

ADVANCED RECEIVER FOR CDMA DOWNLINKField of the Invention

5 The present invention relates to cellular telecommunications systems and in particular receiving code division multiple access signals in multipath propagation environments. The invention is particularly, although not exclusively, related to mobile receivers such as mobile phones and laptop computers in CDMA systems such as the new third generation cellular communication systems.

10 Background of the Invention

Code division multiple access signals overlap in time and frequency, and are distinguished from each other by a unique spreading code such as a Walsh-Hadamard code, for example. In principle, it is possible to recover a wanted signal by multiplying a received composite signal containing the wanted signal
15 by the wanted signal's unique code. This will provide the wanted signal and other components which are easily removed. This assumes that each of the codes employed in a cell are orthogonal to the other codes used by the base station for other users in that cell. In a perfect environment where this orthogonality is maintained, it is possible to retrieve a wanted signal without
20 any interference from other signals used within the cell. The signals used in a cell have a further code superimposed on them to distinguish them from signals from other cells.

In practical environments where multi-path propagation exists, the orthogonality of received signals is seriously compromised. This results in the
25 wanted signal comprising interference components from the other signals employed in the cell, as well as signals from other cells. This is known as

multiple access interference (MAI), comprising intra-cell MAI (from signals used within the cell) and inter-cell MAI (from signals from other cells).

RAKE receivers are typically used to increase the signal-to-noise ratio of the wanted signal, however this does not specifically target MAI. RAKE receivers have a number of inputs and are arranged to multiply a number of samples of an incoming composite signal (containing the wanted signal) by the wanted signal's spreading code in order to obtain an improved wanted signal. Each input of the RAKE receiver may be coupled to a separate antenna element such that the copies of the wanted signal received by each antenna element are correlated with the received composite signal on other antenna elements, but noise received by different antenna elements are not correlated and hence some spatial diversity can be applied to the system. Alternatively, or additionally, the inputs to the RAKE receiver may be time delayed to compensate for operating a communication system in a multi-path environment in which copies of the wanted signal arrive at the receiver at different times. The outputs of the RAKE receiver are coherently combined to produce a higher strength wanted signal. Examples of RAKE receivers are shown in US Patent Nos. 5,305,349 and 6,026,115. By increasing the signal to noise ratio of the received wanted signal, bit error rate is to some extent mitigated, however the existence of MAI is still a significant degrading factor in these types of CDMA receivers.

Various intra-cell MAI suppression methods have been proposed in the literature, however these methods only suppress part of the MAI; in particular they do not target inter-cell MAI. Examples of these MAI suppression methods which are largely based on adaptive equalisation are described in: Markku J. Heikkila, "Interference Suppression in CDMA Downlink through adaptive channel equalisation", IEEE Vehicular Technology Conference, 1999; Stefan Werner, Jorma Lilleberg, "Downlink channel decorrelation in CDMA systems with long codes", IEEE Vehicular Technology Conference,

1999; Irfan Ghauri, Dirk T.M. Slock, "Linear Receivers for the DS-CDMA Downlink Exploiting Orthogonality of Spreading Sequences", IEEE Vehicular Technology Conference, 1998; Hooli, K, Latva-aho, M and Juntti, M, "Multiple access interference Suppression with linear clip equaliser in WCDMA downlink receivers", Globecom'99; Hooli, K, Latva-aho, M and Juntti, M, "Inter-path Interference Suppression in WCDMA Systems with Low Spreading Factors", Vehicular Technology Globecom'99.

Summary of the Invention

The present invention seeks to provide an improved or at least alternative receiver and receiving method for code division multiple access signals.

In general terms the present invention proposes recovering a predetermined number of space and time aligned composite signal samples each containing signals transmitted from a single transmitter. This enables the reduction of joint intra-cell and inter-cell MAI in received signals from the transmitter of one of a number of base stations in a multipath propagation environment and in the presence of signals from the other base station transmitters. The composite signal samples are recovered by receiving a number of signal samples containing composite signals from a number of base stations and applying a mathematical operation which separates out the received composite signal components from each base station. Each of the composite signal components are spatially and temporally aligned so that it is a simple matter to retrieve a wanted signal by multiplying the composite signal component from the base station of the wanted signal by the wanted signal's code.

This has a number of advantages including reducing or eliminating both inter-cell and intra-cell MAI. The inter-cell MAI is removed by separating out the received composite signals from each base station. The intra-cell MAI is removed as the composite signals separated out are comprised of a number

of time aligned or orthogonal signals from a single base station so that despreading this composite signal results in only the wanted signal being retrieved.

5 This method can suppress inter-cell and intra-cell MAI even without soft hand over.

In one aspect the present invention provides a method of receiving a wanted CDMA signal from a combination of said signal and other CDMA signals from a plurality of base stations, the method comprising:

10 determining a number of received signal samples from a receiving antenna arrangement to define a received signal vector;

estimating multi-path fading channels between said base stations and said antenna arrangement to determine a channel matrix;

15 multiplying said received signal vector by a matrix operator which is dependent on said channel matrix in order to recover a composite signal from each said base station;

detecting the wanted signal from one of said composite signals.

20 The received signal samples are space and/or time diverse. The space diverse samples are received from M different antennas of said antenna arrangement, where $M > N$, and N is the number of transmitters. The sampling rate is 1 chip.

In one alternative, $M = N + 1$. However the greater the number M of antenna elements, the better the recovery performance.

An alternative, or addition, to multiple spaced apart antenna elements is to use a single or reduced number of antenna elements and to sample at a

higher rate. In order to replace M antennas with 1 antenna, the time diverse samples are taken every $t = (\text{chip duration})/M$.

An advantage of this alternative is that it requires less antenna elements and hence uses a smaller volume of a mobile terminal for the antenna arrangement. This is particularly important for handheld terminals in which
5 miniaturisation is an important technical and commercial consideration.

Estimating the channel matrix is done using estimators in known manner, where the amplitude and phase transfer function between a transmitting antenna and a receiving antenna is estimated using known pilot tones.

10 Detecting the wanted signal is achieved by multiplying this signal by its unique code, for example a Walsh-Hadamard code. This process is well known in the art and is known inter alia as despreading.

Preferably, the matrix operator is the matrix conjugate transpose of the channel matrix multiplied by the inverse of the product of the channel matrix
15 multiplied by the matrix conjugate transpose of the channel matrix.

In order to reduce the processing power required by the terminal, the matrix operator is preferably calculated iteratively.

In a second aspect, the present invention provides a receiver for receiving a wanted CDMA signal from a combination of said signal and other CDMA
20 signals from a plurality of base stations, the receiver comprising:

means for determining a number of received signal samples from a receiving antenna arrangement to define a received signal vector;

means for estimating multi-path fading channels between said base stations and said antenna arrangement to determine a channel matrix;

means for multiplying said received signal vector by a matrix operator which is dependent on said channel matrix in order to recover a composite signal from each said base station;

5 means for detecting the wanted signal from one of said composite signals.

Brief Description of the Drawings

The present invention is described with reference to the following drawings, by way of example only and without intending to be limiting, in which:

10 Figure 1 illustrates schematically a mobile communications system operating in a multi-path propagation environment;

Figure 2 shows schematically a prior art receiver architecture incorporating a RAKE receiver;

Figure 3 shows schematically a prior art receiver architecture using adaptive equalisation;

15 Figure 4 shows a cellular WCDMA system having multiple base stations;

Figure 5a shows a cellular WCDMA system according to the present invention;

Figure 5b shows a receiver architecture according to the present invention;

20 Figure 6 shows a graph of BER versus E_b/N_0 for the receiver architecture of Figure 5b compared with that of Figure 2.

Detailed Description

Figure 1 shows a base station 1 and a mobile terminal 7 in a multipath propagation environment. Multipath effects are particularly prevalent in city centres and similar locations where the terminal 7 is surrounded by signal scattering objects such as buildings and vehicles. Such scattering objects are referenced "X" in figure 1. The characteristics of these paths will change over time as the terminal 7 and objects around the terminal move about. This "fading" is countered to some extent by employing two or more antennas at one or both of the base station 1 and terminal 7. This provides at least spatial diversity, and may also be used for advanced wireless communications techniques such as space time coding.

Two signal propagation paths P_{11a} and P_{11b} are shown between transmitting antenna T1 of the base station 1 and receiving antenna R1 of the terminal 7. In practice there may be many more paths between any pair of transmitting and receiving antennas. It can be seen that path P_{11a} is shorter than P_{11b} so that two copies displaced in time of a wanted signal from transmitting antenna T1 will be received by receiving antenna R1. P_{12a} indicates a path between transmitting antenna T1 of the base station 1 and receiving antenna R2 of the terminal 7. The second antenna R2 of the terminal provides receiver spatial diversity which further increases the received signal power of a wanted signal. However some mechanism is required for coherently combining these time displaced wanted signal copies.

Figure 2 shows a prior art wireless communications system in which the receiving terminal 7 utilises a RAKE receiver 8. As previously described, in a CDMA system each data or voice channel in a cell is multiplexed with a higher frequency code, each code used in a cell being orthogonal to the others. In the terminal 7 the RAKE receiver 8 comprises a number of Rake fingers each having a multiplier 9 which multiplies the incoming composite signals received

from R1 and R2 by the unique code of the wanted channel associated with that terminal 7. Each of the Rake fingers also has a delay element 10, each introducing a different amount of delay prior to the code multiplying function 9. The delays are set to try to match the delays between the various incoming
5 copies of the wanted signal, which are displaced in time due to the multipath nature of the propagation environment. The outputs from each Rake finger are then coherently combined (11), taking account of their delays, to generate the wanted signal.

Because a number of copies or samples of the wanted signal have been used
10 in generating the final signal, the signal to noise ratio of this final signal is higher than would otherwise be the case. However because of the multipath environment, chip alignment between copies of the wanted signal and some copies of other signals from the base station will not be maintained. This will result in components of other channels overlapping with samples of the
15 wanted signal such that there is no longer complete orthogonality between the channels. This results in intra-cell multiple access interference (MAI), which is indicated in the figures as 1c. The multipath propagation environment also results in multiple time-displaced copies of signals from other base stations, some of which overlap with the wanted signal to reduce orthogonality between
20 these signals. This results in inter-cell multiple access interference (MAI), which is indicated 1b. Inter-cell MAI is caused by different multipath propagation than inter-cell MAI and whilst the use of RAKE receivers 8 increases signal to noise ratio of the wanted signal, it does not address MAI.

Figure 3 shows another type of prior art wireless communications system
25 which uses adaptive equalisation to minimise intra-cell MAI. The system uses pilot tones 3 transmitted by the base station 1', and known by the receiving terminals 7' of the system. The terminals use a channel estimation function 6 which determines the composite channel characteristics between any pair of transmitting and receiving antennas, using the received pilot tones. The

composite channel characteristic is defined by the propagation paths between the antenna pairs, for example P_{11a} and P_{11b} between antennas T1 and R1. A channel matrix H can then be estimated, the elements H_{tr} of the matrix defining a transfer function for signals travelling between a transmitting antenna (T1) and receiving antennas (R1, R2). Once this channel matrix H has been estimated by the channel estimation function 6, its inverse H^{-1} is determined. This function (H^{-1}) is implemented using an equaliser 12 such that received samples (r_1, r_2) of incoming signals sampled by the receiving antennas R1 and R2 are multiplied by the inverse channel matrix H^{-1} . This process retrieves a combined and time aligned sample (r_3) of the original signals (s) transmitted from the base station antenna T1. As the channel signals are now orthogonal it is a simple matter to extract the wanted channel (4) by multiplying the composite signal sample (r_3) by the wanted channel's unique code as shown. It can be seen therefore that intra-cell MAI (1c) can be substantially reduced. However inter-cell MAI (1b) remains, and this can account for 1/3 of all MAI and is therefore a significant source of interference and hence performance degradation in such systems.

A schematic representation of a cellular CDMA system downlink is shown in figure 4. It can be seen that in this case, signals (s) from 3 base stations 20 may be received strongly by the terminal 27. Signals from more distant base stations (not shown) may also be received by the terminal 27. The inter-cell signals (s_2-s_N) contribute to MAI, and are not addressed adequately by known systems.

A schematic representation of a cellular CDMA system according to the present invention is shown in figure 5a. A preferred embodiment receiver according to the present invention is shown in figure 5b. Signals ($s_1 - s_N$) from a number of base stations or transmitters ($20_1 - 20_N$) are received by the terminal 27. Signals (s) from each base station are coded with a pseudo-random code unique to each base station. Typically the number of base

stations which strongly effect a receiver is small, normally 2-3 other base stations. If a base station is too far from a receiver, its signal will be too weak to contribute significantly to MAI.

5 The terminal 27 comprises a number (M) of antenna elements, and a signal processing function which incorporates a number (N) of channel estimation functions 26, one for each base station ($20_1 - 20_N$), and a matrix calculation function 25. The terminal 27 also comprises a descrambler or despreader for obtaining a wanted signal.

10 The antenna elements (R_1-R_M) are spatially separated to obtain spatially diverse samples (r_1-r_M) of the incoming combined signal ($s_1+s_2+...+s_N$). The sampling rate is 1 chip, or every symbol in the spreading code. The antennas elements should be separated by more than or equal to half a wavelength of the carrier. The number of antenna elements is at least $N+1$ where N is the number of transmitters 20 that will strongly influence MAI. In a typical cellular system therefore, the number of antennas will be 4.

Alternatively a single antenna (R) could be used in which different samples are taken at different times. Where time diverse samples are used instead of spaced apart multiple antenna element samples, the sampling rate is (1 chip)/M; where M is the number of antenna elements that would otherwise be required. A combination of spatially and time diverse samples could also be used.

25 The channel estimation functions 26 are used to create a channel matrix H' , each element H'_{mn} representing the composite channel characteristic between any one base station transmission antenna (T_1-T_M) and any one receiving antenna (R_1-R_M). Channel estimators are well known and any suitable type may be used.

The signal received by the m th antenna element (R_m) in the desired user's receiver can be represented as follows:

$$r_m = \sum_{n=1}^N H_{mn} S_n \quad (1)$$

- 5 where s_n is the composite signal from each base station ($20n$). The total signals received by M antennas in desired user's receiver can be represented as

$$\mathbf{r} = \begin{bmatrix} r_1 \\ \vdots \\ r_M \end{bmatrix} = \begin{bmatrix} H_{11} \cdots H_{1N} \\ \vdots \\ H_{M1} \cdots H_{MN} \end{bmatrix} \begin{bmatrix} S_1 \\ \vdots \\ S_N \end{bmatrix} \quad (2)$$

10

- The transmitted signal for the desired user is in one of the composite base station signals $S_1, S_2, \dots, S_N$. Without loss of generality, assume the wanted signal is in S_1 . Namely, $S_2, \dots, S_N$ are the inter-cell MAI for the desired user, the other parts except the wanted signal in composite signal in S_1 is intra-cell MAI for the desired user.
- 15

The procedure of this embodiment MAI suppression method is as follows:

1. Organize the received signals from all antennas as $\mathbf{r}$ shown in Eqn (2).
2. Estimate H_{11} to H_{MN} , respectively, using the pilot signals from different base stations (cells).
- 20 3. For the organized signals for the desired user shown in Eqn (2), construct a matrix

$$\mathbf{H}^+ = \left(\begin{bmatrix} H_{11} \cdots H_{1N} \\ \vdots \\ H_{M1} \cdots H_{MN} \end{bmatrix}^h \begin{bmatrix} H_{11} \cdots H_{1N} \\ \vdots \\ H_{M1} \cdots H_{MN} \end{bmatrix} \right)^{-1} \begin{bmatrix} H_{11} \cdots H_{1N} \\ \vdots \\ H_{M1} \cdots H_{MN} \end{bmatrix}^h \quad (3)$$

where $(\)^h$ denotes matrix conjugate transpose, $(\)^{-1}$ denotes matrix inverse.

4. Right-multiply $\mathbf{H}^+$ with the received signals $\mathbf{r}$ shown in Eqn (2) to recover
5 the separated composite signals $S_1, S_2, \dots, S_N$

$$\begin{bmatrix} S_1 \\ \vdots \\ S_N \end{bmatrix} = \left(\begin{bmatrix} H_{11} & \cdots & H_{1N} \\ \vdots & & \vdots \\ H_{M1} & \cdots & H_{MN} \end{bmatrix}^h \begin{bmatrix} H_{11} & \cdots & H_{1N} \\ \vdots & & \vdots \\ H_{M1} & \cdots & H_{MN} \end{bmatrix} \right)^{-1} \begin{bmatrix} H_{11} & \cdots & H_{1N} \\ \vdots & & \vdots \\ H_{M1} & \cdots & H_{MN} \end{bmatrix}^h \mathbf{r} = \mathbf{H}^+ \mathbf{r} \quad (4)$$

Ignore $S_2, \dots, S_N$ and extract S_1 . So far, the inter-cell MAI has been cancelled completely.

- 10 5. Descramble and despread S_1 directly. Since all the signals in S_1 are orthogonal to each other, intra-cell MAI has been cancelled during the descrambling and despreading.

- The sample signals $(r_1 - r_M)$ received by the terminal antennas $(R_1 - R_M)$ are
15 right multiplied by the channel matrix operator $\mathbf{H}^+$ to recover the separated and time and space aligned composite signals $(s_1 - s_N)$ from each of the base stations or transmitters 20. By correcting for the composite channel characteristics or fading H_{mn} between each base station and the terminal receiving antennas (R) , the signals from the base stations are time aligned so
20 that their codes remain orthogonal.

Because all the signals (s1) from the wanted base station (20₁) are orthogonal, this composite signal (s1) is then simply multiplied by the wanted signal code to retrieve the wanted signal. Thus both inter-cell and intra-cell MAI have been removed from the wanted signal.

- 5 The channel estimation 26 and matrix computation 25 functions may be implemented in hardware, for example an ASIC, or in software performed by a processor on-board the terminal.

Preferably the matrix operations are implemented using iterative algorithms to reduce complexity. A preferred iterative computation for the pseudo-inverse
10 channel matrix H^+ is as follows:

Let $H_n = [H_{n-1} \ h_n]$ be an $M \times n$ matrix, where $M \geq n$, H_{n-1} is the matrix including the first $n-1$ columns of H_n , h_n is the n th column of H_n and $\text{rank}(H_n) = n$.

$$H_n^+ = \begin{bmatrix} H_{n-1}^+ - H_{n-1}^+ h_n e_n^1 \Delta_n^{-1} \\ e_n^T \Delta_n^{-1} \end{bmatrix},$$

$$e_n = [I_n - H_{n-1} H_{n-1}^+] h_n,$$

$$\Delta_n^{-1} = (h_n^H e_n)^{-1},$$

- Other matrix operators could alternatively be used which, when operating on
15 the received signal sample matrix (r_1 - r_M) output composite signals (s1-s_n) from each base station or transmitter (T). That is a time and space aligned sample of the composite signal containing the wanted signal is separately derived and may then simply be multiplied by the wanted signal's code to obtain the wanted signal in the normal way. The matrix operator should be
20 "tall", that is M must be larger than N where M is the number of uncorrelated samples for one spreading data, and N is the number of transmitters.

Figure 6 shows a graph of Bit-error-rate (BER) versus signal-noise-ratio (E_b/N_0), comparing the results from a receiver according to figure 5 with a

known receiver using a RAKE receiver (figure 2). It can be seen that the BER of the RAKE receiver does not reduce significantly with increased signal to noise ratio, however by contrast the receiver of figure 5 shows a marked improvement. This is due to cancellation of MAI by the receiver of figure 5.

- 5 The system of figure 5 may be used in a simple receiver spatial diversity mode as shown, or using transmitter diversity where multiple transmitting antennas T at each base station transmit the same signals. In a further modification, Space Time Coding techniques may be used in which complex but different symbols are transmitted from each antenna T of a base station.
- 10 However this requires additional antennas at the receiver – for example doubling the number of transmit antennas requires a doubling of the number of receiving antennas.

The invention has been described with reference to a preferred embodiment thereof. Alterations and modifications as would be obvious to those skilled in

15 the art are intended to be incorporated within the scope hereof.



CLAIMS

1. A method of receiving a wanted CDMA signal from a combination of said signal and other CDMA signals from a plurality of base stations, the method comprising:

5 determining a number of received signal samples from a receiving antenna arrangement to define a received signal vector;

estimating multi-path fading channels between said base stations and said antenna arrangement to determine a channel matrix;

10 multiplying said received signal vector by a matrix operator which is dependent on said channel matrix in order to recover a composite signal from each said base station;

detecting the wanted signal from one of said composite signals.

2. A method according to claim 1, wherein said received signal samples are space and/or time diverse.

15 3. A method according to claim 2, wherein the space diverse samples are received from M different antennas of said antenna arrangement, where $M > N$, and N is the number of transmitters.

4. A method according to claim 2 or 3 wherein the time diverse samples are taken every $t = (\text{chip duration})/M$, where $M > N$, and N is the
20 number of transmitters.

5. A method according to any preceding claim, wherein the matrix operator is the matrix conjugate transpose of the channel matrix multiplied by the inverse of the product of the channel matrix multiplied by the matrix conjugate transpose of the channel matrix.



6. A method as claimed in any preceding claim, wherein the matrix operator is calculated iteratively according to the computation:

$$H_n^+ = \begin{bmatrix} H_{n-1}^+ - H_{n-1}^+ h_n e_n^1 \Delta_n^{-1} \\ e_n^T \Delta_n^{-1} \end{bmatrix},$$

$$e_n = [I_n - H_{n-1}^+ H_{n-1}^+] h_n,$$

$$\Delta_n^{-1} = (h_n^H e_n)^{-1},$$

7. A receiver for receiving a wanted CDMA signal from a combination of said signal and other CDMA signals from a plurality of base stations, the receiver comprising:

means for determining a number of received signal samples from a receiving antenna arrangement to define a received signal vector;

means for estimating multi-path fading channels between said base stations and said antenna arrangement to determine a channel matrix;

means for multiplying said received signal vector by a matrix operator which is dependent on said channel matrix in order to recover a composite signal from each said base station;

means for detecting the wanted signal from one of said composite signals.