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Title: INTERFERENCE CANCELLATION UNDER NON-STATIONARY CONDITIONS

Abrégé/Abstract:
A method for timing and frequency synchronization in a wireless system is provided. The method comprises the steps of receiving a burst of symbols, selecting a subset of the burst of symbols, iteratively adjusting the subset of the burst of symbols by a plurality of
(57) Abrégé(suite)/Abstract(continued):
timing offsets and calculating, for each timing offset, a first performance metric corresponding to the adjusted subset. The method further comprises the steps of determining one of the plurality of timing offsets to be a preferred timing offset based upon the first performance metric thereof, iteratively rotating the subset of the burst of symbols by a plurality of frequency offsets and calculating, for each frequency offset, a second performance metric corresponding to the rotated subset, and determining one of the plurality of frequency offsets to be a preferred frequency offset based upon the second performance metric thereof.
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INTERFERENCE CANCELLATION UNDER NON-STATIONARY CONDITIONS

BACKGROUND

Reference to Co-Pending Applications for Patent


Field

[0002] The present invention generally relates to wireless communication and, in particular, relates to interference cancellation under non-stationary conditions.

Background

[0003] In many communication systems utilizing GSM, GPRS, EDGE or the like, a receiver’s ability to properly decode a received signal depends upon the receiver’s ability to accurately estimate symbol timing and frequency. As wireless communications become ever more prevalent, however, increasing amounts of interference can negatively impact a receiver’s ability to do so.

SUMMARY

[0004] According to one aspect of the subject technology, optimal timing and frequency (by which to rotate the received samples) are jointly obtained in a wireless communication system by parametrizing the subspace into possible timing and
frequency hypotheses and searching through them. Joint Max Likelihood of frequency and timing may be performed sequentially or in parallel.

[0005] According to certain aspects of the subject technology, an interference suppression filter is tuned to various parameters, and then optimal pairs (of time and frequency) are picked by minimizing the prediction error using a known sequence (midamble or quasi-midamble, e.g., data aided). The algorithm boosts the received signal quality under strong interference whereas non-coherent estimation would degrade significantly.

[0006] According to one aspect of the subject technology, a method for timing and frequency synchronization in a wireless system comprises the steps of receiving a burst of symbols, selecting a subset of the burst of symbols, iteratively adjusting the subset of the burst of symbols by a plurality of timing offsets and calculating, for each timing offset, a first performance metric corresponding to the adjusted subset. The method further comprises the steps of determining one of the plurality of timing offsets to be a preferred timing offset based upon the first performance metric thereof, iteratively rotating the subset of the burst of symbols by a plurality of frequency offsets and calculating, for each frequency offset, a second performance metric corresponding to the rotated subset, and determining one of the plurality of frequency offsets to be a preferred frequency offset based upon the second performance metric thereof.

[0007] According to another aspect of the subject technology, a method for timing and frequency synchronization in a wireless system comprises the steps of receiving a burst of symbols, selecting a subset of the burst of symbols, iteratively adjusting the subset of the burst of symbols by a plurality of timing offsets and a plurality of frequency offsets, calculating, for each combination of timing and frequency offsets, a performance metric corresponding to the adjusted subset, and determining one of the combination of timing and frequency offsets to be a preferred combination based upon the performance metric thereof.

[0008] According to another aspect of the subject technology, a wireless apparatus comprises a receiver configured to receive a burst of symbols, and a processor. The processor is configured to select a subset of the burst of symbols, iteratively adjust the subset of the burst of symbols by a plurality of timing offsets and calculate, for each
timing offset, a first performance metric corresponding to the adjusted subset. The processor is further configured to determine one of the plurality of timing offsets to be a preferred timing offset based upon the first performance metric thereof, iteratively rotate the subset of the burst of symbols by a plurality of frequency offsets and calculate, for each frequency offset, a second performance metric corresponding to the rotated subset, and determine one of the plurality of frequency offsets to be a preferred frequency offset based upon the second performance metric thereof.

[0009] According to another aspect of the subject technology, a wireless apparatus comprises a receiver configured to receive a burst of symbols, and a processor. The processor is configured to receive a burst of symbols, select a subset of the burst of symbols, iteratively adjust the subset of the burst of symbols by a plurality of timing offsets and a plurality of frequency offsets, calculate, for each combination of timing and frequency offsets, a performance metric corresponding to the adjusted subset, and determine one of the combination of timing and frequency offsets to be a preferred combination based upon the performance metric thereof.

[0010] According to another aspect of the subject technology, a wireless apparatus comprises means for receiving a burst of symbols, means for selecting a subset of the burst of symbols, means for iteratively adjusting the subset of the burst of symbols by a plurality of timing offsets and for calculating, for each timing offset, a first performance metric corresponding to the adjusted subset, means for determining one of the plurality of timing offsets to be a preferred timing offset based upon the first performance metric thereof, means for iteratively rotating the subset of the burst of symbols by a plurality of frequency offsets and calculating, for each frequency offset, a second performance metric corresponding to the rotated subset, and means for determining one of the plurality of frequency offsets to be a preferred frequency offset based upon the second performance metric thereof.

[0011] According to another aspect of the subject technology, a wireless apparatus comprises means for receiving a burst of symbols, means for selecting a subset of the burst of symbols, means for iteratively adjusting the subset of the burst of symbols by a plurality of timing offsets and a plurality of frequency offsets, means for calculating, for each combination of timing and frequency offsets, a performance metric corresponding to the adjusted subset, and means for determining one of the combination of timing and
frequency offsets to be a preferred combination based upon the performance metric thereof.

[0012] According to another aspect of the subject technology, a computer-program product for use in a wireless communication system comprises a computer readable medium having a set of instructions stored thereon, the set of instructions being executable by one or more processors and the set of instructions comprising instructions for receiving a burst of symbols, instructions for selecting a subset of the burst of symbols, instructions for iteratively adjusting the subset of the burst of symbols by a plurality of timing offsets and for calculating, for each timing offset, a first performance metric corresponding to the adjusted subset, instructions for determining one of the plurality of timing offsets to be a preferred timing offset based upon the first performance metric thereof, instructions for iteratively rotating the subset of the burst of symbols by a plurality of frequency offsets and for calculating, for each frequency offset, a second performance metric corresponding to the rotated subset, and instructions for determining one of the plurality of frequency offsets to be a preferred frequency offset based upon the second performance metric thereof.

[0013] According to another aspect of the subject technology, a computer-program product for use in a wireless communication system comprises a computer readable medium having a set of instructions stored thereon, the set of instructions being executable by one or more processors and the set of instructions comprising instructions for receiving a burst of symbols, instructions for selecting a subset of the burst of symbols, instructions for iteratively adjusting the subset of the burst of symbols by a plurality of timing offsets and a plurality of frequency offsets, instructions for calculating, for each combination of timing and frequency offsets, a performance metric corresponding to the adjusted subset, and instructions for determining one of the combination of timing and frequency offsets to be a preferred combination based upon the performance metric thereof.

[0014] It is understood that other configurations of the subject technology will become readily apparent to those skilled in the art from the following detailed description, wherein various configurations of the subject technology are shown and described by way of illustration. As will be realized, the subject technology is capable of other and different configurations and its several details are capable of modification
in various other respects, all without departing from the scope of the subject technology. Accordingly, the drawings and detailed description are to be regarded as illustrative in nature and not as restrictive.

**BRIEF DESCRIPTION OF THE DRAWINGS**

[0015] FIG. 1 illustrates exemplary frame and burst formats in GSM in accordance with one aspect of the subject technology;

[0016] FIG. 2 is a flow chart illustrating a method for suppressing interference in accordance with one aspect of the subject technology;

[0017] FIG. 3 is a flow chart illustrating a method for suppressing interference in accordance with one aspect of the subject technology;

[0018] FIG. 4 illustrates a receiver for use in a wireless communication system in accordance with one aspect of the subject technology;

[0019] FIG. 5 illustrates a subset of symbols, including the first midamble symbol, that a receiver selects in accordance with one aspect of the subject technology;

[0020] FIG. 6 illustrates a method for suppressing interference in accordance with one aspect of the subject technology;

[0021] FIG. 7 illustrates a receiver for use in a wireless communication system in accordance with one aspect of the subject technology;

[0022] FIG. 8 illustrates a method for suppressing interference in accordance with one aspect of the subject technology;

[0023] FIG. 9 illustrates a receiver for use in a wireless communication system in accordance with one aspect of the subject technology;

[0024] FIG. 10 illustrates a receiver for use in a wireless communication system in accordance with one aspect of the subject technology; and

[0025] FIG. 11 is a block diagram illustrating a computer system with which certain aspects of the subject technology may be implemented.
FIG. 1 shows exemplary frame and burst formats in GSM. The timeline for downlink transmission is divided into multiframes. For traffic channels used to send user-specific data, each multiframe, such as exemplary multiframe 101, includes 26 TDMA frames, which are labeled as TDMA frames 0 through 25. The traffic channels are sent in TDMA frames 0 through 11 and TDMA frames 13 through 24 of each multiframe, as identified by the letter “T” in FIG. 1. A control channel, identified by the letter “C,” is sent in TDMA frame 12. No data is sent in the idle TDMA frame 25 (identified by the letter “I”), which is used by the wireless devices to make measurements for neighbor base stations.

Each TDMA frame, such as exemplary TDMA frame 102, is further partitioned into eight time slots, which are labeled as time slots 0 through 7. Each active wireless device/user is assigned one time slot index for the duration of a call. User-specific data for each wireless device is sent in the time slot assigned to that wireless device and in TDMA frames used for the traffic channels.

The transmission in each time slot is called a “burst” in GSM. Each burst, such as exemplary burst 103, includes two tail fields, two data fields, a training sequence (or midamble) field, and a guard period (GP). The number of bits in each field is shown inside the parentheses. GSM defines eight different training sequences that may be sent in the training sequence field. Each training sequence, such as midamble 104, contains 26 bits and is defined such that the first five bits are repeated and the second five bits are also repeated. Each training sequence is also defined such that the correlation of that sequence with a 16-bit truncated version of that sequence is equal to (a) sixteen for a time shift of zero, (b) zero for time shifts of ±1, ±2, ±3, ±4, and ±5, and (3) a zero or non-zero value for all other time shifts.

One approach to locating a midamble in a burst of symbols serially compares hypotheses regarding the midamble position to determine which hypothesis provides the highest correlation energy between the known midamble sequence and the hypothesized position in the burst of symbols. This method is very sensitive to interference from multi-paths of the same midamble sequence, which can cause the correlation energy of inaccurate hypotheses to be affected by time-delayed copies thereof.
Non-Coherent Frequency and Timing estimation suffers from performance degradation under presence of strong interference. According to one aspect of the subject technology, by semi-coherently estimating the optimal timing and frequency, performance in the presence of interference can be greatly improved.

According to one aspect of the subject technology, optimal timing and frequency (by which to rotate the received samples) are jointly obtained by parametrizing the subspace into possible hypotheses and searching through them. Joint Max Likelihood of frequency and timing may be further simplified to a sequential search to provide optimal performance.

According to one aspect of the subject technology, an interference suppression filter is tuned to various parameters, and then optimal pairs (of time and frequency) are picked by minimizing the prediction error using a known sequence (midamble or quasi-midamble, e.g., data aided). The algorithm boosts the received signal quality under strong interference whereas non-coherent estimation would degrade significantly.

For example, given a set of spatial and temporal samples at time $k$:

$$\hat{x}_k = \begin{bmatrix} x_k(1) \\ x_k(2) \\ \vdots \\ x_k(M) \end{bmatrix}, \hat{s}_k = \begin{bmatrix} s_k \\ s_{k-1} \\ \vdots \\ s_{k-v} \end{bmatrix}$$

where $s_k$ is the midamble / quasi-midamble signal at time $k$, $\hat{s}_k$ is a $(v+1) \times 1$ midamble / quasi-midamble vector, and $\hat{x}_k$ is a $M \times 1$ received midamble / quasi-midamble vector, a set of spatial temporal samples can be defined as

$$X_k = \begin{bmatrix} \hat{x}_k \\ \hat{x}_{k-1} \\ \vdots \\ \hat{x}_{k-L} \end{bmatrix}$$
where $X_k$ is a $M \times (L + 1) \times 1$ vector of spatial temporal samples with a spatial length of $M$ and a temporal length of $L + 1$. Accordingly, a spatial/temporal structured matrix can be constructed, such that

$$[X] = [X_k X_{k+1}, \ldots X_{k+p-\nu}],$$

where $[X]$ is a $M \times (L + 1) \times p - \nu$ matrix, and $p$ is the length of the midamble or quasi-midamble (data aided).

Accordingly, given $[X]$ and $\tilde{S}_k = [\tilde{S}_k, \tilde{S}_{k+1}, \ldots \tilde{S}_{k+p-\nu}]$, ($\nu + 1) \times p - \nu$, a suppression filter $W_{SAC}$ can be computed according to one aspect of the subject disclosure by estimating a reference sequence of symbols at the channel input:

$$W_{SAC} = \arg \min \|W[X] - \tilde{Z}\|^2$$

where $W = (\nu + 1) \times M \times (L + 1)$ and $\tilde{Z} = \tilde{S}_k, (\nu + 1) \times (p - \nu)$.

The foregoing equation can be rewritten as

$$W_{SAC} = \tilde{Z} [X]^T, (\nu + 1) \times M \times (L + 1)$$

or, more particularly, as

$$W_{SAC} = \tilde{S}_k, [X]^T, \left\{[X][X]^T\right\}^{-1}.$$
(the lowest measured error), \(\tau(n)\) (the optimal timing hypothesis number) and \(f(n)\) (the optimal frequency hypothesis number). The method proceeds to the timing loop 202 (as \(k\) is initialized to a zero value). In the timing loop, a set of spatial temporal samples are selected corresponding to timing hypothesis number \(\Delta\). Filter weights for a filter \(W_{\Delta}\) are calculated based upon the timing hypothesis, as set forth in greater detail above, and the filter is applied to the symbols to estimate a midamble \(\hat{S}_{\Delta}\). The error \(e(\Delta)\) in the estimated midamble is determined based upon the previously known values for the midamble \(S\). The error is smoothed, and is compared to \(e_{\text{min}}\), the lowest calculated error thus far. As \(e_{\text{min}}\) is initially set to \(\infty\), the first iteration will necessarily involve redefining \(e_{\text{min}}\) to the first calculated error value. Accordingly, \(\tau(n)\), the optimal timing hypothesis yet calculated, will be set to \(\Delta\). Then, as long as \(\Delta\) is less than \(\Delta_{\text{max}}\) (the total number of hypotheses in the parameterized space), the hypothesis \(\Delta\) is indexed by one, and timing loop 202 repeats. Once timing loop 202 has iteratively calculated errors for each timing hypothesis \(\Delta\), an optimal hypothesis \(\tau(n)\) will have been selected, and the method proceeds to frequency loop 203. In a similar fashion to timing loop 202, frequency loop 203 iteratively calculates midamble estimation errors for each frequency hypothesis (at the optimal timing delay), and determines the optimal frequency hypothesis. In this manner, an optimal timing/frequency pair are serially determined from the parameterized timing/frequency subspace, and are used in the processing of the symbols to minimize errors arising from interference.

[0037] According to one aspect of the subject disclosure, one drawback of using this algorithm for frequency synchronization is that the training sequence may be too short to reliably estimate small frequency offsets (e.g., on the order of few hundred Hz), as the curvature over midamble is essentially flat. Hence the need for an error smoothening filter, which makes the implementation more complicated in the field where the frequency offset between interferer and the desired signal can change from burst to burst. Accordingly, in order to obtain better and more accurate estimates on a burst to burst basis without the need to smoothen the midamble estimation error estimates, the signal to noise ratio may be used over the entire burst instead of the midamble estimation error, in accordance with one aspect of the subject disclosure. In order to obtain this signal to noise ratio, the burst is equalized (post MLSE) and the
signal to noise ratio is determined using the hard decisions. This approach is illustrated in accordance with one aspect of the subject disclosure in FIG. 3. As can be seen with reference to FIG. 3, the timing loop includes an estimation of the signal to noise ratio \( E_s/N_o \), which estimation is used to

[0038] In a manner similar to that illustrated in exemplary FIG. 2, the method illustrated in FIG. 3 includes a timing loop 301 and a frequency loop 302. In the timing loop, a set of spatial temporal samples are selected corresponding to timing hypothesis number \( \tau \). Filter weights for a filter \( W_t \) are calculated based upon the timing hypothesis, as set forth in greater detail above, and the filter is applied to the symbols to estimate a midamble \( \hat{S}_r \). The error \( \epsilon_r \) in the estimated midamble is determined based upon the previously known values for the midamble \( S \). The error is smoothed, and is compared to \( \epsilon_{\min} \), the lowest calculated error thus far. As \( \epsilon_{\min} \) is initially set to \( \infty \), the first iteration will necessarily involve redefining \( \epsilon_{\min} \) to the first calculated error value. Accordingly, \( \Delta t_{sd}(n) \), the optimal timing hypothesis yet calculated, will be set to \( \tau \).

Then, as long as \( \tau \) is less than \( N \) (the total number of hypotheses in the parameterized space), the hypothesis \( \tau \) is indexed by one, and timing loop 301 repeats. Once timing loop 301 has iteratively calculated errors for each timing hypothesis \( \tau \), an optimal hypothesis \( \Delta t_{sd}(n) \) will have been selected, and the method proceeds to frequency loop 302. Frequency loop 302 iteratively calculates a signal to noise ratio for each frequency hypothesis (at the optimal timing delay), and determines the optimal frequency hypothesis. In this manner, an optimal timing/frequency pair are serially determined from the parameterized timing/frequency subspace, and are used in the processing of the symbols to minimize errors arising from interference.

[0039] According to one aspect, the signal to noise ratio \( E_s/N_o \) determined in frequency loop 302 is based upon hard decisions. In this regard, the SNR may be equal to \( \| \hat{H} \|_F / \| WX - \hat{H} \hat{S} \|_F \), where \( \hat{S} \) is a Toeplitz matrix of estimated symbols after the equalization of the entire burst, which also includes the known training sequence \( S \).

[0040] FIG. 4 illustrates a receiver for use in a wireless communication system in accordance with one aspect of the subject technology. Receiver 400 includes an
antenna 410 configured to receive a wireless signal. While receiver 400 may be used in various communication systems, for clarity, receiver 400 is specifically described herein with respect to a GSM system. The received signal is provided to a pre-processor 420 which demodulates the signal to generate received samples. Pre-processor 420 may include a GMSK-to-BPSK rotator that performs phase rotation on the received samples. Timing estimator 430 receives the samples from pre-processor 420 and generates a plurality of timing hypotheses regarding where a training sequence of symbols (i.e., midamble) begins in the burst of data. Interference suppressor 440 iteratively performs single antenna interference cancellation on the symbols for each timing hypothesis, calculating different filter weights for each timing hypothesis, and midamble estimator 450 generates a midamble estimation error for each hypothesis, as described in greater detail above. Timing decision circuit 460 compares the midamble estimation errors for each hypothesis and selects the hypothesis with the lowest midamble estimation error. The selection of a hypothesis by timing decision circuit 460 represents the position in the burst of symbols where the midamble is estimated to begin. Frequency estimator 470 receives the samples from timing decision circuit 460 and generates a plurality of frequency hypotheses regarding a frequency on which symbols are transmitted. Interference suppressor 440 iteratively performs single antenna interference cancellation on the symbols for each frequency hypothesis, calculating different filter weights for each frequency hypothesis, and midamble estimator 450 generates a midamble estimation error for each hypothesis, as described in greater detail above. Frequency decision circuit 480 compares the midamble estimation errors for each hypothesis and selects the hypothesis with the lowest midamble estimation error. The selection of a hypothesis by frequency decision circuit 480 represents the optimal frequency at which to receive the burst of symbols. The signal is then provided to data processor 490, which processes the received symbols based upon the selected timing and frequency hypotheses, and outputs the data corresponding to the received symbols.

[0041] According to one aspect of the subject disclosure, timing estimator may generate a plurality of timing hypotheses by opening a “window” around the estimated beginning of the midamble sequence. The position of the first symbol of the midamble sequence can be estimated for a given burst, based upon the known structure of each burst. For example, as illustrated in FIG. 1, the beginning of midamble 104 in burst 103 begins in the 62nd bit of the burst. Based upon this known structure, timing estimator
430 selects a window 105 of bits representing a series of hypotheses regarding where the first midamble symbol may be located. Exemplary window 105 is illustrated in greater detail in FIG. 5.

[0042] As can be seen with reference to FIG. 5, exemplary window 105 comprises 11 symbols, labeled Δ=0 to Δ=10. Each Δ value represents the position of the symbol in the window. With reference to the position of a symbol in the entire burst, however, the Δ value is offset by an offset value (e.g., Δ=5 may be offset by 61 to represent the position of this symbol in the entire burst). For the first seven symbols in window 105, timing estimator 430 generates a channel estimate from a sequence of five contiguous symbols (representing the five-tap channel format of GSM). For example, symbol Δ=0 corresponds to channel estimate \( \hat{h}(t_0) \), symbol Δ=1 corresponds to channel estimate \( \hat{h}(t_1) \), etc. Each of these channel estimates is then processed by interference suppressor 440 and midamble estimator 450 to determine estimated midamble symbols corresponding thereto, in order to determine a midamble estimation error therefor.

[0043] While in the present exemplary aspect, window 105 has been illustrated as consisting of exactly 11 symbols, the scope of the present invention is not limited to such an arrangement. Rather, as will be readily apparent to one of skill in the art, any window size (up to the size of the entire data burst) may be selected. For example, in accordance with one aspect of the subject technology, the size of the search window may be chosen to be twice the size of the expected minimum propagation delay. Alternatively, the search window size may be parameterized based on any other metric known to those of skill in the art.

[0044] According to one aspect, a channel estimate \( \hat{h} \) may be generated by timing estimator 430 by correlating the received samples (corresponding to the hypothesized delay) with the reference samples (i.e., the known midamble sequence) for each hypothesis. Based on the correlation \( R_{ys}(\Delta) \) between received signal \( y \) and midamble sequence \( s \) for a hypothesized delay \( \Delta \), the channel estimate may be calculated as follows:

\[
\hat{h}^{(\delta)} = [R_{ys}(\delta), R_{ys}(\delta+1), \ldots, R_{ys}(\delta+4)] \quad \text{for} \quad \delta = 0, 1, \ldots, 6
\]  

(1)
\[
\delta^* = \arg\max_{\delta} \left\{ \| h_{1,\delta} \|^2 \right\}
\]  
(2)

\[
\hat{h} = \left[ R_{\delta,1} \left( \delta^* \right) R_{\delta,2} \left( \delta^* + 1 \right) \ldots R_{\delta,\delta^*} \left( \delta^* + 4 \right) \right].
\]  
(3)

[0045] To test the hypothesis corresponding to each channel estimate, interference suppressor 440 performs SAIC on each estimated channel. SAIC is a method by which oversampled and/or real/imaginary decomposition of a signal is used to provide virtual antennas with separate sample sequences, such that weights may be applied to the virtual antennas to form a beam in the direction of a desired transmitter and a beam null in the direction of an undesired interference source. In general, SAIC may be achieved with one or multiple actual antennas at the receiver by using space-time processing, where “space” may be virtually achieved with inphase and quadrature components, and “time” may be achieved using late and early samples.

[0046] For example, given a set of spatial and temporal samples at a time \( k \):

\[
\bar{X}_k = \begin{bmatrix} x_k(1) \\ x_k(2) \\ \vdots \\ x_k(M) \end{bmatrix}, \bar{s}_k = \begin{bmatrix} s_k \\ s_{k-1} \\ \vdots \\ s_{k-\nu} \end{bmatrix}
\]

where \( s_k \) is the midamble / quasi-midamble signal at time \( k \), \( \bar{s}_k \) is a \((\nu + 1) \times 1\) midamble / quasi-midamble vector, and \( \bar{X}_k \) is a \( M \times 1 \) received midamble / quasi-midamble vector, a set of spatial temporal samples can be defined as

\[
X_k = \begin{bmatrix} \bar{X}_k \\ \bar{X}_{k-1} \\ \vdots \\ \bar{X}_{k-L} \end{bmatrix}
\]

where \( X_k \) is a \( M \times (L + 1) \times 1 \) vector of spatial temporal samples with a spatial length of \( M \) and a temporal length of \( L + 1 \). Accordingly, a spatial/temporal structured matrix can be constructed, such that

\[
[X] = \begin{bmatrix} X_k & X_{k+1} & \ldots & X_{k+\nu} \end{bmatrix},
\]
where \( [X] \) is a \( M \times (L+1) \times p - \nu \) matrix, and \( p \) is the length of the midamble or quasi-midamble (data aided).

[0047] Accordingly, given \( [X] \) and \( \tilde{x}_k = [x_{k+1}, \cdots, x_{k+p-\nu}] \), \((\nu + 1) \times (p - \nu)\), a suppression filter \( W_{SAIC} \) can be computed according to one aspect of the subject disclosure by estimating a reference sequence of symbols at the channel input:

\[
W_{SAIC} = \arg \min W \left[ X \right] - Z \right]^2
\]

where \( W = (\nu + 1) \times M \times (L + 1) \) and \( Z = \tilde{x}_k, (\nu + 1) \times (p - \nu) \).

[0048] The foregoing equation can be rewritten as

\[
W_{SAIC} = \tilde{Z} [X]^T, (\nu + 1) \times M \times (L + 1)
\]

or, more particularly, as

\[
W_{SAIC} = \tilde{x}_k [X]^T \left\{ [X][X]^T \right\}^{-1}.
\]

[0049] The output of interference suppressor 440 is in the form \( \hat{S} \), where \( \hat{S} \) represents an estimate of the midamble sequence. The difference between the estimated and known midamble sequences is determined according to Equation 7, below:

\[
\| S - \hat{S} \|^2 = e_m (t_i)
\]

to obtain a midamble estimation error \( e_m (t_i) \) for each time \( t_i \). Each time \( t_i \) is equal to the hypothesized position \( T_i \) plus an offset \( T_s \) from the beginning of the burst:

\[
t_i = T_i + T_s
\]

[0050] Once the midamble estimation error \( e_m (t_i) \) for each time \( t_i \) is determined, timing decision block 460 determines which hypothesis corresponds to the lowest estimation error \( e_m \), and the other hypothesized timing values are discarded.
According to one aspect of the subject disclosure, the foregoing method for interference suppression enjoys a number of benefits when compared to a method utilizing channel output beamforming. For example, as can be seen with reference to Equation 4, the interference suppression filter weights are calculated by minimizing the cost function

\[ J = \min \left( \| W \left[ X \right] - S \|^2 \right). \]  \hspace{1cm} (9)

Accordingly, the suppression filter weights (of Equation 6) have the dimensionality of \( \nu \times M \left( L + 1 \right) \), and the filtered output has the dimensionality of \( \nu \times \left( p - \nu \right) \). Accordingly, the size of the filter weights grows linearly with the number of antennas (whether real or virtual), and the size of the filtered output sample matrix remains constant even as the number of antennas (or virtual antennas) grows. This offers dramatic improvements in computational simplicity and storage requirements over a channel output setup, in which the interference suppression filter weights are calculated by minimizing the cost function

\[ J = \min \left( \| W \left[ X \right] - HS \|^2 \right), \]  \hspace{1cm} (10)

which results in suppression filter weights with a dimensionality of \( M \times M \left( L + 1 \right) \) and a filtered output with a dimensionality of \( M \times \left( p - \nu \right) \) (i.e., where the number of filter weights scale geometrically with the number of antennas, and where the size of the filtered output sample matrix increases linearly with the number of antennas).

Such a channel output setup further involves greater storage and backend ISI equalization using non-linear equalizers (such as an MLSE, where the number of input streams must be set equal to \( M \)). In the channel input setup, the number of input streams for the backend ISI equalization is only \( \nu \), and the number of back-substitutions in the computation of the filter weights is reduced (not being proportional to the number of antennas, as in the channel output setup). Despite the computational simplicity, however, the performance of the system is at least as good as, if not better than, the channel output setup. In this regard, the channel input setup provides good robustness against channel estimation error, which tends to dominate the performance of a GERAN receiver when interference is present.
According to one aspect of the subject disclosure, data processor 490 comprises a soft output generator that receives the signal from frequency decision block 480 and generates soft decisions that indicate the confidence in the detected bits. A soft output generator may implement an Ono algorithm, as is well known to those of skill in the art. Data processor 490 may further comprise a de-interleaver that de-interleaves the soft decisions, and passes the soft decisions to a Viterbi decoder that decodes the deinterleaved soft decisions and outputs decoded data.

FIG. 6 illustrates a method for suppressing interference in accordance with one aspect of the subject technology. The method begins in step 601, in which a burst of symbols are received. In step 602, a subset of the burst of symbols is selected. According to one aspect of the subject disclosure, the subset of the burst of symbols includes a first midamble symbol. In step 603, the subset selected in step 602 is iteratively adjusted by a plurality of timing offsets. In step 604, a plurality of weights for an interference filter are calculated for each timing offset, based upon the burst of symbols. In step 605, the burst of symbols are filtered, for each timing offset, using the interference suppression filter with the corresponding plurality of weights to determine an estimated midamble sequence. In step 606, the estimated midamble sequence for each timing offset is compared to a previously known midamble sequence to determine a midamble estimation error for that timing offset. One of the plurality of timing offsets is determined, in step 607, to be a preferred timing offset, based upon the midamble estimation error thereof. According to one aspect of the subject disclosure, the preferred midamble timing offset is the timing offset corresponding to the lowest midamble estimation error. In step 608, the subset of the burst of symbols are iteratively rotated by a plurality of frequency offsets. In step 609, a plurality of weights for an interference filter are calculated for each frequency offset, based upon the burst of symbols. In step 610, the burst of symbols are filtered, for each frequency offset, using the interference suppression filter with the corresponding plurality of weights to determine an estimated midamble sequence. In step 611, the estimated midamble sequence for each frequency offset is compared to a previously known midamble sequence to determine a midamble estimation error for that frequency offset. One of the plurality of frequency offsets is determined, in step 612, to be a preferred frequency offset, based upon the midamble estimation error thereof.
[0056] According to one aspect of the subject disclosure, a parallel approach to locating an optimal frequency/timing hypothesis pair may be utilized, with a corresponding increase in computational complexity over a serial approach (e.g., where there are 5 frequency hypotheses and 7 timing hypotheses, a serial approach may involve determining a prediction error 12 times, whereas a parallel approach will involve determining a prediction error 35 times). Nevertheless, a parallel approach may provide even more accurate estimation of timing and frequency for improved performance.

[0057] FIG. 7 illustrates a receiver for use in a wireless communication system in accordance with one aspect of the subject technology. Receiver 700 includes an antenna 710 configured to receive a wireless signal. The received signal is provided to a pre-processor 720 which demodulates the signal to generate received samples. Pre-processor 720 may include a GMSK-to-BPSK rotator that performs phase rotation on the received samples. Timing and frequency estimator 730 receives the samples from pre-processor 720 and generates a plurality of timing and frequency hypotheses regarding where a training sequence of symbols (i.e., midamble) begins in the burst of data (timing) and at which frequency the symbols can be optimally received (frequency). Interference suppressor 740 iteratively performs single antenna interference cancellation on the symbols for each timing and frequency hypothesis pair, calculating different filter weights for each hypothesis pair, and midamble estimator 750 generates a midamble estimation error for each hypothesis pair, as described in greater detail above. Timing and frequency decision circuit 760 compares the midamble estimation errors for each hypothesis pair and selects the pair with the lowest midamble estimation error. The selection of a hypothesis pair by timing and frequency decision circuit 760 represents the position in the burst of symbols where the midamble is estimated to begin, and the optimal frequency at which to receive the burst of symbols. The signal is then provided to data processor 770, which processes the received symbols based upon the selected timing and frequency hypotheses, and outputs the data corresponding to the received symbols.

[0058] FIG. 8 illustrates a method for suppressing interference in accordance with one aspect of the subject technology. The method begins in step 801, in which a burst of symbols are received. In step 802, a subset of the burst of symbols is selected.
According to one aspect of the subject disclosure, the subset of the burst of symbols includes a first midamble symbol. In step 803, the subset selected in step 802 is iteratively adjusted by a plurality of timing and frequency offsets. In step 804, a plurality of weights for an interference filter are calculated for each timing and frequency offset pair, based upon the burst of symbols. In step 805, the burst of symbols are filtered, for each pair of offsets, using the interference suppression filter with the corresponding plurality of weights to determine an estimated midamble sequence. In step 806, the estimated midamble sequence for each offset pair is compared to a previously known midamble sequence to determine a midamble estimation error for that timing offset. One of the plurality combination of timing and frequency offsets is determined, in step 807, to be a preferred combination, based upon the midamble estimation error thereof. According to one aspect of the subject disclosure, the preferred combination is the combination corresponding to the lowest midamble estimation error.

[0059] FIG. 9 illustrates a receiver for use in a wireless communication system in accordance with one aspect of the subject technology. Receiver 900 includes an antenna module 910 configured to receive a wireless signal. While receiver 900 may be used in various communication systems, for clarity, receiver 900 is specifically described herein with respect to a GSM system. The received signal is provided to a pre-processor module 920 which demodulates the signal to generate received samples. Pre-processor module 920 may include a GMSK-to-BPSK rotator that performs phase rotation on the received samples. Timing estimator module 930 receives the samples from pre-processor module 920 and generates a plurality of timing hypotheses regarding where a training sequence of symbols (i.e., midamble) begins in the burst of data. Interference suppressor module 940 iteratively performs single antenna interference cancellation on the symbols for each timing hypothesis, calculating different filter weights for each timing hypothesis, and midamble estimator module 950 generates a midamble estimation error for each hypothesis, as described in greater detail above. Timing decision circuit 960 compares the midamble estimation errors for each hypothesis and selects the hypothesis with the lowest midamble estimation error. The selection of a hypothesis by timing decision module 960 represents the position in the burst of symbols where the midamble is estimated to begin. Frequency estimator module 970 receives the samples from timing decision module 960 and generates a
plurality of frequency hypotheses regarding a frequency on which symbols are transmitted. Interference suppressor module 940 iteratively performs single antenna interference cancellation on the symbols for each frequency hypothesis, calculating different filter weights for each frequency hypothesis, and midamble estimator module 950 generates a midamble estimation error for each hypothesis, as described in greater detail above. Frequency decision circuit 980 compares the midamble estimation errors for each hypothesis and selects the hypothesis with the lowest midamble estimation error. The selection of a hypothesis by frequency decision module 980 represents the optimal frequency at which to receive the burst of symbols. The signal is then provided to data processor module 990, which processes the received symbols based upon the selected timing and frequency hypotheses, and outputs the data corresponding to the received symbols.

[0060] FIG. 10 illustrates a receiver for use in a wireless communication system in accordance with one aspect of the subject technology. Receiver 1000 includes an antenna module 1010 configured to receive a wireless signal. The received signal is provided to a pre-processor module 1020 which demodulates the signal to generate received samples. Pre-processor module 1020 may include a GMSK-to-BPSK rotator that performs phase rotation on the received samples. Timing and frequency estimator module 1030 receives the samples from pre-processor module 1020 and generates a plurality of timing and frequency hypotheses regarding where a training sequence of symbols (i.e., midamble) begins in the burst of data (timing) and at which frequency the symbols can be optimally received (frequency). Interference suppressor module 1040 iteratively performs single antenna interference cancellation on the symbols for each timing and frequency hypothesis pair, calculating different filter weights for each hypothesis pair, and midamble estimator module 1050 generates a midamble estimation error for each hypothesis pair, as described in greater detail above. Timing and frequency decision module 1060 compares the midamble estimation errors for each hypothesis pair and selects the pair with the lowest midamble estimation error. The selection of a hypothesis pair by timing and frequency decision module 1060 represents the position in the burst of symbols where the midamble is estimated to begin, and the optimal frequency at which to receive the burst of symbols. The signal is then provided to data processor module 1070, which processes the received symbols based upon the
selected timing and frequency hypotheses, and outputs the data corresponding to the
received symbols.

[0061] FIG. 11 is a block diagram that illustrates a computer system 1100 upon
which an aspect may be implemented. Computer system 1100 includes a bus 1102 or
other communication mechanism for communicating information, and a processor 1104
coupled with bus 1102 for processing information. Computer system 1100 also
includes a memory 1106, such as a random access memory ("RAM") or other dynamic
storage device, coupled to bus 1102 for storing information and instructions to be
executed by processor 1104. Memory 1106 may also be used for storing temporary
variable or other intermediate information during execution of instructions to be
executed by processor 1104. Computer system 1100 further includes a data storage
device 1110, such as a magnetic disk or optical disk, coupled to bus 1102 for storing
information and instructions.

[0062] Computer system 1100 may be coupled via I/O module 1108 to a display
device (not illustrated), such as a cathode ray tube ("CRT") or liquid crystal display
(“LCD”) for displaying information to a computer user. An input device, such as, for
example, a keyboard or a mouse may also be coupled to computer system 1100 via I/O
module 1108 for communicating information and command selections to processor
1104.

[0063] According to one aspect, timing and frequency estimation is performed by a
computer system 1100 in response to processor 1104 executing one or more sequences
of one or more instructions contained in memory 1106. Such instructions may be read
into memory 1106 from another machine-readable medium, such as data storage device
1110. Execution of the sequences of instructions contained in main memory 1106
causes processor 1104 to perform the process steps described herein. One or more
processors in a multi-processing arrangement may also be employed to execute the
sequences of instructions contained in memory 1106. In alternative aspects, hard-wired
circuitry may be used in place of or in combination with software instructions to
implement various aspects. Thus, aspects are not limited to any specific combination of
hardware circuitry and software.
The term “machine-readable medium” as used herein refers to any medium that participates in providing instructions to processor 1104 for execution. Such a medium may take many forms, including, but not limited to, non-volatile media, volatile media, and transmission media. Non-volatile media include, for example, optical or magnetic disks, such as data storage device 1110. Volatile media include dynamic memory, such as memory 1106. Transmission media include coaxial cables, copper wire, and fiber optics, including the wires that comprise bus 1102. Transmission media can also take the form of acoustic or light waves, such as those generated during radio frequency and infrared data communications. Common forms of machine-readable media include, for example, floppy disk, a flexible disk, hard disk, magnetic tape, any other magnetic medium, a CD-ROM, DVD, any other optical medium, punch cards, paper tape, any other physical medium with patterns of holes, a RAM, a PROM, an EPROM, a FLASH EPROM, any other memory chip or cartridge, a carrier wave, or any other medium from which a computer can read.

Those of skill in the art would appreciate that the various illustrative blocks, modules, elements, components, methods, and algorithms described herein may be implemented as electronic hardware, computer software, or combinations of both. Furthermore, these may be partitioned differently than what is described. To illustrate this interchangeability of hardware and software, various illustrative blocks, modules, elements, components, methods, and algorithms have been described above generally in terms of their functionality. Whether such functionality is implemented as hardware or software depends upon the particular application and design constraints imposed on the overall system. Skilled artisans may implement the described functionality in varying ways for each particular application.

It is understood that the specific order or hierarchy of steps or blocks in the processes disclosed is an illustration of exemplary approaches. Based upon design preferences, it is understood that the specific order or hierarchy of steps or blocks in the processes may be rearranged. The accompanying method claims present elements of the various steps in a sample order, and are not meant to be limited to the specific order or hierarchy presented.

The previous description is provided to enable any person skilled in the art to practice the various aspects described herein. Various modifications to these aspects
will be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other aspects. Thus, the claims are not intended to be limited to the aspects shown herein, but is to be accorded the full scope consistent with the language claims, wherein reference to an element in the singular is not intended to mean “one and only one” unless specifically so stated, but rather “one or more.” Unless specifically stated otherwise, the term “some” refers to one or more. Pronouns in the masculine (e.g., his) include the feminine and neuter gender (e.g., her and its) and vice versa. All structural and functional equivalents to the elements of the various aspects described throughout this disclosure that are known or later come to be known to those of ordinary skill in the art are expressly incorporated herein by reference and are intended to be encompassed by the claims. Moreover, nothing disclosed herein is intended to be dedicated to the public regardless of whether such disclosure is explicitly recited in the claims. No claim element is to be construed under the provisions of 35 U.S.C. §112, sixth paragraph, unless the element is expressly recited using the phrase “means for” or, in the case of a method claim, the element is recited using the phrase “step for.”
WHAT IS CLAIMED IS:

1. A method for timing and frequency synchronization in a wireless system, comprising the steps of:
   receiving a burst of symbols;
   selecting a subset of the burst of symbols;
   iteratively adjusting the subset of the burst of symbols by a plurality of timing offsets;
   calculating, for each timing offset, a first performance metric corresponding to the adjusted subset;
   determining one of the plurality of timing offsets to be a preferred timing offset based upon the first performance metric thereof;
   iteratively rotating the subset of the burst of symbols by a plurality of frequency offsets;
   calculating, for each frequency offset, a second performance metric corresponding to the rotated subset; and
   determining one of the plurality of frequency offsets to be a preferred frequency offset based upon the second performance metric thereof.

2. The method according to claim 1, wherein the first performance metric is a midamble estimation error.

3. The method according to claim 2, wherein the midamble estimation error is calculated for each timing offset by:
   calculating a plurality of weights for an interference suppression filter based upon the subset of the burst of symbols;
   filtering the burst of symbols using the interference suppression filter with the corresponding plurality of weights to obtain an estimated midamble sequence; and
   comparing the estimated midamble sequence with a previously-known midamble sequence to determine the midamble estimation error.

4. The method according to claim 3, wherein the plurality of weights are calculated by solving for
\[ W_{SAC} = \hat{s}_k [X]^T \left\{ [X][X]^T \right\}^{-1}, \]

where \( \hat{s}_k \) is a vector corresponding to an estimate of the subset of symbols, \([X]\) is a matrix of spatial temporal samples of the burst of symbols, and \([X]^T\) is a transpose of \([X]\).

5. The method according to claim 3, wherein the interference suppression filter is a single antenna interference cancellation filter.

6. The method according to claim 3, wherein the interference suppression filter is a dual antenna interference cancellation filter.

7. The method according to claim 1, wherein the second performance metric is a midamble estimation error.

8. The method according to claim 7, wherein the midamble estimation error is calculated for each frequency offset by:
   calculating a plurality of weights for an interference suppression filter based upon the subset of the burst of symbols;
   filtering the burst of symbols using the interference suppression filter with the corresponding plurality of weights to obtain an estimated midamble sequence; and
   comparing the estimated midamble sequence with a previously-known midamble sequence to determine the midamble estimation error.

9. The method according to claim 8, wherein the plurality of weights are calculated by solving for
   \[ W_{SAC} = \hat{s}_k [X]^T \left\{ [X][X]^T \right\}^{-1}, \]
   where \( \hat{s}_k \) is a vector corresponding to an estimate of the subset of symbols, \([X]\) is a matrix of spatial temporal samples of the burst of symbols, and \([X]^T\) is a transpose of \([X]\).

10. The method according to claim 8, wherein the interference suppression filter is a single antenna interference cancellation filter.
11. The method according to claim 1, wherein the subset of the burst of symbols includes a first midamble symbol.

12. The method according to claim 11, wherein the plurality of timing offsets are determined by estimating a position of the first midamble symbol in the burst of symbols and selecting the subset of the burst of symbols from symbols centered around the estimated position.

13. A method for timing and frequency synchronization in a wireless system, comprising the steps of:
   receiving a burst of symbols;
   selecting a subset of the burst of symbols;
   iteratively adjusting the subset of the burst of symbols by a plurality of timing offsets and a plurality of frequency offsets;
   calculating, for each combination of timing and frequency offsets, a performance metric corresponding to the adjusted subset; and
   determining one of the combination of timing and frequency offsets to be a preferred combination based upon the performance metric thereof.

14. The method according to claim 13, wherein the performance metric is a midamble estimation error.

15. The method according to claim 14, wherein the midamble estimation error is calculated for each combination of timing and frequency offsets by:
   calculating a plurality of weights for an interference suppression filter based upon the subset of the burst of symbols;
   filtering the burst of symbols using the interference suppression filter with the corresponding plurality of weights to obtain an estimated midamble sequence; and
   comparing the estimated midamble sequence with a previously-known midamble sequence to determine the midamble estimation error.

16. The method according to claim 15, wherein the plurality of weights are calculated by solving for

\[ W_{\text{mag}} = \tilde{X}_k [X] \left( [X][X]^t \right)^{-1}, \]

where \( \tilde{X}_k \) is a vector corresponding to an estimate of the subset of symbols, \([X]\)
is a matrix of spatial temporal samples of the burst of symbols, and $[X]^T$ is a transpose of $[X]$.

17. The method according to claim 15, wherein the interference suppression filter is a single antenna interference cancellation filter.

18. The method according to claim 15, wherein the interference suppression filter is a dual antenna interference cancellation filter.

19. A wireless apparatus, comprising:
   a receiver configured to receive a burst of symbols; and
   a processor configured to:
       select a subset of the burst of symbols;
       iteratively adjust the subset of the burst of symbols by a plurality of timing offsets;
       calculate, for each timing offset, a first performance metric corresponding to the adjusted subset;
       determine one of the plurality of timing offsets to be a preferred timing offset based upon the first performance metric thereof;
       iteratively rotate the subset of the burst of symbols by a plurality of frequency offsets;
       calculate, for each frequency offset, a second performance metric corresponding to the rotated subset; and
       determine one of the plurality of frequency offsets to be a preferred frequency offset based upon the second performance metric thereof.

20. The wireless apparatus according to claim 19, wherein the first performance metric is a midamble estimation error.

21. The wireless apparatus according to claim 20, wherein the processor is configured to calculate the midamble estimation error for each timing offset by:
   calculating a plurality of weights for an interference suppression filter based upon the subset of the burst of symbols;
   filtering the burst of symbols using the interference suppression filter with the corresponding plurality of weights to obtain an estimated midamble sequence; and
comparing the estimated midamble sequence with a previously-known midamble sequence to determine the midamble estimation error.

22. The wireless apparatus to claim 21, wherein the processor is configured to calculate the plurality of weights by solving for

\[ W_{\text{LOC}} = \tilde{s}_k [X]^T \left\{ [X][X]^T \right\}^{-1}, \]

where \( \tilde{s}_k \) is a vector corresponding to an estimate of the subset of symbols, \([X]\) is a matrix of spatial temporal samples of the burst of symbols, and \([X]^T\) is a transpose of \([X]\).

23. The wireless apparatus according to claim 21, wherein the interference suppression filter is a single antenna interference cancellation filter.

24. The wireless apparatus according to claim 21, wherein the interference suppression filter is a dual antenna interference cancellation filter.

25. The wireless apparatus according to claim 19, wherein the second performance metric is a midamble estimation error.

26. The wireless apparatus according to claim 25, wherein the processor is configured to calculate the midamble estimation error for each frequency offset by:

- calculating a plurality of weights for an interference suppression filter based upon the subset of the burst of symbols;
- filtering the burst of symbols using the interference suppression filter with the corresponding plurality of weights to obtain an estimated midamble sequence; and
- comparing the estimated midamble sequence with a previously-known midamble sequence to determine the midamble estimation error.

27. The wireless apparatus according to claim 26, wherein the processor is configured to calculate the plurality of weights by solving for

\[ W_{\text{LOC}} = \tilde{s}_k [X]^T \left\{ [X][X]^T \right\}^{-1}, \]

where \( \tilde{s}_k \) is a vector corresponding to an estimate of the subset of symbols, \([X]\)
is a matrix of spatial temporal samples of the burst of symbols, and $[X]^T$ is a transpose of $[X]$.

28. The wireless apparatus according to claim 26, wherein the interference suppression filter is a single antenna interference cancellation filter.

29. The wireless apparatus according to claim 19, wherein the subset of the burst of symbols includes a first midamble symbol.

30. The wireless apparatus according to claim 29, wherein the processor is configured to determine the plurality of timing offsets by estimating a position of the first midamble symbol in the burst of symbols and selecting the subset of the burst of symbols from symbols centered around the estimated position.

31. A wireless apparatus, comprising:
   a receiver configured to receive a burst of symbols; and
   a processor configured to:
   receive a burst of symbols;
   select a subset of the burst of symbols;
   iteratively adjust the subset of the burst of symbols by a plurality of timing offsets and a plurality of frequency offsets;
   calculate, for each combination of timing and frequency offsets, a performance metric corresponding to the adjusted subset; and
   determine one of the combination of timing and frequency offsets to be a preferred combination based upon the performance metric thereof.

32. The wireless apparatus according to claim 31, wherein the performance metric is a midamble estimation error.

33. The wireless apparatus according to claim 32, wherein the processor is configured to calculate the midamble estimation error for each combination of timing and frequency offsets by:
   calculating a plurality of weights for an interference suppression filter based upon the subset of the burst of symbols;
   filtering the burst of symbols using the interference suppression filter with the
corresponding plurality of weights to obtain an estimated midamble sequence; and
comparing the estimated midamble sequence with a previously-known
midamble sequence to determine the midamble estimation error.

34. The wireless apparatus according to claim 33, wherein the processor is
configured to calculate the plurality of weights by solving for
\[
W_{\text{DAC}} = \ddot{\mathbf{s}}_k \left( \left[ X \right]^T \left\{ \left[ X \right] \left[ X \right]^T \right\}^{-1} \right),
\]
where \( \ddot{\mathbf{s}}_k \) is a vector corresponding to an estimate of the subset of symbols, \( \left[ X \right] \)
is a matrix of spatial temporal samples of the burst of symbols, and \( \left[ X \right]^T \) is a transpose
of \( \left[ X \right] \).

35. The wireless apparatus according to claim 33, wherein the interference
suppression filter is a single antenna interference cancellation filter.

36. The wireless apparatus according to claim 33, wherein the interference
suppression filter is a dual antenna interference cancellation filter.

37. A wireless apparatus, comprising:
means for receiving a burst of symbols;
means for selecting a subset of the burst of symbols;
means for iteratively adjusting the subset of the burst of symbols by a plurality
of timing offsets;
means for calculating, for each timing offset, a first performance metric
corresponding to the adjusted subset;
means for determining one of the plurality of timing offsets to be a preferred
timing offset based upon the first performance metric thereof;
means for iteratively rotating the subset of the burst of symbols by a plurality of
frequency offsets and calculating, for each frequency offset, a second performance
metric corresponding to the rotated subset; and
means for determining one of the plurality of frequency offsets to be a preferred
frequency offset based upon the second performance metric thereof.

38. The wireless apparatus according to claim 37, wherein the first
performance metric is a midamble estimation error.
39. The wireless apparatus according to claim 38, wherein the means for calculating the midamble estimation error for each timing offset comprise:

means for calculating a plurality of weights for an interference suppression filter based upon the subset of the burst of symbols;

means filtering the burst of symbols using the interference suppression filter with the corresponding plurality of weights to obtain an estimated midamble sequence;

and

means for comparing the estimated midamble sequence with a previously-known midamble sequence to determine the midamble estimation error.

40. The wireless apparatus according to claim 39, wherein the means for calculating the plurality of weights comprise means for solving for

\[ W_{SAEC} = \tilde{\tilde{z}}_h \begin{bmatrix} X \end{bmatrix}^T \left\{ \begin{bmatrix} X \end{bmatrix} \begin{bmatrix} X \end{bmatrix}^T \right\}^{-1}, \]

where \( \tilde{\tilde{z}}_h \) is a vector corresponding to an estimate of the subset of symbols, \( \begin{bmatrix} X \end{bmatrix} \) is a matrix of spatial temporal samples of the burst of symbols, and \( \begin{bmatrix} X \end{bmatrix}^T \) is a transpose of \( \begin{bmatrix} X \end{bmatrix} \).

41. The wireless apparatus according to claim 39, wherein the interference suppression filter is a single antenna interference cancellation filter.

42. The wireless apparatus according to claim 39, wherein the interference suppression filter is a dual antenna interference cancellation filter.

43. The wireless apparatus according to claim 37, wherein the second performance metric is a midamble estimation error.

44. The wireless apparatus according to claim 43, wherein the means for calculating the midamble estimation error for each frequency offset comprise:

means for calculating a plurality of weights for an interference suppression filter based upon the subset of the burst of symbols;

means for filtering the burst of symbols using the interference suppression filter with the corresponding plurality of weights to obtain an estimated midamble sequence;

and
means for comparing the estimated midamble sequence with a previously-known midamble sequence to determine the midamble estimation error.

45. The wireless apparatus according to claim 44, wherein the means for calculating the plurality of weights comprise means for solving for

\[ W_{\text{SOC}} = \tilde{s}_k [X]^T \left\{ \left[ X \right] \left[ X \right]^T \right\}^{-1}, \]

where \( \tilde{s}_k \) is a vector corresponding to an estimate of the subset of symbols, \( [X] \) is a matrix of spatial temporal samples of the burst of symbols, and \( [X]^T \) is a transpose of \( [X] \).

46. The wireless apparatus according to claim 44, wherein the interference suppression filter is a single antenna interference cancellation filter.

47. The wireless apparatus according to claim 37, wherein the subset of the burst of symbols includes a first midamble symbol.

48. The wireless apparatus according to claim 47, wherein the plurality of timing offsets are determined by estimating a position of the first midamble symbol in the burst of symbols and selecting the subset of the burst of symbols from symbols centered around the estimated position.

49. A wireless apparatus, comprising:

means for receiving a burst of symbols;
means for selecting a subset of the burst of symbols;
means for iteratively adjusting the subset of the burst of symbols by a plurality of timing offsets and a plurality of frequency offsets;
means for calculating, for each combination of timing and frequency offsets, a performance metric corresponding to the adjusted subset; and
means for determining one of the combination of timing and frequency offsets to be a preferred combination based upon the performance metric thereof.

50. The wireless apparatus according to claim 49, wherein the performance metric is a midamble estimation error.
51. The wireless apparatus according to claim 50, wherein means for calculating the midamble estimation error for each combination of timing and frequency offsets comprises:

means for calculating a plurality of weights for an interference suppression filter based upon the subset of the burst of symbols;

means for filtering the burst of symbols using the interference suppression filter with the corresponding plurality of weights to obtain an estimated midamble sequence; and

means for comparing the estimated midamble sequence with a previously-known midamble sequence to determine the midamble estimation error.

52. The wireless apparatus according to claim 51, wherein the means for calculating the plurality of weights comprise means for solving for

\[ W_{\text{SAE}} = \tilde{s}_k [X]^T \left( [X] [X]^T \right)^{-1}, \]

where \( \tilde{s}_k \) is a vector corresponding to an estimate of the subset of symbols, \([X]\) is a matrix of spatial temporal samples of the burst of symbols, and \([X]^T\) is a transpose of \([X]\).

53. The wireless apparatus according to claim 51, wherein the interference suppression filter is a single antenna interference cancellation filter.

54. The method according to claim 51, wherein the interference suppression filter is a dual antenna interference cancellation filter.

55. A computer-program product for use in a wireless communication system comprising a computer readable medium having a set of instructions stored thereon, the set of instructions being executable by one or more processors and the set of instructions comprising:

instructions for receiving a burst of symbols;

instructions for selecting a subset of the burst of symbols;

instructions for iteratively adjusting the subset of the burst of symbols by a plurality of timing offsets;

instructions for calculating, for each timing offset, a first performance metric corresponding to the adjusted subset;
instructions for determining one of the plurality of timing offsets to be a preferred timing offset based upon the first performance metric thereof;

instructions for iteratively rotating the subset of the burst of symbols by a plurality of frequency offsets and for calculating, for each frequency offset, a second performance metric corresponding to the rotated subset; and

instructions for determining one of the plurality of frequency offsets to be a preferred frequency offset based upon the second performance metric thereof.

56. The computer-program product according to claim 55, wherein the first performance metric is a midamble estimation error.

57. The computer-program product according to claim 56, wherein instructions for calculating the midamble estimation error for each timing offset comprise:

instructions for calculating a plurality of weights for an interference suppression filter based upon the subset of the burst of symbols;

instructions for filtering the burst of symbols using the interference suppression filter with the corresponding plurality of weights to obtain an estimated midamble sequence; and

instructions for comparing the estimated midamble sequence with a previously-known midamble sequence to determine the midamble estimation error.

58. The computer-program product according to claim 57, wherein the instructions for calculating the plurality of weights comprise instructions for solving for

\[ W_{\text{SOC}} = \tilde{\xi}_k X^T \left( X X^T \right)^{-1}, \]

where \( \tilde{\xi}_k \) is a vector corresponding to an estimate of the subset of symbols, \( [X] \) is a matrix of spatial temporal samples of the burst of symbols, and \( [X]^T \) is a transpose of \( [X] \).

59. The computer-program product according to claim 57, wherein the interference suppression filter is a single antenna interference cancellation filter.

60. The computer-program product according to claim 57, wherein the interference suppression filter is a dual antenna interference cancellation filter.
61. The computer-program product according to claim 55, wherein the second performance metric is a midamble estimation error.

62. The computer-program product according to claim 61, wherein the instructions for calculating the midamble estimation error for each frequency offset comprise:

instructions for calculating a plurality of weights for an interference suppression filter based upon the subset of the burst of symbols;

instructions for filtering the burst of symbols using the interference suppression filter with the corresponding plurality of weights to obtain an estimated midamble sequence; and

instructions for comparing the estimated midamble sequence with a previously-known midamble sequence to determine the midamble estimation error.

63. The computer-program product according to claim 62, wherein the instructions for calculating the plurality of weights comprise instructions for solving for

$$W_{\text{LOC}} = \hat{\mathbf{s}}_\lambda \left[ \mathbf{X} \mathbf{X}^T \right]^{-1} \left[ \mathbf{X} \left[ \mathbf{X} \mathbf{X}^T \right]^{-1} \right],$$

where \( \hat{\mathbf{s}}_\lambda \) is a vector corresponding to an estimate of the subset of symbols, \( \mathbf{X} \) is a matrix of spatial temporal samples of the burst of symbols, and \( \mathbf{X}^T \) is a transpose of \( \mathbf{X} \).

64. The computer-program product according to claim 62, wherein the interference suppression filter is a single antenna interference cancellation filter.

65. The computer-program product according to claim 62, wherein the subset of the burst of symbols includes a first midamble symbol.

66. The computer-program product according to claim 65, wherein the plurality of timing offsets are determined by estimating a position of the first midamble symbol in the burst of symbols and selecting the subset of the burst of symbols from symbols centered around the estimated position.

67. A computer-program product for use in a wireless communication system comprising a computer readable medium having a set of instructions stored
thereon, the set of instructions being executable by one or more processors and the set of instructions comprising:

- instructions for receiving a burst of symbols;
- instructions for selecting a subset of the burst of symbols;
- instructions for iteratively adjusting the subset of the burst of symbols by a plurality of timing offsets and a plurality of frequency offsets;
- instructions for calculating, for each combination of timing and frequency offsets, a performance metric corresponding to the adjusted subset; and
- instructions for determining one of the combination of timing and frequency offsets to be a preferred combination based upon the performance metric thereof.

68. The computer-program product according to claim 67, wherein the performance metric is a midamble estimation error.

69. The computer-program product according to claim 68, wherein the instructions for calculating the midamble estimation error for each combination of timing and frequency offsets comprise:

- instructions for calculating a plurality of weights for an interference suppression filter based upon the subset of the burst of symbols;
- instructions for filtering the burst of symbols using the interference suppression filter with the corresponding plurality of weights to obtain an estimated midamble sequence; and
- instructions for comparing the estimated midamble sequence with a previously-known midamble sequence to determine the midamble estimation error.

70. The computer-program product according to claim 69, wherein the instructions for calculating the plurality of weights comprise instructions for solving for

\[ W_{MAC} = \hat{s}_\lambda \left[ X \right]^T \left\{ \left[ X \right] \left[ X^T \right]^{-1} \right\}, \]

where \( \hat{s}_\lambda \) is a vector corresponding to an estimate of the subset of symbols, \( \left[ X \right] \) is a matrix of spatial temporal samples of the burst of symbols, and \( \left[ X \right]^T \) is a transpose of \( \left[ X \right] \).

71. The computer-program product according to claim 69, wherein the interference suppression filter is a single antenna interference cancellation filter.
72. The computer-program product according to claim 69, wherein the interference suppression filter is a dual antenna interference cancellation filter.
Set $k = 0, \Delta = 0, \epsilon_{\text{min}} = \infty$
$c(n) = 0, f(n) = f_0$

$\Omega = \{0, 1, \ldots, q\}$
$T = \{0, 1, 2, \ldots, \Delta_{\text{max}}\}$

$k = k + 1$
$c(0, n) = \epsilon_{\text{min}}$

Frequency loop

- Apply $c(n)$
- $X_0 = \text{rotate}(X_0, f_0)$
- Form $X_0X_0^T$
- Form $W_0 = SX_0^T[X_0X_0^T]^{-1}$
- MIMO filter $S_0 = W_0X_0$

- Compute error $c(k) = ||S - S_0||^2$
- Error smoothing $c(k, n) = (1 - \beta)c(k) + \beta c(k, n-1)$

- $k = k + 1$
- $c(k, n) < \epsilon_{\text{min}}$

- Set $f(n) = f_k, \epsilon_{\text{min}} = c(k, n)$

Timing loop

- $X_0 \rightarrow X(t=\Delta)$
- Form $X_0X_0^T$
- Form $W_0 = SX_0^T[X_0X_0^T]^{-1}$
- MIMO filter $S_0 = W_0X_0$

- Compute error $c(\Delta) = ||S - S_0||^2$
- Error smoothing $c(\Delta, n) = (1 - \alpha)c(\Delta) + \alpha c(\Delta, n-1)$

- $\Delta = \Delta + 1$
- $c(\Delta, n) < \epsilon_{\text{min}}$

- Set $c(\Delta, n) = \epsilon_{\text{min}}$

Output $c(n), f(n)$

FIG. 2
FIG. 6

START

601

RECEIVE A BURST OF SYMBOLS

602

SELECT A SUBSET OF THE BURST OF SYMBOLS

603

ITERATIVELY ADJUST THE SUBSET OF THE BURST OF SYMBOLS BY A PLURALITY OF TIMING OFFSETS

604

CALCULATE, FOR EACH TIMING OFFSET, A PLURALITY OF WEIGHTS FOR AN INTERFERENCE SUPPRESSION FILTER BASED UPON THE SUBSET OF THE BURST OF SYMBOLS

605

FILTER, FOR EACH TIMING OFFSET, THE BURST OF SYMBOLS USING THE INTERFERENCE SUPPRESSION FILTER WITH THE CORRESPONDING PLURALITY OF WEIGHTS TO OBTAIN AN ESTIMATED MIDAMBLE SEQUENCE

606

COMPARE, FOR EACH TIMING OFFSET, THE ESTIMATED MIDAMBLE SEQUENCE WITH A PREVIOUSLY-KNOWN MIDAMBLE SEQUENCE TO DETERMINE THE MIDAMBLE ESTIMATION ERROR

607

DETERMINE ONE OF THE PLURALITY OF TIMING OFFSETS TO BE A PREFERRED TIMING OFFSET BASED UPON THE MIDAMBLE ESTIMATION ERROR THEREOF

608

ITERATIVELY ROTATE THE SUBSET OF THE BURST OF SYMBOLS BY A PLURALITY OF FREQUENCY OFFSETS

609

CALCULATE, FOR EACH FREQUENCY OFFSET, A PLURALITY OF WEIGHTS FOR AN INTERFERENCE SUPPRESSION FILTER BASED UPON THE SUBSET OF THE BURST OF SYMBOLS

610

FILTER, FOR EACH FREQUENCY OFFSET, THE BURST OF SYMBOLS USING THE INTERFERENCE SUPPRESSION FILTER WITH THE CORRESPONDING PLURALITY OF WEIGHTS TO OBTAIN AN ESTIMATED MIDAMBLE SEQUENCE

611

COMPARE, FOR EACH FREQUENCY OFFSET, THE ESTIMATED MIDAMBLE SEQUENCE WITH A PREVIOUSLY-KNOWN MIDAMBLE SEQUENCE TO DETERMINE THE MIDAMBLE ESTIMATION ERROR

612

DETERMINE ONE OF THE PLURALITY OF FREQUENCY OFFSETS TO BE A PREFERRED FREQUENCY OFFSET BASED UPON THE MIDAMBLE ESTIMATION ERROR THEREOF

END
FIG. 7

700

710

720

PRE-PROCESSOR

730

TIMING AND FREQUENCY ESTIMATOR

740

INTERFERENCE SUPPRESSOR

750

MIDAMBLE ESTIMATOR

760

TIMING AND FREQUENCY DECISION

770

PROCESSOR
FIG. 8

START

801

RECEIVE A BURST OF SYMBOLS

802

SELECT A SUBSET OF THE BURST OF SYMBOLS

803

ITERATIVELY ADJUST THE SUBSET OF THE BURST OF SYMBOLS BY A PLURALITY OF TIMING OFFSETS AND A PLURALITY OF FREQUENCY OFFSETS

804

CALCULATE, FOR EACH COMBINATION OF TIMING AND FREQUENCY OFFSETS, A PLURALITY OF WEIGHTS FOR AN INTERFERENCE SUPPRESSION FILTER BASED UPON THE SUBSET OF THE BURST OF SYMBOLS

805

FILTER, FOR EACH COMBINATION OF TIMING AND FREQUENCY OFFSETS, THE BURST OF SYMBOLS USING THE INTERFERENCE SUPPRESSION FILTER WITH THE CORRESPONDING PLURALITY OF WEIGHTS TO OBTAIN AN ESTIMATED MIDAMBLE SEQUENCE

806

COMPARE, FOR EACH COMBINATION OF TIMING AND FREQUENCY OFFSETS, THE ESTIMATED MIDAMBLE SEQUENCE WITH A PREVIOUSLY-KNOWN MIDAMBLE SEQUENCE TO DETERMINE THE MIDAMBLE ESTIMATION ERROR

807

DETERMINE ONE OF THE COMBINATION OF TIMING AND FREQUENCY OFFSETS TO BE A PREFERRED COMBINATION BASED UPON THE MIDAMBLE ESTIMATION ERROR THEREOF

END
FIG. 11

1104 - PROCESSOR
1110 - DATA STORAGE
1102 - I/O MODULE
1100 - MEMORY
1106 - CHANNEL 1
1108 - CHANNEL 2
START

Timing loop

Set $\tau = 0$, $\varepsilon_{\text{init}} = \infty$

Form $X_tX_t^T$

Form $W_t = SX_t^T(X_tX_t^T)^{-1}$

MIMO filter $S_t = W_tX_t$

Compute error $\varepsilon(t) = \|S_t - \hat{S}_t\|^2$

Error smoothing $\varepsilon_{\text{smooth}}(t, n) = (1-\alpha)\varepsilon(t) + \alpha \varepsilon_{\text{smooth}}(t, n-1)$

If $\varepsilon_{\text{smooth}}(t, n) < \varepsilon_{\text{init}}$, then $\tau < N$

Set $\Delta f_{\text{M}}(n) = \tau$, $\varepsilon_{\text{init}} = \varepsilon_{\text{smooth}}(t, n)$

Frequency loop

Apply $\Delta f_{\text{M}}(n)$

$H = \text{cor} (TSC, X_{\text{M}}(n))$

Set $k = 0$, $(E_b/N_0)_{\text{max}} = 0$

$X_k = \text{rotate}(X_{\text{M}}(n), \Delta f_k)$

$H_k = \text{rotate}(H, \Delta f_k)$

Form $X_kX_k^T$

Form $W_k = H_kSX_k^T(X_kX_k^T)^{-1}$

MIMO filter $H_k\hat{S}_k = W_kX_k$

Channel re-estimation

MLSE

$E_b/N_0$ estimation

If $E_b/N_0 > (E_b/N_0)_{\text{max}}$, then $k < P$

Set $\Delta f_{\text{M}}(n) = \Delta f_k$

$(E_b/N_0)_{\text{max}} = E_b/N_0$

Output $\Delta f_{\text{M}}(n)$,