

**METHOD AND DEVICE FOR MIMO SYNCHRONISATION IN THE PRESENCE OF
INTERFERENCES**

The invention relates to a method and a device allowing a modem
5 to be synchronized, both in time and in frequency, on a transmitter of digital data by microwave channel, in the absence and in the presence of interferences (accidental or deliberate), for a system incorporating several antennas both in transmission and in reception, or MIMO system (the abbreviation for Multiple Input Multiple Output).

10 In the microwave channel digital data transmission systems, the synchronization (time/frequency) is performed, from sequences of known symbols from the receiver and interleaved between the information symbols, by correlation between the signal received and a reference signal constructed from known symbols. The result is compared to a threshold to
15 decide on the synchronization. The methods allowing a modem to be synchronized on a transmitter of digital data are fairly well known for single input multiple output, SIMO, transmission systems. For example, the publication by D.M. Duglos, R.A. Scholtz, entitled "Acquisition of spread spectrum signals by an adaptive array," IEEE Trans. Acou. Speech.Signal
20 Proc., vol. 37, no. 8, pp. 1253–1270, 1989, and the publication by L.E. Brennan, I.S. Reed, entitled "An adaptive array signal processing algorithm for communications", IEEE Trans. Aerosp. Electronic Systems, vol. 18, no. 1, pp. 124–130, 1982, describe such methods for temporal synchronization. The patent EP 0 665 665 from the applicant relates to an improvement of
25 these techniques.

In the case of the MIMO-type systems, the methods known to the applicant for an MIMO synchronization robust to interferences correspond to the generalized likelihood ratio test GLRT receivers and minimum mean square error or MMSE receivers described, for example, in the publication of
30 [3] D. W. Bliss, P. A. Parker "Temporal synchronization of MIMO wireless communication in the presence of interference", IEEE Trans. Signal

Process., vol. 58, no.3, pp.1794-1806, Mar. 2010. However, the GLRT method described in this publication is complex to implement, because it requires the computation of a determinant and of a matrix inversion at each position tested, which becomes costly when the number of antennas of the system increases. The MMSE method, less costly, becomes suboptimal for the non-orthogonal sequences. There is therefore a need to have alternative receivers with reduced complexity that aim to retain the performance levels of the abovementioned GLRT receiver.

The invention relates to a method for time/frequency synchronization of a signal in a transmission system comprising M transmitters and N receivers, the N receivers being linked to a processor suitable for processing the signals and for transmitting a result to a demodulator, in the presence of interferences, characterized in that it comprises at least the following steps:

on the processor:

- computing a correlation matrix R_{ss} of reference signals transmitted by the M transmitting sensors, computing its inverse R_{ss}^{-1} ,
- for each index l corresponding to a possible instant of synchronization, with l varying up to a position $l + Etal$, where $Etal$ is the maximum temporal spread of the channel, when l corresponds to the first position tested for which there is an overshoot of the threshold, reiterating the following steps:
 - estimating the correlation matrix of noise $\hat{R}(l)$ received on the N sensors in reception,
 - computing the inverse of the estimated correlation matrix, $\hat{R}^{-1}(l)$
 - for each index Δf corresponding to a possible frequency offset for the frequency synchronization, between Δf_{min} and Δf_{max} ,
 - estimating an intercorrelation matrix between the signals received on the N sensors in reception, offset by $-\Delta f$, and the

learning sequences transmitted by the M antennas in transmission, $\hat{R}_{XS}(l, \Delta f)$,

- computing a synchronization criterion by determining the trace $\text{Tr}[\cdot]$ of a matrix resulting from the product formed by the inverse correlation matrix of the learning sequences R_{ss}^{-1} , the conjugate transpose of the estimate of the intercorrelation matrix of the signals received and of the matrix of the learning sequences $\hat{R}_{XS}(l, \Delta f)^H$, the inverse of an estimate of the noise matrix $\hat{R}^{-1}(l)$ and the estimate of the intercorrelation matrix between the observations received and the learning sequences

$\hat{R}_{XS}(l, \Delta f)$:

$$C(l, \Delta f) = \text{EGLRT3}(l, \Delta f) = \text{Tr}[R_{SS}^{-1} \hat{R}_{XS}(l, \Delta f)^H \hat{R}^{-1}(l) \hat{R}_{XS}(l, \Delta f)]$$

- comparing the value of the criterion $C(l, \Delta f)$ obtained to a threshold value η , if the value of the criterion $C(l, \Delta f)$ exceeds the threshold value η , then considering the index l as a potential candidate for the temporal instant allowing the synchronization and the offset Δf as a potential candidate for the synchronization frequency offset, reiterating the process for $\Delta f - \delta$ and $\Delta f + \delta$, where δ is the frequency analysis pitch and reiterating the process up to the position $l + \text{Etal}$, where Etal is the maximum temporal spread of the channel, determining one or more values of possible instant l , and of possible offset Δf and triggering the signal synchronization and acquisition method,
- if the value of the criterion $C(l, \Delta f)$ is less than the threshold value, incrementing the value of Δf by up to a possible new detection. In this case, reiterating the preceding steps described when there is detection. In the absence of detection, incrementing the value of l and reiterating the overall process

including the loop on Δf to a possible new detection. In this case, reiterating the preceding steps described when there is detection.

According to a variant embodiment, the noise matrix is estimated by likening it to the inverse of the correlation matrix of the signals received $\hat{R}_{xx}(l)$ and the criterion of joint computation of the index and of the synchronization offset is produced by the following formula: by determining the trace of a matrix resulting from the product formed by the inverse correlation matrix of the learning sequences, the conjugate transpose of the estimate of the intercorrelation matrix of the signals received and of the matrix of the learning sequences, the inverse of an estimate of the noise matrix $\hat{R}^{-1}(l) = \hat{R}_{xx}^{-1}(l)$ and the estimate of the intercorrelation matrix between the observations received and the learning sequences:

$$C(l, \Delta f) = E0_GLRT3(l, \Delta f) = \text{Tr}[R_{SS}^{-1} \hat{R}_{XS}(l, \Delta f)^H \hat{R}_{XX}^{-1}(l) \hat{R}_{XS}(l, \Delta f)].$$

In the case where the M reference sequences transmitted by the M transmitting sensors are orthogonal, the computation of the synchronization index is performed, for example, by using the following formula:

$$C(l, \Delta f) = E0_GLRT3(l, \Delta f) \triangleq \sum_{i=1}^M \frac{\hat{r}_{XS_i}(l, \Delta f)^H \hat{R}_X(l)^{-1} \hat{r}_{XS_i}(l, \Delta f)}{r_{Si}}$$

where the vector $\hat{r}_{XS_i}(l, \Delta f)$ is the intercorrelation vector between the observations offset by $-\Delta f$ and the learning sequence transmitted by a transmitter i for a tested synchronization position l, defined by:

$$\hat{r}_{XS_i}(l, \Delta f) \triangleq \frac{1}{K} \sum_{n=0}^{K-1} x((k+l)) s_i(k)^* \exp(-j2\pi\Delta f k T_e)$$

where $s_i(k)$ is the component i of $s(k)$ and where T_e is the sampling period.

According to a variant embodiment, the estimated noise matrix,

$\hat{R}_1^{-1}(l, \Delta f)$, can be estimated by subtracting the contributions of the synchronization sequences in the estimate of the correlation matrix of the signals received, assuming that the signal containing the reference sequences is aligned in time and in frequency with the observation matrix and the criterion is obtained by the following formula:

$$\hat{R}_1(l, \Delta f) = \hat{R}_{xx}(l) - \hat{R}_{xs}(l, \Delta f) R_{ss}^{-1} \hat{R}_{xs}(l, \Delta f)^H$$

$$C(l, \Delta f) = E1_GLRT3(l, \Delta f) = \text{Tr}[R_{ss}^{-1} \hat{R}_{xs}(l, \Delta f)^H \hat{R}_1^{-1}(l, \Delta f) \hat{R}_{xs}(l, \Delta f)]$$

R_{ss}^{-1} inverse of the correlation matrix of the reference sequences,

$\hat{R}_{xs}(l, \Delta f)$ estimate of the intercorrelation matrix and its transpose $\hat{R}_{xs}(l, \Delta f)^H$.

The M reference sequences are, for example, orthogonal sequences, the criterion is obtained by the following formula:

$$C(l, \Delta f) = E1_GLRT3(l, \Delta f) \triangleq \sum_{i=1}^M \frac{\hat{r}_{xs_i}(l, \Delta f)^H \hat{R}_1^{-1}(l, \Delta f) \hat{r}_{xs_i}(l, \Delta f)}{r_{si}}$$

where the vector $\hat{r}_{xs_i}(l, \Delta f)$ is the intercorrelation vector between the observations offset by $-\Delta f$ and the learning sequence transmitted by a transmitter i for a tested synchronization position l, defined above, where $s_i(k)$ is the component i of $\mathbf{s}(k)$ and $\hat{R}_1^{-1}(l, \Delta f)$ the inverse of the estimate of the noise matrix.

According to a variant, an observation matrix ($N \times K'$) is constructed with K' chosen and set in order for the channel matrix H and the noise matrix to be stationary on the temporal horizon set by K' and the estimated matrix

$\hat{R}'_{xx}(l) = \frac{X'(l)X'(l)^H}{K'}$ is used for $K'-K+1$ tested positions with $X'(l)$ an observation matrix defined from the K' signal samples.

For applications where the noises are decorrelated on the antennas but of different powers, the criterion is, for example, obtained by the following formula:

$$C(l, \Delta f) = E0_Diag_GLRT3(l, \Delta f) = \text{Tr}[R_{ss}^{-1} \hat{R}_{xs}(l, \Delta f)^H \hat{R}_0^{-1}(l) \hat{R}_{xs}(l, \Delta f)]$$

R_{ss}^{-1} inverse of the correlation matrix of the reference sequences,

$\hat{R}_{xs}(l, \Delta f)$ estimate of the intercorrelation matrix and its transpose $\hat{R}_{xs}(l, \Delta f)^H$

$$5 \quad \hat{R}_0^{-1}(l) = \text{Diag}(\hat{\eta}_{10}(l), \hat{\eta}_{20}(l), \dots, \hat{\eta}_{N0}(l))^{-1}.$$

η_{ij} is the power of the noise on the reception antenna i ,

$$\hat{\eta}_{0i}(l) \triangleq \frac{1}{NK} \sum_{k=0}^{K-1} \mathbf{x}(k+l)^H \mathbf{x}(k+l) \text{ with } \mathbf{x}(k+l) \text{ the envelope of the signals at}$$

the reception antenna output.

- 10 For white noise applications, the synchronization criterion can be obtained by the following formula:

$$C(l, \Delta f) = E0_BB_GLRT3(l, \Delta f) = \text{Tr}[R_{ss}^{-1} \hat{R}_{xs}(l, \Delta f)^H \hat{R}_{xs}(l, \Delta f)] / \text{Tr}[\hat{R}_{xx}(l)] = \text{Tr}[\hat{R}_{xs}(l, \Delta f) R_{ss}^{-1} \hat{R}_{xs}(l, \Delta f)^H] / \text{Tr}[\hat{R}_{xx}(l)]$$

$\text{Tr}[\cdot]$ is the trace of a matrix,

- 15 R_{ss}^{-1} the inverse of the correlation matrix of the reference sequences,

$\hat{R}_{xs}(l, \Delta f)$ the estimate of the intercorrelation matrix and its transpose $\hat{R}_{xs}(l, \Delta f)^H$,

$\hat{R}_{xx}(l)$ the estimate of the correlation matrix of the signals received.

- 20 For applications where the M synchronization sequences are decorrelated and orthogonal, the following formula is for example used:

$$\text{GLRT1}'(l, \Delta f) = \sum_{i=1}^M \frac{\hat{\mathbf{r}}_{xs_i}(l, \Delta f)^H \hat{\mathbf{r}}_{xs_i}(l, \Delta f)}{\hat{r}_x(l) r_{si}}$$

According to a variant, the intercorrelation vector $\hat{\mathbf{r}}_{xs_i}(l, \Delta f)$ can be determined for each position l to be tested and for each frequency offset

Δf belonging to the interval $[-\Delta f_{max}, \Delta f_{max}]$, where $\Delta f_{max} = M_d \delta$ where δ is the offset search pitch and where $2 M_d + 1$ is the number of Doppler cells to be tested, by using the following formula:

$$\hat{r}_{xsi}(l, \Delta f) = \left(\frac{1}{K}\right) \sum_{k=0}^{K-1} x(l + F_{sur} * k) s_i^*(k) e^{-2j\pi \frac{\Delta f}{F_s} k F_{sur}}$$

with F_{sur} the upsampling factor of the input signal relative to the symbol frequency F_s , where Δf_{max} is given as a function of the maximum speed of movement of the transmitters and receivers.

According to a variant embodiment, the length K of a learning sequence is subdivided into T slices of length K_0 with $K = T * K_0$, T being chosen in order for the phase rotation induced by the frequency offset to be negligible, there is estimated, for each tested synchronization position l , an intercorrelation vector on each slice t and for each Doppler cell m ($m = -M_d, \dots, +M_d$), with the pitch $\Delta f'$:

$$\hat{r}_{xsi}(l, m) = \left(\frac{1}{K}\right) \sum_{t=0}^{T-1} \hat{r}_{xsi,t}(l) e^{-2j\pi \frac{m \Delta f'}{F_s} t K_0}$$

and by determining the correlation matrix by the following formula:

$$\hat{R}_{xx}(l) = \left(\frac{1}{K}\right) \sum_{k=0}^{K-1} x(l + F_{sur} * k) x^H(l + F_{sur} * k)$$

F_{sur} is the upsampling frequency, F_s the symbol frequency.

The Doppler offset associated with a path detected on a synchronization position can be estimated by parabolic interpolation from criteria computed on the position l_0 for the three Doppler cells (m_0-1) , m_0 and (m_0+1) :

$$\widehat{\Delta f} = \left(m_0 + \frac{1}{2} \frac{c(l_0, m_0+1) - c(l_0, m_0-1)}{c(l_0, m_0-1) + c(l_0, m_0+1) - 2c(l_0, m_0)} \right) \cdot \Delta f'.$$

Fourier transforms or fast Fourier transforms can be used to compute the intercorrelations performed on each learning sequence:

$$\hat{r}_{xsi}(l, m) = \left(\frac{1}{K}\right) \sum_{t=0}^{T-1} \hat{r}_{xsi,t}(l) e^{-2j\pi \frac{t.m}{T}}$$

For a signal containing a data frame comprising synchronization sequences TS, these sequences TS are for example used and the following steps are executed:

- 5 the pitch $\Delta f'$ depends on the positions of the two extreme sequences TS of the data frame:

$$\Delta f' = \frac{\text{DELTA_PHI_MAX}}{2 \cdot \pi \cdot (p_{N_{TS}-1} + (I-1)K_0 - p_0)} \cdot F_s$$

for each tested synchronization position l , an intercorrelation vector is estimated on each slice t of each learning sequence j by the following formula:

$$10 \quad \hat{r}_{xsi,t,j}(l) = \sum_{k=0}^{K_0-1} x(l + F_{sur} * (k + p_j + t \cdot K_0)) s_{i,j}^*(k + t \cdot K_0)$$

$$\hat{r}_{xsi}(l, m) = \left(\frac{1}{KN_{TS}}\right) \sum_{j=0}^{N_{TS}-1} \left(\sum_{t=0}^{T-1} \hat{r}_{xsi,t,j}(l) e^{-2j\pi \frac{m \cdot \Delta f'}{F_s} \cdot t \cdot K_0} \right) e^{-2j\pi \frac{m \cdot \Delta f'}{F_s} (p_j - p_0)}$$

by computing the correlation matrices on the N_{TS} learning sequences by the following formula:

$$\hat{R}_{xx}(n) = \left(\frac{1}{KN_{TS}}\right) \sum_{j=0}^{N_{TS}-1} \left(\sum_{k=0}^{K-1} x(n + F_{sur} * (k + p_j)) x^H(n + F_{sur} * (k + p_j)) \right)$$

- 15 - N_{TS} , the number of learning sequences on which the computation of the synchronization criterion is performed,
- $s_{i,j}(k)$, the learning sequence of index j ($j=0, \dots, N_{TS}-1$) transmitted on the transmission antenna i ,
- p_j , the index of the first symbol of the learning sequence j , common to
- 20 all the transmission antennas.

Other features and advantages of the present invention will become apparent from the following description given in light of the figures of the attached drawings which represent:

- figure 1, a functional diagram of a data transmission system comprising several transmitters and a reception device comprising at least one antenna according to the invention,
- figure 2, a flow diagram relating an example of steps of the method according to the invention, and
- figure 3, schematically represents an example of frame on a transmission antenna.

Figure 1 represents an example of data transmission in a system 1 comprising M transmitting sensors $C_1, \dots, C_M$, narrowband antennas for example, and N receiving sensors $R_1, \dots, R_N$, for example narrowband antennas. The data sequences transmitted are received by the N receivers in an environment including noise with interferences. The receiving sensors are linked with a processor 2 which will be adapted to execute the steps of the method according to the invention in order to determine the instant of synchronization allowing the acquisition of the signals from the computation of a criterion which will be described hereinbelow. The processor can then transmit the instants and the offsets of synchronization thus obtained to a demodulator 3 allowing the demodulation of the useful symbols transmitted. The demodulator 3 notably comprises a decision module adapted to align the equalizer as a function of the observations and of the instants found for the synchronization according to a principle known to the person skilled in the art. The synchronization step is a prerequisite to this demodulation. It makes it possible not only to detect the presence of the useful signal on the reception antennas but it also makes it possible to know the positions of the reference symbols and those of the symbols to be demodulated. Finally, it also makes it possible to shrewdly align the equalizers to be implemented before the demodulation for a maximum of performance levels. The demodulation step will be performed by using techniques known to the person skilled in the art and will not be detailed. The result of the implementation of the method according to the invention corresponds to an optimization of the detection of a signal.

Take an MIMO link ($M \times N$) with M narrowband antennas in transmission and N narrowband antennas in reception, and $\mathbf{s}(k)$ ($0 \leq k \leq K-1$) the vector ($M \times 1$), of length K , of the learning sequences transmitted simultaneously on the transmission antennas at the instant k . Assuming a propagation channel with flat fading and when the temporal and frequency synchronization are perfect, the complex envelopes of the signals at the output of the N reception antennas, for an optimal synchronization instant l_0 and for an optimal frequency offset Δf_0 can be written as the sum of the contributions of the useful signals and of the total noise sampled:

$$\mathbf{x}_0(k+l_0) = \mathbf{x}(k+l_0) \exp(-j2\pi\Delta f_0(k+l_0)T_e) = \mathbf{H}\mathbf{s}(k) + \mathbf{v}(k+l_0) \quad (1)$$

In this expression, T_e is the sampling period, $\mathbf{x}(k+l_0)$ corresponds to the vector formed by the signals received on the reception sensors at the instant $k+l_0$, $\mathbf{x}_0(k+l_0)$ is the vector at the instant $k+l_0$ of the observations offset by $-\Delta f_0$, $\mathbf{H}$ is the channel matrix ($N \times M$) and $\mathbf{v}(k+l_0)$ the total noise vector offset by $-\Delta f_0$ and sampled at the instant $k+l_0$, which contains the potential contribution of the multiuser interferences or MUI, of the scramblers and of the background noise. By using $\mathbf{X}_l = [\mathbf{x}_0(l), \dots, \mathbf{x}_0(l+K-1)]$ and $\mathbf{V}_l = [\mathbf{v}(l), \dots, \mathbf{v}(l+K-1)]$ to denote the matrices ($N \times K$) of the observations offset optimally and of the total noise for the synchronization position tested l , and $\mathbf{S} = [\mathbf{s}(0), \dots, \mathbf{s}(K-1)]$ to denote the matrix ($M \times K$) of the learning sequences, the matrix of the observations $\mathbf{X}_{l_0}$ for the optimal sampling position is written

$$\mathbf{X}_{l_0} = \mathbf{H}\mathbf{S} + \mathbf{V}_{l_0}. \quad (2)$$

The observation matrix $\mathbf{X}_{l_0}$ corresponds to the signals received on the receiving sensors offset optimally for the instants $k+l_0$ ($0 \leq k \leq K-1$). The series of the theoretical justifications, deals with the case where the frequency offset does not exist since, in the model (2), it has been compensated and the case where it is taken into account.

The issue of the temporal synchronization of an MIMO link can be considered as an issue of detection with two hypotheses. The first hypothesis H_1 obtained for the optimal synchronization instant $l=l_0$ is that the matrix of

the learning sequences S is perfectly aligned in time with the observation matrix X_l corresponding to the model (2). The second hypothesis H_0 is that there is no signal in the observation matrix X_l . The two hypotheses, for the synchronization position l tested, are therefore:

$$\begin{aligned} H_0: X_l &= V_l \\ H_1: X_l &= HS + V_l \end{aligned} \quad (3)$$

For each temporal position l tested, the synchronization then consists in creating a synchronization criterion which is a function of the observations X_l and in comparing the value of this criterion to a threshold value η . If the threshold is exceeded for a possible synchronization index l , then the index is decided as candidate likely to be the correct synchronization instant or moment. The performance levels of a synchronization criterion are characterized by the probability of a correct detection P_D under the hypothesis H_1 for a given probability of false alarm P_{FA} (in the case of absence of signal), corresponding to the probability of exceeding the threshold under the hypothesis H_0 .

Before explaining the steps of the synchronization method according to the invention, a few recaps on the obtaining of the receiver (how the criterion is determined to define the synchronization instant) that allows the synchronization according to the prior art are given.

According to the optimum theory in the Neyman-Pearson sense, the optimal statistic for detection of the matrix S from the observation matrix X (the tested position index l has been removed here to simplify the notations) is the test of the likelihood ratio LRT (Likelihood Ratio Test) which consists in comparing the function $LRT \triangleq p_{H_1}(X|S, H, R) / p_{H_0}(X|R)$ to a threshold, where $p_{H_i}(X| \dots)$ ($i=0,1$) is the conditional probability density of X under H_i . To compute this test statistic, it is assumed that the noise samples $v(k)$ are Gaussian of zero mean, stationary, temporally white, circular with a correlation matrix $R = E[v(k)v(k)^H]$, where ^{H} signifies the conjugate transpose. The expression of LRT then takes the following form:

$$LRT = \frac{\prod_{k=0}^{K-1} p_{H_1}(v(k)|s(k), H, R)}{\prod_{k=0}^{K-1} p_{H_0}(v(k)|R)} \quad (4)$$

For the model, the following is obtained:

$$\begin{aligned} p_{H_0}(v(k)|R) &= \frac{1}{\pi^N \det(R)} e^{-x(k)^H R^{-1} x(k)} \\ p_{H_1}(v(k)|s(k), H, R) &= \frac{1}{\pi^N \det(R)} e^{-(x(k)-Hs(k))^H R^{-1} (x(k)-Hs(k))} \end{aligned} \quad (5, 6)$$

where $\det(R)$ means the determinant of the matrix R . The values of R and of H being unknown, their estimate in the maximum likelihood sense, EMV, is used under each of the hypotheses H_1 and H_0 . This leads to the statistic GLRT2 known from the abovementioned prior art, with:

$$GLRT\ 2 = \det[I_K - \hat{P}_s \hat{P}_x]^K \quad (7)$$

where I_K is the identity matrix of dimension K , $\hat{P}_s$ and $\hat{P}_x$ are matrices ($K \times K$) corresponding to the projectors onto the spaces generated by the lines of S and of X respectively; defined by $\hat{P}_s \triangleq S^H (SS^H)^{-1} S$ and $\hat{P}_x \triangleq X^H (XX^H)^{-1} X$.

By defining the matrices

$R_{ss} \triangleq SS^H/K$, $\hat{R}_{xx} \triangleq XX^H/K$ et $\hat{R}_{xs} \triangleq XS^H/K$ and by using the properties of the determinant, it is easy to demonstrate that the formula (7) is also written as:

$$\begin{aligned} GLRT\ 2 &= \det[I_N - \hat{R}_{xx}^{-1} \hat{R}_{xs} R_{ss}^{-1} \hat{R}_{xs}^H]^K \\ &= \det[I_M - R_{ss}^{-1} \hat{R}_{xs}^H \hat{R}_{xx}^{-1} \hat{R}_{xs}]^K \end{aligned} \quad (8)$$

The expression assumes a number M of antennas in transmission less than or equal to K .

The two formulae (7) and (8) show that, for each synchronization position l tested, ($X = X_l$), the receiver known from the prior art requires the computation of at least one inversion of matrix ($N \times N$), $\hat{R}_{xx}^{-1}$ and that of the

determinant of a matrix ($P \times P$), where $P = \text{Inf}(K, N, M)$ which can be prohibitive when K is great and the system comprises a large number of antennas.

It can be seen that the computation of the determinant is all the more costly when the number of transmission and reception antennas is high. The idea of the present invention is therefore to offer receivers with reduced complexity that have performance levels at least similar to those of the prior art, even greater.

A first variant implementation of the method is based on the GLRT receiver under the hypothesis that the channel matrix H is unknown in the presence of a total noise of zero mean, stationary, circular, Gaussian, the covariance matrix R of which is assumed known. This GLRT receiver is called GLRT3 hereinbelow.

The estimate of the channel matrix H under the hypothesis H_1 is given by:

$$\hat{H} = \hat{R}_{xs} R_{ss}^{-1} \quad (9)$$

where $\hat{R}_{xs}$ corresponds to the estimate of the intercorrelation matrix of the signals received and of the reference signals, and R_{ss}^{-1} corresponds to the inverse of the correlation matrix of the reference signals.

R being the assumed known noise matrix, a sufficient statistic is obtained from (4) by replacing H by its estimate (9). By using the formulae (5) and (6) and by taking the logarithm of (4), a sufficient statistic or a new criterion of computation of the synchronization instant is obtained:

$$GLRT\ 3 = \text{Tr} \left[R_{ss}^{-1} \hat{R}_{xs}^H R^{-1} \hat{R}_{xs} \right] \quad (10)$$

with:

R_{ss}^{-1} the inverse of the correlation matrix of the reference signals,

$\hat{R}_{xs}^H$ the conjugate transpose of the estimate of the intercorrelation matrix of the signals received and of the reference signals,

R^{-1} the inverse of the noise matrix, assumed stationary,

$\hat{R}_{xs}$ the estimate of the intercorrelation matrix of the signals received and of the reference signals.

By revealing the instant l , the formula (10) is written:

$$C(l) = GLRT3(l) = Tr \left[R_{ss}^{-1} \hat{R}_{xs}^H(l) R^{-1} \hat{R}_{xs}(l) \right] \quad (10a) \text{ with:}$$

- 5 $\hat{R}_{xs}^H(l)$ the conjugate transpose of the estimate of the intercorrelation matrix of the signals received and of the reference signals, for a possible instant l for the synchronization,

$\hat{R}_{xs}(l)$ the estimate of the intercorrelation matrix of the signals received and of the reference signals for a possible synchronization instant l ,

- 10 R^{-1} the inverse of the noise matrix.

This method notably presents the advantage of not involving the computation of a determinant, of reducing the complexity of the receiver.

- However, in practice, the matrix R is unknown and has to be estimated at each synchronization position tested l by an estimated noise
15 matrix $\hat{R}(l)$. By replacing R with its estimate $\hat{R}(l)$ in the formula (10a), an optimized receiver is obtained that makes it possible to determine the instant of synchronization of the signals, the criterion for determining a synchronization instant l being written as follows:

$$C(l) = EGLRT3(l) = Tr \left[R_{ss}^{-1} \hat{R}_{xs}^H(l) \hat{R}^{-1}(l) \hat{R}_{xs}(l) \right] \quad (10b)$$

- 20 Figure 2 schematically represents the various steps of the method implemented by the invention taking account of the frequency offset. Upstream, the value of the correlation matrix of the reference sequences and its inverse have been determined, 200, 201, R_{ss} and R_{ss}^{-1} ,

- l is initialized at an initial value $l_{\text{initial}} = 1$, for example, 202

- 25 For a possible synchronization instant l ,

- the estimated value of the correlation matrix $\hat{R}(l)$ of the estimated noise is determined, 203, then the inverse of this

matrix $\hat{R}^{-1}(l)$ will be computed 204, the estimate $\hat{R}_{xs}(l)$ of the
intercorrelation matrix between the signals received on the N
sensors in reception “offset” by $-\Delta f$ and of the reference
signals and the learning sequences transmitted by the M
5 transmission antennas $\hat{R}_{xs}(l, \Delta f)$ is computed 205, this
computation is performed for each index Δf corresponding to a
possible frequency offset for the frequency synchronization
between the values Δf_{min} and Δf_{max} ,

- the synchronization criterion $C(l, \Delta f)$ is determined by
10 determining the matrix resulting from the product formed by the
inverse correlation matrix of the learning sequences, the joint
transpose of the estimate of the intercorrelation matrix of the
signals received and of the matrix of the learning sequences $\hat{R}_{xs}(l, \Delta f)^H$, inverse of the intercorrelation matrix between the
15 observations received and the learning sequences $\hat{R}_{xs}(l, \Delta f)$, for
example, 206,

$C(l, \Delta f) = \text{EGLRT3}(l, \Delta f) = \text{Tr}[R_{SS}^{-1} \hat{R}_{xs}(l, \Delta f)^H \hat{R}^{-1}(l) \hat{R}_{xs}(l, \Delta f)]$, other
computation examples for the criterion $C(l)$ will be given in the
description, then

- the value of the criterion found $C(l, \Delta f)$ will be compared to a
20 threshold value η , 207,
- if the value of the criterion $C(l, \Delta f)$ is greater than the threshold
value η , the index l found is used as candidate for the
synchronization instant, the offset Δf as a potential candidate for
25 the synchronization frequency offset, 208, if there is detected
on a first initial position $l_{initial}$, a first candidate position for the
correct synchronization is obtained, the method will iterate the
process for $\Delta f - \delta$ and $\Delta f + \delta$, where δ is the frequency analysis

- pitch and up to the position $l_{\text{initial}} + E_{\text{tal}}$ and inform the member which decides on the synchronization of all the threshold overshoots between initial and $l_{\text{initial}} + E_{\text{tal}}$, the decision member counts all of the values l and of the possible offset values Δf for which there is threshold overshoot, if there is a single value of l , then the synchronization instant corresponds to this position l , if there are several values of l , then the decision member deduces therefrom that the transmission channel has multiple paths with a number of separate paths equal to the number of overshoot values l found and with an effective channel spread equal to the difference between the overshoot positions l_{min} and l_{max} ; the decision member then uses this information to align the equalizer according to a method known to the person skilled in the art,
- if the value of the criterion $C(l)$ is less than the threshold, there will be iteration on l , $l = l + 1$, and the value of Δf will be incremented up to the maximum value, 209, up to a possible detection and if a detection is made, the steps described previously are reiterated when the criterion $C(l)$ exceeds the threshold. To know the value of the noise matrix R , a possible variant embodiment is to use as matrix $\hat{R}(l)$ the estimated value of the noise matrix R under the hypothesis H_0 , $\hat{R}_0$, for a value l , denoted $\hat{R}_0(l)$.

The estimate of the noise matrix in the case where there is no signal in the observation matrix is equal to the estimate of the correlation matrix of the signals received $\hat{R}_0(l) = \hat{R}_{xx}(l) = \hat{R}(l)$, which leads to a criterion receiver making it possible to determine the synchronization instant defined by:

$$C(l) = E0 - GLRT3(l) = Tr \left[R_{ss}^{-1} \hat{R}_{ss}^H(l) \hat{R}_{ss}^{-1}(l) \hat{R}_{ss}(l) \right] \quad (11), \text{ or}$$

$$C(l) = E0 - GLRT3(l, \Delta f) = Tr \left[R_{ss}^{-1} \hat{R}_{xs}^H(l, \Delta f) \hat{R}_{xx}^{-1}(l) \hat{R}_{xs}(l, \Delta f) \right]$$

when the frequency offset is taken into account.

For orthogonal sequences, the receiver can also be written as follows:

$$5 \quad C(l) = E0 - GLRT3(l) = \sum_{i=1}^M \frac{\hat{r}_{xsi}^H(l) \hat{R}_{xx}^{-1}(l) \hat{r}_{xsi}(l)}{r_{si}} \quad (12)$$

Or, by taking into account the frequency offset

$$C(l, \Delta f) = E0 - GLRT3(l, \Delta f) \triangleq \sum_{i=1}^M \frac{\hat{r}_{xsi}^H(l, \Delta f) \hat{R}_{xx}^{-1}(l) \hat{r}_{xsi}(l, \Delta f)}{r_{si}}$$

10 In (12), the vector $\hat{r}_{xsi}(l)$ is the intercorrelation vector between the observations and the learning sequence transmitted by the transmission antenna i for the tested synchronization position l, defined by

$$\hat{r}_{xsi}(l) \triangleq \frac{1}{K} \sum_{k=0}^{K-1} \mathbf{x}((k+l)) s_i(k)^* \quad (13)$$

where $s_i(k)$ is the component i of $\mathbf{s}(k)$ ($s_i(k)$ therefore corresponds to the learning sequence transmitted on the antenna i and where * signifies conjugate complex, and by taking account of the frequency offset, with the vector $\hat{r}_{xsi}(l, \Delta f)$ corresponding to the intercorrelation vector between the observations offset by $-\Delta f$ and the learning sequence transmitted by a transmitter i for a tested synchronization position l, defined by:

$$\hat{r}_{xsi}(l, \Delta f) \triangleq \frac{1}{K} \sum_{n=0}^{K-1} \mathbf{x}((k+l)) s_i(k)^* \exp(-j2\pi\Delta f k T_e)$$

where $s_i(k)$ is the component i of $\mathbf{s}(k)$.

20 According to a variant embodiment, the value of the noise matrix R will be estimated under a hypothesis H_1 considering that the signal matrix is aligned in time with the observation matrix.

The estimated value $\hat{R}_1(l)$ of the matrix R under the hypothesis H_1 for the position l tested under a hypothesis H_1 is defined by

$\hat{R}_1(l) = \hat{R}_{xx}(l) - \hat{R}_{xs}(l) \hat{R}_{ss}^{-1} \hat{R}_{xs}^H(l) = \hat{R}(l)$. In this estimated value $\hat{R}_1(l)$, the contributions of the synchronization sequences have been removed from $\hat{R}_{xx}(l)$.

The synchronization criterion for an instant l will therefore be
5 computed from the following formula:

$$C(l) = E1 - GLRT3(l) = Tr \left[R_{ss}^{-1} \hat{R}_{xs}^H(l) \hat{R}_1^{-1}(l) \hat{R}_{xs}(l) \right] \quad (14)$$

In the case where the M synchronization sequences are orthogonal, the criterion will become:

$$C(l) = E1 - GLRT3(l) = \sum_{i=1}^M \frac{\hat{r}_{xsi}^H(l) \hat{R}_1^{-1}(l) \hat{r}_{xsi}(l)}{r_{si}} \quad (15)$$

10 In the hypothesis where the signal is aligned in time and in frequency, the formulae become:

$$\hat{R}_1^{-1}(l, \Delta f) = \hat{R}_{xx}^{-1}(l) \hat{R}_{xs}^{-1}(l, \Delta f) R_{ss}^{-1} \hat{R}_{xs}^{-1}(l, \Delta f)^H$$

$$C(l, \Delta f) = E1_GLRT3(l, \Delta f) = Tr[R_{ss}^{-1} \hat{R}_{xs}^{-1}(l, \Delta f)^H \hat{R}_1^{-1}(l, \Delta f) \hat{R}_{xs}(l, \Delta f)]$$

R_{ss}^{-1} inverse of the correlation matrix of the reference sequences, and
15 $\hat{R}_{xs}(l, \Delta f)$ estimate of the intercorrelation matrix and its transpose $\hat{R}_{xs}^{-1}(l, \Delta f)^H$.

In the exemplary implementation explained by (11), the use of the criterion to determine the synchronization requires both the computation of the matrix ($N \times N$) $\hat{R}_{xx}(l)$ on K observation samples and the inversion of this
20 same matrix ($N \times N$). In the case where the number N of reception sensors is high, the resulting complexity can become prohibitive.

One way to reduce the computation complexity is to reduce the frequency with which the value of the matrix $\hat{R}_{xx}(l)$ is computed for an instant l and that of its inverse $\hat{R}_{xx}^{-1}(l)$, for example by a factor $\beta > 1$. The
25 idea is to estimate the correlation matrix of the observations over a greater

time horizon than that of the learning sequences, that is to say over K' samples instead of K with $K' > K$ and to use this matrix for the $\beta = K' - K + 1$ positions tested contained in the horizon of this matrix. The value of K' is limited by the fact that the matrices H and R have to remain stationary on this horizon.

The principle of this variant embodiment for the position l tested will consist in constructing an observation matrix ($N \times K'$) defined by $X'(l) = [x(l), \dots, x(K'+l-1)]$, constructed from K' samples which are chosen such that $K' > K$ and that can be used for $\beta = K' - K + 1$ samples tested.

The estimated matrix $\hat{R}_{xx}(l)$ is then replaced in the formula (12) by the estimated matrix $\hat{R}'_{xx}(l)$ defined by $\hat{R}'_{xx}(l) = \frac{X'(l)X'(l)^H}{K'}$ for the β positions tested. The last $K' - K$ samples tested are data samples given instead of synchronization sequences. Since the data samples associated with the different reception antennas are not correlated, this variant embodiment will be able to be used only in the case of orthogonal sequences.

In certain operating conditions, the noise $v(k) (0 \leq k \leq K-1)$ can be assumed zero mean, stationary, circular, Gaussian, but of diagonal correlation matrix R such $R = \text{Diag}(\eta_1, \eta_2, \dots, \eta_N)$, where η_i is the power of the noise on the reception antenna i , assumed unknown in the same way as the channel matrix H . To know in this case the value of the noise matrix R , one possible variant embodiment is to use the estimated value, in the EMV sense, of the powers η_i under the hypothesis H_0 , $\hat{\eta}_{i0}$. This estimate is written, for the position tested l :

$$\hat{\eta}_{i0}(l) \triangleq \frac{1}{K} \sum_{k=0}^{K-1} x_i(k+l) x_i(k+l)^* \quad (16)$$

Consequently, an estimated matrix of R for the tested position l is obtained by $\hat{R}'_0(l) = \text{Diag}(\hat{\eta}_{10}(l), \hat{\eta}_{20}(l), \dots, \hat{\eta}_{N0}(l))$. By inserting this estimate into (10a), the following synchronization criterion is obtained:

$$C(l) = E0 - \text{Diag} - \text{GLRT3}(l) = \text{Tr} \left[R_{ss}^{-1} \hat{R}_{xs}^H(l) \hat{R}_0'^{-1}(l) \hat{R}_{xs}(l) \right] \quad (17)$$

5 and by taking account of the “frequency offset” parameter, the criterion is written

$$C(l, \Delta f) = E0 - \text{Diag} - \text{GLRT3}(l, \Delta f) = \text{Tr} \left[R_{ss}^{-1} \hat{R}_{xs}^H(l, \Delta f) \hat{R}_0'^{-1}(l) \hat{R}_{xs}(l, \Delta f) \right].$$

In other operating conditions, the noise $v(k)(0 \leq k \leq K-1)$ can be assumed zero mean, stationary, circular, Gaussian and temporally white, of correlation matrix R proportional to the identity and such that $R = \eta I$. In this case, the powers η_i are the same and equal to η , unknown in the same way as the channel matrix H . To know in this case the value of the noise matrix R , one possible variant embodiment is to use the estimated value, in the EMV sense, of the power η under the hypothesis H_0 , $\hat{\eta}_0$. This estimate is written, 15 for the tested position l

$$\hat{\eta}_0(l) \triangleq \frac{1}{NK} \sum_{k=0}^{K-1} x(k+l)^H x(k+l) = \frac{1}{N} \text{Tr}(\hat{R}_{xx}(l)) \quad (18)$$

Subsequently, an estimated matrix of R for the tested position l is obtained by $\hat{R}'_0(l) = \hat{\eta}_0(l) I$. By inserting this estimate into (10a), the following synchronization criterion $C(l)$ is obtained:

$$20 \quad E0 - \text{BB} - \text{GLRT3}(l) = \frac{\text{Tr} \left[R_{ss}^{-1} \hat{R}_{xs}^H(l) \hat{R}_{xs}(l) \right]}{\text{Tr} \left[\hat{R}_{xx}(l) \right]} = \frac{\text{Tr} \left[\hat{R}_{xs}(l) R_{ss}^{-1} \hat{R}_{xs}^H(l) \right]}{\text{Tr} \left[\hat{R}_{xx}(l) \right]} = \text{GLRT1} \quad (19)$$

which corresponds to the GLRT1 receiver, that is to say the receiver (4) under the hypothesis of a noise that is unknown, centered, circular, Gaussian, stationary and temporally and spatially white and of an unknown channel matrix H .

25 For applications of white noise type taking account of the frequency offset, the criterion becomes

$C(l, \Delta f) =$

$$E0 - BB - GLRT3(l, \Delta f) = \frac{Tr \left[R_{ss}^{-1} \hat{R}_{ss}^H(l, \Delta f) \hat{R}_{ss}(l, \Delta f) \right]}{Tr \left[\hat{R}_{xx}(l) \right]} = \frac{Tr \left[\hat{R}_{ss}(l, \Delta f) R_{ss}^{-1} \hat{R}_{ss}^H(l, \Delta f) \right]}{Tr \left[\hat{R}_{xx}(l) \right]} = GLRT1$$

$Tr[]$ is the trace of a matrix,

R_{ss}^{-1} the inverse of the correlation matrix of the reference sequences,

5 $\hat{R}_{xs}(l, \Delta f)$ the estimate of the intercorrelation matrix and its transpose $\hat{R}_{xs}(l, \Delta f)^H$,

$\hat{R}_{xx}(l)$ the estimate of the correlation matrix of the signals received.

For applications where the M synchronization sequences are decorrelated and orthogonal, the expression (19) is transformed into:

$$10 \quad C(l) = GLRT1'(l, \Delta f) = \sum_{i=1}^M \frac{\hat{r}_{xsi}^H(l) \hat{r}_{xsi}(l, \Delta f)}{\hat{r}_x(l) r_{si}} \quad (20)$$

where $\hat{r}_x(l) = Tr \left[\hat{R}_{xx}(l) \right]$.

In reality, the signal received at the reception point is often affected by a frequency offset, denoted Δf_o , which is due to the inaccuracy of the frequency synthesis of the local oscillators OLs of the transmitter and of the receiver and to the speed of the mobile transmitters and receivers in transmission and in reception (Doppler effect). It is assumed in this patent that the mixes in transmission and in reception are performed with synchronous local oscillators OLs, that is to say that all the signals in transmission are transmitted with the same frequency offset Δf_{o1} and that all the signals received are received with the same frequency offset Δf_{o2} , with $\Delta f_o = \Delta f_{o1} + \Delta f_{o2}$.

In the presence of a frequency offset Δf_o , the signal received on the optimal synchronization position l_0 , sampled at the symbol rate, is written:

$$25 \quad \mathbf{x}(k+l_0) = \mathbf{H}\mathbf{s}(k) e^{j2\pi\Delta f_o(k+l_0)/F_s} + \mathbf{v}(k+l_0) \quad (21)$$

where F_s is the symbol frequency.

The various criteria described in the present invention are based on the estimations:

- of the powers, $\hat{r}_{s_i}$, of the learning sequences,
- of the correlation matrices $\hat{R}$, $\hat{R}(l)$ or $\hat{R}_{xx}(l)$,
- 5 - of the intercorrelation vectors $\hat{r}_{xsi}$ where i corresponds to the index of the transmission antenna, or $\hat{r}_{xsi}(l)$.

By definition, $\hat{r}_{s_i}$ is not affected by a frequency offset. Similarly, the correlation matrix $\hat{R}_{xx}(l)$ is not affected by a frequency offset. Its asymptotic value is, for the optimal synchronization position:

$$10 \quad R_{xx} = H R_{ss} H^H + R \quad (22)$$

By contrast, the intercorrelation vector between the signal received and the reference sequence $s_i(k)$ is affected by the frequency offset. In effect, the following is obtained on the synchronization position l_0 :

$$\hat{r}_{xsi}(l_0, \Delta f_0) \triangleq \frac{1}{K} \left(\sum_{k=0}^{K-1} |s_i(k)|^2 e^{2j\pi \frac{\Delta f_0}{F_s} k} \right) e^{j2\pi \Delta f_0 l_0 / F_s} \mathbf{h}_i \quad (23)$$

- 15 where $\mathbf{h}_i$ is the channel vector, of size $N \times 1$, associated with the transmission antenna i (there is: $H = [\mathbf{h}_1 \dots \mathbf{h}_M]$). This formula shows that, if the frequency offset Δf_0 is too great, the integration is no longer performed coherently: the MIMO synchronization algorithm must therefore take account of the frequency offset for the computation of the intercorrelation vectors $\hat{r}_{xsi}(l)$.

- 20 Hereinbelow, an explanation is given as to how the frequency offset is taken into account in the computation of each intercorrelation vector $\hat{r}_{xsi}(l)$ involved in the synchronization criterion.

The MIMO synchronization algorithm used in the presence of a frequency offset jointly estimates the optimum synchronization position l_0 and the frequency offset Δf_0 associated with each useful signal propagation path, by replacing, in the equations, the reference signal $s_i(k)$ by the reference

5 signal offset in frequency for the tested offset Δf : $s_i(k)e^{2j\pi\frac{\Delta f}{F_s}k}$. Or, which is equivalent, by replacing the observation vector $\mathbf{x}(k)$ by an offset vector $\mathbf{x}(k)\exp(-j2\pi k\Delta f/F_s)$.

The intercorrelation vector $\hat{\mathbf{r}}_{xsi}$ can thus be written, for each frequency offset tested and for each synchronization position tested:

$$\hat{\mathbf{r}}_{xsi}(l, \Delta f) = \left(\frac{1}{K}\right) \sum_{k=0}^{K-1} \mathbf{x}(l + F_{sur} * k) s_i^*(k) e^{-2j\pi\frac{\Delta f}{F_s}k.F_{sur}} \quad (24)$$

10 with $\Delta f \in [-\Delta f_{max}; +\Delta f_{max}]$ and F_{sur} the upsampling factor of the input signal relative to the symbol frequency.

The range of frequencies to be tested $[-\Delta f_{max}; \Delta f_{max}]$ depends on the accuracy of the transmission and reception OLs denoted DELTA_OL_MAX, on the maximum speed of the mobiles, denoted VMAX, on

15 the antenna frequency, denoted F_{ant} :

$$\Delta f_{max} = 2 \left(\text{DELTA_OL_MAX} + \frac{VMAX}{c} \right) F_{ant} \quad (25)$$

In order to reduce the computation power, the intercorrelation vectors are computed at the pitch $\Delta f'$. The pitch $\Delta f'$ is determined in such a way that the maximum phase variation on the learning sequence is less than a value denoted DELTA_PHI_MAX:

$$\Delta f' = \frac{\text{DELTA_PHI_MAX}}{2 \cdot \pi \cdot K} \cdot F_s \quad (26)$$

20 The number of Doppler cells to be tested depends on Δf_{max} and on pitch $\Delta f'$, where $\text{ceil}()$ is the function which, with a given real number, associates the immediately higher integer number:

$$M_d = \text{ceil}\left(\frac{\Delta f_{max}}{\Delta f'}\right) \quad (27)$$

The algorithm therefore computes the intercorrelation vectors $\hat{\mathbf{r}}_{xsi}(l, m)$ for each synchronization position to be tested l and for m lying between

$-M_d$ and $+M_d$:

$$\hat{\mathbf{r}}_{xsi}(l, m) = \left(\frac{1}{K}\right) \sum_{k=0}^{K-1} \mathbf{x}(l + F_{sur} * k) s_i^*(k) e^{-2j\pi \frac{m\Delta f'}{F_s} \cdot k \cdot F_{sur}} \quad (28)$$

5 In order to reduce the computation power, each learning sequence of length K is subdivided into T slices of length K_0 , with $K = T \cdot K_0$, on which the phase rotation induced by the frequency offset is less than DELTA_PHI_MAX for the maximum frequency offset Δf_{max} :

$$K_0 = \text{ceil}\left(\frac{\text{DELTA_PHI_MAX}}{2 \cdot \pi \cdot \Delta f_{max}} \cdot F_s\right) \quad (29)$$

10 For each synchronization position tested l , an intercorrelation vector is estimated on each slice t by the following formula:

$$\hat{\mathbf{r}}_{xsi,t}(l) = \sum_{k=0}^{K_0-1} \mathbf{x}(l + F_{sur} * (k + t \cdot K_0)) s_i^*(k + t \cdot K_0) \quad (30)$$

These elementary vectors are independent of the frequency offset.

15 From the elementary correlations computed in this first step, for each synchronization position l , the intercorrelation vector $\hat{\mathbf{r}}_{xsi}(l, m)$ is computed for the different Doppler cells m ($m = -M_d, \dots, +M_d$), with the pitch $\Delta f'$.

$$\hat{\mathbf{r}}_{xsi}(l, m) = \left(\frac{1}{K}\right) \sum_{t=0}^{T-1} \hat{\mathbf{r}}_{xsi,t}(l) e^{-2j\pi \frac{m\Delta f'}{F_s} \cdot t \cdot K_0} \quad (31)$$

20 The different MIMO synchronization criteria are then obtained, for each position l and for each Doppler cell m , by the different formulae described in the patent, by replacing the intercorrelation vectors by the intercorrelation vectors of the above formula and by computing the correlation matrices by the following formula:

$$\hat{\mathbf{R}}_{xx}(l) = \left(\frac{1}{K}\right) \sum_{k=0}^{K-1} \mathbf{x}(l + F_{sur} * k) \mathbf{x}^H(l + F_{sur} * k) \quad (32)$$

25 If the criterion exceeds the synchronization threshold for the position l_0 and the Doppler cell m_0 , a path is detected on the position l_0 , with a frequency offset $m_0 \Delta f'$.

In order to enhance the resolution obtained on the frequency offset, the Doppler offset associated with the path detected on this position is estimated by parabolic interpolation from the criteria computed on the position l_0 for the three Doppler cells (m_0-1) , m_0 and (m_0+1) :

$$\widehat{\Delta f} = \left(m_0 + \frac{1}{2} \frac{c(l_0, m_0 + 1) - c(l_0, m_0 - 1)}{c(l_0, m_0 - 1) + c(l_0, m_0 + 1) - 2 \cdot c(l_0, m_0)} \right) \cdot \Delta f' \quad (33)$$

5 Based on the number of Doppler cells to be tested, it is possible to reduce the computation power by using TFD, or TFR if T is a power of 2, to compute the intercorrelation vectors on each learning sequence:

$$\hat{\mathbf{r}}_{xsi}(l, m) = \left(\frac{1}{K} \right) \sum_{t=0}^{T-1} \hat{\mathbf{r}}_{xsi,t}(l) e^{-2j\pi \frac{t \cdot m}{T}} \quad (34)$$

The resolution is then equal to:

$$\Delta f_r = \frac{F_s}{T \cdot K_0} = \frac{F_s}{K} \quad (35)$$

10 If the resolution is insufficient, an improvement by a factor p can be obtained by performing $p-1$ TFD operations (or TRF operations depending on the value of T), on the vectors $\hat{\mathbf{r}}_{xsi,t}(l)$ frequency offset as follows:

$\hat{\mathbf{r}}_{xsi,t}(l) e^{-2j\pi \frac{t \cdot k}{T \cdot p}}$ for $k = 1, \dots, p-1$, p is a factor defined as a function of the desired improvement.

15 The frame on which the synchronization is performed can comprise several sequences TS, that the synchronization criterion can exploit, as well as one or more sequences of information symbols as is represented in figure 3.

The following notations are used:

- 20
- N_{TS} , the number of learning sequences on which the computation of the synchronization criterion is performed,
 - $s_{i,j}(k)$, the learning sequence of index j ($j=0, \dots, N_{TS}-1$) transmitted on the transmission antenna i ,
 - p_j , the index of the first symbol of the learning sequence j , common to
- 25 all the transmission antennas.

In order to improve the detection performance levels, the above algorithm can be generalized, by advantageously using the N_{TS} learning sequences available on the frame, as follows:

The pitch $\Delta f'$ depends on the positions of the two extreme sequences TS:

$$\Delta f' = \frac{\text{DELTA_PHI_MAX}}{2 \cdot \pi \cdot (p_{N_{TS}-1} + (I-1)K_0 - p_0)} \cdot F_s \quad (36)$$

5 For each synchronization position tested I , an intercorrelation vector is estimated on each slice t of each learning sequence j by the following formula:

$$\hat{r}_{xsi,t,j}(l) = \sum_{k=0}^{K_0-1} x(l + F_{sur} * (k + p_j + t \cdot K_0)) s_{i,j}^*(k + t \cdot K_0) \quad (37)$$

10 From the elementary correlations computed in this first step on the different slices of each learning sequence, for each synchronization position I , the intercorrelation vector $\hat{r}_{xsi}(l, m)$ is computed for the different Doppler cells m ($m = -M_d, \dots, +M_d$), with the pitch $\Delta f'$, by a coherent integration on the N_{TS} learning sequences.

$$\hat{r}_{xsi}(l, m) = \left(\frac{1}{KN_{TS}} \right) \sum_{j=0}^{N_{TS}-1} \left(\sum_{t=0}^{T-1} \hat{r}_{xsi,t,j}(l) e^{-2j\pi \frac{m \Delta f'}{F_s} \cdot t \cdot K_0} \right) e^{-2j\pi \frac{m \Delta f'}{F_s} (p_j - p_0)} \quad (38)$$

15 The various MIMO synchronization criteria are then obtained for each position I and for each Doppler cell m by the synchronization criteria defined above, by replacing the intercorrelation vectors by the intercorrelation vectors of the above formula and by computing the correlation matrices on the N_{TS} learning sequences by the following formula:

$$\hat{R}_{xx}(n) = \left(\frac{1}{KN_{TS}} \right) \sum_{j=0}^{N_{TS}-1} \left(\sum_{k=0}^{K-1} x(n + F_{sur} * (k + p_j)) x^H(n + F_{sur} * (k + p_j)) \right) \quad (39)$$

20 The method and the system according to the invention make it possible to perform a synchronization in an MIMO context in the presence of interferences by reducing the computations compared to the prior art, with no loss in performance levels.

CLAIMS

1 – A method for synchronizing a signal in a transmission system comprising M transmitters and N receivers, the N receivers being linked to a processor
 5 (2) suitable for processing the signals and for transmitting a result to a demodulator, in the presence of interferences, comprising at least the following steps:

on the processor (2)

- computing (200) a correlation matrix R_{ss} of reference signals
 10 transmitted by the M transmitting sensors, computing its inverse R_{ss}^{-1} (201),
- for each index l corresponding to a possible instant of synchronization, with l varying up to a position $l + Etal$, where $Etal$ is the maximum temporal spread of the channel, when l corresponds to the first
 15 position tested for which there is an overshoot of the threshold, reiterating the following steps:
 - estimating (203) the correlation matrix of noise $\hat{R}(l)$ received on the N sensors in reception,
 - computing (204) the inverse of the estimated correlation matrix,
 20 $\hat{R}^{-1}(l)$,
 - for each index Δf corresponding to a possible frequency offset for the frequency synchronization, between Δf_{min} and Δf_{max} ,
 - estimating an intercorrelation matrix (205) between the signals received on the N sensors in reception, offset by $-\Delta f$, and the
 25 learning sequences transmitted by the M antennas in transmission, $\hat{R}_{XS}(l, \Delta f)$,
 - computing (206) a synchronization criterion by determining the trace $Tr[]$ of a matrix resulting from the product formed by the

inverse correlation matrix of the learning sequences R_{ss}^{-1} , the conjugate transpose of the estimate of the intercorrelation matrix of the signals received and of the matrix of the learning sequences $\hat{R}_{xs(l, \Delta f)}^H$, the inverse of an estimate of the noise matrix $\hat{R}^{-1}(l)$ and the estimate of the intercorrelation matrix between the observations received and the learning sequences $\hat{R}_{xs(l, \Delta f)}$:

$$C(l, \Delta f) = \text{EGLRT3}(l, \Delta f) = \text{Tr}[R_{ss}^{-1} \hat{R}_{xs(l, \Delta f)}^H \hat{R}^{-1}(l) \hat{R}_{xs(l, \Delta f)}],$$

- comparing (207) the value of the criterion $C(l, \Delta f)$ obtained to a threshold value η , if the value of the criterion $C(l, \Delta f)$ exceeds the threshold value η (208), then considering the index l as a potential candidate for the temporal instant allowing the synchronization and the offset Δf as a potential candidate for the synchronization frequency offset, reiterating the process for $\Delta f - \delta$ and $\Delta f + \delta$, where δ is the frequency analysis pitch and reiterating the process up to the position $l + \text{Etal}$, where Etal is the maximum temporal spread of the channel, determining one or more values of possible instant l , and of possible offset Δf and triggering the signal synchronization and acquisition method,
- if the value of the criterion $C(l, \Delta f)$ is less than the threshold value, incrementing the value of Δf by up to a possible new detection. In this case, reiterating the preceding steps described when there is detection. In the absence of detection, incrementing the value of l (209) and reiterating the overall process including the loop on Δf up to a possible new detection. In this case, reiterating the preceding steps described when there is detection.

- 2 – The method as claimed in claim 1, characterized in that the noise matrix is estimated by likening it to the inverse of the correlation matrix of the signals received $\hat{R}_{xx}(l)$ and the criterion of joint computation of the index and
- 5 of the synchronization offset is produced by the following formula: by determining the trace of a matrix resulting from the product formed by the inverse correlation matrix of the learning sequences, the conjugate transpose of the estimate of the intercorrelation matrix of the signals received and of the matrix of the learning sequences, the inverse of an estimate of the noise
- 10 matrix $\hat{R}^{-1}(l) = \hat{R}_{xx}^{-1}(l)$ and the estimate of the intercorrelation matrix between the observations received and the learning sequences:

$$C(l, \Delta f) = E0_GLRT3(l, \Delta f) = \text{Tr}[R_{ss}^{-1} \hat{R}_{xs}(l, \Delta f)^H \hat{R}_{xx}^{-1}(l) \hat{R}_{xs}(l, \Delta f)].$$

- 3 – The method as claimed in claim 2, characterized in that, in the case
- 15 where the M reference sequences transmitted by the M transmitting sensors are orthogonal, the computation of the synchronization index is performed by using the following formula:

$$C(l, \Delta f) = E0_GLRT3(l, \Delta f) \triangleq \sum_{i=1}^M \frac{\hat{r}_{xs_i}(l, \Delta f)^H \hat{R}_{xx}^{-1}(l) \hat{r}_{xs_i}(l, \Delta f)}{r_{si}}$$

- where the vector $\hat{r}_{xs_i}(l, \Delta f)$ is the intercorrelation vector between the
- 20 observations offset by $-\Delta f$ and the learning sequence transmitted by a transmitter i for a tested synchronization position l, defined by: $\hat{r}_{xs_i}(l, \Delta f) \triangleq$

$$\frac{1}{K} \sum_{n=0}^{K-1} x((k+l)) s_i(k)^* \exp(-j2\pi\Delta f k T_e)$$

where $s_i(k)$ is the component i of $\mathbf{s}(k)$.

- 25 4 – The method as claimed in claim 1, characterized in that the estimated noise matrix, $\hat{R}_1(l, \Delta f)$, is estimated by subtracting the contributions of the

synchronization sequences in the estimate of the correlation matrix of the signals received, assuming that the signal containing the reference sequences is aligned in time and in frequency with the observation matrix and the criterion is obtained by the following formula:

$$5 \quad \hat{R}_1(l, \Delta f) = \hat{R}_{XX}(l) - \hat{R}_{XS}(l, \Delta f) R_{SS}^{-1} \hat{R}_{XS}(l, \Delta f)^H$$

$$C(l, \Delta f) = E1_GLRT3(l, \Delta f) = \text{Tr}[R_{SS}^{-1} \hat{R}_{XS}(l, \Delta f)^H \hat{R}_1^{-1}(l, \Delta f) \hat{R}_{XS}(l, \Delta f)]$$

R_{SS}^{-1} inverse of the correlation matrix of the reference sequences,

$\hat{R}_{XS}(l, \Delta f)$ estimate of the intercorrelation matrix and its transpose $\hat{R}_{XS}(l, \Delta f)^H$.

- 10 5 – The method as claimed in claim 4, characterized in that, when the M reference sequences are orthogonal sequences, the criterion is obtained by the following formula:

$$C(l, \Delta f) = E1_GLRT3(l, \Delta f) \triangleq \sum_{i=1}^M \frac{\hat{r}_{XS_i}(l, \Delta f)^H \hat{R}_1^{-1}(l, \Delta f) \hat{r}_{XS_i}(l, \Delta f)}{r_{Si}}$$

- 15 where the vector $\hat{r}_{XS_i}(l, \Delta f)$ is the intercorrelation vector between the observations offset by $-\Delta f$ and the learning sequence transmitted by a transmitter i for a tested synchronization position l, defined by:

$$\hat{r}_{XS_i}(l, \Delta f) \triangleq \frac{1}{K} \sum_{n=0}^{K-1} x((k+l)) s_i(k)^* \exp(-j2\pi\Delta f k T_e)$$

where $s_i(k)$ is the component i of $\mathbf{s}(k)$ and $\hat{R}_1^{-1}(l, \Delta f)$ the inverse of the estimate of the noise matrix.

20

- 6 – The method as claimed in one of the preceding claims, characterized in that an observation matrix ($N \times K'$) is constructed with K' chosen and set in order for the channel matrix H and the noise matrix to be stationary on the temporal horizon set by K' and the estimated matrix

$\hat{R}_{xx}(l) = \frac{X'(l)X'(l)^H}{K'}$ is used for $K'-K+1$ tested positions with $X'(l)$ an observation matrix defined from the K' signal samples.

- 7 – The method as claimed in one of the preceding claims, characterized in that, for applications where the noises are decorrelated on the antennas but of different powers, the criterion is obtained by the following formula:

$$C(l, \Delta f) = E0_Diag_GLRT3(l, \Delta f) = \text{Tr}[R_{ss}^{-1} \hat{R}_{xs}(l, \Delta f)^H \hat{R}_0^{-1}(l) \hat{R}_{xs}(l, \Delta f)]$$

R_{ss}^{-1} inverse of the correlation matrix of the reference sequences,

$\hat{R}_{xs}(l, \Delta f)$ estimate of the intercorrelation matrix and its transpose $\hat{R}_{xs}(l, \Delta f)^H$

10 $\hat{R}_0^{-1}(l) = \text{Diag}(\hat{\eta}_{10}(l), \hat{\eta}_{20}(l), \dots, \hat{\eta}_{N0}(l))^{-1},$

η_i is the power of the noise on the reception antenna i ,

$$\hat{\eta}_{00}(l) \triangleq \frac{1}{NK} \sum_{k=0}^{K-1} \mathbf{x}(k+l)^H \mathbf{x}(k+l) \text{ with } \mathbf{x}(k+l) \text{ the envelope of the}$$

signals at the reception antenna output.

- 15 8 – The method as claimed in one of claims 1 to 6, characterized in that for white noise applications, the synchronization criterion is obtained by the following formula:

$$C(l, \Delta f) = E0_BB_GLRT3(l, \Delta f) = \text{Tr}[R_{ss}^{-1} \hat{R}_{xs}(l, \Delta f)^H \hat{R}_{xs}(l, \Delta f)] / \text{Tr}[\hat{R}_{xx}(l)] = \text{Tr}[\hat{R}_{xs}(l, \Delta f) R_{ss}^{-1} \hat{R}_{xs}(l, \Delta f)^H] / \text{Tr}[\hat{R}_{xx}(l)]$$

- 20 $\text{Tr}[]$ is the trace of a matrix,

R_{ss}^{-1} the inverse of the correlation matrix of the reference sequences,

$\hat{R}_{xs}(l, \Delta f)$ the estimate of the intercorrelation matrix and its transpose $\hat{R}_{xs}(l, \Delta f)^H$,

$\hat{R}_{xx}(l)$ the estimate of the correlation matrix of the signals received.

9 – The method as claimed in claim 8, characterized in that, for applications where the M synchronization sequences are decorrelated and orthogonal, the following formula is used

$$\text{GLRT1}'(l, \Delta f) = \sum_{i=1}^M \frac{\hat{r}_{xsi}(l, \Delta f)^H \hat{r}_{xsi}(l, \Delta f)}{\hat{r}_x(l) r_{si}}$$

- 5 10 – The method as claimed in one of the preceding claims, characterized in that the synchronization position l and the frequency offset are estimated jointly by using the reference signal offset in frequency associated with each propagation path of the signal to estimate each intercorrelation vector $\hat{r}_{xsi}(l)$ between the signal received and the component reference signal of the
- 10 intercorrelation matrix $\hat{R}_{xs}(l)$.

- 11 – The method as claimed in claim 10, characterized in that an intercorrelation vector $\hat{r}_{xsi}(l)$ is determined for each frequency offset and for each position l to be tested and for m Doppler cells belonging to an interval
- 15 $[-M_d, +M_d]$ with M_d the number of Doppler cells to be tested by using the following formula:

$$\hat{r}_{xsi}(l, \Delta f) = \left(\frac{1}{K}\right) \sum_{k=0}^{K-1} x(l + F_{sur} * k) s_i^*(k) e^{-2j\pi \frac{\Delta f}{F_s} k F_{sur}}$$

with $\Delta f \in [-\Delta f_{max}; +\Delta f_{max}]$, F_{sur} the upsampling factor of the input signal relative to the symbol frequency F_s , where Δf_{max} is given as a function of the maximum speed of movement of the transmitters and receivers.

20

- 12 – The method as claimed in claim 11, characterized in that the length K of a learning sequence is subdivided into T slices of length K_0 with $K=T * K_0$, T being chosen in order for the phase rotation induced by the frequency offset to be negligible, there is estimated, for each tested synchronization position l ,
- 25 an intercorrelation vector on each slice t and for each Doppler cell m ($m = -M_d, \dots, +M_d$), with the pitch $\Delta f'$.

$$\hat{r}_{xsi}(l, m) = \left(\frac{1}{K}\right) \sum_{t=0}^{T-1} \hat{r}_{xsi,t}(l) e^{-2j\pi \frac{m \Delta f'}{F_s} \cdot t \cdot K_0}$$

and by determining the correlation matrix by the following formula:

$$\hat{R}_{xx}(l) = \left(\frac{1}{K}\right) \sum_{k=0}^{K-1} \mathbf{x}(l + F_{sur} * k) \mathbf{x}^H(l + F_{sur} * k)$$

F_{sur} is the upsampling frequency, F_s the symbol frequency.

- 13 – The method as claimed in one of claims 11 or 12, characterized in that
 5 the Doppler offset associated with a path detected on a synchronization position is estimated by parabolic interpolation from criteria computed on the position l_0 for the three Doppler cells (m_0-1) , m_0 and (m_0+1) :

$$\widehat{\Delta f} = \left(m_0 + \frac{1}{2} \frac{c(l_0, m_0+1) - c(l_0, m_0-1)}{c(l_0, m_0-1) + c(l_0, m_0+1) - 2 \cdot c(l_0, m_0)} \right) \cdot \Delta f'.$$

- 14 – The method as claimed in claim 13, characterized in that Fourier
 transforms or fast Fourier transforms are used to compute the
 10 intercorrelations performed on each learning sequence:

$$\hat{r}_{xsi}(l, m) = \left(\frac{1}{K}\right) \sum_{t=0}^{T-1} \hat{r}_{xsi,t}(l) e^{-2j\pi \frac{t \cdot m}{T}}$$

- 15 – The method as claimed in one of claims 10 to 14, characterized in that,
 for a signal containing a data frame comprising synchronization sequences
 15 TS, these sequences TS are used and the following steps are executed:
 the pitch $\Delta f'$ depends on the positions of the two extreme sequences TS of
 the data frame:

$$\Delta f' = \frac{\text{DELTA_PHI_MAX}}{2 \cdot \pi \cdot (p_{N_{TS}-1} + (I-1)K_0 - p_0)} \cdot F_s$$

- for each tested synchronization position l , an intercorrelation vector is
 estimated on each slice t of each learning sequence j by the following
 20 formula:

$$\hat{r}_{xsi,t,j}(l) = \sum_{k=0}^{K_0-1} \mathbf{x}(l + F_{sur} * (k + p_j + t \cdot K_0)) s_{i,j}^*(k + t \cdot K_0)$$

$$\hat{\mathbf{r}}_{xsi}(l, m) = \left(\frac{1}{KN_{TS}} \right) \sum_{j=0}^{N_{TS}-1} \left(\sum_{t=0}^{T-1} \hat{\mathbf{r}}_{xsi,t,j}(l) e^{-2j\pi \frac{m \Delta f'}{F_s} \cdot t \cdot K_0} \right) e^{-2j\pi \frac{m \Delta f'}{F_s} (p_j - p_0)}$$

by computing the correlation matrices on the N_{TS} learning sequences by the following formula:

$$\hat{\mathbf{R}}_{xx}(n) = \left(\frac{1}{KN_{TS}} \right) \sum_{j=0}^{N_{TS}-1} \left(\sum_{k=0}^{K-1} \mathbf{x}(n + F_{sur} * (k + p_j)) \mathbf{x}^H(n + F_{sur} * (k + p_j)) \right)$$

- N_{TS} , the number of learning sequences on which the computation of the synchronization criterion is performed,
- $s_{i,j}(k)$, the learning sequence of index j ($j=0, \dots, N_{TS}-1$) transmitted on the transmission antenna i ,
- p_j , the index of the first symbol of the learning sequence j , common to all the transmission antennas.