

ADAPTIVE METHOD FOR COMBATING INTERFERENCE IN A MULTI-RECEPTION-CHANNEL RECEIVER

The field of the invention is antenna processing and it relates to a receiving method implemented in a multichannel receiver, and to a receiver implementing this method. The invention is applicable to radiocommunications and in particular military radiocommunications, whatever the configuration (ground-ground, ground-air or air-air), with no limitation on the frequency band used and particularly in the HF (high-frequency) band, UHF (ultra-high-frequency) band or the C band (4 GHz to 8 GHz). It is in particular applicable to radio transmissions in which a signal is received in the presence of interference, whether it be intentional or not.

During the propagation of a radioelectric signal generated by phase, frequency and/or amplitude modulation of a carrier with a series of symbols, said signal is subject to a number of sources of degradation.

The sources of degradation include the noise intrinsic to the receiver, which may be modelled as a white Gaussian noise. When the signal is received by a plurality of sensors, the noise is assumed to be spatially white (independence between the sensors) and the correlation matrix of the noise may be written $R = \text{diag}(\sigma_k^2)$ where σ_k^2 is the noise power received by the sensor k . In the rest of the document, this noise is said to be temporally and spatially white.

These sources of degradation also include paths associated with multiple reflections of the electromagnetic wave during its propagation. These multipaths are due to reflections from various elements in the surrounding environment, such as buildings or the Earth's relief, but may also originate, as is often the case when HF (high-frequency) transmissions are being processed, from reflections from the various ionospheric layers of the atmosphere. These reflections generate replicas of the signal, which replicas are shifted in time, in phase and/or in amplitude. When the multipaths are received in a time interval shorter than the duration of a symbol, they may sum constructively or destructively. Flat fading is then spoken of, which

requires, in order to improve the quality of the reception, implementation of techniques allowing diversity to be created: time diversity in case of mobility, this type of mobility being obtained by interleaving and coding data over a duration longer than the coherence time of the propagation channel;

5 frequency diversity, which is obtained by way of a frequency hopping mechanism and data coding; or spatial diversity, which is obtained by using a plurality of judiciously spaced transmission and/or reception antennae. When the multipaths are received in a time interval that is longer than the duration of a symbol, they generate inter-symbol interference that degrades the

10 quality of the radio link: selective fading is then spoken of. To remedy this problem, it is then necessary to use propagation channel coding techniques to improve the robustness of the signal, equalization techniques, which seek to estimate the propagation channel and to recombine in time and in phase the various paths, or antenna-processing techniques that aim to optimize the

15 reception of the various useful paths by effectively recombining the signals delivered by the various reception antennae.

Lastly, the sources of degradation include interference related to jamming, whether it be intentional (intentional wideband jamming for example) or unintentional (other signals transmitted via the same frequency

20 resource). Specific processing for combating jamming are then necessary, such as error-correction coding, notch-filter jammer mitigation, frequency hopping or antenna-processing techniques that aim, by judiciously recombining the signals received by an array of sensors, to eliminate the influence of the interference while optimizing the reception of the useful

25 signal.

Among all of the techniques allowing the various sources of degradation affecting the reception of a useful signal to be combated, antenna-processing techniques are the most promising since they allow, via processing of the

30 signals received by the various antennae of an array, the reception of the useful signal to be optimized in the presence of flat fading, selective fading and interference.

To implement most of the aforementioned types of processing, it is conventional to insert into the transmitted signal sequences (called learning

sequences) that are known by the receiver, the sequences allowing the propagation channel in which the interference is present to be estimated. These sequences are repeated periodically, thus allowing variations in the characteristics of the transmission channel to be followed.

5 Single reception-channel or SISO (single input single output) processing reaches its limits when the level of interference becomes excessive or when the propagation conditions are too complex (flat fading even though the coherence bandwidth of the channel is wider than the frequency hop bandwidth, selective fading the passband of which is too large
10 to be equalizable, wideband interference, etc.). It is then necessary to combine it with multi-reception-channel processing, the exploitation of the space diversity created by the use of a plurality of antennae allowing advantage to be taken of the difference between the transmission channels of each antenna.

15 Multi-reception-channel processing includes processing in which the antenna diversity is created on transmission, this type of processing being called MISO (multiple input single output) processing, processing in which the antenna diversity is created on reception, this type of processing being called SIMO (single input multiple output) processing, and processing in
20 which the antenna diversity is created both on transmission and on reception, this type of processing being called MIMO (multiple input multiple output) processing.

The invention is applicable to the case of SIMO processing.

25 In the absence of interference, various receivers may be envisaged depending on the characteristics of the useful propagation channel. When the fading is "flat" (absence of interference between symbols) the optimum processing to implement is the called MRC (maximal ratio-combining) processing.

30 In a multichannel receiver implementing MRC, the signals delivered by the various reception channels are recombined in phase and in amplitude (depending on the power of the signal) so as to maximize the SNR (signal-to-noise ratio) of the useful signal. Thus, in the presence of a temporally and

spatially white noise (i.e. in the absence of interference) and for flat fading (absence of interference between symbols) MRC processing allows space diversity to be optimally exploited.

More precisely, when the fading is flat, the signal vector received by the
5 sensor array may be written:

$$\mathbf{x}(n) = \mathbf{h} s(n) + \mathbf{b}(n) \quad (1)$$

where $s(n)$ is the emitted signal in the sample n , $\mathbf{h}$ is the propagation channel vector and $\mathbf{b}(n)$ is the reception noise vector.

The signal output from the MRC recombination may then be written:

$$y(n) = \frac{\sum \frac{h_i^* x_i(n)}{\sigma_i^2}}{\sum \frac{|h_i|^2}{\sigma_i^2}}, \quad (2)$$

where σ_i^2 is the noise power received by the sensor i .

10

When the fading is "selective" (presence of interference between symbols), the receiver sees its performance degraded and it is necessary to implement multi-reception-channel equalization. A number of multi-reception-channel equalization solutions have been proposed in the literature.

15 When they are designed to operate in non-jammed environments, i.e. environments in which the noise present in each of the reception channels is temporally white and not correlated between the reception channels (i.e. spatially white), these equalization solutions are what are called "non-anti-jamming" solutions.

20 Among these techniques, the optimal solution in terms of maximum likelihood is a receiver based on the FAST-BBST (French acronym for *Filtre Adapté Spatio-Temporel en Bruit Blanc Spatialement et Temporellement* or Spatio-Temporal Filter Adapted for Temporally and Spatially White Noise) followed by a decision unit based on a Viterbi algorithm. The FAST-BBST
25 consists in obtaining an estimation of the propagation channel, then in suitably filtering the propagation channel in each of the reception channels and lastly summing the signals output from the suitable filters. When output from the FAST-BBST, the signal to noise ratio of the current symbol is

maximized and any residual interference between symbols is treated by the Viterbi algorithm.

The main drawback of this receiver, which is optimal in the absence of interference, whether the fading be selective or flat, is that the Viterbi
 5 algorithm requires a computational power that increases as M^L , where M is the order of the constellation and L the size of the propagation channel. Thus, this receiver may be implemented on waveforms such as GSM (Global System for Mobile communication) for which $M=2$ and $L=5$, but not on more recent waveforms, for which the modulation bandwidth is wider and in which
 10 the constellations are of higher order. An alternative to the Viterbi algorithm, and which is less expensive in terms of computational power, is to implement a single-reception-channel equalizer at the output of the FAST-BBST. The single-reception-channel equalizer may be any other type of equalizer known to those skilled in the art, such as for example a DFE (decision feedback
 15 equalizer) a BDFE (block-DFE) or a transverse equalizer.

Solutions in which MRC is implemented post-equalization are an alternative to solutions based on the FAST-BBST

In these solutions, a single-reception-channel equalization is carried out independently in each reception channel and then the estimated (and
 20 therefore unconfirmed) symbols output from each equalizer are recombined depending on the estimated SNR output from each equalizer.

This MRC processing is "almost" optimal in the absence of interference (the "almost" originating from the fact that the equivalent spatio-temporal filter implemented by this solution is different from the optimal filter i.e. the FAST-
 25 BBST) whether the fading be selective or not, and may be adapted to combat narrow-band jammers when a notch-filtering technique is implemented in each of the single-reception-channel equalizers provided in each of the reception channels.

However, the performance of such non-anti-jamming, multi-reception-
 30 channel equalization methods is no longer satisfactory if the interference is not narrow-band interference. The implementation of other types of SIMO processing is then necessary.

To allow operation in a jammed environment, in which the noise received by the various channels is no longer spatially white, it is known to use what are called "anti-jamming" multi-reception-channel equalization methods i.e. methods incorporating techniques for combating the interference associated with jamming and spatially non-white noise. These methods are also known as antenna filtering techniques (when they are referred to in this way, the antenna is considered to be composed of a plurality of elementary antennae and the antenna filtering aims to recombine the signals delivered by these various elementary antennae so as to optimize the reception of the useful signal in the presence of interference) or even as adaptive antenna techniques (to underline the fact that the processing used is able to automatically adapt to variations in interference and propagation conditions).

These techniques were developed from the 1960s. Initially, they were based on spatial filtering (therefore without equalization) of the received signals, i.e. with an amplitude/phase weighting in each sensor. Then from the 1980s/1990s, spatio-temporal structures allowing veritable multi-reception-channel equalization of the received signals were proposed, in order to accommodate the evolution of the waveforms and the increase in the bandwidths of the modulations.

In this respect, mention may be made of European patent EP 0669729 B1, which describes a method comprising the following:

- prior preprocessing for spatially decorrelating the background-noise-plus-interference component and the received signal, allowing some of the interference to be removed. For this decorrelation it is necessary to estimate, for each of the reception channels, the propagation channel and samples of the total noise (noise plus interference) in the learning sequences, and then to calculate the correlation matrix R associated with the total noise,
- the implementation of non-anti-jamming, multi-reception-channel equalization processing, in which:
 - for each of the reception channels, the propagation channel and the residual noise in the preprocess signal are estimated;

- depending on the calculated estimate of the propagation channel, each of the reception channels is filtered with a suitable temporal filter so as to optimize the signal-to-noise ratio obtained in the current symbol;
- 5 • the various reception channels are recombined with one another; and
- post-recombination the signal is equalized, the equalization possibly being carried out by a Viterbi algorithm if computational power permits, or by any other
- 10 single-reception-channel equalizer.

The method described in this patent is particularly advantageous since it is optimal when the noise is temporally white but not necessarily spatially white (temporally white background noise and temporally white interference,

15 in a single propagation path). However, the computational power required to implement it is a problem.

European patent EP 0867079 B1 aims to decrease this complexity of implementation. This time round, the patent seeks to estimate a vector w

20 composed of one coefficient per channel and used in a step of antenna processing and channel recombination, conjointly with a vector h estimated for the propagation channel associated with the recombined signal. The vectors are calculated so as to minimize the mean squared error in the learning sequences. The spatial filtering by w is followed by a step of single-

25 reception-channel equalization. All of the computations aim to point the direction of the spatial filter in the direction of the main path in the case of a multipath propagation channel. The reception of the main path is therefore optimized, however, in the case where the useful signal is transmitted in a multipath propagation channel, this method does not entirely take advantage

30 of the secondary paths. The solution is therefore not optimal when the propagation channel is a multipath channel, the power delivered via the additional paths being exploited sub-optimally.

French patent FR 2758926 adds another temporal dimension to the spatial filtering of the preceding patent. In this patent, a multisensor spatial correlation matrix R is constructed for the background noise plus interference using the same method as in the aforementioned patent EP 0669729 B1. In this patent, the spatio-temporal filtering of the various channels of the receiver is carried out directly using the matrix $\hat{W} = [\hat{w}(0), \hat{w}(1), \dots, \hat{w}(L-1)]$, $\hat{w}(n)$ being the component of index n of the multisensor channel matrix, without performing the prior preprocessing for spatially decorrelating the background-noise-plus-interference component and the received signal carried out in patent EP 0669729 B1. This receiver is optimal when the total noise is temporally white. In the one-dimensional signal obtained after this spatio-temporal filtering, the various useful paths present in the various reception channels have been recombined in phase for the current symbol. Interference associated with jammers and with useful paths outside the equalization window are eliminated, but the interference between symbols associated with the various paths contained in the window of the equalizer are still present. For this reason, the spatial-temporal filtering is followed by a step in which the signal obtained by summing the various reception channels is subjected to a complementary single-reception-channel equalization. This equalization may be carried out using the Viterbi algorithm, if computational power permits, or any other single-reception-channel equalizer.

The solution provided by this patent application is adapted to the problem of the rejection of jammers and to the exploitation of all of the paths in the window of an equalizer. However, it is quite complex to implement.

The invention proposes to improve the anti-jamming multi-reception-channel equalization method described in the preceding patent by providing a multi-reception-channel equalization method carried out in the frequency domain, thus allowing the complexity of the required calculations to be decreased while preserving the sought-after properties of rejection of jammers and exploitation of paths located in the window of the equalizer. In the multi-reception-channel equalization method according to the invention,

the correlation matrix of the noise and jamming signal(s) may be calculated in various ways that are more or less advantageous in terms of complexity.

Specifically, the invention relates to a method for receiving and carrying out anti-jamming equalization on a signal in a multi-reception-channel receiver. The signal comprises at least one learning sequence formed from
 5 known symbols and at least one sequence of useful data, which sequence is formed from unknown symbols. This method, which is one subject of the invention, comprises steps of:

- receiving the signal in a plurality of reception channels of the receiver,
 10 and transposing and discretizing the multi-reception-channel signal received in the reception channels of the receiver into a discretized baseband equivalent multi-reception-channel signal;
- synchronizing the discretized baseband multi-reception-channel signal;
- 15 • calculating an impulse response in the frequency domain of the multi-reception-channel propagation channel $\hat{\mathbf{h}}(f)$ and a correlation matrix $\hat{\mathbf{R}}$ of the noise and interference, from at least one portion corresponding to a learning sequence of said synchronized multi-reception-channel signal;
- 20 • transposing to the frequency domain at least one portion corresponding to a sequence of useful data of the synchronized multi-reception-channel signal, and filtering with the vector $\mathbf{w}(f)$, where

$$\mathbf{w}(f) = \frac{\hat{\mathbf{R}}^{-1}\hat{\mathbf{h}}(f)}{1 + \hat{\mathbf{h}}(f)^H \hat{\mathbf{R}}^{-1} \hat{\mathbf{h}}(f)},$$

the signal resulting from said filtering being a single-reception-channel signal in the frequency domain; and

- 25 • transposing said single-reception-channel signal to the temporal domain.

The method according to the invention allows the transmitted symbols to be estimated and comprises the rejection of interference. In this respect, it is indeed a question of an anti-jamming multi-reception-channel equalization
 30 method.

According to one embodiment of the method for receiving and carrying out anti-jamming equalization of the invention, the impulse response in the

frequency domain of the multi-reception-channel propagation channel $\hat{\mathbf{h}}(f)$ is calculated in the time domain. It comprises steps of:

- calculating a matrix $\hat{R}_{DX}$ expressing the intercorrelation between a learning sequence and a portion corresponding to said learning sequence of the synchronized multi-reception-channel signal;
- calculating an autocorrelation matrix $\hat{R}_{XX}$ of said portion corresponding to a learning sequence of said synchronized multi-reception-channel signal;
- calculating a multi-sensor propagation-channel matrix $\hat{H}$ from the matrix $\hat{R}_{DX}$ and from an autocorrelation matrix R_{DD} of said learning sequence:
 $\hat{H} = \hat{R}_{DX}^H R_{DD}^{-1}$, where ^{H} is the conjugate-transpose operator, and
- calculating the impulse response in the frequency domain of the multi-reception-channel propagation channel $\hat{\mathbf{h}}(f)$ for each reception channel of the receiver, by Fourier transformation of the vectors $\hat{\mathbf{h}}_k(n)$ forming the columns of the matrix $\hat{H}$.

In this embodiment, the correlation matrix $\hat{R}$ of the noise and interference is obtained using the formula:

$$\hat{R} = \hat{R}_{XX} - \hat{H} \hat{R}_{DX}.$$

The matrices R_{DD} , $\hat{R}_{DX}$ and $\hat{R}_{XX}$ are for their part calculated using the following formulae:

$$\begin{aligned} R_{DD} &= \frac{1}{P-L+1} \sum_{n=L-1}^{P-1} \mathbf{d}(n) \mathbf{d}(n)^H, \\ \hat{R}_{DX} &= \frac{1}{P-L+1} \sum_{n=L-1}^{P-1} \mathbf{d}(n) \mathbf{x}(n)^H, \\ \hat{R}_{XX} &= \frac{1}{P-L+1} \sum_{n=L-1}^{P-1} \mathbf{x}(n) \mathbf{x}(n)^H, \end{aligned}$$

where

- $\mathbf{d}(n)$ is a vector formed from the symbols of a learning sequence;

- $x(n)$ is a vector formed from the symbols received in a portion corresponding to the learning sequence $d(n)$ of said synchronized multi-reception-channel signal;
- P is the number of symbols in said learning sequence $d(n)$; and
- 5 - L is a length of an equalization window.

According to another embodiment of the method for receiving and carrying out anti-jamming equalization of the invention, the impulse response in the frequency domain of the multi-reception-channel propagation channel
 10 $\hat{h}(f)$ is calculated from data transposed to the frequency domain. It comprises steps of:

- estimating the time impulse response of the propagation channel $\hat{h}_k(n)$ for each channel k of the receiver, from at least one learning sequence and at least one portion corresponding to said one or more
 15 frequency-domain-transposed learning sequences of the synchronized multi-reception-channel signal
- decreasing the noise in the time impulse responses of the propagation channel $\hat{h}_k(n)$ for each reception channel k of the receiver, by zeroing the values $\hat{h}_k(n)$ associated with the portions for which the signal
 20 cannot be equalized; and
- calculating vectors $\hat{h}(f)$ by frequency interpolation of the $\hat{h}_k(n)$.

In this embodiment, the correlation matrix $\hat{R}$ of the noise and interference may be calculated via steps of:

- 25 • determining, in the estimated time impulse responses $\hat{h}_k(n)$, the positions I_b of samples corresponding to noise, and generating vectors $\hat{b}_k(n) = \hat{h}_k(n)$ for n belonging to I_b ;
- calculating noise vectors $\hat{b}(n)$ from the $\hat{b}_k(n)$; and
- calculating the matrix $\hat{R}$:

$$\hat{R} = \sum_{n \in I_b} \hat{b}(n) \hat{b}(n)^H.$$

Advantageously, when the signal comprises a plurality of learning sequences, the step of determining the time impulse response for each channel k of the multi-reception-channel receiver is carried out for N_{TS} learning sequences. $\hat{h}_{k,i}(n)$ then designates the time impulse response
 5 estimated for the reception channel k from the learning sequence i . In this embodiment, the calculation of the correlation matrix $\hat{R}$ of the noise and interference comprises steps of:

- determining, in the estimated time impulse responses $\hat{h}_{k,i}(n)$, the positions I_u of samples corresponding to the useful signal, and the
 10 positions I_b of samples corresponding to noise, and generating vectors $\hat{u}_{k,i}(n) = \hat{h}_{k,i}(n)$ for n belonging to I_u , and vectors $\hat{b}_{k,i}(n) = \hat{h}_{k,i}(n)$ for n belonging to I_b ;
- calculating useful-signal vectors $\hat{u}_i(n)$ from the $\hat{u}_{k,i}(n)$, and noise vectors $\hat{b}_i(n)$ from the $\hat{b}_{k,i}(n)$;
- 15 • estimating a correlation matrix $\hat{R}_{XX}$ of the total signal total, where

$$\hat{R}_{XX} = \frac{1}{N_{TS}} \sum_{i=0}^{N_{TS}-1} \left(\sum_{n \in I_u} \hat{u}_i(n) \hat{u}_i(n)^H + \sum_{n \in I_b} \hat{b}_i(n) \hat{b}_i(n)^H \right)$$

- estimating the average useful-signal vector:

$$\hat{u}_m(n) = \frac{1}{N_{TS}} \sum_{i=0}^{N_{TS}-1} \hat{u}_i(n);$$

- estimating a correlation matrix $\hat{R}_{SS}$ of the received useful signal:

$$\hat{R}_{SS} = \sum_{n \in I_u} \hat{u}_m(n) \hat{u}_m(n)^H;$$

- and calculating the matrix $\hat{R}$:

$$\hat{R} = \frac{1}{L_{TS}} (\hat{R}_{XX} - \hat{R}_{SS}).$$

20 Lastly, the invention relates to a multi-reception-channel receiver allowing reception and anti-jamming equalization of a signal comprising at least one learning sequence formed from known symbols and at least one sequence of useful data, which sequence is formed from unknown symbols. The receiver according to the invention is configured to receive the signal in
 25 each of its reception channels, and to transpose and discretize the multi-reception-channel signal into a discretized baseband equivalent multi-

reception-channel signal. It comprises at least one piece of equipment for processing the signal, which is configured to implement a method for receiving and carrying out anti-jamming equalization by executing steps of:

- 5 • synchronizing the discretized baseband multi-reception-channel signal ;
- calculating an impulse response in the frequency domain of the multi-reception-channel propagation channel $\hat{\mathbf{h}}(f)$ and a correlation matrix $\hat{\mathbf{R}}$ of the noise and interference, from at least one portion corresponding to a learning sequence of said synchronized multi-reception-channel signal;
- 10 • transposing to the frequency domain at least one portion corresponding to a sequence of useful data or of the synchronized multi-reception-channel signal, and filtering with the vector $\mathbf{w}(f)$, where

$$\mathbf{w}(f) = \frac{\hat{\mathbf{R}}^{-1} \hat{\mathbf{h}}(f)}{1 + \hat{\mathbf{h}}(f)^H \hat{\mathbf{R}}^{-1} \hat{\mathbf{h}}(f)},$$

- 15 the signal resulting from said filtering being a single-reception-channel signal in the frequency domain; and
- transposing said single-reception-channel signal to the time domain.

Description

20 The invention will be better understood and other features and advantages will become more clearly apparent on reading the following nonlimiting description, and by virtue of the appended figures, in which:

- Figure 1a shows a frame structure allowing the invention to be implemented and known to those skilled in the art;
- 25 • Figure 1b shows a multi-reception-channel receiver in which the receiving method according to the invention is implemented;
- Figure 2a shows a frame structure corresponding to a single-carrier waveform designed so as to be equalizable in the frequency domain;

- Figure 2b shows a frame structure corresponding to a single-carrier waveform designed to be equalizable in the frequency domain, in which the sequences of useful data comprise a cyclic suffix;
- 5 • Figure 2c shows the realization of the anti-jamming multi-reception-channel equalization processing implemented in the frequency domain according to the invention;
- Figure 2d shows the structure of the learning sequences in the frames allowing one embodiment of the invention to be implemented;
- 10 • Figures 3a and 3b illustrate the transformations applied to the estimate of the pulse response in the time domain during the implementation of one of the embodiments of the invention; and
- Figure 4 shows the various steps of the anti-jamming multi-reception-channel equalization method according to the invention.

15

Figure 1a shows the frame structure 100 of a single-carrier signal intended to be equalized, independently of the modulation used for its transmission. This structure comprises learning sequences 101, which consist of reference symbols known by the transmitter and the receiver, that
 20 are transmitted in alternation with sequences (102) of useful data, which sequences consist of useful symbols, or information symbols. This frame structure is common to most present-day single- and multi-carrier communication standards. Mention may be made, by way of example, of the GSM (Global System for Mobile communications) standard, the 3G (3rd
 25 generation) standard, the LTE (Long Term Evolution, or 4G) standard, the various DVB (Digital Video Broadcasting) standards, and many others.

The aim of the learning sequences is to allow time and frequency synchronization of the receiver, and the estimation of the propagation channel with a view to compensation thereof by way of an equalizer or any
 30 other suitable technique. Their positions in the frame are known by the receiver.

The length of the learning sequences, and their distribution within the transmitted signal, depends on waveform-related implementational

constraints (such as for example the length of the frames, the maximum movement rate, the type of propagation channel, etc.). In the rest of the document, the learning sequences will be considered to be of an identical size equal to P symbols, and the data sequences will be considered to be of an identical size equal to N symbols. The invention is applied in exactly the same way when the sizes of the learning sequences and data sequences vary, or when the learning sequences are not all identical.

Figure 1b shows a multi-reception-channel receiver in which the reception method according to the invention is implemented.

The receiver 110 comprises at least 2 antennae (or sensors) 111 and 112, that are intended to receive a signal. Each of the antennae is the entrance point of one of the reception channels of the receiver. It also comprises one radio chain 121 and 122 per reception channel, the objective of which is to convert the analog signal received at the carrier frequency into a discretized baseband signal. To do this, the radio chain implements means for converting the carrier frequency of the signal. One conventional embodiment consists in first transposing the signal to an intermediate frequency, then in converting it into baseband equivalent discrete signals by way of a local oscillator, a phase shifter and mixers that respectively create a first reception channel I in phase and a second reception channel Q in phase quadrature with the input signal. The signals delivered by the mixers are discretized by analogue/digital converters, or ADCs. Means for filtering the signal at various stages of the transposition of the signal may also be implemented in order to prevent spectral leakage effects associated with the frequency transpositions and reductions in the sampling rate. The signal output from the radio chain is a baseband digital signals sampled at a rate higher than the symbol rate of the modulation (generally an integer multiple of the symbol rate).

Downstream of the radio chain, the receiver comprises computing means 130 responsible for the execution of all the signal-processing algorithms required to ensure the good reception of the signal. These computing means may for example take the form of a reprogrammable computing machine such as a processor, a DSP (digital signal processor) or

a microcontroller, or the form of a dedicated computing machine such as an FPGA (Field-programmable gate array) or an ASIC (application specific integrated circuit), or take the form of any other hardware module allowing computations to be executed.

5

The computing means are responsible for the synchronization 140 of the receiver. The objective of the synchronization is to select the best sampling time, and to measure and compensate for time and frequency shifts due to the propagation of the signal and to the speed and imprecision of the local oscillators of the emitter and receiver. The synchronization is generally achieved using the learning sequences. The synchronization time and frequency position is identical for all the channels. It may be determined by synchronizing each of the channels independently then by choosing the position providing the best performance, or by a specific multi-reception-channel synchronizing method, such as that described in the European patent EP 0665665 B1, the latter solution providing a better performance in terms of robustness to noise and interference. The resulting signal then takes the form of a synchronized multi-reception-channel signal, generally sampled at the symbol rate.

20

The computing means are also responsible for the anti-jamming multi-reception-channel equalization 150 of the signal. The role of the anti-jamming multi-reception-channel equalization consists of optimizing the reception of all of the multipaths associated with the useful signal and in removing undesired interfering signals by generating "holes" in the radiation pattern of the antennae in the direction of the interferers and the multipaths the delay spread of which is outside the equalization window. The length of the window of the multi-reception-channel equalizer is an implementational choice that is made depending on a compromise between the probability that a propagation channel will have a spread larger than this size, and the complexity required to implement it. The multi-reception-channel equalization may be carried out either in the time domain or in the frequency domain, such as described below in this document.

30

The invention is implemented in this portion of the receiver, and is not affected by the equalization and antenna-processing algorithms chosen. It also relates to anti-jamming multi-reception-channel equalization of the signal carried out in the frequency domain. The signal resulting from this
 5 equalization is a single-reception-channel signal sampled at the symbol rate, in which signal the influence of the various sources of degradation, such as jammers and multipaths associated with the propagation of the radio wave, have been minimized or even removed. It corresponds to an estimation $\hat{s}(n)$ of the series of symbols emitted in the block

10 Lastly, the computing means are responsible for all of the signal-processing algorithms 160 required to reconstruct the transmitted useful bits from the estimate $\hat{s}(n)$ of the series of transmitted symbols. These algorithms are for example algorithms for channel decoding, deinterleaving, decrypting, etc. the implementational parameters and choice of which depends on the
 15 communication standard used. Depending on the type of algorithm used, the estimated symbols $\hat{s}(n)$ transmitted to the computing means may be confirmed or unconfirmed symbols. They may also be associated with an estimation of the SNR in order to allow a log likelihood ratio (LLR) to optionally be calculated.

20

below, the following notations will be used:

- P is the length of the learning sequences, in number of symbols;
- L is the length of the window of the equalizer, in number of symbols. This window corresponds to the maximum spread of
 25 paths able to be equalized. When the propagation channel comprises multipaths the spread of which is larger than this distance L , these paths will be seen as interfering signals;
- A (capital) designates a matrix;
- $\mathbf{a}$ (bold) designates a vector;
- 30 • $\hat{}$ designates an estimated quantity;
- $x_k(n)$ designates the signal received in the reception channel k for the symbol n ;

- $x(n)$ designates the multi-sensor signal received for the symbol n ,
- $x(f)$ designates the multi-sensor signal received and transposed to the frequency domain, for the frequency f ;
- 5 • $x_k(f)$ designates the signal received in the reception channel k and transposed to the frequency domain, for the frequency f ,
- $d(n)$ designates the signal transmitted in the learning sequences for the symbol n ;
- 10 • $s(n)$ designates the signal transmitted in the information sequences;
- K designates the number of reception channels of the receiver;
- $\mathbf{h}(n)$ is the multi-reception-channel vector, of size K , containing the impulse response of the multi-sensor propagation channel, for the symbol n , where $n = 0, \dots, L - 1$;
- 15 • $h_k(n)$ is the time impulse response of the propagation channel, which response is obtained in the reception channel k , where $k = 1, \dots, K$ and $n = 0, \dots, L - 1$;
- $\mathbf{b}(n)$ is a vector of size K designating the total reception noise (background noise plus any interference, plus any useful multipaths located outside of the equalization window, i.e. that arrive before the first path comprised in the equalization window, or the delay of which is greater than L symbols with respect to this first path);
- 20 • R designates the autocorrelation matrix of the total reception noise;
- 25 • ^{T} designates the transpose operator;
- ^{H} designates the conjugate-transpose operator; and
- $E[a]$ designates the mathematical likelihood of a .

30 The invention therefore applies to a multi-reception-channel signal, following a synchronizing step.

After synchronization, the signal vector received by the sensor array may be written:

$$\mathbf{x}(n) = \sum_{i=0}^{L-1} e(n-i)\mathbf{h}(i) + \mathbf{b}(n) \quad (3)$$

where $e(n)$ is the transmitted signal, equalling $d(n)$ for the learning sequences and $s(n)$ for the information sequences.

5

If:

- the vector of size L formed from the learning symbols is written $\mathbf{d}(n) = [d(n), d(n-1), \dots, d(n-L+1)]^T$; and
- if the multi-sensor propagation-channel matrix formed from the

10

vectors $\mathbf{h}(i)$ of size (K, L) is written $H = [\mathbf{h}(0), \mathbf{h}(1), \dots, \mathbf{h}(L-1)]$;

then this relationship may be written $\mathbf{x}(n) = H\mathbf{d}(n) + \mathbf{b}(n)$.

The invention relates to an anti-jamming multi-reception-channel equalization method the realization of which comprises only one single step of spatio-frequential filtering of the signal, which step is equivalent to spatio-temporal filtering carried out in the frequency domain. This multi-reception-channel equalization method is suitable for the reception of a single-carrier waveform designed to be equalized in the frequency domain, i.e. a waveform for which the data blocks comprise a cyclic prefix, according to the structure described in Figure 2A, or for which a cyclic prefix may be obtained, and for the reception of a multi-carrier waveform (such as for example an OFDM waveform).

The frame structure 200 described in Figure 2a comprises, in addition to the sequences 102 of useful data, of size L_{DATA} , and the learning sequences 101, of size P , sequences 201, which are called cyclic prefixes, of size L_{CP} . These sequences are constructed by copying the last L_{CP} symbols 202 of the information sequences before this sequence, and make it possible to ensure the absence of interference between the various blocks of information sequences and learning sequences. The length L of the propagation channel that can be equalized is then equal to the length of the

30

cyclic prefix plus one: $L = L_{CP} + 1$. The total size of the information sequence is then equal to $N = L_{DATA} + L_{CP}$.

In order to optimize the useful feed rate, the addition of a cyclic prefix to
 5 each block of information sequences may however be avoided in one of the following two ways:

- the learning sequences may play the role of cyclic prefixes provided that the two learning sequences 101 surrounding a data block 102 are identical; or
- 10 • a cyclic prefix may be generated using what is called a “zero-padding” technique on the learning sequences, as is for example described in “Cyclic Prefixing or Zero Padding for Wireless Multicarrier Transmissions” by B. Muquet *et al.*, IEEE Transactions Communications, vol. 50, December 2002.

15 In this way, a cyclic prefix is artificially introduced, thereby allowing the frame format described in Figure 1a to be used for multi-reception-channel equalization in the frequency domain.

Advantageously, a cyclic suffix may also be added to the structure of
 20 the equalized frame. Figure 2b shows a frame structure incorporating such a cyclic suffix 221, the L_{CS} samples composing this suffix being obtained by copying the first L_{CS} samples 222 of the useful portion of the sequence 102 of useful data.

The objective of the cyclic suffix is to compensate for a lack of precision
 25 in the synchronization position. It is of a size L_{CS} equal to a few samples (typically smaller than or equal to 2 samples), the samples of the cyclic suffix being equal to the first samples of the sequence of useful data. Its presence is advantageous, and the invention is applied in exactly the same way as when L_{CS} is equal to zero. The total size of the information sequence is then
 30 equal to $N = L_{DATA} + L_{CP} + L_{CS}$.

The equalizable multipaths are then those located in a window of size L starting from the first path, where $L = L_{CP} + 1$, and those located upstream of the synchronization position by a distance smaller than L_{CS} .

5 Figure 2c shows the realization of the anti-jamming multi-reception-channel equalization processing 150 implemented in the frequency domain according to the invention. This processing comprises, for each reception channel of the received multi-reception-channel signal, transposing the signal to the frequency domain by way of a Fourier transform 231 of the data blocks
10 received in each of the reception channels. Thus, $x(f) = DFT\{x(n)\}$, DFT being the acronym of discrete Fourier transform, for $f = 0, \dots, L_{DATA} - 1$ and $n = 0, \dots, L_{DATA} - 1$.

The spatial filter $\hat{w}(f)$ 232 is then applied to each of the reception channels, for each frequency, where:

15

$$\hat{w}(f) = \frac{\hat{R}^{-1}\hat{h}(f)}{1 + \hat{h}(f)^H \hat{R}^{-1}\hat{h}(f)}. \quad (4)$$

At the end of this spatio-frequency filtering, the signal is a frequency-equalized single-reception-channel signal that may be written:

$$y(f) = \hat{w}(f)^H x(f).$$

20 It is then returned to the time domain via an inverse Fourier transform 233, then normalized.

The filtering of the received multi-reception-channel signal with the spatio-temporal filter $\hat{w}(f)$ thus performs the following functions: jammer rejection, equalization and the summation of the reception channels of the input signal.

25

This signal is normalized by estimating the SINR (signal-to-interference-plus-noise ratio) using the two following formulae:

$$\eta = \frac{1}{N} \sum_{f=0}^{L_{DATA}-1} \frac{\hat{\mathbf{h}}(f)^H \hat{\mathbf{R}}^{-1} \hat{\mathbf{h}}(f)}{1 + \hat{\mathbf{h}}(f)^H \hat{\mathbf{R}}^{-1} \hat{\mathbf{h}}(f)} \quad (5)$$

and:

$$SINR = \frac{\eta}{1 - \eta} \quad (6)$$

The equalized signal is normalized by multiplying the signal returned to the frequency domain by $1/\eta$. The series of estimated symbols in the block of length L_{DATA} are thus equal to:

$$\hat{s}(n) = \frac{1}{\eta} DFT^{-1}\{y(f)\} \quad (7)$$

5 where $n = 0, \dots, L_{DATA} - 1$.

Advantageously, in all of the above processing, FFTs (fast Fourier transforms) may be used instead of discrete Fourier transforms. The use of fast Fourier transforms allows the processing to be accelerated and the
10 complexity of the frequency transposition of the signal to be decreased. The use of FFTs requires the use of particular sizes of data blocks, generally of powers of 2. However, it is possible to use FFTs on any size of data block by inserting null data in order to obtain the desired size, this technique being known as “zero-padding”.

15

All of the anti-jamming multi-reception-channel equalization processing applied in the time domain is therefore based on the estimation of the vectors $\hat{\mathbf{h}}(f)$, which describe the multi-reception-channel impulse response of the propagation channel for each frequency f , and of the autocorrelation matrix $\hat{\mathbf{R}}$
20 of the total noise.

These calculations may be carried out in the time domain or in the frequency domain.

1st embodiment: calculation of the vectors $\hat{\mathbf{h}}(f)$ and the matrix $\hat{\mathbf{R}}$ in the time domain.

25 In this embodiment, the equalizable multipaths are those located in a window of size L starting from the synchronization position, with $L = L_{CP} + 1$,

where L_{CP} is the size of the cyclic prefix used for the information sequences. In this embodiment, the learning sequences do not necessarily possess a cyclic prefix.

- 5 This embodiment is based on the calculation, in the time domain, of the following matrixes, from the learning sequences:

$$R_{DD} = \frac{1}{P-L+1} \sum_{n=L-1}^{P-1} \mathbf{d}(n)\mathbf{d}(n)^H, \quad (8)$$

$$\hat{R}_{DX} = \frac{1}{P-L+1} \sum_{n=L-1}^{P-1} \mathbf{d}(n)\mathbf{x}(n)^H, \quad (9)$$

$$\hat{R}_{XX} = \frac{1}{P-L+1} \sum_{n=L-1}^{P-1} \mathbf{x}(n)\mathbf{x}(n)^H, \quad (10)$$

- 10 where R_{DD} is the autocorrelation matrix of the learning signal, $\hat{R}_{DX}$ the matrix expressing the intercorrelation between the learning signal and the received corresponding signal, and $\hat{R}_{XX}$ the autocorrelation matrix of the received signal.

- The matrices are respectively of sizes (L, L) , (L, K) , and (K, K) . Since the matrix R_{DD} is calculated from the learning signal, the result of this calculation is known in advance and may advantageously be stored in a
15 memory of the receiver.

The multi-sensor propagation-channel matrix $\hat{H}$ is then calculated directly from the matrices calculated beforehand:

$$\hat{H} = \hat{R}_{DX}^H R_{DD}^{-1}. \quad (11)$$

- 20 $\hat{H}$ is of size (K, L) and is formed from the estimated vectors $\hat{\mathbf{h}}(n)$ of the propagation channel:

$$\hat{H} = [\hat{\mathbf{h}}(0) \dots \hat{\mathbf{h}}(L-1)]. \quad (12)$$

The vectors $\hat{\mathbf{h}}(f)$ i.e. the multi-reception-channel impulse response of the propagation channel for each frequency f , are then obtained by performing, in each channel k of the matrix $\hat{H}$, a Fourier transform of the impulse response of the propagation channel $\hat{h}_k(n)$, where $n = 0, \dots, L - 1$.

- 5 The vectors $\hat{h}_k(n)$ are of size L . In order to be applied to the input signal transposed to the frequency domain $\mathbf{x}(f)$, $\mathbf{w}(f)$ (and therefore $\hat{\mathbf{h}}(f)$), must be of size equal to that of the Fourier transform 231, which is generally equal to L_{DATA} . It is therefore necessary to interpolate the vector $\hat{\mathbf{h}}(f)$, this interpolation possibly and advantageously consisting of completing the $\hat{h}_k(n)$
10 with zero values.

$$\hat{h}_k(n) = 0 \text{ for } n = L, \dots, L_{DATA} - 1 \quad (13)$$

In this way, $\hat{h}_k(f)$ equals:

$$\hat{h}_k(f) = DFT\{\hat{h}_k(n)\}, \quad (14)$$

where $n = 0, \dots, L_{DATA} - 1$; $f = 0, \dots, L_{DATA} - 1$; and $k = 1, \dots, K$

- 15 The correlation matrix $R = E[\mathbf{b}(n)\mathbf{b}(n)^H]$ of the noise and interference is calculated directly using the matrix $\hat{H}$ and the matrices $\hat{R}_{DX}$ and $\hat{R}_{XX}$ by way of the following,:

$$\hat{R} = \hat{R}_{XX} - \hat{H}\hat{R}_{DX}. \quad (15)$$

This matrix $\hat{R}$, of size $(K \times K)$, will be used to calculate the coefficients of the spatial filter applied in the step of spatio-frequency equalization.

- 20 Thus, the calculation of the vectors $\hat{\mathbf{h}}(f)$ and of the matrix $\hat{R}$ is extremely simple, inexpensive in terms of required computational power, and therefore rapid, this being an advantage once the feed rate or number of channels begins to increase.

- 25 2nd embodiment: calculation of the vectors $\hat{\mathbf{h}}(f)$ and of the matrix $\hat{R}$ in the frequency domain.

In this embodiment, an estimation of the propagation channel is calculated in the frequency domain for each reception channel, then an

inverse Fourier transform allows the estimates in the time domain to be obtained. The total correlation matrix $\hat{R}$ of the noise is calculated from elements of the impulse response of the channel corresponding to noise samples.

5 The advantage of this second embodiment is that it allows the computational power required when the length L of the impulse response of the propagation channel increases to be decreased

10 In order to be able to carry out the channel estimation in the frequency domain on the basis of the learning sequences, a cyclic prefix, and optionally a cyclic suffix, of lengths equal to the lengths of the cyclic prefixes and suffixes of the information sequences, are introduced into the learning-sequence frame structure.

Figure 2d shows the structure of learning sequences in frames allowing the invention to be implemented according to one of its embodiments. The learning sequences comprise cyclic prefixes 241 obtained by copying the L_{CP} last samples 242 of the useful portion of the learning sequence, and optionally cyclic suffixes 243 obtained by copying the L_{CS} first samples 244 of the useful portion of the learning sequence. The total length of the learning sequence is then equal to $P = L_{TS} + L_{CP} + L_{CS}$.

20

The estimation of $\hat{h}(f)$ consists in carrying out a frequency estimation of the propagation channel for each reception channel k . This estimation is obtained in several steps:

- Time estimation of the propagation channel, from frequency representations of the signal:

25

this step is carried out, for each learning sequence, by performing an inverse Fourier transform of the impulse response calculated from the signals in the frequency domain, for each of the reception channels of the receiver:

$$\hat{h}_k(n) = IDFT\left\{\frac{x_k(f)}{d(f)}\right\}, \quad (16)$$

where $d(f) = DFT\{d(t)\}$, for $n = 0, \dots, L_{TS} - 1$ and $f = 0, \dots, L_{TS} - 1$.

30

- Reduction in the noise in the impulse response:

this step allows the contributions associated with noise and any interference, to the estimate of the propagation channel, to be removed. It consists in forcing the values of $\hat{h}_k$ located in ranges located outside of the window of the equalizer to zero. To do this, the number of noise samples is called L_b , where $L_b = L_{TS} - L_{CS} - L$.

$$\hat{h}_k(n) = \begin{cases} \hat{h}_k(n) & \text{for } n \in [0; L - 1] \cup [L + L_b; L_{TS} - 1] \\ 0 & \text{for } n \in [L; L + L_b - 1] \end{cases}. \quad (17)$$

- Averaging of the time responses

this optional step consists in taking advantage of the stability of the propagation channel over a plurality of successive learning sequences to smooth the estimation noise. This averaging may, depending on the circumstances, take into account the pulse responses estimated from all of the learning sequences of the frame, or be limited to the sequences surrounding the block of useful data in question. It may also be associated with a weighting of the estimates, the weighting factor depending on a signal quality criterion such as an estimate of the power level of the received signal, an estimate of the signal-to-noise ratio, or any other criterion known to those skilled in the art.

In the case where the averaging takes into account all of the propagation channel time responses, it may be expressed as follows:

$$\hat{h}_k(n) = \frac{1}{N_{TS}} \sum_{i=1}^{N_{TS}} \hat{h}_{k,i}(n), \quad (18)$$

for $n \in [0; L - 1] \cup [L + L_b; L_{TS} - 1]$, $\hat{h}_{k,i}(n)$ being the impulse response estimated for the reception channel k and the learning sequence i , and N_{TS} being the number of learning sequences considered.

25

- Frequency interpolation of the response of the propagation channel:

so as to be able to be applied to the useful signal, the estimate of the impulse response of the propagation channel in the frequency domain must be of size equal to the size (generally L_{DATA}) of the Fourier transform 231 applied to the information sequences of the signal. A simple way of achieving this
 5 interpolation consists in completing the impulse response estimated in the time domain with zero values before taking its Fourier transform:

$$\hat{h}_k^{ZP}(n) = \begin{cases} \hat{h}_k(n) & \text{for } n = [0; L + L_b - 1] \\ 0 & \text{for } n = [L + L_b; L_{DATA} - L_{CS} - 1] \\ \hat{h}_k(n) & \text{for } n = [L_{DATA} - L_{CS}; L_{DATA} - 1] \end{cases} \quad (19)$$

where $\hat{h}_k^{ZP}(n)$ is the impulse response in the time domain after addition of zeros.

The impulse response in the frequency domain is calculated, for each of
 10 the reception channels, as follows:

$$\hat{h}_k(f) = DFT\{\hat{h}_k^{ZP}(n)\}, \quad (20)$$

for n varying from 0 to $L_{DATA} - 1$ and k varying from 1 to K .

Figures 3a and 3b illustrate the transformations applied to the impulse response $\hat{h}_k(n)$ estimated with Equation (16) in this embodiment of the
 15 equalization method according to the invention.

Figure 3a shows an estimated impulse response. This response has a portion 311, of size L (or $L_{CP} + 1$), in which the multipaths are comprised in the window of the equalizer, a portion 312, of size L_b , in which the response relates to interference and multipaths located outside of the equalizer, and a
 20 portion 313, of size L_{CS} , corresponding to the propagation channel estimated from the cyclic suffix.

Figure 3b shows the impulse response after the successive processing operations that are applied thereto. The portion 322 relating to the interference has been replaced by zero values in the step of noise reduction.
 25 An additional portion 324 corresponds to the zeros introduced in the frequency interpolation step, the number L_{ZP} of zeros introduced being $L_{ZP} = L_{DATA} - L_{TS}$.

The autocorrelation matrix $\hat{R}$ of the total noise is calculated from the previously calculated impulse responses.

This calculation assumes that the samples of the propagation-channel impulse response calculated in the time domain with Equation (16) contain the useful signal, denoted $\hat{u}_k(n)$, when $n \in I_u = [0; L - 1] \cup [L + L_b; L_{TS} - 1]$, and noise, denoted $\hat{b}_k(n)$, when $n \in I_b = [L; L + L_b - 1]$.

The received useful-signal and noise vectors of each learning sequence will be denoted $\hat{\mathbf{u}}(n)$ and $\hat{\mathbf{b}}(n)$, respectively:

$$\begin{aligned}\hat{\mathbf{u}}(n) &= [\hat{u}_1(n) \dots \hat{u}_K(n)]^T, \\ \hat{\mathbf{b}}(n) &= [\hat{b}_1(n) \dots \hat{b}_K(n)]^T.\end{aligned}\tag{21}$$

10

Furthermore, when these sequences are calculated from learning sequence i , they will be denoted $\hat{\mathbf{u}}_i(n)$ and $\hat{\mathbf{b}}_i(n)$.

According to a first embodiment, the autocorrelation matrix $\hat{R}$ of the total noise is calculated directly from samples of estimated noise:

$$\hat{R} = \sum_{n \in I_b} \hat{\mathbf{b}}(n) \hat{\mathbf{b}}(n)^H.\tag{22}$$

15

Advantageously, the matrix $\hat{R}$ may be estimated by averaging the values of the noise received in a plurality of learning sequences:

$$\hat{R} = \frac{1}{N_{TS}} \sum_{i=0}^{N_{TS}-1} \left(\sum_{n \in I_b} \hat{\mathbf{b}}_i(n) \hat{\mathbf{b}}_i(n)^H \right).\tag{23}$$

Weighting coefficients may be added in order to adjust the contribution of the noise estimates of each of the learning sequences by a factor dependent on the quality of the received signal.

20

The invention therefore indeed allows an autocorrelation matrix $\hat{R}$ of the total noise of a multi-reception-channel signal to be calculated simply and straightforwardly and said matrix to be used for multi-reception-channel equalization of a signal in which the noise is not necessarily spatially and temporally white.

According to a second embodiment that is applicable when a plurality of learning sequences are available, the autocorrelation matrix $\hat{R}$ of the total noise is calculated in the following way:

- Estimation of the correlation matrix of the total signal (useful signal + total noise) received for all of the learning sequences:

$$\hat{R}_{XX} = \frac{1}{N_{TS}} \sum_{i=0}^{N_{TS}-1} \left(\sum_{n \in I_u} \hat{\mathbf{u}}_i(n) \hat{\mathbf{u}}_i(n)^H + \sum_{n \in I_b} \hat{\mathbf{b}}_i(n) \hat{\mathbf{b}}_i(n)^H \right). \quad (24)$$

Advantageously, the preceding equations may be adjusted so as to weight the signal estimated from each of the learning sequences by a factor dependent on the quality of the received signal.

- Estimation of the received average useful-signal vectors:

$$\mathbf{u}_m(n) = \frac{1}{N_{TS}} \sum_{i=0}^{N_{TS}-1} \hat{\mathbf{u}}_i(n), \quad (25)$$

where $\hat{\mathbf{u}}_m(n)$ is the average useful-signal vector.

- Estimation of the correlation matrix of the received useful signal:

$$\hat{R}_{SS} = \sum_{n \in I_u} \hat{\mathbf{u}}_m(n) \hat{\mathbf{u}}_m(n)^H, \quad (26)$$

where $\hat{R}_{SS}$ is the correlation matrix of the useful signal.

The correlation matrix of the total noise is then obtained by subtracting the correlation matrix of the useful signal from the correlation matrix of the received total signal:

$$\hat{R} = \frac{1}{L_{TS}} (\hat{R}_{XX} - \hat{R}_{SS}). \quad (27)$$

With this estimating method, the calculated autocorrelation matrix $\hat{R}$ of the total noise is equal to the matrix $\hat{R}$ calculated in the preceding embodiment when $N_{TS} = 1$, though the computational load is slightly greater. However, if the number of learning sequences considered is increased, the matrix resulting from the second method of calculation may allow performance to be optimized when the propagation channel is particularly poor, such as for example when the propagation channel is what is called a Rayleigh channel that may be characterized, in mobility situations and in the vicinity of fading, by a very great variability in the useful channel received over a time horizon corresponding to a plurality of successive learning sequences. In this situation, the second method of calculation of the matrix tends to lead to an overestimation of the noise level with respect to the first estimation, this being the desired result. Specifically, since the noise level is overestimated, the LLRs (log likelihood ratios) associated with this horizon will be poor, this possibly allowing a decoding algorithm to prefer those portions of the frame which have not been subject to these particularly poor channel conditions, and therefore the performance of the receiver to be improved.

20

Independently of whether the vectors $\hat{\mathbf{h}}(f)$ and the autocorrelation matrix $\hat{R}$ of the total noise are estimated from a signal in the time domain or in the frequency domain, the complexity of implementation of the invention is decreased, in particular because it does not require banks of correlators to be implemented in parallel.

25

The operations carried out are based on transpositions of the signal to the frequency domain, these possibly and advantageously being achieved using fast Fourier transforms (FFTs), very optimized implementations of which are frequently incorporated into receiver architectures and the complexity and computation time of which are extremely low.

30

The invention relates to an anti-jamming multi-reception-channel equalization method implemented in the frequency domain. The steps of this method are illustrated in Figure 4.

5 The first step 401 of the method consists in reception of the transmitted signal, which contains learning sequences and data sequences, by a plurality of sensors, or antennae. Analogue and digital processing operations are applied to the received multi-reception-channel signal so as to digitize it, these processing operations comprising the transposition of the signal to a baseband or intermediate frequency, the associated filtering operations, and
10 analogue/digital conversion in each of the reception channels.

The second step 402 of the method consists in the time and frequency synchronization of the received signal, this step possibly and advantageously being carried out by means of a multi-reception-channel synchronization algorithm. This step furthermore makes it possible to learn which portions of
15 the received multi-reception-channel signal correspond to the data sequences, and which portions correspond to the learning sequences.

The third step 403 of the method consists in calculating, for each of the reception channels of the receiver, an impulse response in the frequency domain of the multi-reception-channel propagation channel $\hat{h}(f)$, and a
20 correlation matrix $\hat{R}$ of the noise and interference.

This step is carried out on the basis of the (known) content of the learning sequence, and of the received multi-reception-channel signal corresponding to this learning sequence. A plurality of embodiments (detailed above) allow this calculation to be made. Certain of these embodiments use
25 the multi-reception-channel signal received in the time domain, others use this signal after it has been transposed to the frequency domain. In certain embodiments, the impulse response is estimated for a plurality of learning sequences, then averaged.

The fourth step 404 of the method consists in transposing, to the
30 frequency domain, each reception channel of the received multi-reception-channel signal and in particular the data corresponding to the sequences of useful data.

The fifth step 405 of the method consists in filtering, in the frequency domain, those portions of the received multi-reception-channel signal which correspond to the sequences of useful data, with a spatio-temporal filter given by the vector $w(f)$, where

$$w(f) = \frac{\hat{R}^{-1}\hat{h}(f)}{1 + \hat{h}(f)^H \hat{R}^{-1}\hat{h}(f)}.$$

5

After the filtering of the multi-reception-channel signal with the filter $w(f)$, the resulting signal is a frequency-equalized anti-jamming single-reception-channel signal. Advantageously, this step is followed by a step of normalizing the single-reception-channel signal.

10 Lastly, the sixth step 406 of the method consists in transposing the single-reception-channel signal to the frequency domain, by way of an inverse Fourier transform.

As regards everything relating to the estimation of the spatio-frequential
15 filter $w(f)$, the steps of the method are carried out on the basis of the received learning sequences, these sequences thus being known by the receiver. The calculations may be performed for each learning sequence. The processing is then able to follow rapid variations in the propagation channel. They may also be performed for each learning sequence, and
20 combined together, so as to smooth noise-related calculation errors.

The invention is compatible with any transmission standard in which a single-carrier signal is received by a multi-reception-channel receiver, but also with standards using multi-carrier signals. It is also compatible with
25 burst-mode transmissions, such as for example transmissions using frequency hopping.

The presented multi-reception-channel equalization methods are only optimal in the presence of temporally white noise. They guarantee a jamming
30 combat capacity, including against useful paths that do not enter into the

equalization window. The described processing operations may be easily added in front of the other processing operations carried out in an existing multi-reception-channel receiver in order to provide thereto an anti-jamming capacity that they do not themselves have, without requiring these existing
5 operations to be modified.

In addition, the spatio-frequential filtering applied in the frequency domain, and the proposed calculations of the correlation matrix of the total noise, are very simple to implement and require only a few calculations to be made, thereby making the invention compatible with a high-feed-rate
10 implementation or a receiver comprising a high number of reception channels.

CLAIMS

1. Method for receiving and carrying out anti-jamming equalization on a signal in a multi-reception-channel receiver, said signal comprising at least one learning sequence (101) formed from known symbols and at least one sequence (102) of useful data, which sequence is formed from unknown symbols, the method being characterized in that it comprises steps of:

- receiving said signal in a plurality of reception channels of the receiver, and transposing and discretizing (401, 111, 121, 112, 122) the multi-reception-channel signal into a discretized baseband equivalent multi-reception-channel signal;
- synchronizing (402, 140) the discretized baseband multi-reception-channel signal;
- calculating (403, 150) an impulse response in the frequency domain of the multi-reception-channel propagation channel $\hat{\mathbf{h}}(f)$ and a correlation matrix $\hat{R}$ of the noise and interference, from at least one portion corresponding to a learning sequence of said synchronized multi-reception-channel signal;
- transposing (404, 231) to the frequency domain at least one portion corresponding to a sequence of useful data of the synchronized multi-reception-channel signal, and filtering (405, 232) with the vector $\mathbf{w}(f)$, where

$$\mathbf{w}(f) = \frac{\hat{R}^{-1}\hat{\mathbf{h}}(f)}{1 + \hat{\mathbf{h}}(f)^H \hat{R}^{-1} \hat{\mathbf{h}}(f)},$$

the signal resulting from said filtering being a single-reception-channel signal in the frequency domain; and

- transposing (406, 233) said single-reception-channel signal to the temporal domain.

2. Method for receiving and carrying out anti-jamming equalization according to Claim 1, wherein the calculation of the impulse response in the frequency domain of the multi-reception-channel propagation channel $\hat{\mathbf{h}}(f)$ comprises steps of:

- calculating a matrix $\hat{R}_{DX}$ expressing the intercorrelation between a learning sequence and a portion corresponding to said learning sequence of the synchronized multi-reception-channel signal;
- calculating an autocorrelation matrix $\hat{R}_{XX}$ of said portion corresponding to a learning sequence of said synchronized multi-reception-channel signal;
- calculating a multi-sensor propagation-channel matrix $\hat{H}$ from the matrix $\hat{R}_{DX}$ and from an autocorrelation matrix R_{DD} of said learning sequence:
 $\hat{H} = \hat{R}_{DX}^H R_{DD}^{-1}$, where ^{H} is the conjugate-transpose operator, and
- calculating the impulse response in the frequency domain of the multi-reception-channel propagation channel $\hat{h}(f)$ for each reception channel of the receiver, by Fourier transformation of the vectors $\hat{h}_k(n)$ forming the columns of the matrix $\hat{H}$.

15

3. Receiving and equalizing method according to Claim 2, wherein the correlation matrix $\hat{R}$ of the noise and interference is obtained using the formula:

$$\hat{R} = \hat{R}_{XX} - \hat{H} \hat{R}_{DX}.$$

- 20 4. Method for receiving and carrying out anti-jamming equalization according to one of Claims 2 and 3, wherein said matrices R_{DD} , $\hat{R}_{DX}$ and $\hat{R}_{XX}$ are calculated using the following formulae:

$$R_{DD} = \frac{1}{P-L+1} \sum_{n=L-1}^{P-1} \mathbf{d}(n) \mathbf{d}(n)^H,$$

$$\hat{R}_{DX} = \frac{1}{P-L+1} \sum_{n=L-1}^{P-1} \mathbf{d}(n) \mathbf{x}(n)^H,$$

$$\hat{R}_{XX} = \frac{1}{P-L+1} \sum_{n=L-1}^{P-1} \mathbf{x}(n) \mathbf{x}(n)^H,$$

where

- $\mathbf{d}(n)$ is a vector formed from the symbols of a learning sequence;

- $x(n)$ is a vector formed from the symbols received in a portion corresponding to the learning sequence $d(n)$ of said synchronized multi-reception-channel signal;
- P is the number of symbols in said learning sequence $d(n)$; and
- 5 - L is a length of an equalization window.

5. Method for receiving and carrying out anti-jamming equalization according to Claim 1, wherein the calculation of the impulse response in the frequency domain of the multi-reception-channel propagation channel $\hat{h}(f)$ comprises steps of:

- estimating the time impulse response of the propagation channel $\hat{h}_k(n)$ for each channel k of the receiver, from at least one learning sequence and at least one portion corresponding to said one or more frequency-domain-transposed learning sequences of the synchronized multi-reception-channel signal
- 15 • decreasing the noise in the time impulse responses of the propagation channel $\hat{h}_k(n)$ for each reception channel k of the receiver, by zeroing the values $\hat{h}_k(n)$ associated with the portions for which the signal cannot be equalized; and
- 20 • calculating vectors $\hat{h}(f)$ by frequency interpolation of the $\hat{h}_k(n)$.

6. Method for receiving and carrying out anti-jamming equalization according to Claim 5, wherein the calculation of the correlation matrix $\hat{R}$ of the noise and interference comprises steps of:

- 25 • determining, in the estimated time impulse responses $\hat{h}_k(n)$, the positions I_b of samples corresponding to noise, and generating vectors $\hat{b}_k(n) = \hat{h}_k(n)$ for n belonging to I_b ;
- calculating noise vectors $\hat{b}(n)$ from the $\hat{b}_k(n)$; and
- calculating the matrix $\hat{R}$:

$$\hat{R} = \sum_{n \in I_b} \hat{b}(n) \hat{b}(n)^H.$$

7. Method for receiving and carrying out anti-jamming equalization according to Claim 5, the signal comprising a plurality of learning sequences, wherein said step of determining the time impulse response for each channel k of the multi-reception-channel receiver is carried out for N_{TS} learning sequences, $\hat{h}_{k,i}(n)$ designating the time impulse response estimated for the reception channel k from the learning sequence i , and wherein the calculation of the correlation matrix $\hat{R}$ of the noise and interference comprises steps of:

- determining, in the estimated time impulse responses $\hat{h}_{k,i}(n)$, the positions I_u of samples corresponding to the useful signal, and the positions I_b of samples corresponding to noise, and generating vectors $\hat{u}_{k,i}(n) = \hat{h}_{k,i}(n)$ for n belonging to I_u , and vectors $\hat{b}_{k,i}(n) = \hat{h}_{k,i}(n)$ for n belonging to I_b ;
- calculating useful-signal vectors $\hat{u}_i(n)$ from the $\hat{u}_{k,i}(n)$, and noise vectors $\hat{b}_i(n)$ from the $\hat{b}_{k,i}(n)$;
- estimating a correlation matrix $\hat{R}_{XX}$ of the total signal total, where

$$\hat{R}_{XX} = \frac{1}{N_{TS}} \sum_{i=0}^{N_{TS}-1} \left(\sum_{n \in I_u} \hat{u}_i(n) \hat{u}_i(n)^H + \sum_{n \in I_b} \hat{b}_i(n) \hat{b}_i(n)^H \right)$$

- estimating the average useful-signal vector:

$$\hat{u}_m(n) = \frac{1}{N_{TS}} \sum_{i=0}^{N_{TS}-1} \hat{u}_i(n);$$

- estimating a correlation matrix $\hat{R}_{SS}$ of the received useful signal:

$$\hat{R}_{SS} = \sum_{n \in I_u} \hat{u}_m(n) \hat{u}_m(n)^H;$$

- and calculating the matrix $\hat{R}$:

$$\hat{R} = \frac{1}{L_{TS}} (\hat{R}_{XX} - \hat{R}_{SS}).$$

20

8. Multi-reception-channel receiver (110) allowing reception and anti-jamming equalization of a signal comprising at least one learning sequence (101) formed from known symbols and at least one sequence (102) of useful data, which sequence is formed from unknown symbols, said receiver being configured to receive the signal in each of its reception channels, and to transpose and discretize the multi-reception-channel signal into a discretized

25

baseband equivalent multi-reception-channel signal (401) and being characterized in that it comprises at least one piece of equipment (130) for processing the signal, which is configured to implement a method for receiving and carrying out anti-jamming equalization by executing steps of:

- 5 • synchronizing (402) the discretized baseband multi-reception-channel signal;
- calculating (403) an impulse response in the frequency domain of the multi-reception-channel propagation channel $\hat{\mathbf{h}}(f)$ and a correlation matrix $\hat{\mathbf{R}}$ of the noise and interference, from at least one portion
- 10 corresponding to a learning sequence of said synchronized multi-reception-channel signal;
- transposing (404) to the frequency domain at least one portion corresponding to a sequence of useful data or of the synchronized multi-reception-channel signal, and filtering (405) with the vector $\mathbf{w}(f)$,
- 15 where

$$\mathbf{w}(f) = \frac{\hat{\mathbf{R}}^{-1}\hat{\mathbf{h}}(f)}{1 + \hat{\mathbf{h}}(f)^H \hat{\mathbf{R}}^{-1} \hat{\mathbf{h}}(f)},$$

the signal resulting from said filtering being a single-reception-channel signal in the frequency domain; and

- transposing (406) said single-reception-channel signal to the time domain.