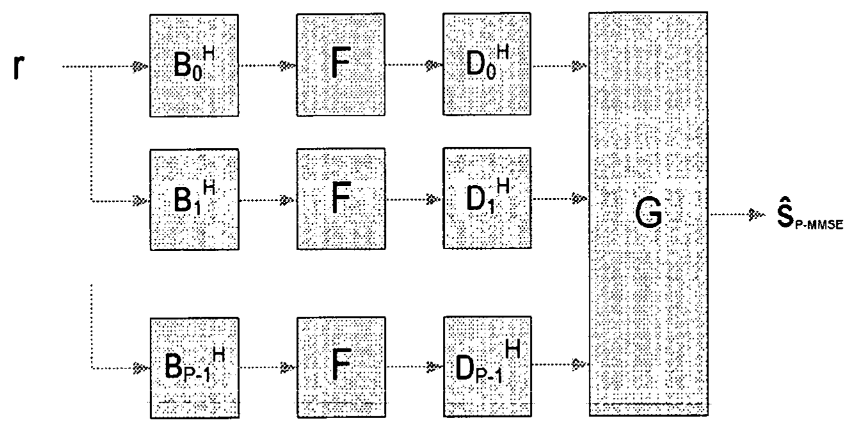


Fig. 6

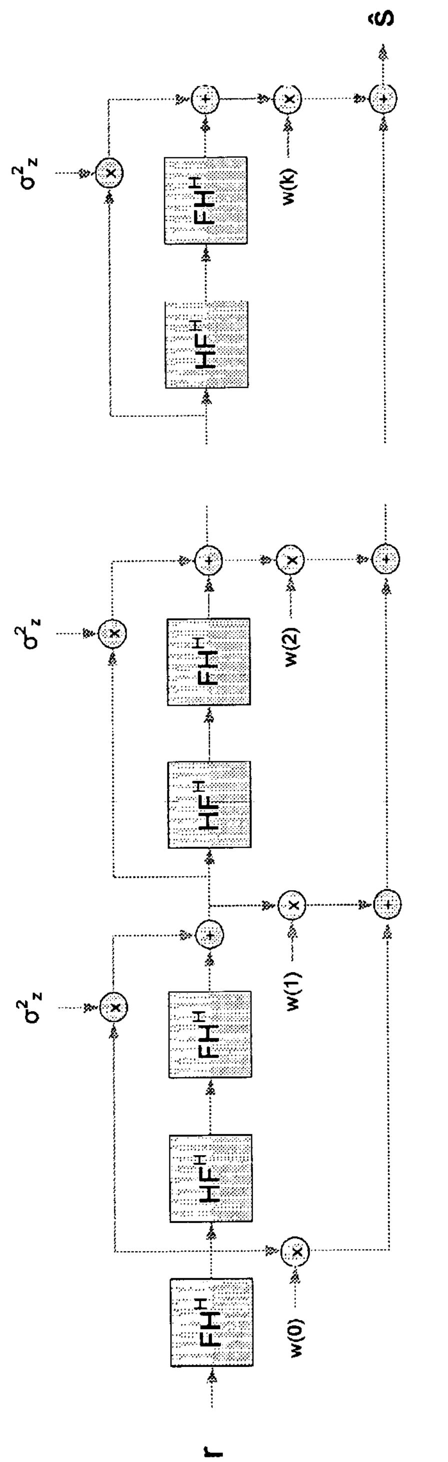


Fig. 7

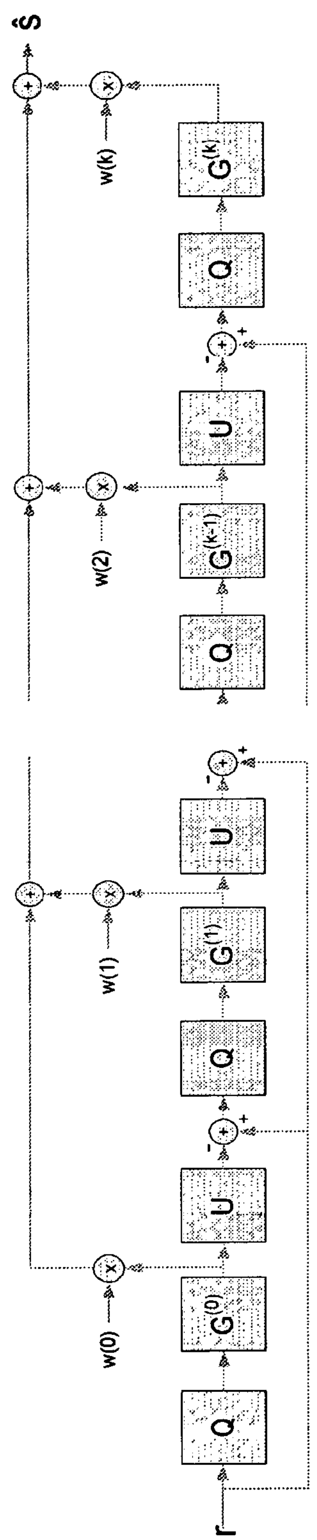


Fig. 8

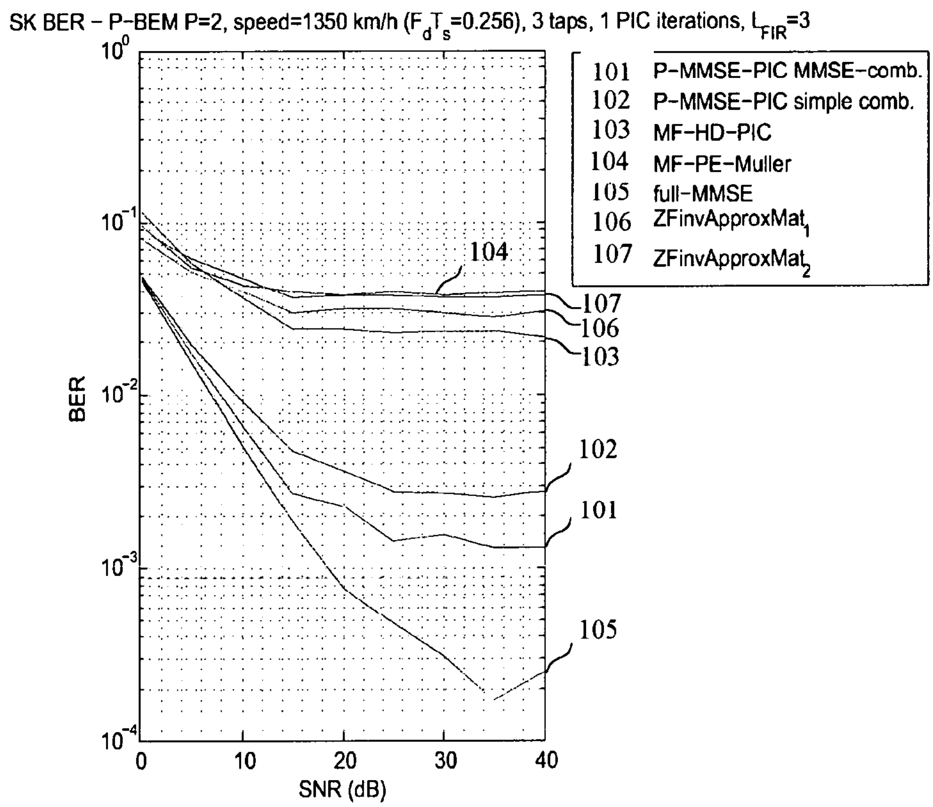

SK BER – P-BEM P=2, speed=1350 km/h (F_dT_s=0.256), 3 taps, 1 PIC iterations, L_{FIR}=3
BER
SNR (dB)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
10
20
30
40
101 P-MMSE-PIC MMSE-comb.
102 P-MMSE-PIC simple comb.
103 MF-HD-PIC
104 MF-PE-Muller
105 full-MMSE
106 ZFinvApproxMat$_1$
107 ZFinvApproxMat$_2$
104
107
106
103
102
101
105

Fig. 9

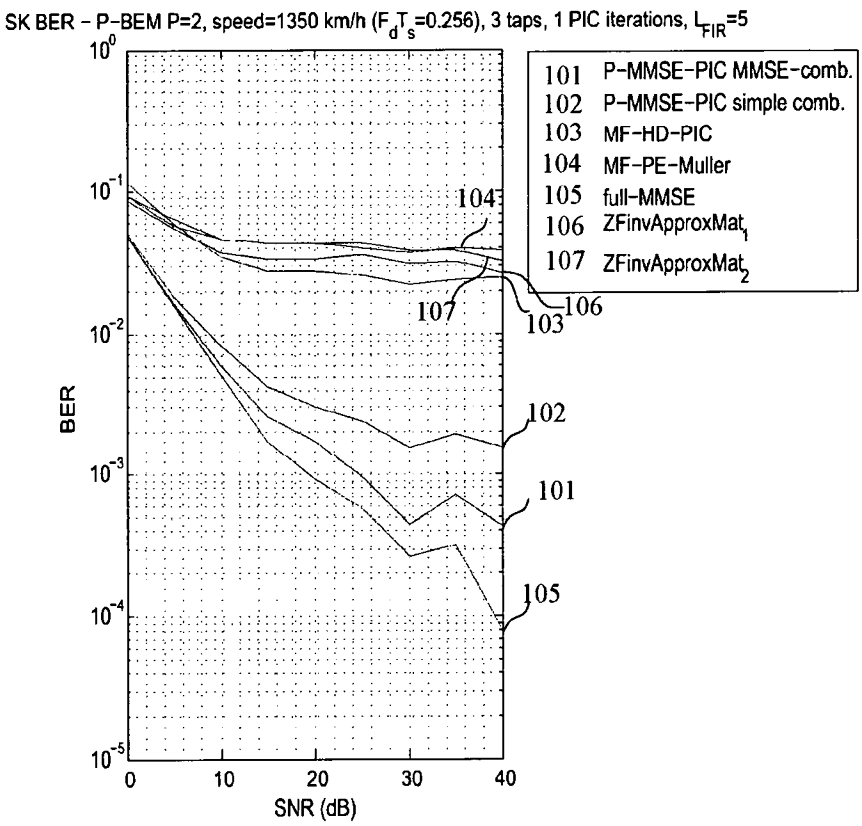

SK BER - P-BEM P=2, speed=1350 km/h (F_dT_s=0.256), 3 taps, 1 PIC iterations, L_{FIR}=5
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
BER
0
10
20
30
40
SNR (dB)
101 P-MMSE-PIC MMSE-comb.
102 P-MMSE-PIC simple comb.
103 MF-HD-PIC
104 MF-PE-Muller
105 full-MMSE
106 ZFinvApproxMat$_1$
107 ZFinvApproxMat$_2$
104
107
103
106
102
101
105

Fig. 10

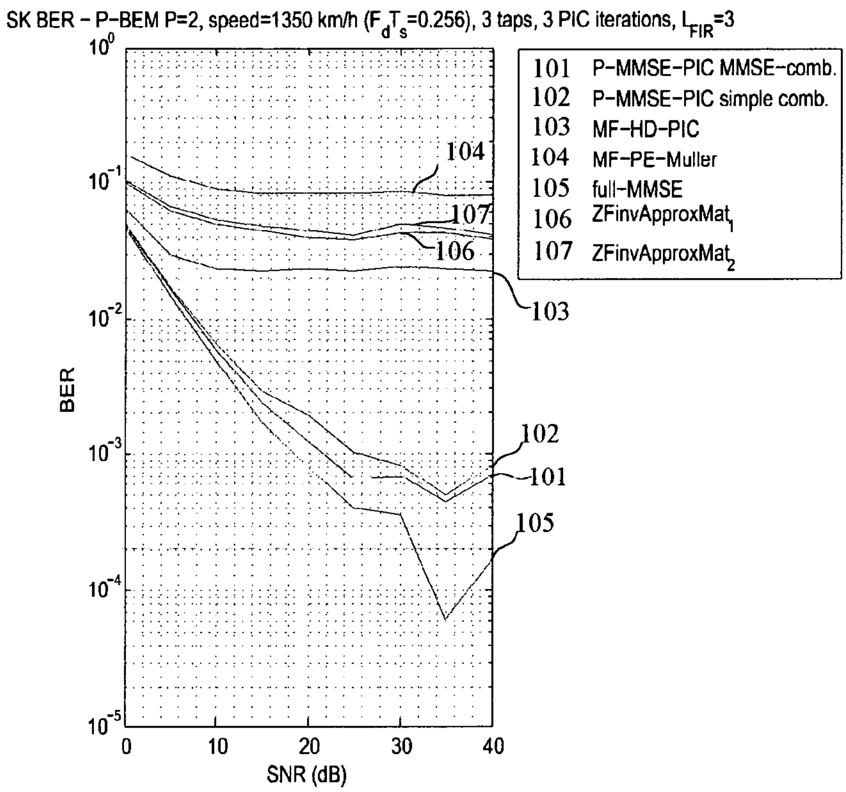
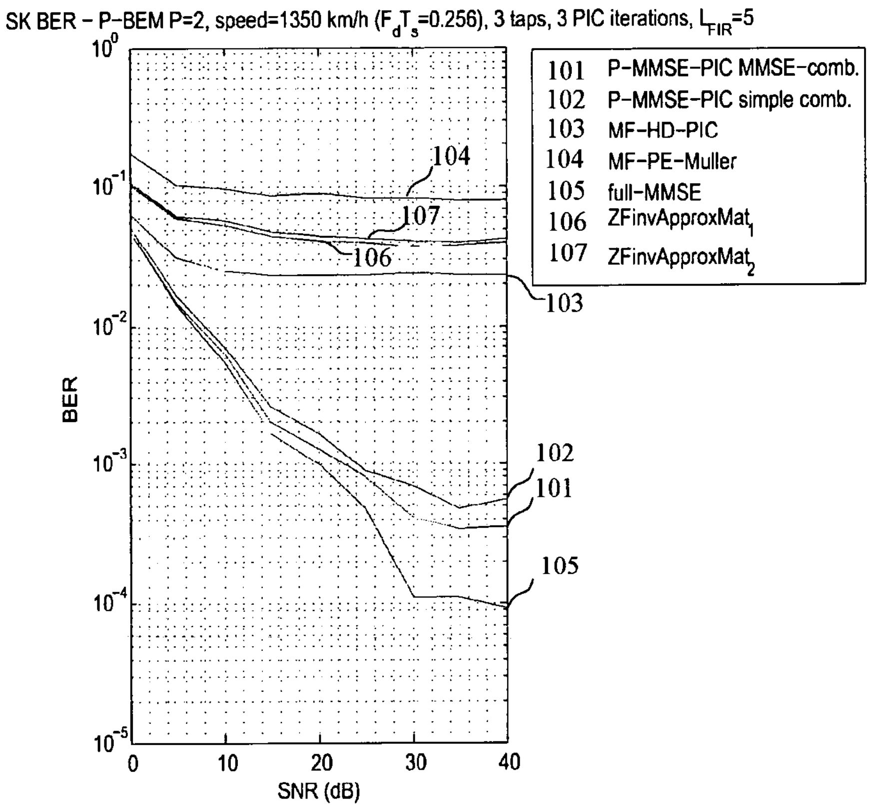

SK BER - P-BEM P=2, speed=1350 km/h (F_dT_s=0.256), 3 taps, 3 PIC iterations, L_{FIR}=3
BER
SNR (dB)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
10
20
30
40
101 P-MMSE-PIC MMSE-comb.
102 P-MMSE-PIC simple comb.
103 MF-HD-PIC
104 MF-PE-Muller
105 full-MMSE
106 ZFinvApproxMat$_1$
107 ZFinvApproxMat$_2$
104
107
106
103
102
101
105

Fig.11


SK BER - P-BEM P=2, speed=1350 km/h (F_dT_s=0.256), 3 taps, 3 PIC iterations, L_{FIR}=5
101 P-MMSE-PIC MMSE-comb.
102 P-MMSE-PIC simple comb.
103 MF-HD-PIC
104 MF-PE-Muller
105 full-MMSE
106 ZFinvApproxMat$_1$
107 ZFinvApproxMat$_2$
BER
SNR (dB)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
10
20
30
40
104
107
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103
102
101
105

Fig.12

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2010/001557

A. CLASSIFICATION OF SUBJECT MATTER
INV. H04L25/03 H04L27/26
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H04L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, INSPEC, COMPENDEX

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 1 860 810 A (FUJITSU LTD [JP]) 28 November 2007 (2007-11-28) abstract paragraphs [0007] - [0011] paragraphs [0020] - [0064] figures 3,7-10 -----	1-11
A	EP 1 043 875 A (NEC USA INC [US]) 11 October 2000 (2000-10-11) abstract paragraphs [0002] - [0018] paragraphs [0023] - [0049] paragraphs [0073] - [0084] paragraphs [0106] - [0115] figure 1 -----	1-11

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
20 May 2010	28/05/2010

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Dhibi, Youssef

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2010/001557

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EP 1860810	A	28-11-2007	CN	101138181	A	05-03-2008
			WO	2006098011	A1	21-09-2006
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			US	7023938	B1	04-04-2006