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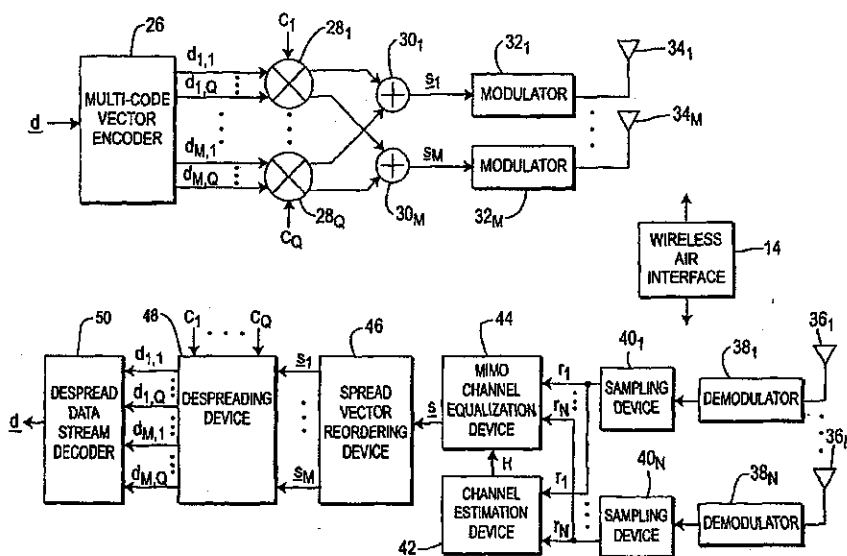
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- (71) Applicant: **INTERDIGITAL TECHNOLOGY CORPORATION** [US/US]; 300 Delaware Avenue, Suite 527, Wilmington, DE 19801 (US).
- (72) Inventor: **ZEIRA, Ariela**; 239 West Neck Road, Huntington, NY 11743 (US).
- (74) Agents: **VOLPE, Anthony, S. et al.**; Volpe and Koenig, P.C., Suite 400, One Penn Center, 1617 John F. Kennedy Blvd, Philadelphia, PA 19103 (US).
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(54) Title: EFFICIENT MULTIPLE INPUT MULTIPLE OUTPUT SYSTEM FOR MULTI-PATH FADING CHANNELS



(57) Abstract: Data is transferred in a wireless communication system, such as a wireless spread spectrum communication system. Data is encoded to produce a plurality of data streams (Fig. 2). For each of a plurality of transmitting antennas (34), the data streams are used to produce a vector for transmission. Each transmission vector is transmitted by its transmitting antenna through a wireless air interface experiencing multipath. Multipath components from each transmitted transmission vector are received by a plurality of receiving antennas (36). The received multipath components are equalized to recover the transmission vectors. The data is recovered from the recovered transmission vectors.

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For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

EFFICIENT MULTIPLE INPUT MULTIPLE OUTPUT SYSTEM FOR MULTI-PATH FADING CHANNELS

FIELD OF INVENTION

This invention relates generally to wireless communication systems. In particular, the invention relates to transferring signals using antenna arrays.

BACKGROUND

A multiple input multiple output (MIMO) system is described in Figure 1. Multiple transmission and/or reception antennas 12₁ to 12_M (12), 16₁ to 16_N (16) are used to transfer the communication. Each antenna 12, 16 is spatially separated from the other antennas 12, 16. A transmitter 10 using its antenna array 12 transmits a communication to a receiver 18 through a wireless air interface 18. The receiver 18 receives the communication using its antenna array 16. Using both multiple transmission and reception antennas 12, 16 is referred to as multiple input multiple output (MIMO) processing.

Typically, MIMO processing employs multiple antennas at both the base station transmitter and user equipment receiver. While the deployment of base station antenna arrays is already commonly used in wireless communication systems, the simultaneous deployment of base station and user equipment arrays enable significant increases in capacity and data rates by opening up multiple signaling dimensions.

Available MIMO algorithms address a single-path fading channels. However, wireless communication systems are characterized by multipath fading channels. Algorithms that are designed for single-path fading channels, typically exhibit severe degradation in presence of multipath.

Accordingly, it is desirable to have other MIMO systems.

SUMMARY

In accordance with a first aspect of the present invention, there is provided a method for recovering data transmitted from a plurality of

transmitting antennas and received by a plurality of receiving antennas, the method comprising: receiving a signal at each of the receiving antennas; sampling each received antenna signal to produce a combined received signal; estimating a overall channel response comprising a channel response for each transmitting and receiving antenna combination; processing a block-column of the overall channel response to produce a diagonal matrix; processing the combined received signal to effectively take a block-Fourier transform of the combined received signal; using the diagonal matrix and the effective block-Fourier transform of the combined received signal to produce a Fourier transform of a spread data vector; processing the Fourier transform of the spread data vector to produce the spread data vector; and despreading the spread data vector to recover the transmitted data.

In accordance with a second aspect of the present invention, there is provided a method for recovering data transmitted from a plurality of transmitting antennas and received by a plurality of receiving antennas, the method comprising: receiving a signal at each of the receiving antennas; sampling each received antenna signal to produce a combined received signal; estimating a overall channel response comprising a channel response for each transmitting and receiving antenna combination; producing a cross channel correlation matrix using the overall channel response; processing a block-column of the cross channel correlation matrix to produce a cross correlation diagonal matrix; processing a block-column of the overall channel response matrix to produce a channel response diagonal matrix; processing the combined received signal to effectively take a block-Fourier transform of the combined received signal; combining the channel response diagonal matrix and the effective blockFourier transform of the combined received signal to produce a combined result; using the cross correlation diagonal matrix and the combined result to produce a Fourier transform of a spread data vector; processing the Fourier

transform of the spread data vector to produce the spread data vector; and despreading the spread data vector to recover the transmitted data.

In accordance with a third aspect of the present invention, there is provided a user equipment comprising: means for receiving a signal at each of a plurality of receiving antennas, each of the received signals including signals transmitted from a plurality of antennas at a single site; means for sampling each received antenna signal to produce a combined received signal; means for estimating a overall channel response comprising a channel response for each transmitting and receiving antenna combination; means for processing a block-column of the overall channel response to produce a diagonal matrix; means for processing the combined received signal to effectively take a block-Fourier transform of the combined received signal; means for using the diagonal matrix and the effective block-Fourier transform of the combined received signal to produce a Fourier transform of a spread data vector; means for processing the Fourier transform of the spread data vector to produce the spread data vector; and means for despreading the spread data vector to recover the transmitted data.

In accordance with a fourth aspect of the present invention, there is provided a user equipment comprising: means for receiving a signal at each of a plurality of receiving antennas, each of the received signals including signals transmitted from a plurality of antennas at a single site; means for sampling each received antenna signal to produce a combined received signal; means for estimating a overall channel response comprising a channel response for each transmitting and receiving antenna combination; means for producing a cross channel correlation matrix using the overall channel response; means for processing a block-column of the cross channel correlation matrix to produce a cross correlation diagonal matrix; means for processing a block-column of the overall channel response matrix to produce a channel response diagonal matrix; means for processing the combined received signal to effectively take a block-Fourier transform of the combined received signal; means for combining the channel response diagonal matrix and the effective block-Fourier transform of

the combined received signal to produce a combined result; means for using the cross correlation diagonal matrix and the combined result to produce a Fourier transform of a spread data vector; means for processing the Fourier transform of the spread data vector to produce the spread data vector; and means for despreading the spread data vector to recover the transmitted data.

In accordance with a fifth aspect of the present invention, there is provided a user equipment comprising: a plurality of receiving antennas for receiving signals from a plurality of transmitting antennas at a single site; a plurality of sampling devices for sampling a received version of the received signals as received by each of the plurality of receiving antennas to produce a combined received signal; a channel estimation device for determining a channel response for each receiving and transmitting antenna combination and producing an overall channel response; a MIMO channel equalization device for processing the combined received signal and the overall channel response using a block-Fourier transform based algorithm to produce a spread data vector; and a despreading device for despreading the spread data vector to recover data of the received signals.

In accordance with a sixth aspect of the present invention, there is provided a method for transferring data in a wireless spread spectrum communication system, the method comprising: providing a plurality of transmitting antennas; encoding data to produce a plurality of data streams for each of the plurality of codes; spreading the plurality of data streams with the plurality of spreading codes; for each transmitting antenna, combining one of the spread data streams of each code together to produce a spread data vector; each transmitting antenna transmitting its spread data vector; receiving the transmitted spread data vectors by each of a plurality of receiving antennas as a received version; and recovering the data using the received versions.

In accordance with a seventh aspect of the present invention, there is provided a method for transferring data in a wireless communication system, the

method comprising: providing a plurality of transmitting antennas; encoding data to produce a plurality of data streams; for each transmitting antenna, using the data streams to produce a vector for transmission; transmitting each transmission vector by its transmitting antenna through a wireless air interface experiencing multipath; receiving multipath components from each transmitted transmission vector by a plurality of receiving antennas; equalizing the received multipath components to recover the transmission vectors; and recovering data from the recovered transmission vectors.

BRIEF DESCRIPTION OF THE DRAWING(S)

Figure 1 is an illustration of a transmitter and a receiver using multiple antennas.

Figure 2 is a simplified block diagram of a preferred MIMO transmitter and receiver.

Figure 3A is an embodiment of a MIMO channel equalization device.

Figure 3B is a flow chart of a MIMO channel equalization embodiment.

Figure 4A is an alternate embodiment of a MIMO channel equalization device.

Figure 4B is a flow chart of a MIMO channel equalization alternate embodiment.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT(S)

Figure 2 is a simplified block diagram of a multiple input multiple output (MIMO) transmitter and receiver system. The transmitter 20 can be used in a user equipment, a base station or both and the receiver 22 may be used in a base station, a user equipment or both. The MIMO system preferably uses a code division multiple access (CDMA) air interface as shown in Figure 2, such as a frequency division duplex (FDD)/CDMA, time division duplex (TDD)/CDMA or time division synchronous code division multiple access (TD-SCDMA) air interface, although other air interfaces may be used.

[0020] A data vector $\underline{d}$ is to be transmitted through the wireless air interface by the transmitter 20. The transmitter 20 has M antennas 34₁ to 34_M (34) in the antenna array. If transmission spatial diversity is not used, M is one, (a single antenna). The antennas 34 are spatially separated so that a low correlation between their received signals is obtained. For use at a base station transmitter having an angle spread in the range of 1 to 10 degrees, the antenna separation is preferably several wavelengths, such as four wavelengths. For use at a UE receiver, since the angle spread tends to be large, a smaller separation may be used, such as half a wavelength. Based on the implementation, the spatial separations may have other values.

[0021] For a preferred implementation of transferring a multicode transmission as illustrated in Figure 2, the data vector $\underline{d}$ to be transmitted by the M antennas 34 is encoded by a multicode vector encoder 26. For each of the Q spreading codes C_1 to C_Q , the data is split into M separate data streams $d_{1,1}$ to $d_{M,Q}$ prior to spreading. The total number of produced data streams is $M \cdot Q$. To illustrate for C_1 , data streams $d_{1,1}$ to $d_{M,1}$ are produced. Each of the M streams is associated with an antenna 34.

[0022] For each code, the data streams are spread by their code using a corresponding spreading device 28₁ to 28_Q (28), such as a mixer. The spread data streams associated with the same antenna 34 are input into a combiner 30₁ to 30_M (30), such as an adder, associated with that antenna 34 of the M antennas 34, producing M spread data vectors, $\underline{s}_1$ to $\underline{s}_M$. Each combined spread data vector, $\underline{s}_1$ to $\underline{s}_M$, is modulated to radio frequency by a modulator 32₁ to 32_M (32) and radiated by its associated antenna 34 through the wireless air interface 24.

[0023] The preferred multicode receiver implementation as shown in Figure 2 is for use when all of the multicode transmissions experience the same channel response with respect to a transmission and reception antenna pair. This typically occurs in the downlink. Alternately in the uplink, the receiver 22 of Figure 2 can be used to process a single user's transmissions, when multiple users are transmitting. The other user transmissions are treated as noise.

[0024] At the receiver 22, each transmission antenna's radiated signal is received by each of the N reception antennas 36₁ to 36_N, as a combined received signal. If reception spatial diversity is not used, N is one, (a single antenna). N is preferably equal to or greater than M . Each received antenna's signal is demodulated to baseband by a demodulator 38₁ to 38_N (38). Each demodulated signal is sampled, such as at the chip rate or a multiple of the chip rate, by a sampling device 40₁ to 40_N (40), to produce a received vector for each antenna 36, r_1 to r_N . The combined received vector r comprises r_1 to r_N .

[0025] The combined received vector r is input into a MIMO channel equalization device 44. A training sequence signal r' is input into a channel estimation device 42. The channel estimation device 42 estimates the channel response for each reception and transmission antenna combination. For an i^{th} receiving antenna 36 and a j^{th} transmitting antenna 34, the channel response as a k^{th} instant in time is $h_{i,j}(k)$. The overall channel response for all antenna combinations at the k^{th} instant of time is per Equation 1A.

$$H(k) = \begin{bmatrix} h_{1,1}(k) & \cdots & h_{1,M}(k) \\ \vdots & \vdots & \vdots \\ h_{N,1}(k) & \cdots & h_{N,M}(k) \end{bmatrix}$$

Equation 1A

[0026] The overall channel response is per Equation 1B.

$$H = \begin{bmatrix} H(0) & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ H(1) & H(0) & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ H(2) & H(1) & H(0) & 0 & 0 & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ H(L-1) & H(L-2) & H(L-3) & \cdots & \cdots & H(0) & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & 0 & H(L-1) & \cdots & \cdots & \cdots & H(0) \\ 0 & 0 & 0 & \cdots & 0 & H(L-1) & \cdots & \cdots & H(1) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & H(L-1) \end{bmatrix}$$

Equation 1B

[0027] The overall channel response H is passed to the MIMO channel equalization device 44. The MIMO channel equalization device 44 uses the channel response matrix H and equalizes the received vector $\underline{r}$ to compensate for the channel distortion experienced through the wireless air interface 24, producing a spread data vector $\underline{s}$. The spread data vector $\underline{s}$ is reordered by a spread vector reordering device 46 so that each transmitting antenna's spread data vector $\underline{s}_1$ to $\underline{s}_M$ is recovered. Each transmitting antenna's spread data vector $\underline{s}_1$ to $\underline{s}_M$ is despread by a despreading device 48 using the spreading codes, C_1 to C_Q , to estimate data for each of the M encoded data streams for each antenna, $\underline{d}_{1,1}$ to $\underline{d}_{M,Q}$. A despread data stream decoder 50 combines the data streams $\underline{d}_{1,1}$ to $\underline{d}_{M,Q}$ to recover the original data vector $\underline{d}$.

[0028] Each communication transferred by a particular transmission/reception antenna combination experiences a different multi-path environment than the other transmission/reception antenna combinations, due to the spatial diversity. By processing the received multi-path components of all of the reception antennas 36₁ to 36_N, the capacity and maximum data rate of the system is significantly increased.

[0029] Figure 3A is an embodiment of a MIMO channel equalization device 44 and Figure 3B is a flow chart of a MIMO channel equalization embodiment. Other embodiments for a MIMO channel equalization device, such as Cholesky or approximate Cholesky decomposition, can also be used. The received samples of the channel impulse responses for each antenna pair are per Equation 2.

$$h_{ij}(k), \text{ where } k = 0, \dots, L-1$$

Equation 2

[0030] i is the i^{th} receiving antenna. j is the j^{th} transmitting antenna. k is the k^{th} sample of the impulse response of length L . The channel impulse response of all reception and transmission antenna pairings for the k^{th} sample is per Equation 3.

$$H(k) = \begin{bmatrix} h_{1,1}(k) & \cdots & h_{1,M}(k) \\ \vdots & \vdots & \vdots \\ h_{N,1}(k) & \cdots & h_{N,M}(k) \end{bmatrix}$$

Equation 3

[0031] The transmitted spread data vector $\underline{s}$ has $N_s \cdot M$ dimension vectors $s(k)$. N_s is the number of transmitted data symbols. The overall received vector $\underline{r}$ has $N_s + L - 2$ received vectors of dimension N and is per Equation 4.

$$\begin{bmatrix} \underline{r}(0) \\ \underline{r}(1) \\ \underline{r}(2) \\ \vdots \\ \underline{r}(N_s + L - 2) \end{bmatrix} = \begin{bmatrix} H(0) & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ H(1) & H(0) & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ H(2) & H(1) & H(0) & 0 & 0 & 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ H(L-1) & H(L-2) & H(L-3) & \cdots & \cdots & H(0) & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & 0 & H(L-1) & \cdots & \cdots & \cdots & H(0) \\ 0 & 0 & 0 & \cdots & 0 & H(L-1) & \cdots & \cdots & H(1) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & H(L-1) \end{bmatrix} \begin{bmatrix} \underline{s}(0) \\ \underline{s}(1) \\ \underline{s}(2) \\ \vdots \\ \underline{s}(L-1) \\ \vdots \\ \underline{s}(N_s - 1) \end{bmatrix} + \underline{w}$$

Equation 4

[0032] $\underline{w}$ is the noise vector. Alternately, Equation 4 can be written as Equation 5.

$$\underline{r} = H\underline{s} + \underline{w}$$

Equation 5

The $\underline{r}$ and $\underline{w}$ vectors have a length of $(N_s + L - 1) \cdot N$. The $\underline{s}$ vector has a length of $N_s M$ and H is a $(N_s + L - 1) \cdot N$ by $N_s \cdot M$ matrix.

[0033] As shown in Equation 4, the H matrix is approximately block circulant. To make the H matrix more block circulant, $L-1$ block columns are added to the H matrix, to produce an extended H matrix, and a corresponding number of zeros added to the $\underline{s}$ vector, to produce an extended $\underline{s}$ vector. The $L-1$ column blocks are added in accordance with the H matrix's block circulant structure. After the extending of the H matrix and the $\underline{s}$ vector, the extended H

matrix has a dimension of $(N_s + L - 1) \cdot N$ by $(N_s + L - 1) \cdot M$ and $\underline{g}$ has a length of $(N_s + L - 1) \cdot M$.

[0034] For shorthand, $N_s + L - 1$ is represented by D , so that $D = N_s + L - 1$. The extended H matrix of size DN by DM with blocks of size N by M is decomposed per Equation 6.

$$H_{(N,M)} = F_{(N)}^{-1} \Lambda_{(N,M)} F_{(M)}$$

Equation 6

$F_{(N)}$ is a block Fourier transform with a block size of N by N and $F_{(M)}$ is a block Fourier transform with a block size of M by M . $F_{(N)}$ is per Equation 7.

$$F_{(N)} = F \otimes I_N$$

Equation 7

$\otimes$ is the Kronecker product operation and I_N is an N by N identity matrix.

[0035] $F_{(M)}$ is per Equation 8.

$$F_{(M)} = F \otimes I_M$$

Equation 8

I_M is an M by M identity matrix.

[0036] The block-diagonal matrix $\Lambda_{(N,M)}$ is, preferably, a block-Fourier transform of the first block-column of H , although another column may be used, (after being permuted), step 84. A block-Fourier transform device 62 produces $\Lambda_{(N,M)}$ by taking a block-transform of a column of H . $\Lambda_{(N,M)}$ is preferably derived from Equation 9.

$$\text{diag}_{(N,M)}(\Lambda_{(N,M)}) = F_{(N)} H_{(N,M)}(:, 1:M)$$

Equation 9

$\text{diag}_{(N,M)}(\Lambda_{(N,M)})$ is the block diagonal of $\Lambda_{(N,M)}$. $(:, 1:M)$ represents the first block column of width M . By using a single block column of H to derive $\Lambda_{(N,M)}$, the H matrix is approximated as being a block circulant matrix.

[0037] By substituting Equation 6 into Equation 2, Equation 10 results.

$$\Lambda_{(N,M)} F_{(M)} \underline{s} = F_{(N)} \underline{r}$$

Equation 10

[0038] To solve for $\underline{s}$, initially, a vector $\underline{x}$ is determined per Equation 11, step 86.

$$\underline{x} = F_{(N)} \underline{r}$$

Equation 11

$\underline{x}$ is preferably determined by an N non-block discrete Fourier transform of length D . A block-Fourier transform device 64 produces $\underline{x}$ by taking the block-transform of $\underline{r}$.

[0039] Subsequently, a vector $\underline{y}$ is determined per Equation 12, step 88.

$$\Lambda_{(N,M)} \underline{y} = \underline{x}$$

Equation 12

A $\underline{y}$ determining device 66 produces $\underline{y}$.

[0040] Since $\Lambda_{(N,M)}$ is a block diagonal matrix, $\underline{y}$ is preferably determined on a block-by-block basis by solving D systems of equations of smaller size, such as per Equation 13.

$$\Lambda_{(N,M)}^i \underline{y}_i = \underline{x}_i \quad i = 1, \dots, D$$

Equation 13

$\Lambda_{(N,M)}^i$ is the i^{th} block of $\Lambda_{(N,M)}$. $\underline{y}_i$ is the i^{th} M by 1 sub-vector of $\underline{y}$. $\underline{x}_i$ is the i^{th} N by 1 sub-vector of $\underline{x}$.

[0041] Since $\Lambda_{(N,M)}^i$ is unstructured, one approach to solve Equation 13 is to use Cholesky decomposition of Equation 14 and forward and backward substitution, although other approaches may be used.

$$(\Lambda_{(N,M)}^i)^H \Lambda_{(N,M)}^i$$

Equation 14

[0042] If the number of receiving antennas N is equal to the number of transmitting antennas, $\Lambda_{(N,M)}^i$ is a square matrix and $\underline{y}$ can be determined by

inverting $\Lambda_{(N,M)}^i$. For small values of N , a matrix inversion may be more efficient than performing a Cholesky decomposition.

[0043] The $\underline{s}$ vector is determined per Equation 15, step 90.

$$\underline{s} = F_{(M)}^{-1} \underline{y}$$

Equation 15

A block inverse Fourier transform device 68 is used to produce $\underline{s}$. One approach to determining $\underline{s}$ using Equation 15 is by performing M non-block inverse discrete Fourier transforms of dimension D , although other approaches may be used.

[0044] Figure 4A is an alternate embodiment of a MIMO channel equalization device 44B and Figure 4B is a flow chart of the MIMO channel equalization alternate embodiment. To determine $\underline{s}$, both sides of Equation 2 are multiplied by H^H , per Equation 16.

$$H^H \underline{r} = R \underline{s} + H^H \underline{w} = R \underline{s} + \underline{n}$$

Equation 16

$(\cdot)^H$ is the conjugate transpose operation. $\underline{n}$ is the equalized noise vector. R is the channel cross correlation matrix and is determined by an R determination device 70 using the H matrix, step 92. R for a zero forcing solution is per Equation 17.

$$R = H^H H$$

Equation 17

[0045] For a minimum mean square errors (MMSE) solution, R is per Equation 18.

$$R = H^H H + \sigma^2 I$$

Equation 18

σ^2 is the variance of the noise vector $\underline{w}$ and I is an identity matrix.

[0046] The channel cross correlation matrix R has a structure per Equation 19.

$$R = \begin{bmatrix} R_0 & R_1 & R_2 & R_3 & \cdots & R_{L-1} & 0 & 0 & 0 & 0 & 0 & 0 \\ R_1^H & R_0 & R_1 & R_2 & R_3 & \cdots & R_{L-1} & 0 & 0 & 0 & 0 & 0 \\ R_2^H & R_1^H & R_0 & R_1 & R_2 & R_3 & \cdots & R_{L-1} & 0 & 0 & 0 & 0 \\ R_3^H & R_2^H & R_1^H & R_0 & R_1 & R_2 & R_3 & \cdots & R_{L-1} & 0 & 0 & 0 \\ \vdots & R_3^H & R_2^H & R_1^H & R_0 & R_1 & R_2 & R_3 & \cdots & R_{L-1} & 0 & 0 \\ R_{L-1}^H & \vdots & R_3^H & R_2^H & R_1^H & R_0 & R_1 & R_2 & R_3 & \cdots & R_{L-1} & 0 \\ 0 & R_{L-1}^H & \vdots & R_3^H & R_2^H & R_1^H & R_0 & R_1 & R_2 & R_3 & \cdots & R_{L-1} \\ 0 & 0 & R_{L-1}^H & \vdots & R_3^H & R_2^H & R_1^H & R_0 & R_1 & R_2 & R_3 & \cdots \\ 0 & 0 & 0 & R_{L-1}^H & \vdots & R_3^H & R_2^H & R_1^H & R_0 & R_1 & R_2 & R_3 \\ 0 & 0 & 0 & 0 & R_{L-1}^H & \vdots & R_3^H & R_2^H & R_1^H & R_0 & R_1 & R_2 \\ 0 & 0 & 0 & 0 & 0 & R_{L-1}^H & \vdots & R_3^H & R_2^H & R_1^H & R_0 & R_1 \\ 0 & 0 & 0 & 0 & 0 & 0 & R_{L-1}^H & \vdots & R_3^H & R_2^H & R_1^H & R_0 \end{bmatrix}$$

Equation 19

[0047] After the adding of $L-1$ columns to the H matrix as previously described, a close to block circulant approximation of the R matrix can be derived, referred to as the extended R matrix. The dimensions of the extended R matrix are DM by DM .

[0048] Using the extended R matrix, Equation 20 is used to determine $\underline{s}$.

$$H^H \underline{r} = R \underline{s}$$

Equation 20

[0049] By approximating R and H^H as block circulant matrices, R is decomposed per Equation 21.

$$R = F_{(M)}^{-1} \Lambda_{(M,M)}^R F_{(M)}$$

Equation 21

$\Lambda_{(M,M)}^R$ is preferably derived from a first block column of R per Equation 22, although another column may be used, (after being permuted), step 94.

$$\text{diag}_{(M,M)}(\Lambda_{(M,M)}^R) = F_{(M)} R_{(M,M)}(:, 1:M)$$

Equation 22

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$\text{diag}_{(M,M)}(\Lambda_{(M,M)}^R)$ is the block diagonal of $\Lambda_{(M,M)}^R$. A block-Fourier transform device 72 is used to determine $\Lambda_{(M,M)}^R$ by taking a block-Fourier transform of a block column of R .

[0050] H^H is decomposed per Equation 23.

$$H^H = F_{(M)}^{-1} \Lambda_{(M,N)}^H F_{(N)}$$

Equation 23

[0051] $\Lambda_{(M,N)}^H$ is preferably determined using the first block column of H^H per Equation 24, although another block column may be used, (after being permuted), step 96.

$$\text{diag}_{(M,N)}(\Lambda_{(M,N)}^H) = F_{(M)} H_{(M,N)}^H(:, 1:N)$$

Equation 24

$\text{diag}_{(M,N)}(\Lambda_{(M,N)}^H)$ is the block diagonal of $\Lambda_{(M,N)}^H$.

[0052] A block-Fourier transform device 74 is used to determine $\Lambda_{(M,N)}^H$ by taking a block-Fourier transform of a block-column of H^H .

[0053] By substituting 21 and 23 into 20, Equation 25 results.

$$\Lambda_{(M,N)}^H F_{(N)} \underline{r} = \Lambda_{(M,M)}^R F_{(M)} \underline{s}$$

Equation 25

[0054] Solving for $\underline{s}$, Equation 26 results.

$$\underline{s} = F_{(M)}^{-1} (\Lambda_{(M,M)}^R)^{-1} \Lambda_{(M,N)}^H F_{(N)} \underline{r}$$

Equation 26

[0055] Determining $\underline{s}$ is preferably performed in a four step process. Initially, $\underline{x}$ is determined per Equation 27, step 98.

$$\underline{x} = F_{(N)} \underline{r}$$

Equation 27

The block-Fourier transform is preferably performed by an N non-block Fourier transform of length D . A block-Fourier transform device 76 takes a block-Fourier transform of $\underline{r}$ to determine $\underline{x}$.

[0056] In a second step, $\underline{y}$ is determined per Equation 28, step 100.

$$\underline{y} = \Lambda_{(M,N)}^H \underline{x}$$

Equation 28

A $\underline{y}$ determining device 78 uses $\Lambda_{(M,N)}^H$ and $\underline{x}$ to determine $\underline{y}$.

[0057] In a third step, $\underline{z}$ is determined per Equation 29, step 102.

$$\Lambda_{(M,M)}^R \underline{z} = \underline{y}$$

Equation 29

A $\underline{z}$ determining device 80 determines $\underline{z}$ using $\Lambda_{(M,M)}^R$ and $\underline{y}$.

[0058] Preferably, since $\Lambda_{(M,M)}^R$ is a block diagonal matrix, Equation 29 is solved using D systems of smaller size per Equation 30.

$$(\Lambda_{(M,M)}^R)^i \underline{z}_i = \underline{y}_i \quad i = 1, \dots, D$$

Equation 30

[0059] $(\Lambda_{(M,M)}^R)^i$ is the i^{th} block of $\Lambda_{(M,M)}^R$. $\underline{z}_i$ is the i^{th} M by 1 sub-vector of $\underline{z}$. $\underline{y}_i$ is the i^{th} M by 1 sub-vector of $\underline{y}$.

[0060] Since $(\Lambda_{(M,M)}^R)^i$ is unstructured, one approach to determine $(\Lambda_{(M,M)}^R)^i$ is to use Cholesky decomposition of $((\Lambda_{(M,M)}^R)^i)^H (\Lambda_{(M,M)}^R)^i$ and forward and backward substitution, although other approaches may be used.

[0061] In the fourth step, $\underline{s}$ is determined per Equation 31 by performing an M non-block inverse discrete Fourier transform of dimension D , step 104.

$$\underline{s} = F_{(M)}^{-1} \underline{z}$$

Equation 31

A block-inverse Fourier transform device 82 is used to take an inverse block transform of $\underline{z}$ to produce $\underline{s}$.

[0062] To recover data from the estimated spread data vector $\underline{s}$ using either embodiment, the spread data vector $\underline{s}$ is separated into its M transmitted data streams, $\underline{s}_m$ where $m = 1, \dots, M$, by the spread vector reordering device. The

spread data vector $\underline{s}$ is the result of concatenating the data stream vectors $\underline{s}_m$ and reordering by grouping the same chip intervals together, as per Equation 32.

$$\underline{s} = \begin{bmatrix} s_{1,1} \\ \vdots \\ s_{M,1} \\ \vdots \\ s_{1,N_c} \\ \vdots \\ s_{M,N_c} \end{bmatrix}$$

Equation 32

$s_{m,j}$ demotes the j^{th} chip interval of the m^{th} data stream.

[0063] To recover each spread data vector stream $\underline{s}_m$, the chips of the estimated spread data vector $\underline{s}$ are reordered per Equation 33, producing $\underline{s}_{REORDERED}$.

$$\underline{s}_{REORDERED} = \begin{bmatrix} s_{1,1} \\ \vdots \\ s_{1,N_c} \\ \vdots \\ s_{M,1} \\ \vdots \\ s_{M,N_c} \end{bmatrix} = \begin{bmatrix} \underline{s}_1 \\ \vdots \\ \underline{s}_M \end{bmatrix}$$

Equation 33

[0064] Each of these data stream spread data vectors $\underline{s}_m$ is despread by the corresponding spreading codes, C_1 to C_Q , to estimate the symbols of that data stream by the despreading device 48. The estimated symbols for each data stream are decoded by the despread data stream decoder 50 to recover the original data $\underline{d}$.

* * *

CLAIMS

What is claimed is:

1. A method for recovering data transmitted from a plurality of transmitting antennas and received by a plurality of receiving antennas, the method comprising:

receiving a signal at each of the receiving antennas;

sampling each received antenna signal to produce a combined received signal;

estimating a overall channel response comprising a channel response for each transmitting and receiving antenna combination;

processing a block-column of the overall channel response to produce a diagonal matrix;

processing the combined received signal to effectively take a block-Fourier transform of the combined received signal;

using the diagonal matrix and the effective block-Fourier transform of the combined received signal to produce a Fourier transform of a spread data vector;

processing the Fourier transform of the spread data vector to produce the spread data vector; and

despreading the spread data vector to recover the transmitted data.

2. The method of claim 1 wherein the processing of the block-column of the overall channel response matrix comprises taking a block-Fourier transform of the block-column.

3. The method of claim 1 wherein the processing the combined received signal comprises taking a plurality of non-block discrete Fourier transforms.

4. The method of claim 1 wherein the using the diagonal matrix and the effective block-Fourier transform of the combined received signal uses Cholesky decomposition.

5. The method of claim 1 wherein the using the diagonal matrix and the effective block Fourier transform of the combined received signal uses a matrix inversion of blocks of the diagonal matrix.

6. The method of claim 1 wherein the processing of the Fourier transform of the spread data vector comprises taking a block inverse Fourier transform of the Fourier transform of the spread data vector.

7. A method for recovering data transmitted from a plurality of transmitting antennas and received by a plurality of receiving antennas, the method comprising:

receiving a signal at each of the receiving antennas;

sampling each received antenna signal to produce a combined received signal;

estimating a overall channel response comprising a channel response for each transmitting and receiving antenna combination;

producing a cross channel correlation matrix using the overall channel response;

processing a block-column of the cross channel correlation matrix to produce a cross correlation diagonal matrix;

processing a block-column of the overall channel response matrix to produce a channel response diagonal matrix;

processing the combined received signal to effectively take a block-Fourier transform of the combined received signal;

combining the channel response diagonal matrix and the effective block-Fourier transform of the combined received signal to produce a combined result;

using the cross correlation diagonal matrix and the combined result to produce a Fourier transform of a spread data vector;

processing the Fourier transform of the spread data vector to produce the spread data vector; and

despreading the spread data vector to recover the transmitted data.

8. The method of claim 7 wherein the producing the cross correlation matrix comprises multiplying the overall channel response with a conjugate transpose of the overall channel response.

9. The method of claim 7 wherein the processing the block-column of the cross channel correlation matrix comprises taking a block-Fourier transform of the cross channel correlation matrix block-column.

10. The method of claim 7 wherein the processing the combined received signal comprises taking a plurality of non-block discrete Fourier transforms.

11. The method of claim 7 wherein the processing the block-column of the overall channel response comprises taking a block-Fourier transform of the over channel response block column.

12. The method of claim 7 wherein the combining of the channel response diagonal matrix and the effective block-Fourier transform of the combined received signal is by multiplying.

13. The method of claim 7 wherein the using the cross correlation diagonal matrix and the combined result uses Cholesky decomposition.

14. The method of claim 7 wherein the processing of the Fourier transform of the spread data vector comprises taking a block inverse Fourier transform of the Fourier transform of the spread data vector.

15. A user equipment comprising:

means for receiving a signal at each of a plurality of receiving antennas, each of the received signals including signals transmitted from a plurality of antennas at a single site;

means for sampling each received antenna signal to produce a combined received signal;

means for estimating a overall channel response comprising a channel response for each transmitting and receiving antenna combination;

means for processing a block-column of the overall channel response to produce a diagonal matrix;

means for processing the combined received signal to effectively take a block-Fourier transform of the combined received signal;

means for using the diagonal matrix and the effective block-Fourier transform of the combined received signal to produce a Fourier transform of a spread data vector;

means for processing the Fourier transform of the spread data vector to produce the spread data vector; and

means for despreading the spread data vector to recover the transmitted data.

16. The user equipment of claim 15 wherein the means for processing of the block-column of the overall channel response matrix takes a block-Fourier transform of the block-column.

17. The user equipment of claim 15 wherein the means for processing the combined received signal takes a plurality of non-block discrete Fourier transforms.

18. The user equipment of claim 15 wherein the means for using the diagonal matrix and the effective block-Fourier transform of the combined received signal uses Cholesky decomposition.

19. The user equipment of claim 15 wherein the means for using the diagonal matrix and the effective block Fourier transform of the combined received signal uses a matrix inversion of blocks of the diagonal matrix.

20. The user equipment of claim 15 wherein the means for processing of the Fourier transform of the spread data vector takes a block inverse Fourier transform of the Fourier transform of the spread data vector.

21. A user equipment comprising:

means for receiving a signal at each of a plurality of receiving antennas, each of the received signals including signals transmitted from a plurality of antennas at a single site;

means for sampling each received antenna signal to produce a combined received signal;

means for estimating a overall channel response comprising a channel response for each transmitting and receiving antenna combination;

means for producing a cross channel correlation matrix using the overall channel response;

means for processing a block-column of the cross channel correlation matrix to produce a cross correlation diagonal matrix;

means for processing a block-column of the overall channel response matrix to produce a channel response diagonal matrix;

means for processing the combined received signal to effectively take a block-Fourier transform of the combined received signal;

means for combining the channel response diagonal matrix and the effective block-Fourier transform of the combined received signal to produce a combined result;

means for using the cross correlation diagonal matrix and the combined result to produce a Fourier transform of a spread data vector;

means for processing the Fourier transform of the spread data vector to produce the spread data vector; and

means for despreading the spread data vector to recover the transmitted data.

22. The user equipment of claim 21 wherein the means for producing the cross correlation matrix multiplies the overall channel response with a conjugate transpose of the overall channel response.

23. The user equipment of claim 21 wherein the means for processing the block-column of the cross channel correlation matrix takes a block-Fourier transform of the cross channel correlation matrix block-column.

24. The user equipment of claim 21 wherein the processing the means for combined received signal takes a plurality of non-block discrete Fourier transforms.

25. The user equipment of claim 21 wherein the means for processing the block-column of the overall channel response takes a block-Fourier transform of the over channel response block column.

26. The user equipment of claim 21 wherein the means for combining of the channel response diagonal matrix and the effective block-Fourier transform of the combined received signal is performed by multiplying.

27. The user equipment of claim 21 wherein the means for using the cross correlation diagonal matrix and the combined result uses Cholesky decomposition.

28. The user equipment of claim 21 wherein the means for processing of the Fourier transform of the spread data vector takes a block inverse Fourier transform of the Fourier transform of the spread data vector.

29. A user equipment comprising:

a plurality of receiving antennas for receiving signals from a plurality of transmitting antennas at a single site;

a plurality of sampling devices for sampling a received version of the received signals as received by each of the plurality of receiving antennas to produce a combined received signal;

a channel estimation device for determining a channel response for each receiving and transmitting antenna combination and producing an overall channel response;

a MIMO channel equalization device for processing the combined received signal and the overall channel response using a block-Fourier transform based algorithm to produce a spread data vector; and

a despreading device for despreading the spread data vector to recover data of the received signals.

30. The user equipment of claim 29 further comprising a spread vector reordering device for reordering the spread data vector so that chips of transmitted by each transmitting antenna are grouped together.

31. The user equipment of claim 29 further comprising a despread data stream decoder for decoding data recovered by the depreading device.

32. The user equipment of claim 29 wherein the MIMO channel equalization device comprises:

a block-Fourier transform device for processing a block-column of the overall channel response to produce a diagonal matrix;

a block Fourier transform device for processing the combined received signal to take a block-Fourier transform of the combined received signal; and

a processing device for using the diagonal matrix and the block-Fourier transform of the combined received signal to produce a Fourier transform of the spread data vector; and

an inverse block-Fourier transform device for taking an inverse block Fourier transform of the Fourier transform of the spread data vector.

33. The user equipment of claim 29 wherein the MIMO channel equalization device comprises:

- a cross channel correlation determining device for producing a cross channel correlation matrix using the overall channel response;

- a block-Fourier transform device for processing a block-column of the cross channel correlation matrix to produce a cross correlation diagonal matrix;

- a block-Fourier transform device for processing a block-column of the overall channel response matrix to produce a channel response diagonal matrix;

- a block-Fourier transform device for processing the combined received signal to take a block-Fourier transform of the combined received signal;

- a combining device for combining the channel response diagonal matrix and the block-Fourier transform of the combined received signal to produce a combined result;

- a processing device for using the cross correlation diagonal matrix and the combined result to produce a Fourier transform of the spread data vector; and

- a block-inverse Fourier transform device for processing the Fourier transform of the spread data vector to produce the spread data vector.

34. A method for transferring data in a wireless spread spectrum communication system, the method comprising:

- providing a plurality of transmitting antennas;

- encoding data to produce a plurality of data streams for each of the plurality of codes;

- spreading the plurality of data streams with the plurality of spreading codes;

- for each transmitting antenna, combining one of the spread data streams of each code together to produce a spread data vector;

- each transmitting antenna transmitting its spread data vector;

- receiving the transmitted spread data vectors by each of a plurality of receiving antennas as a received version; and

- recovering the data using the received versions.

35. The method of claim 34 wherein the recovering the data uses a fast Fourier transform based algorithm.

36. The method of claim 34 wherein the recovering the data uses a Cholesky decomposition.

37. The method of claim 34 wherein the recovering the data uses an approximate Cholesky decomposition.

38. A method for transferring data in a wireless communication system, the method comprising:

providing a plurality of transmitting antennas;

encoding data to produce a plurality of data streams;

for each transmitting antenna, using the data streams to produce a vector for transmission;

transmitting each transmission vector by its transmitting antenna through a wireless air interface experiencing multipath;

receiving multipath components from each transmitted transmission vector by a plurality of receiving antennas;

equalizing the received multipath components to recover the transmission vectors; and

recovering data from the recovered transmission vectors.