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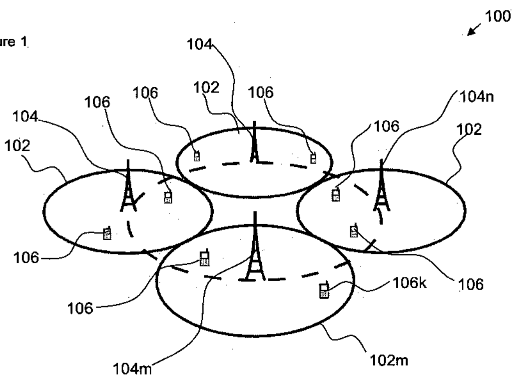
Figure 1



(57) Abstract: A method of communication comprising determining a precoder using channel state information between a plurality of cooperating base stations and a plurality of mobile stations in a distributed manner at each base station, based on minimising inter-cell interference, minimising transfer of channel state information and/or user data between a plurality of cooperating base stations and/or maximising the overall transmission rate; and cooperatively transmitting between the base station and one or more of the mobile stations based on the precoder.

A METHOD OF COMMUNICATION

FIELD OF THE INVENTION

The present invention relates to a method of communication.

BACKGROUND

With the exponential growth of information content, the demand on wireless connectivity to provide people with relevant information regardless of time and location is increasing. Due to the limited frequency resource, may result in more base stations (BSs), increased frequency reuse factor, or even deploying single frequency networks. An aggressive reuse of frequencies may lead to increased interference between BSs. This may lead to interference being a limiting factor, especially in densely populated cellular networks.

Coordination and cooperation among base stations or network MIMO may improve spectral efficiency and may reduce interference. Multicell cooperative communications or network MIMO may be a promising technology for obtaining significant gains in spectral efficiency for interference-limited systems. However, the optimum capacity-achieving strategy for multicell communications may require a system-wide joint Dirty Paper Coding (DPC) by treating all the antennas of the base stations collectively as though they are co-located. In order to do this, channel state information (CSI) and user data may need to be shared among all the different BSs. Such coordination between base stations may be done over backhaul links which may have limited capacity. Due to the latency of the exchange of information between BSs, this strategy may only serve as an ideal upper bound on the practical achievable rates that network MIMO may offer.

Other network MIMO designs are also available, particularly for downlink channels. The Linear block diagonalization (LBD) method nulls out inter-cell interference using linear zero-forcing (ZF) techniques in order to create a block diagonal effective channel from the BSs to the users. Zero-forcing beamforming and game theory optimisation for intelligent scheduling across frequency and time may also be possible. In these cases, joint transmission may be performed using multiple cooperating base stations. However due to limited backhaul capacities and the latency incurred by the exchange of CSI and user data between BSs, joint transmission may be very difficult to implement in a large commercial system.

SUMMARY

In general terms, the present invention relates to a method of precoding a transmission from a base station of a cell to a user of the cell.This may have the advantage of reducing the amount of interferences in intra-cell or out-of-cell channels and may reduce problems relating to the limited backhaul capabilities and latency of information exchange.

According to a first specific expression of the invention, there is provided a method of communication comprising

determining a precoder using channel state information between a plurality of cooperating base stations and a plurality of mobile stations in a distributed manner at each base station, based on minimising inter-cell interference, minimising transfer of channel state information and/or user data between a plurality of cooperating base stations and/or maximising the overall transmission rate; and

cooperatively transmitting between the base station and one or more of the mobile stations based on the precoder.

The channel state information may comprise a plurality of intra-cell communication channels between each base station and a respective plurality of intra-cell mobile stations.

The channel state information may further comprise a plurality of out-of-cell communications channels between each base station and a respective plurality of out-of-cell mobile stations.

The channel state information may be estimated at each base station using an uplink transmission from the plurality of mobile stations to the base station.

The channel state information may be estimated at each mobile station using a downlink transmission from one of the plurality of cooperating base stations to the mobile station.

The precoder may be a linear precoder.

Alternatively the precoder may be a nonlinear precoder.

No user data may be transferred between the plurality of cooperating base stations.

The method may further comprise

calculating a matrix based on a signal-to-leakage-plus-noise ratio using the channel state information; and

precoding the transmission using a precoder obtained from an eigenvalue of the matrix.

The calculating of the matrix may be repeated for each of the plurality of intra-cell mobile stations.

The calculating of the matrix may further comprise dividing a power of a desired signal by a sum of a noise power and a power of a leakage signal.

The calculating of the matrix may further comprise dividing a power of a desired signal by a sum of noise power, a power of a leakage signal and an equivalent noise power due to a channel uncertainty.

The desired signal may be received by a mobile station.

The noise power may depend on a number of receive antennas at the mobile station.

The desired signal may comprise

$$\mathbf{y}_{m,k}^{\text{sig}} = \mathbf{H}_{m,k}\mathbf{q}_{m,k}\sqrt{P_m/K}\,s_{m,k}$$

where

$\mathbf{y}_{m,k}^{\text{sig}}$ is a desired signal from a m-th base station to a k-th user;

$\mathbf{H}_{m,k}$ is a channel state information from the m-th base station to the k-th user;

$\mathbf{q}_{m,k}$ is a beamforming vector from the m-th base station to the k-th user;

$s_{m,k}$ is a data stream of the transmission from the m-th base station to the k-th user;

P_m is a total transmit power from the m-th base station;

K is a number of intra-cell users of a cell;

m is an index denoting the base station and the cell; and

k is an index denoting the user.

The leakage signal may comprise

$$\mathbf{y}_{m,k}^{\text{leak}} = \overline{\mathbf{H}}_{m,k}\mathbf{q}_{m,k}\sqrt{P_m/K}\,s_{m,k}\,.$$

where

$\mathbf{y}_{m,k}^{\text{sig}}$ is a leakage signal from a m-th base station to a k-th user;

$\overline{\mathbf{H}}_{m,k}$ is a channel state information from the m-th base station to a plurality of users other than the k-th user;

$\mathbf{q}_{m,k}$ is a beamforming vector from the m-th base station to the k-th user;

$s_{m,k}$ is a data stream of the transmission from the m-th base station to the k-th user;

P_m is a total transmit power from the m-th base station;

K is a number of intra-cell users of a cell;

m is an index denoting the base station and the cell; and

k is an index denoting the user.

The method may further comprise

calculating a maximum eigenvalue of the matrix using the ratio; and

selecting an eigenvector of the matrix as the beamforming vector, the eigenvector corresponding to the maximum eigenvalue.

The method may further comprise determining a projection matrix based on the multiplication of an orthonormal matrix with a conjugate transpose of an orthonormal matrix.

The desired signal may be received by the plurality of intra-cell mobile stations.

The precoding of the transmission may further comprise

calculating a plurality of eigenvalues of the matrix using the ratio

selecting a plurality of eigenvectors of the matrix corresponding to the largest of the plurality of eigenvalues as the beamforming matrix; and

projecting a channel for use in the transmission using the selected plurality of eigenvectors.

The plurality of eigenvectors may be selected using a lower bound of the ratio.

The covariance matrix of the desired signal may be

$$\mathbf{R}_{\mathrm{y}_{\mathrm{sig}}} = \mathbf{H}\mathbf{V}\mathbf{V}^{H}\mathbf{H}^{H} P/N_{V}$$

where

$\mathbf{R}_{\mathrm{y}_{\mathrm{sig}}}$ is the desired signal;

$\mathbf{H}$ is the channel state information;

$\mathbf{V}$ is the beamforming matrix;

P is a total transmit power of the base station; and

N_V is a dimension of the number of columns of the beamforming matrix.

The covariance matrix of the leakage signal may be

$$\mathbf{R}_{\mathbf{y}_{\text{leak}}} = \overline{\mathbf{H}}\mathbf{V}\mathbf{V}^H\overline{\mathbf{H}}^H P/N_V$$

where

$\mathbf{R}_{\mathbf{y}_{\text{leak}}}$ is the leakage signal;

$\mathbf{H}$ is the channel state information;

$\mathbf{V}$ is the beamforming matrix;

P is a total transmit power of the base station; and

N_V is a dimension of the number of columns of the beamforming matrix.

The selected plurality of eigenvectors may be used to form a plurality of orthonormal basis vectors.

The number of the plurality of eigenvectors selected may be determined by a heuristic value.

The heuristic value may be obtained from a number of transmit antennas at the base station.

The heuristic value may be obtained from the number of receive antennas at the user.

The precoding of the transmission may further comprise applying block diagonal processing on the projected channel to produce the equivalent channel.

The precoding of the transmission may further comprise performing dirty paper coding on the equivalent channel.

The dirty paper coding may be zero forcing dirty paper coding.

The dirty paper coding may use Tomlinson-Harashima precoding.

The method may further comprise

performing singular value decomposition on the channel state information;

selecting a plurality of columns from the decomposed channel state information using a value ϕ_a that is dependent on the number of transmit antennas of the base station;

projecting the selected columns with a projection matrix to obtain a projected channel for use in the transmission; and

precoding the transmission using the projected channel.

The value ϕ_a may be

$$\phi_a = N_T - Kd$$

where

N_T is the number of transmit antennas of the base station;

K is a number of intra-cell users in the cell; and

d is a number of data streams to be transmitted from the base station.

The selecting of the plurality of columns may further comprise obtaining a rank of the channel state information;

finding a minimum value of the rank and the value ϕ_a; and

selecting a plurality of columns from the decomposed channel state information using the minimum value.

The precoding of the transmission may further comprise applying block diagonal processing on the projected channel to produce the equivalent channel.

The precoding of the transmission may further comprise performing dirty paper coding on the equivalent channel.

The dirty paper coding may use Tomlinson-Harashima precoding.

According to a second specific expression of the invention, there is provided an integrated circuit configured to communicate according to any of the methods above.

According to a third specific expression of the invention, there is provided a mobile station configured to communicate according to any of the methods above.

According to a forth specific expression of the invention, there is provided a base station configured to communicate according to any of the methods above.

According to a fifth specific expression of the invention, there is provided a downlink base station cooperation method in which a number of base stations equipped with multiple antennas design their own precoders in a distributed manner, without any explicit information exchange among the cooperating base stations, where the method does not require user data of the cooperating base stations, and require only minimal channel state information,

where each of the cooperating base stations obtains the channel state information between itself and the users under its service, as well as those users served by the cooperating base stations, with which the precoder is designed to simultaneously suppress the interference to the cooperating cells and maximize the overall rate of the users in its own cell, and

where the distributed precoder can incorporate an inaccuracy of the channel state information in its design.

Certain embodiments of the method of transmission of the present invention may have the advantages of:

- having base stations capable of performing transmission processing independently of other base stations;
- having base stations capable of designing their own precoders with minimal requirements from other base stations on the amount of CSI, and with no requirement on user data;
- reducing the amount of information, such as CSI and user data that is exchanged between base stations;
- taking additive noise into account in the precoder;
- being capable of handling interference channels with multiple intra-cell users, in addition to handling interference channels with multiple out-of-cell users;
- requiring at each base station only the CSI associated with the channels from each base station to its served users within its cell, and the interfered users in other cells;
- not requiring the user data from other base stations; and

- handling intra-cell and/or out-of-cell interferences in a distributed manner and thus may require at each base station a shorter processing time and reduced processing effort.

BRIEF DESCRIPTION OF THE DRAWINGS

In order that the invention may be fully understood and readily put into practical effect there shall now be described by way of non-limitative example only, an example embodiment described below with reference to the accompanying illustrative drawings in which:

Figure 1 is an illustration of a cellular network according to the example embodiment;

Figure 2 is a flow chart illustrating a Multicell Leakage Suppression method for precoding a transmission over the cellular network of Figure 1;

Figure 3 is a flow chart illustrating an alternative Projected Channel Dirty Paper Coding (DPC) method for precoding a transmission;

Figure 4 is a flow chart illustrating another alternative Leakage Projected DPC method for precoding a transmission over the cellular network of Figure 1;

Figure 5 is a graph showing the average sum rate per cell of the example embodiments when the number of transmit antennas is varied;

Figure 6 is a graph showing the average sum rate per cell of the example embodiments when a SNR of the transmission is varied;

Figure 7 is a graph showing the average sum rate per cell of the example embodiments when a interference factor is varied;

Figure 8 is a graph showing the average sum rate per cell of the example embodiments when the number of users in a cell is varied from 1 to 8;

Figure 9 is a graph showing the average sum rate per cell of the example embodiments when a channel uncertainty is varied; and

Figure 10 is an illustration of a block diagram of a Tomlinson-Harashima precoding (THP) transceiver design according to the method of precoding of Figure 3 or Figure 4.

DETAILED DESCRIPTION

The following notations may be used in this specification. Bold lowercase letters, e.g. $\mathbf{a}$, are used to denote column vectors, bold uppercase letters, e.g. $\mathbf{A}$, are used to denote matrices, and non-bold letters, e.g. a or A, are used to denote scalar values. $\min(a,b)$ is the minimum of two real numbers a and b. $(\cdot)^T$ and $(\cdot)^H$ denote the matrix transpose and conjugate transpose operations respectively. $\mathrm{E}[\cdot]$ stands for statistical expectation. $C^{P\times Q}$ denotes the space of the complex $P\times Q$ matrices. $\mathbf{1}_{P\times Q}$ is a $P\times Q$ matrix with all elements equal to 1. The distribution of a circularly symmetric complex Gaussian (CSCG) vector with mean vector $\mathbf{m}$ and covariance matrix $\mathbf{R}$ is denoted by $\mathrm{CN}(\mathbf{m},\mathbf{R})$, and ~ means "distributed as". $\mathbf{R}_\mathbf{x} = \mathrm{E}[\mathbf{x}\mathbf{x}^H]$ is the covariance matrix of a vector $\mathbf{x}$. $\|\cdot\|_2$ denotes the vector Euclidean norm, while $\mathbf{I}_N$ denotes the $N\times N$ identity matrix. $\mathrm{Tr}(\mathbf{A})$ stands for the trace of a matrix $\mathbf{A}$. $\det(\mathbf{A})$ denotes the determinant of $\mathbf{A}$. $[\mathbf{A}]_{i,j}$ is the scalar entry of $\mathbf{A}$ in the i-th row and j-th column. $\mathrm{vec}(\mathbf{A})$ is a column vector composed of the entries of $\mathbf{A}$ taken column-wise. $\mathrm{diag}(\mathbf{A})$ represents the diagonal matrix with the same diagonal as the matrix $\mathbf{A}$. $\mathrm{blkdiag}(\mathbf{A}_1,\mathbf{A}_2,\ldots,\mathbf{A}_K)$ denotes a block diagonal matrix whose block diagonal elements are $\mathbf{A}_k, k=1,\ldots,K$.

1. System Model

Figure 1 shows a schematic drawing of a cellular network 100 according to the example embodiment. The cellular network 100 has M number of cells 102 with N_T number of transmit antennas at each base station 104. Each cell has K number of users 106 or mobile stations with N_R number of receive antennas each.

For a synchronous multicell system, the received signal vector $\mathbf{y}_{\text{sys}}$ of the system may be written as

$$\mathbf{y}_{\text{sys}} = \mathbf{H}_{\text{sys}}\mathbf{x}_{\text{sys}} + \mathbf{z}_{\text{sys}} \qquad (1)$$

where $\mathbf{y}_{\text{sys}} = \text{vec}([\mathbf{y}_1, \mathbf{y}_2, \ldots, \mathbf{y}_M]) \in C^{MKN_R \times 1}$, such that $\mathbf{y}_m \in C^{KN_R \times 1}$ is the received signal vector at the m-th cell 102m, $\mathbf{x}_{\text{sys}} = \text{vec}([\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_M]) \in C^{MN_T \times 1}$ is the system transmit signal vector, such that $\mathbf{x}_m \in C^{N_T \times 1}$ is the transmit signal vector from the m-th base station 104m transmitted with the average power constraint P_m. P_m is the average sum power of the transmitted signal from the base station such that $P_m = \text{E}\left[\text{Tr}\left(\mathbf{x}_m \mathbf{x}_m^H\right)\right]$. $\mathbf{z}_{\text{sys}} \sim \text{CN}(\mathbf{0}, N_0 \mathbf{I}_{MKN_R})$ is the additive CSCG noise vector.

The downlink channel matrix $\mathbf{H}_{\text{sys}} \in C^{MKN_R \times MN_T}$ is given by

$$\mathbf{H}_{\text{sys}} = \begin{bmatrix} \mathbf{H}_1 & \mathbf{H}_{2\to1} & \cdots & \mathbf{H}_{M\to1} \\ \mathbf{H}_{1\to2} & \mathbf{H}_2 & \cdots & \mathbf{H}_{M\to2} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{H}_{1\to M} & \mathbf{H}_{2\to M} & \cdots & \mathbf{H}_M \end{bmatrix} \qquad (2)$$

where $\mathbf{H}_m \in C^{KN_R \times N_T}$ denotes the channel matrix modelling the channel state information of the channel from the m-th base station 104m to all its K served users and $\mathbf{H}_{n\to m}$ denotes the channel matrix modelling the channel state information of the channel from the n-th base station 104n to all the K users in the m-th cell 102m.

Using the notation of $\mathbf{y}_m = \text{vec}([\mathbf{y}_{m,1}, \mathbf{y}_{m,2}, \ldots, \mathbf{y}_{m,K}]) \in C^{KN_R \times 1}$, the received signal of the k-th user 106k at the m-th cell 102m may be given by

$$\mathbf{y}_{m,k} = \mathbf{H}_{m,k}\mathbf{x}_m + \sum_{n \neq m}^{M} \mathbf{H}_{n\to m,k}\mathbf{x}_n + \mathbf{z}_{m,k} \qquad (3)$$

where $\mathbf{H}_{m,k} \in C^{N_R \times N_T}$ is the channel matrix modelling the channel state information of the channel from the m-th base station 104m to the k-th user 106k such that $\mathbf{H}_m = [\mathbf{H}_{m,1}^T, \mathbf{H}_{m,2}^T, \ldots, \mathbf{H}_{m,K}^T]^T \in C^{KN_R \times N_T}$. $\mathbf{H}_{n\to m,k} \in C^{N_R \times N_T}$ is the channel matrix modelling the channel state information of the channel from the n-th base station 104n to the k-th user 106k in the m-th cell 102m such that $\mathbf{H}_{n\to m} = [\mathbf{H}_{n\to m,1}^T, \mathbf{H}_{n\to m,2}^T, \ldots, \mathbf{H}_{n\to m,K}^T]^T$, and $\mathbf{z}_{m,k} \sim \text{CN}(\mathbf{0}, N_0\mathbf{I}_{N_R})$ denotes the additive CSCG noise received by the k-th user 106k such that N_0 is the noise variance. To accommodate for multiple data streams transmission, each user may receive d number of data streams from its corresponding own serving base station, such that $d \leq N_R$.

Suppose there are $\overline{K}$ number of out-of-cell users close to the m-th base station 104m, such that the transmission from the base station 104m would potentially cause interference to these out-of-cell users. Let $\overline{\mathbf{H}}_m \in C^{\overline{K}N_R \times N_T}$ model the channel state information of the channels directed towards these $\overline{K}$ number of out-of-cell users. Also, let $\overline{\mathbf{H}}_{m,k} = [\mathbf{H}_{m,1}^T, \ldots, \mathbf{H}_{m,k-1}^T, \mathbf{H}_{m,k+1}^T, \ldots, \mathbf{H}_{m,K}^T, \overline{\mathbf{H}}_m^{\,T}]^T \in C^{(K-1+\overline{K})N_R \times N_T}$ model the channel state information of the channels from the m-th base station 104m to its served users other than the k-th user 106k, and the $\overline{K}$ number of out-of-cell users. $\overline{\mathbf{H}}_m$ thus models the channel state information from the m-th base station 104m to the $\overline{K}$ number of out-of-cell users.

Optionally, in order to provide robustness towards CSI uncertainty, the channel matrix $\mathbf{H}$ modelling the channel state information of a channel may be represented as

$$\mathbf{H} = \hat{\mathbf{H}} + \mathbf{E} \quad (4)$$

where $\mathbf{E}$ is the probabilistic additive error component with independent and identically distributed (i.i.d.) elements of $[\mathbf{E}]_{i,j} \sim \mathrm{CN}(0, \sigma_e^2)$ such that σ_e^2 is a parameter that captures the quality of the channel estimation and is assumed to be known at the transmitter. $\hat{\mathbf{H}}$ is the estimate of the channel available at the transmitter with elements distributed as $\mathrm{CN}(0, 1-\sigma_e^2)$ and can for example be $\mathbf{H}_m$ or $\mathbf{H}_{n\to m}$. $\mathbf{H}$ will have elements distributed as $\mathrm{CN}(0,1)$. This robust representation of the CSI may be used with the Multicell Leakage Suppression method 200 or the Leakage Projected DPC (LPD) method 400 that will be described later and may confer the advantage of increased tolerance towards CSI inaccuracies.

If time division duplex (TDD) is used, the channel state information of the channels from the base station to the intra-cell users and the out-of-cell users (i.e. the CSI respectively denoted $\mathbf{H}_m$ and $\overline{\mathbf{H}}_m$) may be obtained implicitly during the uplink phase using channel reciprocity. This can be done without the need for explicit CSI feedback from the user to the base station. Neighbouring base stations may have their served users perform channel sounding at different times since the training has to be orthogonal.

If frequency division duplex (FDD) is used, the user may estimate the downlink CSI of a transmission from a neighbouring base station and feedback this downlink CSI to its own base station which then sends this CSI via the backhaul to the neighbouring base station.

For both TDD and FDD, no user data has to be exchanged between base stations because the signal to the out-of-cell users is considered as interference and does not increase the desired signal strength of those out-of-cell users. The proposed precoders are able to direct the transmitted energy away from the out-of-cell users such that those out-of-cell users would receive less interference.

2. Distributed Multicell Precoders

In this section, embodiments of decentralized multicell precoding strategies are described for use in multiple-input and multiple-output (MIMO) downlink channels. The embodiments take into account interferences from intra-cell users and out-of-cell users. Typically, the base stations may be equipped with multiple antennas and each cell may be occupied by multiple users each equipped with multiple antennas.

In these embodiments, each base station performs transmit processing independently from other base stations. This may have the advantage of circumventing the problems relating to limited backhaul capacities and the latency of exchanging channel state information (CSI) or user data.

2.1 Multicell Leakage Suppression

Figure 2 shows a Multicell Leakage Suppression method 200 for precoding a transmission over the cellular network 100 of Figure 1. In the Multicell Leakage Suppression method 200, the beamforming vectors to each of the intra-cell users are calculated separately from each other. This is done in a decentralized manner with each base station working independently of the other base stations. The overall effect is that the total interference leakage to other intra-cell users and out-of-cell users is reduced. The method 200 uses the concept of maximizing the signal-to-leakage-plus-noise ratio (SLNR). It is noted that the Multicell Leakage Suppression method 200 for precoding is a linear precoder.

The SLNR is a function of the precoder of only one base station. Optimizing the SLNR may thus be done at a single base station, making it easier to compute and this may also allow for decentralized processing.

The transmit power to each intra-cell user may be defined as P_m/K, where P_m is the total transmit power from the m-th base station 104m, and there are K number of users in the cell. The signal component transmitted by the m-th base station 104m intended for its k-th user 106k is given by $\mathbf{q}_{m,k}\sqrt{P_m/K}s_{m,k}$, where $s_{m,k}$ denotes the data stream from the m-th base station 104m to the k-th user 106k such that $\mathrm{E}\left[s_{m,k}s_{m,k}^H\right]=1$ and $\mathbf{q}_{m,k}$ is a unit norm beamforming vector that is to be found.

While a single data stream per user is considered, the case of multiple data streams per user may be obtained by applying any of the techniques known in the art.

In 210, a matrix $\mathbf{G}_{m,k}$ related to the signal-to-leakage-plus-noise ratio (SLNR) is calculated for the m -th base station 104m and a k -th user 106k. Considering the transmission from the m -th base station 104m to the k -th user 106k in isolation, the desired signal $\mathbf{y}_{m,k}^{\text{sig}}$ received by the k -th user 106k is

$$\mathbf{y}_{m,k}^{\text{sig}} = \mathbf{H}_{m,k}\mathbf{q}_{m,k}\sqrt{P_m/K}s_{m,k} \quad (5)$$

The leakage signal $\mathbf{y}_{m,k}^{\text{leak}}$ directed away from the k -th user 106k is given by

$$\mathbf{y}_{m,k}^{\text{leak}} = \overline{\mathbf{H}}_{m,k}\mathbf{q}_{m,k}\sqrt{P_m/K}s_{m,k} \quad (6)$$

The SLNR $\zeta_{m,k}$ may take the form of a generalized Rayleigh quotient and be defined as

$$\zeta_{m,k} = \frac{\left\|\mathbf{y}_{m,k}^{\text{sig}}\right\|_2^2}{\left\|\mathbf{y}_{m,k}^{\text{leak}}\right\|_2^2 + N_R N_0} = \frac{\mathbf{q}_{m,k}^H \mathbf{H}_{m,k}^H \mathbf{H}_{m,k}\mathbf{q}_{m,k} P_m/K}{\mathbf{q}_{m,k}^H\left(\overline{\mathbf{H}}_{m,k}^H \overline{\mathbf{H}}_{m,k} P_m/K + N_R N_0 \mathbf{I}_{N_T}\right)\mathbf{q}_{m,k}} \quad (7)$$

$\mathbf{H}_{m,k}$ represents the channel state information of the channel from the m -th base station 104m to the k -th user 106k as defined earlier in this description. $\overline{\mathbf{H}}_{m,k}$ represents also as defined earlier, the channel state information of the channels from the m -th base station 104m to its served users other than the k -th user 106k, and the $\overline{K}$ number of out-of-cell users i.e. the channel state information for the interferring communication channels. $N_R N_0$ is the noise power and N_R as defined earlier is the number of receive antennas at the k -th user 106k.

$\zeta_{m,k}$ may be maximized when $\mathbf{q}_{m,k}$ is the generalized eigenvector corresponding to the maximum generalized eigenvalue of the matrix pencil

$$\left(\mathbf{H}_{m,k}^{H}\mathbf{H}_{m,k}P_m/K\,,\overline{\mathbf{H}}_{m,k}^{H}\overline{\mathbf{H}}_{m,k}P_m/K + N_R N_0 \mathbf{I}_{N_T}\right) \qquad (8)$$

which is derived from Equation 7.

Since the second matrix argument is invertible, the solution may be given by $\mathbf{q}_{m,k} = \mathbf{q}_{m,k}^{o}$, where $\mathbf{q}_{m,k}^{o}$ is the unit norm eigenvector corresponding to the maximum eigenvalue of the matrix

$$\mathbf{G}_{m,k} = \left(\overline{\mathbf{H}}_{m,k}^{H}\overline{\mathbf{H}}_{m,k}P_m/K + N_R N_0 \mathbf{I}_{N_T}\right)^{-1}\mathbf{H}_{m,k}^{H}\mathbf{H}_{m,k}P_m/K\ , \qquad (9)$$

$\mathbf{G}_{m,k}$ can be referred to as the SLNR matrix and is notably derived from the SLNR $\zeta_{m,k}$ of Equation 7.

In 220, a precoder for each user is obtained from the SLNR matrix $\mathbf{G}_{m,k}$ by maximizing the SLNR, $\zeta_{m,k}$.

The obtaining 220 of the precoder for each user comprises the calculation 230 of a maximum eigenvalue of the SLNR matrix for each user. In 230, the maximum eigenvalue is thus calculated using the matrix $\mathbf{G}_{m,k}$ of Equation 9.

The obtaining 220 of the equivalent channel further comprises selecting 240 an eigenvector of the SLNR matrix corresponding to the maximum eigenvalue of the SLNR matrix. In 240, the unit norm eigenvector $\mathbf{q}_{m,k}^{o}$ corresponding to the maximum eigenvalue of $\mathbf{G}_{m,k}$ is calculated. The unit norm beamforming vector $\mathbf{q}_{m,k}$ is thus obtained as $\mathbf{q}_{m,k} = \mathbf{q}^{o}_{m,k}$. This unit norm beamforming vector $\mathbf{q}_{m,k}$ is taken to be the precoder for the *k*-th user.

In 250, the estimation 210 of the SLNR matrix and the obtaining 220 of the precoder is repeated for all k-th intra-cell user 106k, where k = 1 to *K*.

In 260, the transmission $s_{m,k}$ is performed using the obtained precoders. By doing so, the base station transmits

$$\mathbf{x} = \sum_{k=1}^{K} \mathbf{q}_{m,k} \sqrt{P_m / K}\, s_{m,k} \tag{10}$$

2.2 Projected Channel DPC

Figure 3 shows an alternative Projected Channel DPC method 300 for precoding a transmission over the cellular network 100 of Figure 1. The cell index subscript m denoting the m-th base station 104m is omitted in this section for notational simplicity. However, it should still be clear from the equations and description that the base station processing is decentralized. It is noted that the Projected Channel DPC method 300 for precoding is a nonlinear precoder.

Thus with the notation simplified, it is noted, for example that $\mathbf{H}$ now denotes the channel state information $\mathbf{H}_m$, and $\overline{\mathbf{H}}$ now denotes the channel state information $\overline{\mathbf{H}}_m$.

In 310, singular value decomposition (SVD) is performed on the channel state information $\overline{\mathbf{H}}$. This may be done as

$$\overline{\mathbf{H}} = \overline{\mathbf{U}}\mathbf{S}\overline{\mathbf{V}}^{H} \tag{11}$$

In 320, a matrix $\overline{\mathbf{V}}_{(\phi)}$ is selected using columns from the matrix $\overline{\mathbf{V}}$ of the decomposed channel state information $\overline{\mathbf{H}}$. This selection comprises obtaining 330 a value ϕ_a, obtaining 340 a rank ϕ_r, finding 350 a minimum value of ϕ_a and ϕ_r, and selecting 360 the columns from the decomposed channel state information $\overline{\mathbf{V}}$ using the minimum value.

In 330, a value ϕ_a is then obtained.

$$\phi_a = N_T - Kd \quad (12)$$

ϕ_a may be interpreted as the degrees of freedom (DoF) available for nulling the interference to the out-of-cell users.

In 340, the rank ϕ_r of $\overline{\mathbf{H}}$ is obtained. ϕ_r may be interpreted as the DoF required to null the interference to the out-of-cell users completely. Zero-forcing (ZF) processing may thus be performed to null transmission to the out-of-cell users.

In 350, the minimum value between the rank ϕ_r and the value ϕ_a is obtained as ϕ. Thus, let $\phi = \min(\phi_a, \phi_r)$.

In 360, columns are selected from $\overline{\mathbf{V}}$ using the value ϕ. The ϕ number of largest singular values of are found and the columns of $\overline{\mathbf{V}}$ corresponding to these largest singular values of $\overline{\mathbf{H}}$ are selected. These selected columns are formed into the matrix $\overline{\mathbf{V}}_{(\phi)}$.

In 370, the channel state information $\mathbf{H}$ is projected onto the null space of $\overline{\mathbf{V}}_{(\phi)}{}^{H}$.

$$\mathbf{H}_{\perp} = \mathbf{H}\left(\mathbf{I} - \overline{\mathbf{V}}_{(\phi)}\overline{\mathbf{V}}_{(\phi)}{}^{H}\right) \tag{13}$$

The $\mathbf{H}_{\perp}$ that results is thus the projected channel.

In 380, block diagonal (BD) DPC processing may be applied to the projected channel $\mathbf{H}_{\perp}$. This produces the equivalent channel $\mathbf{L}$ that may be used for transmissions to the intra-cell users. A lower triangular equivalent channel may be created as

$$\mathbf{W}^{H}\mathbf{H}_{\perp}\mathbf{Q} = \mathbf{L} \tag{14}$$

$\mathbf{W}$ is a block diagonal matrix such that $\mathbf{W} = \mathrm{blkdiag}(\mathbf{W}_1, \mathbf{W}_2, \ldots, \mathbf{W}_K)$ and $\mathbf{Q}$ is the transmit beamforming matrix. $\mathbf{W}$ and $\mathbf{Q}$ have orthonormal columns. The matrices $\mathbf{W}$, $\mathbf{L}$, and $\mathbf{Q}$ can be obtained from Equation 14 by performing decomposition using block diagonal geometric mean decomposition (BD-GMD). Alternatively, a block diagonal singular value decomposition (SVD) can also be used to obtain the required matrices $\mathbf{W}$, $\mathbf{L}$, and $\mathbf{Q}$ such that Equation 14 is satisfied.

In 390, the data streams $\mathbf{s}$ to be transmitted from the base station are processed by performing Tomlinson-Harashima precoding (THP) to produce the pre-transmit signal $\tilde{\mathbf{x}}$, and transmission pre-equalization may then be applied to the pre-transmit signal. The transmission pre-equalization matrix is $\mathbf{F} = \mathbf{QO}$, where $\mathbf{O}$ is a diagonal matrix containing the power allocation for the respective intra-cell users. The transmit signal $\mathbf{x}$ can then be transmitted to the intra-cell users from the base station.

After the transmission is made from the m-th base station 104m, the k-th receiving intra-cell user 106k may then decode the received signal using the receive beamforming matrix $\mathbf{W}_k$. It is noted that if $\phi_a \geq \phi_r$, the m-th base station 104m may not cause interference to the users in the cells neighbouring the m-th cell 102m. In contrast, if $\phi_a < \phi_r$, some interference may be present.

2.3 Leakage Projected DPC

Figure 4 shows a second alternative Leakage Projected DPC method 400 for precoding a transmission over the cellular network 100 of Figure 1.

The Leakage Projected DPC (LPD) method 400 combines the favourable features of both the Projected Channel DPC method 300 and the Multicell Leakage Suppression method 200, and may allow for distributed downlink processing. The LPD method 400 performs channel projection using the SLNR, and thereafter does DPC with a focus on intra-cell users. The LPD method 400 may take noise into account in the leakage-based projection that is applied in the steps 410 to 450. It is noted that the LPD method 400 for precoding is a nonlinear precoder.

The cell index subscript m denoting the m-th base station 104m is once again omitted in this section for notational simplicity, although it should still be clear from the equations and description that the base station processing is decentralized. Thus with the notation simplified, it is noted, for example that $\mathbf{H} \in C^{KN_R \times N_T}$ now denotes the channel state information $\mathbf{H}_m$, and $\overline{\mathbf{H}}$ now denotes the channel state information $\overline{\mathbf{H}}_m$.

Assume that the m-th base station performs beamforming using the beamforming matrix $\mathbf{V} \in C^{N_T \times N_V}$ where $\mathbf{V}^H\mathbf{V} = \mathbf{I}_{N_V}$. N_V denotes the number of columns present in the beamforming matrix $\mathbf{V}$. Equal power loading of P/N_V may be applied to each column of $\mathbf{V}$. $\mathbf{V}$ and N_V are to be determined.

In 410, the cell signal-to-leakage-plus-noise ratio (SLNR) ζ_C for a m-th cell 102m is derived. The cell SLNR ζ_C refers to the ratio of the desired signal power within a cell, to the sum of the out-of-cell leakage signal power and noise power. The cell SLNR differs from the user SLNR in that the desired signal power for the former is the power of the desired signals received by the intra-cell users belonging to a cell, whereas the desired signal power for the latter is the power of the desired signal for a specific user.

The desired signal vector received by the intra-cell users is denoted as $\mathbf{y}^{\text{sig}} \in C^{KN_R \times 1}$, where

$$\mathbf{y}^{\text{sig}} = \mathbf{H}\mathbf{V}\sqrt{P/N_V}\,\mathbf{s} \tag{15}$$

The noise vector received by the intra-cell users is $\mathbf{z} \sim \text{CN}(\mathbf{0}, N_0\mathbf{I}_{KN_R})$. P is the average sum power of the transmitted signal from the m-th base station 104m such that $P = \text{E}\left[\text{Tr}\left(\mathbf{x}\mathbf{x}^H\right)\right]$, where $\mathbf{x} = \mathbf{V}\sqrt{P/N_V}\,\mathbf{s}$ and the expectation is taken over the random vector $\mathbf{s}$ where $\text{E}\left[\mathbf{s}\mathbf{s}^H\right] = \mathbf{I}_{N_V}$. The leakage signal vector to the out-of-cell users is given by $\mathbf{y}^{\text{leak}} \in C^{\overline{K}N_R \times 1}$, where

$$\mathbf{y}^{\text{leak}} = \overline{\mathbf{H}}\mathbf{V}\sqrt{P/N_V}\,\mathbf{s} \tag{16}$$

The covariance matrices of the desired signal, noise, and leakage signal are given, respectively, by

$$\mathbf{R}_{\mathbf{y}_{\text{sig}}} = \mathbf{H}\mathbf{V}\mathbf{V}^H\mathbf{H}^H P/N_V \qquad (17)$$

$$\mathbf{R}_{\mathbf{z}} = N_0\mathbf{I}_{KN_R} \qquad (18)$$

$$\mathbf{R}_{\mathbf{y}_{\text{leak}}} = \overline{\mathbf{H}}\mathbf{V}\mathbf{V}^H\overline{\mathbf{H}}^H P/N_V \qquad (19)$$

The cell SLNR, ζ_C, is defined as

$$\zeta_C = \frac{\mathrm{Tr}\left(\mathbf{H}\mathbf{V}\mathbf{V}^H\mathbf{H}^H P/N_V\right)}{\mathrm{Tr}\left(\overline{\mathbf{H}}\mathbf{V}\mathbf{V}^H\overline{\mathbf{H}}^H P/N_V\right) + N_0 K N_R}$$

$$= \frac{\sum_{k=1}^{N_V} \mathbf{v}_k^H\left(\mathbf{H}^H\mathbf{H}P\right)\mathbf{v}_k}{\sum_{k=1}^{N_V} \mathbf{v}_k^H\left(\overline{\mathbf{H}}^H\overline{\mathbf{H}}P + N_0 K N_R \mathbf{I}_{N_T}\right)\mathbf{v}_k}$$

$$= \frac{\sum_{k=1}^{N_V} \mathbf{v}_k^H \mathbf{G}_A \mathbf{v}_k}{\sum_{k=1}^{N_V} \mathbf{v}_k^H \mathbf{G}_B \mathbf{v}_k} \qquad (20)$$

where

$$\mathbf{G}_A = \rho\mathbf{H}^H\mathbf{H},$$

$$\mathbf{G}_B = \rho\overline{\mathbf{H}}^H\overline{\mathbf{H}} + KN_R\mathbf{I}_{N_T}, \text{ and}$$

$$\rho = P/N_0. \qquad (21)$$

In 420, a projection matrix is obtained from the SLNR. Given a value for N_V, it may be difficult to find $\mathbf{V}$ to maximize ζ_C. A lower bound, ζ_L, of the cell SLNR may be maximized as defined by

$$\zeta_L = \min_{k=1,\ldots,N_V} \frac{\mathbf{v}_k^H \mathbf{G}_A \mathbf{v}_k}{\mathbf{v}_k^H \mathbf{G}_B \mathbf{v}_k} \qquad (22)$$

By maximizing ζ_L,

$$\zeta_{L.\max} = \max_{\mathbf{V}^H\mathbf{V}=\mathbf{I}_{N_V}} \min_{k=1,\ldots,N_V} \frac{\mathbf{v}_k^H \mathbf{G}_A \mathbf{v}_k}{\mathbf{v}_k^H \mathbf{G}_B \mathbf{v}_k}$$

$$= \max_{\mathrm{V}:\dim(\mathrm{V})=N_V} \min_{\mathbf{v}\in\mathrm{V}} \frac{\mathbf{v}^H \mathbf{G}_A \mathbf{v}}{\mathbf{v}^H \mathbf{G}_B \mathbf{v}} \qquad (23)$$

Using the generalized Courant-Fischer Max-Min Theorem, $\zeta_{L.\max}$ may be equal to the N_V-th largest eigenvalue of a matrix $\mathbf{G}_S$, where $\mathbf{G}_S$ may be referred to as the cell SLNR matrix and is defined to be

$$\mathbf{G}_S = \mathbf{G}_B^{-1}\mathbf{G}_A \qquad (24)$$

It is noted that $\mathbf{G}_S$ may be obtained from $\zeta_{L,\max}$ as defined in Equation 23.

The obtaining 420 of the projection matrix comprises the calculation 430 of a plurality of eigenvalues of the matrix $\mathbf{G}_S$ obtained from the cell SLNR expression.

The obtaining 420 of the projection matrix further comprises selecting 440 a plurality of eigenvectors from a matrix $\mathbf{G}_S$. In 440, the beamforming matrix $\mathbf{V}$ may then be selected as the N_V number of orthonormal basis vectors of the eigenspace spanned by the N_V number of dominant eigenvectors of $\mathbf{G}_S$. These N_V number of dominant eigenvectors of $\mathbf{G}_S$ correspond to the N_V largest eigenvalues of $\mathbf{G}_S$.

If the condition of $N_V \geq K$ is fulfilled, K users may be supported. Also, the condition of $N_V \leq \min(N_T, KN_R)$ may be fulfilled as a result of the dimensions of the system 100. As the number of transmit antennas N_T at each base station 104 increases, a larger value of N_V may be used. As an example, N_V may be chosen to be $N_T - \overline{K}N_R$, in order to have sufficient DoF for suppressing the interference to the $\overline{K}N_R$ antennas of the out-of-cell users.

A heuristic value of N_V may be obtained by

$$N_V = N_Q = \min\left(\max\left(K, N_T - \overline{K}N_R\right), KN_R, N_T\right) \tag{25}$$

This heuristic value of $N_V = N_Q$ may have the advantage of having worked well in simulations.

In 450, the channel state information $\mathbf{H}$ is projected using the matrix $\mathbf{V}$. The projection may be done using $\mathbf{V}\mathbf{V}^H$ to get

$$\mathbf{H}_{\perp} = \mathbf{H}\mathbf{V}\mathbf{V}^H \tag{26}$$

This projection strikes a balance between improving the desired signal power directed to the intra-cell users and reducing the interference power to the out-of-cell users.

In 460, block diagonal DPC may be applied to the projected channel $\mathbf{H}_{\perp}$. This produces the equivalent channel $\mathbf{L}$.

$$\mathbf{W}^H\mathbf{H}_{\perp}\mathbf{Q} = \mathbf{L} \tag{27}$$

$\mathbf{W}$ is a block diagonal matrix $\mathbf{W} = \text{blkdiag}(\mathbf{W}_1, \mathbf{W}_2, \ldots, \mathbf{W}_K)$ and $\mathbf{Q}$ is the transmit beamforming matrix. $\mathbf{W}$ and $\mathbf{Q}$ have orthonormal columns. The matrices $\mathbf{W}$, $\mathbf{L}$, and $\mathbf{Q}$ can be obtained from Equation 27 by performing decomposition using BD-GMD. Alternatively, a block diagonal SVD can also be used to obtain the required matrices $\mathbf{W}$, $\mathbf{L}$, and $\mathbf{Q}$ such that Equation 27 is satisfied.

In 470, the data streams to be transmitted from the base station are coded by performing transmission pre-equalization. The transmission pre-equalization matrix is $\mathbf{F} = \mathbf{QO}$, where $\mathbf{O}$ is a diagonal matrix containing the power allocation for the respective intra-cell users. The coded data streams can then be transmitted to the intra-cell users from the base station.

After the transmission is made from the m -th base station 104m, the k -th receiving intra-cell user 106k may then decode the received signal using the receive beamforming matrix $\mathbf{W}_k$.

Optionally, the Leakage Projected DPC (LPD) method 400 may be implemented as a Robust LPD variant as is described next. The Robust LPD variant may be capable of overcoming channel state information uncertainties. The base station 104 that is transmitting may have knowledge of the error variance σ_e^2.

In the Robust LPD variant, the effective additive noise due to the receiver noise and the CSI error is $\overline{N}_0 = N_0 + \sigma_e^2 P$. Accounting for the CSI error, the following value of ρ may be used in Equation 21.

$$\rho = P/\overline{N}_0. \tag{28}$$

Corresponding, the values of $\mathbf{H}$ and $\overline{\mathbf{H}}$ that are used in Equation 21 may be substituted by the estimates of the channels $\mathbf{H}$ and $\overline{\mathbf{H}}$ respectively available at the transmitter. The other steps of the Robust LPD variant can then be performed as is described for the LPD method 400.

In such a case, the effective noise due to the errors in the channel state information may be $N_{0,e} = \sigma_e^2 P$ at each receive antenna. P denotes the average transmit power of the base station. Thus the effective additive noise due to the receiver noise and the channel state information error at each receive antenna may be $\overline{N}_0 = N_0 + N_{0,e}$ where N_0 is the power of the additive noise when the channel state information is correct.

Results contrasting the performance of Robust LPD with the Leakage Projected DPC (LPD) method 400 when the channel uncertainty σ_e^2 is varied will be shown later in Figure 9.

Figure 10 is an block diagram of a Tomlinson-Harashima precoding (THP) transceiver design 1000 according to embodiments of the Projected Channel Dirty Paper Coding (DPC) method 300 or the Leakage Projected DPC method 400.

A data stream 1002 to be transmitted from a m -th base station 104m is provided as $\mathbf{s}$. In 1004, 1010, and 1012, Tomlinson-Harashima precoding is performed, to produce a pre-transmit signal $\tilde{\mathbf{x}}$. The modulo 1004, interference pre-subtraction 1010 and compensation 1012 is configured in a feedback loop. In 470, transmit pre-equalization is performed on the pre-transmit signal $\tilde{\mathbf{x}}$ to produce $\mathbf{x}$ which is transmitted from the base station 104m.

In 1006, the transmitted signal $\mathbf{x}$ is carried over transmission channels. In each transmission channel, the signal $\mathbf{x}$ undergoes channel distortion 1008 and corruption 1014 by additive noise $\mathbf{z}$.

In 1020, the signal transmitted from the base station 104m may be received at the intra-cell users 106 as $\mathbf{y}$. For the k-th intra-cell user, where $k = 1...K$, receive beamforming processing may be performed using the receive beamforming matrix $\mathbf{W}_k^H$.

In 1022, equalization is performed on the processed received signal $\tilde{\mathbf{y}}$ at each k-th intra-cell user. This may be done for each k-th intra-cell user by multiplying $\tilde{\mathbf{y}}$ with $(N_0\Gamma_k)^{-1/2}$. This equalization will have the effect of compensating for the channel gain. A equalized received signal $\hat{\mathbf{y}}$ is produced at each k-th intra-cell user after 1022.

In 1024, the equalized signal $\hat{\mathbf{y}}$ undergoes modulo to produced the received data stream $\tilde{\mathbf{s}}$.

Simulation Results

Numerical simulations were conducted to evaluate the performance of the precoders. Unless otherwise stated, these simulations use the following parameters. The cellular network 100 of the simulation is taken to have M =4 cells. Each base station 104 has N_T number of transmit antennas and each cell has K number of users 106k. Each user has N_R =1 receive antennas. Each intra-cell channel link is taken to have a channel gain of the distribution $\mathrm{CN}(\mathbf{0},1)$. Each out-of-cell channel link is taken to have a channel gain of the distribution $\mathrm{CN}(\mathbf{0},\alpha^2)$, where α is the interference factor. A low value of α represents low inter-cell interference while a high value of α indicates high inter-cell interference.

The value of $\mathbf{C}_M$ is taken to be

$$\mathbf{C}_M = \begin{bmatrix} 1 & 0 & 0 & \alpha^2 \\ 1 & \alpha^2 & 0 & 0 \\ \alpha^2 & 1 & 0 & 0 \\ 0 & 1 & \alpha^2 & 0 \\ 0 & \alpha^2 & 1 & 0 \\ 0 & 0 & 1 & \alpha^2 \\ 0 & 0 & \alpha^2 & 1 \\ \alpha^2 & 0 & 0 & 1 \end{bmatrix} \quad (29)$$

and $\mathbf{C}_V = \mathbf{C}_M \otimes \mathbf{1}_{N_R,N_T}$.

$\mathbf{C}_M$ denotes the variance of the channel gain of each channel link from the base stations (represented by the columns) to the users (represented by the rows). $\mathbf{C}_V$ denotes the variance of the channel gain of each channel link from the antennas of the base stations (represented by the columns) to the antennas of the users (represented by the rows). $\mathbf{1}_{N_R,N_T}$ denotes a $N_R \times N_T$ matrix with all elements equal to 1.

The number of transmit antennas at each base station 104 is taken to be $N_T = 8$, while the signal-to-noise ratio (SNR) of the transmission from each base station is taken to be 15dB. $\alpha = 0.5$ and $K = 4$. 1000 Monte Carlo runs are performed for each simulation.

In each of the simulations, the results for the following scenarios are presented in the respective graphs:

- where there is no cooperation between base stations and BD-GMD is used to support multiple intra-cell users (i.e. the curve labelled as "No cooperation");
- where each base station uses an orthogonal channel and BD-GMD is used to support multiple intra-cell users (i.e. the curve labelled as "2 orthogonal channels");
- where the Multicell Leakage Suppression method 200 of precoding is used (i.e. the curve labelled as "Multicell leakage suppression"); and
- where Projected Channel DPC method 300 of precoding is used (i.e. the curve labelled as "Projected channel DPC");
- where Leakage Projected DPC method 400 of precoding is used (i.e. the curve labelled as "LPD").

Figure 5 is a graph showing the average sum rate per cell when the number of transmit antennas N_T is varied. In this simulation, $K = 4$. It can be seen that in this simulation, when N_T is greater than 5, the Projected Channel DPC method (curve 530), Multicell Leakage Suppression method (curve 540) and Leakage Projected DPC method (curve 550) have a higher sum rate than the case where there is no cooperation between base stations (curve 510) and the case where each base station uses an orthogonal channel (curve 520).

Figure 6 is a graph showing the average sum rate per cell when the SNR of the transmission is varied. In this simulation, $N_T = 8$ and $K = 4$. Once again, it can be seen that when the SNR is greater or equal to 10 dB, the Projected Channel DPC method (curve 630), Multicell Leakage Suppression method (curve 640) and Leakage Projected DPC method (curve 650) have a higher sum rate than the case where there is no cooperation between base stations (curve 610) and the case where each base station uses an orthogonal channel (curve 620).

It can be seen from Figure 6 that the Projected Channel DPC method (curve 630), Multicell Leakage Suppression method (curve 640) and Leakage Projected DPC method (curve 650) may yield a linear increase in data rate as the SNR increases, as long as there are sufficient transmit antennas N_T in the high SNR regime. In contrast, where there is no base station cooperation (curve 610), the sum rate may level off at a high SNR.

Figure 7 is a graph showing the average sum rate per cell when the interference factor α is varied. In this simulation, $N_T = 8$ and $K = 4$. It can be seen that when the amount of interference is higher i.e. the interference factor α is greater than 0.3, the Projected Channel DPC method (curve 730), Multicell Leakage Suppression method (curve 740) and Leakage Projected DPC method (curve 750) have a higher sum rate than the case where there is no cooperation between base stations (curve 710) and the case where each base station uses an orthogonal channel (curve 720). Also, the Projected Channel DPC (curve 730) shows only a constant performance when interference is increased because the Projected Channel DPC method 300 may completely removes the interference, no matter how large or small it is. The Leakage Projected DPC method (curve 750) has a higher sum rate than the Projected Channel DPC (curve 730) because it may allow some interference, in return for higher desired signal strength to the intra-cell users.

Figure 8 is a graph showing the average sum rate per cell when the number of users K in a cell is varied from 1 to 8. In this simulation, $N_T = 8$. It can be seen that when the number of users is low i.e. where K is lesser than 6, the Projected Channel DPC method (curve 830), Multicell Leakage Suppression method (curve 840) and Leakage Projected DPC method (curve 850) have a higher sum rate than the case where there is no cooperation between base stations (curve 810) and the case where each base station uses an orthogonal channel (curve 820).

Figure 9 is a graph showing the average sum rate per cell when the channel uncertainty σ_e^2 is varied. In this simulation, $N_T = 8$ and $K = 4$. This simulation was also done for Robust LPD. It can be seen that where the channel uncertainty is low i.e. where σ_e^2 is lesser than -13 dB, the Projected Channel DPC method (curve 930), Multicell Leakage Suppression method (curve 940), Leakage Projected DPC method (curve 950) and Robust LPD (curve 960) have a higher sum rate than the case where there is no cooperation between base stations (curve 910) and the case where each base station uses an orthogonal channel (curve 920). It can also be seen that as σ_e^2 increases, the Robust LPD method may exhibit an improved performance over the Leakage Projected DPC method.

The numerical results for the simulations show that the Multicell Leakage Suppression method 200, the Projected Channel DPC method 300 and Leakage Projected DPC method 400 may out-perform the non-cooperating single-cell processing approach. In particular, the Leakage Projected DPC method 400 may perform the best in terms of having a higher sum rate and may also exhibit greater robustness in varying interference conditions.

In this specification, the terms “user” and “mobile station” have been used interchangeably to refer to a mobile station as will be understood by a person skilled in the art.

The described embodiments should not be construed as limitative. For example, while the described embodiments describe the precoding as a method, it would be apparent that the method may be implemented as a device, more specifically as an Integrated Circuit (IC). In this case, the IC may include a processing unit configured to perform the various method steps discussed earlier, but otherwise operate according to a relevant communication protocol. For example, the example embodiment is particularly useful in a cellular network, such as a 4G network, but it should be apparent that the example embodiment may also be used in other wireless communication networks. Thus mobile station devices, base station and other network infrastructure may incorporate such ICs or otherwise be programmed or configured to operate according to the described method.

While various example embodiments have been described in the detailed description, it will be understood by those skilled in the technology concerned that many variations in details of design, construction and/or operation may be made without departing from the scope as claimed.

CLAIMS

1. A method of communication comprising

determining a precoder using channel state information between a plurality of cooperating base stations and a plurality of mobile stations in a distributed manner at each base station, based on minimising inter-cell interference, minimising transfer of channel state information and/or user data between a plurality of cooperating base stations and/or maximising the overall transmission rate; and

cooperatively transmitting between the base station and one or more of the mobile stations based on the precoder.

2. The method according to claim 1, wherein the channel state information comprises a plurality of intra-cell communication channels between each base station and a respective plurality of intra-cell mobile stations.

3. The method according to any preceding claim, wherein the channel state information further comprises a plurality of out-of-cell communications channels between each base station and a respective plurality of out-of-cell mobile stations.

4. The method according to any preceding claim, wherein the channel state information is estimated at each base station using an uplink transmission from the plurality of mobile stations to the base station.

5. The method according to any preceding claim, wherein the channel state information is estimated at each mobile station using a downlink transmission from one of the plurality of cooperating base stations to the mobile station.

6. The method according to any preceding claim wherein the precoder is a linear precoder.

7. The method according to any of claims 1 to 5 wherein the precoder is a nonlinear precoder.

8. The method according to any preceding claim wherein no user data is transferred between the plurality of cooperating base stations.

9. The method according to any of claims 6 to 8, further comprising

calculating a matrix based on a signal-to-leakage-plus-noise ratio using the channel state information; and

precoding the transmission using a precoder obtained from an eigenvalue of the matrix.

10. The method according to claim 9 when dependent on claim 2, wherein the calculating of the matrix is repeated for each of the plurality of intra-cell mobile stations.

11. The method according to claims 9 or 10, wherein the calculating of the matrix further comprises dividing a power of a desired signal by a sum of a noise power and a power of a leakage signal.

12. The method according to any of claims 9 or 10, wherein the calculating of the matrix further comprises dividing a power of a desired signal by a sum of noise power,

a power of a leakage signal and an equivalent noise power due to a channel uncertainty.

13. The method according to claim 11 or 12, wherein the desired signal is received by a mobile station.

14. The method according to claim 13 wherein the noise power depends on a number of receive antennas at the mobile station.

15. The method according to claim 14, wherein the desired signal comprises

$$\mathbf{y}_{m,k}^{\text{sig}} = \mathbf{H}_{m,k}\mathbf{q}_{m,k}\sqrt{P_m/K}s_{m,k}$$

where

$\mathbf{y}_{m,k}^{\text{sig}}$ is a desired signal from a m-th base station to a k-th user;

$\mathbf{H}_{m,k}$ is a channel state information from the m-th base station to the k-th user;

$\mathbf{q}_{m,k}$ is a beamforming vector from the m-th base station to the k-th user;

$s_{m,k}$ is a data stream of the transmission from the m-th base station to the k-th user;

P_m is a total transmit power from the m-th base station;

K is a number of intra-cell users of a cell;

m is an index denoting the base station and the cell; and

k is an index denoting the user.

16. The method according to claims 14 or 15, wherein the leakage signal comprises

$$\mathbf{y}_{m,k}^{\text{leak}} = \overline{\mathbf{H}}_{m,k}\mathbf{q}_{m,k}\sqrt{P_m/K}s_{m,k}\,.$$

where

$\mathbf{y}_{m,k}^{\text{sig}}$ is a leakage signal from a m-th base station to a k-th user;

$\overline{\mathbf{H}}_{m,k}$ is a channel state information from the m-th base station to a plurality of users other than the k-th user;

$\mathbf{q}_{m,k}$ is a beamforming vector from the m-th base station to the k-th user;

$s_{m,k}$ is a data stream of the transmission from the m-th base station to the k-th user;

P_m is a total transmit power from the m-th base station;

K is a number of intra-cell users of a cell;

m is an index denoting the base station and the cell; and

k is an index denoting the user.

17. The method according to any of claims 14 to 16, further comprising calculating a maximum eigenvalue of the matrix using the ratio; and selecting an eigenvector of the matrix as the beamforming vector, the eigenvector corresponding to the maximum eigenvalue.

18. The method according to claim 14, further comprising determining a projection matrix based on the multiplication of an orthonormal matrix with a conjugate transpose of an orthonormal matrix.

19. The method according to claim 18, wherein the desired signal is received by the plurality of intra-cell mobile stations.

20. The method according to claims 18 or 19, wherein the precoding of the transmission further comprises

calculating a plurality of eigenvalues of the matrix using the ratio

selecting a plurality of eigenvectors of the matrix corresponding to the largest of the plurality of eigenvalues as the beamforming matrix; and

projecting a channel for use in the transmission using the selected plurality of eigenvectors.

21. The method according to claim 20, wherein the plurality of eigenvectors is selected using a lower bound of the ratio.

22. The method according to claim 21, wherein the covariance matrix of the desired signal is

$$\mathbf{R}_{\mathbf{y}_{\text{sig}}} = \mathbf{H}\mathbf{V}\mathbf{V}^{H}\mathbf{H}^{H}P/N_{V}$$

where

$\mathbf{R}_{\mathbf{y}_{\text{sig}}}$ is the desired signal;

$\mathbf{H}$ is the channel state information;

$\mathbf{V}$ is the beamforming matrix;

P is a total transmit power of the base station; and

N_V is a dimension of the number of columns of the beamforming matrix.

23. The method according to claim 22, wherein the covariance matrix of the leakage signal is

$$\mathbf{R}_{\mathbf{y}_{\text{leak}}} = \overline{\mathbf{H}}\mathbf{V}\mathbf{V}^{H}\overline{\mathbf{H}}^{H}P/N_{V}$$

where

$\mathbf{R}_{y_{\text{leak}}}$ is the leakage signal;

$\mathbf{H}$ is the channel state information;

$\mathbf{V}$ is the beamforming matrix;

P is a total transmit power of the base station; and

N_V is a dimension of the number of columns of the beamforming matrix.

24. The method according to any of claims 20 to 23, wherein the selected plurality of eigenvectors is used to form a plurality of orthonormal basis vectors.

25. The method according to any of claims 20 to 24, wherein the number of the plurality of eigenvectors selected is determined by a heuristic value.

26. The method according to claim 25, wherein the heuristic value is obtained from a number of transmit antennas at the base station.

27. The method according to claims 25 or 26, wherein the heuristic value is obtained from the number of receive antennas at the user.

28. The method according to any of claims 20 to 27, wherein the precoding of the transmission further comprises applying block diagonal processing on the projected channel to produce the equivalent channel.

29. The method according to any of claims 18 to 28, wherein the precoding of the transmission further comprises performing dirty paper coding on the equivalent channel.

30. The method according to claim 29, wherein the dirty paper coding is zero forcing dirty paper coding.

31. The method according to claim 29, wherein the dirty paper coding uses Tomlinson-Harashima precoding.

32. The method according to claim 8, further comprising

performing singular value decomposition on the channel state information;

selecting a plurality of columns from the decomposed channel state information using a value ϕ_a that is dependent on the number of transmit antennas of the base station;

projecting the selected columns with a projection matrix to obtain a projected channel for use in the transmission; and

precoding the transmission using the projected channel.

33. The method according to claim 32, wherein the value ϕ_a is

$$\phi_a = N_T - Kd$$

where

N_T is the number of transmit antennas of the base station;

K is a number of intra-cell users in the cell; and

d is a number of data streams to be transmitted from the base station.

34. The method according to claims 32 or 33, wherein the selecting of the plurality of columns further comprises

obtaining a rank of the channel state information;

finding a minimum value of the rank and the value ϕ_a; and

selecting a plurality of columns from the decomposed channel state information using the minimum value.

35. The method according to any of claims 32 to 34, wherein the precoding of the transmission further comprises applying block diagonal processing on the projected channel to produce the equivalent channel.

36. The method according to any of claims 32 to 35, wherein the precoding of the transmission further comprises performing dirty paper coding on the equivalent channel.

37. The method according to claim 36, wherein the dirty paper coding uses Tomlinson-Harashima precoding.

38. An integrated circuit configured to communicate according to the method in any of claims 1 to 37.

39. A mobile station configured to communicate according to the method in any of claims 1 to 37.

40. A base station configured to communicate according to the method in any of claims 1 to 37.

41. A downlink base station cooperation method in which a number of base stations equipped with multiple antennas design their own precoders in a distributed manner, without any explicit information exchange among the cooperating base stations,

where the method does not require user data of the cooperating base stations, and require only minimal channel state information,

where each of the cooperating base stations obtains the channel state information between itself and the users under its service, as well as those users served by the cooperating base stations, with which the precoder is designed to simultaneously suppress the interference to the cooperating cells and maximize the overall rate of the users in its own cell, and

where the distributed precoder can incorporate an inaccuracy of the channel state information in its design.

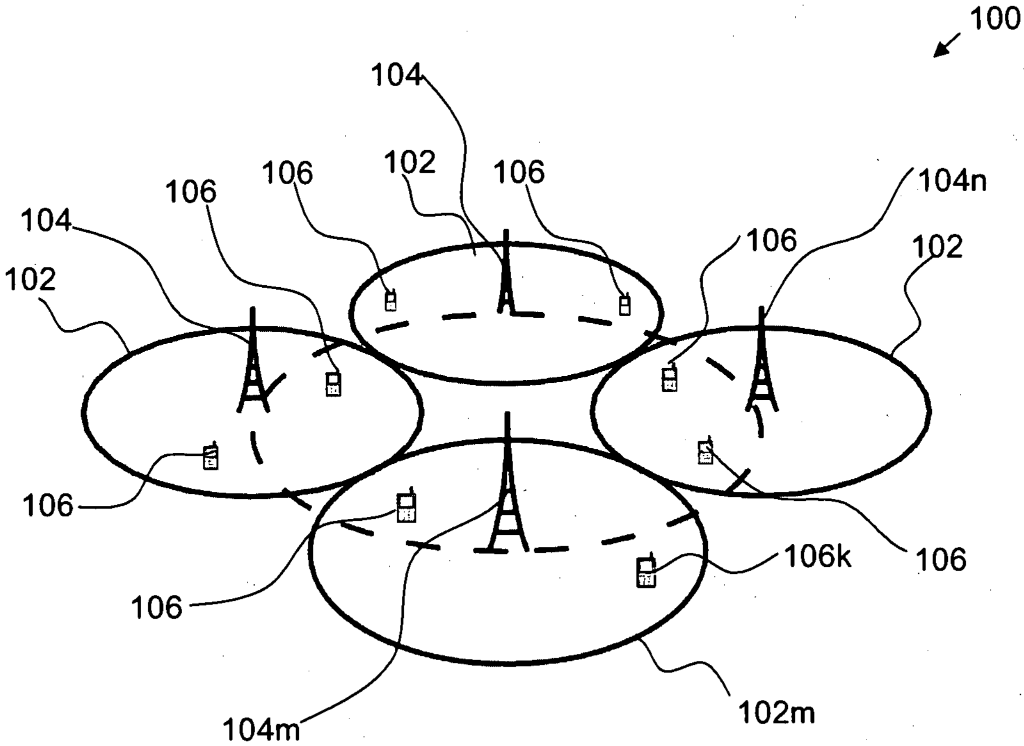

100
104
102
106
106
104n
106
106
102
104
102
106
106
106k
106
106
104m
102m

Figure 1

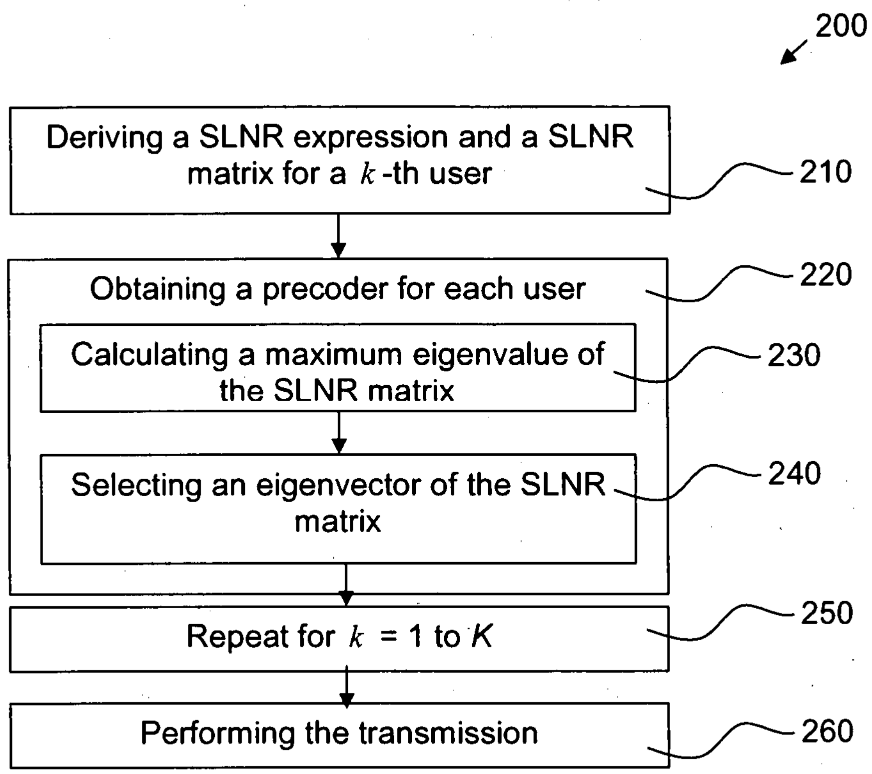

200
Deriving a SLNR expression and a SLNR matrix for a k -th user
210
Obtaining a precoder for each user
220
Calculating a maximum eigenvalue of the SLNR matrix
230
Selecting an eigenvector of the SLNR matrix
240
Repeat for k = 1 to K
250
Performing the transmission
260

Figure 2

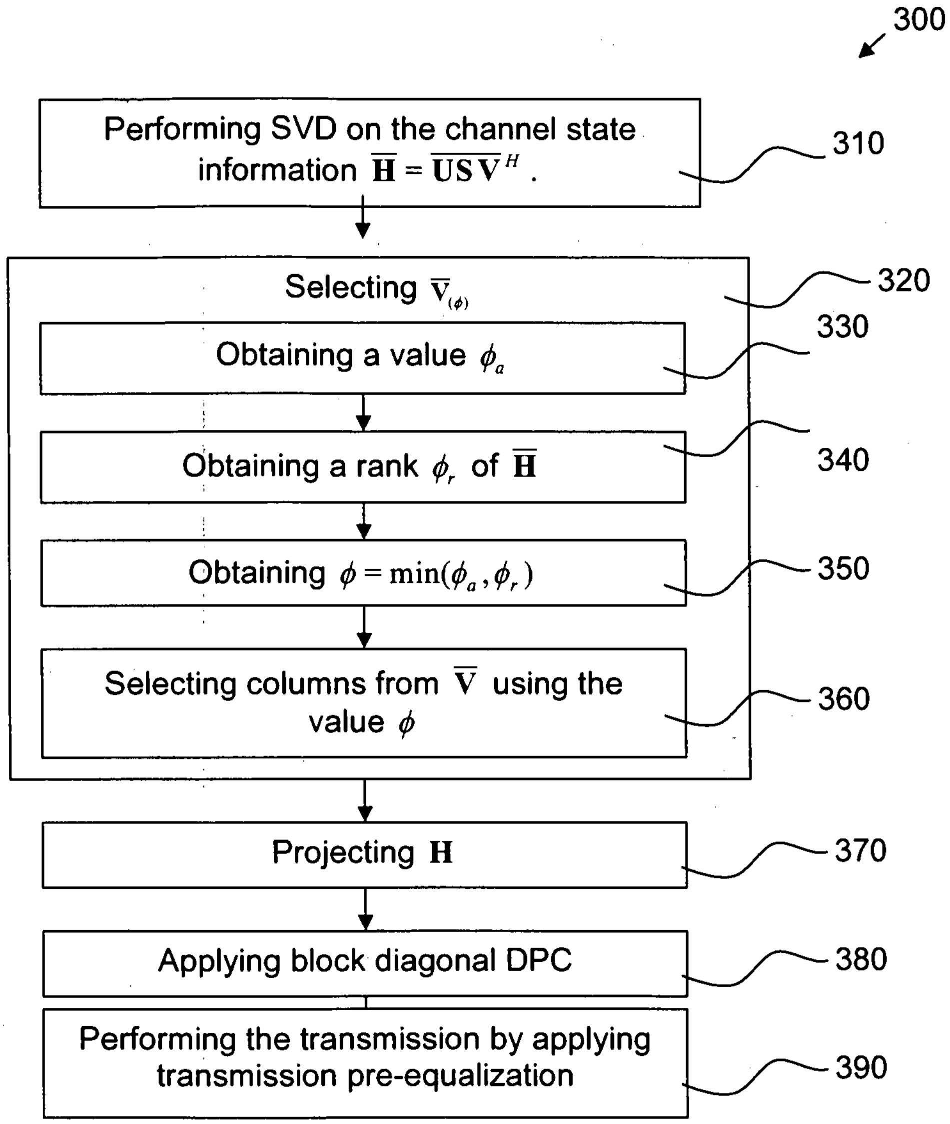

300
Performing SVD on the channel state information $\overline{\mathbf{H}} = \overline{\mathbf{U}}\mathbf{S}\overline{\mathbf{V}}^H$.
310
Selecting $\overline{\mathbf{V}}_{(\phi)}$
320
Obtaining a value ϕ_a
330
Obtaining a rank ϕ_r of $\overline{\mathbf{H}}$
340
Obtaining $\phi = \min(\phi_a, \phi_r)$
350
Selecting columns from $\overline{\mathbf{V}}$ using the value ϕ
360
Projecting $\mathbf{H}$
370
Applying block diagonal DPC
380
Performing the transmission by applying transmission pre-equalization
390

Figure 3

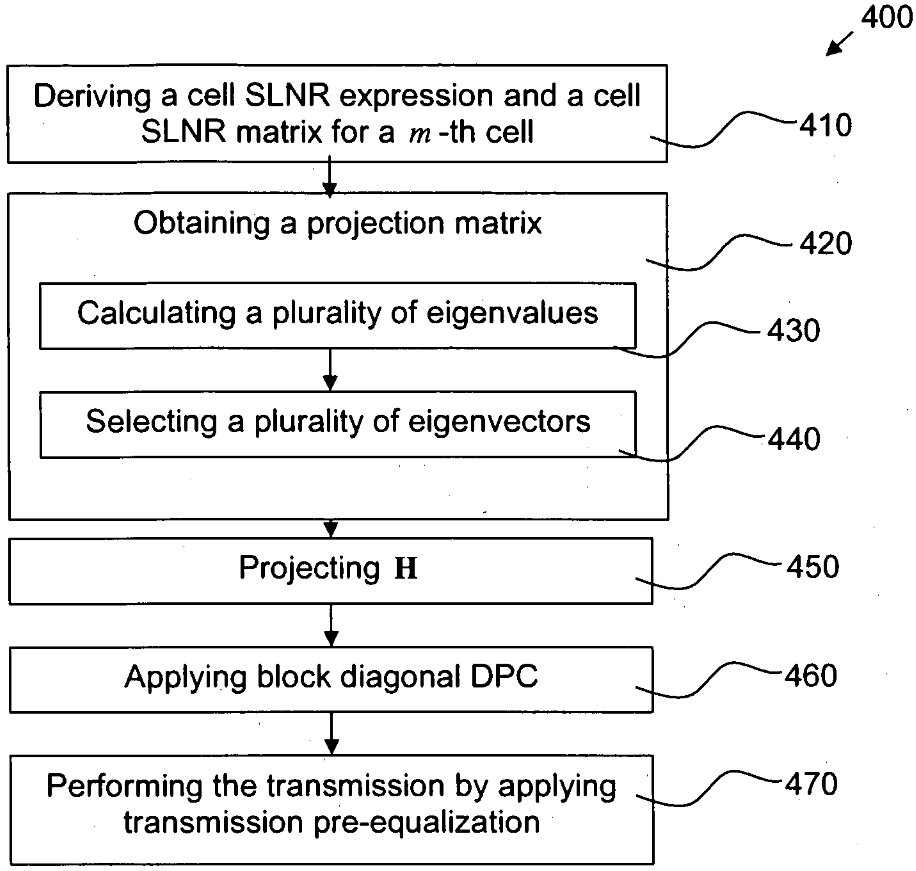

400
Deriving a cell SLNR expression and a cell SLNR matrix for a m-th cell
410
Obtaining a projection matrix
420
Calculating a plurality of eigenvalues
430
Selecting a plurality of eigenvectors
440
Projecting $\mathbf{H}$
450
Applying block diagonal DPC
460
Performing the transmission by applying transmission pre-equalization
470

Figure 4

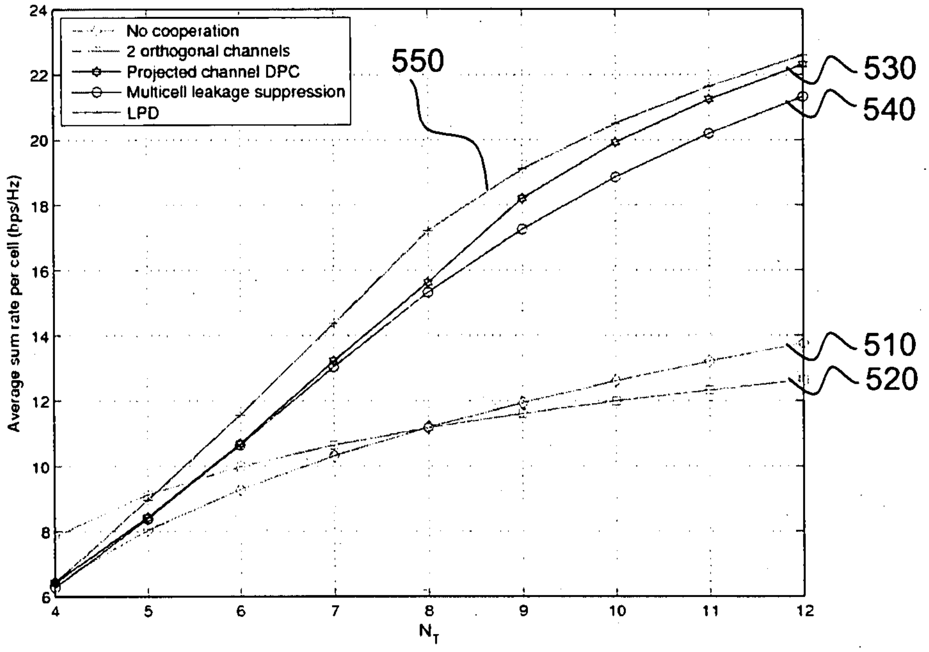


Figure 5

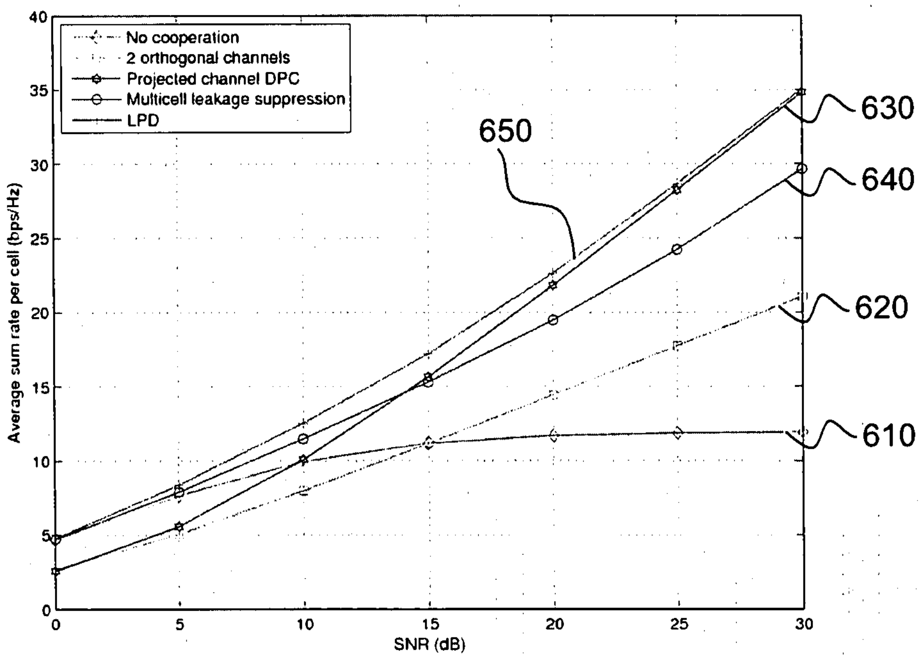


Figure 6

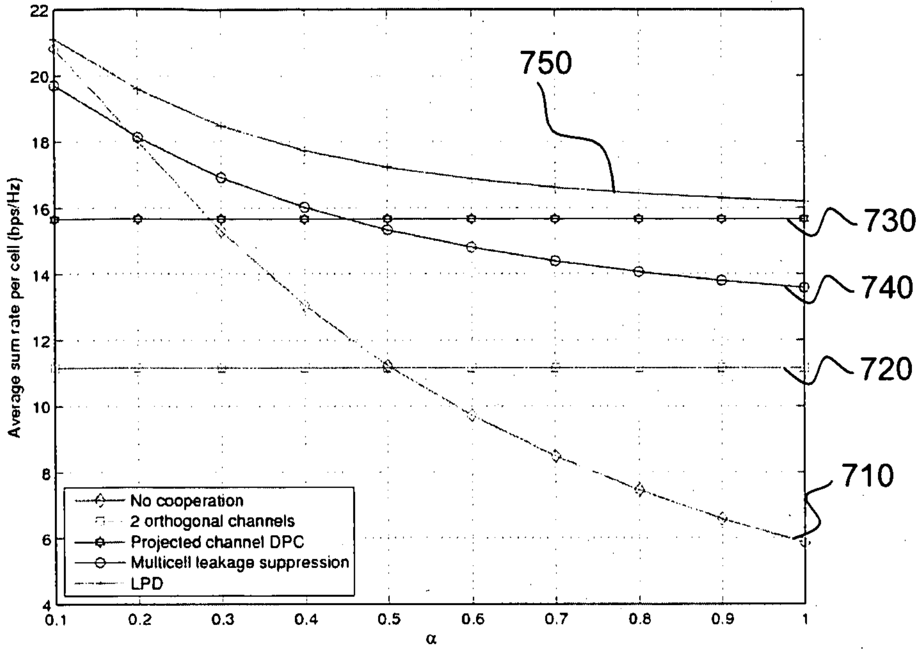


Figure 7

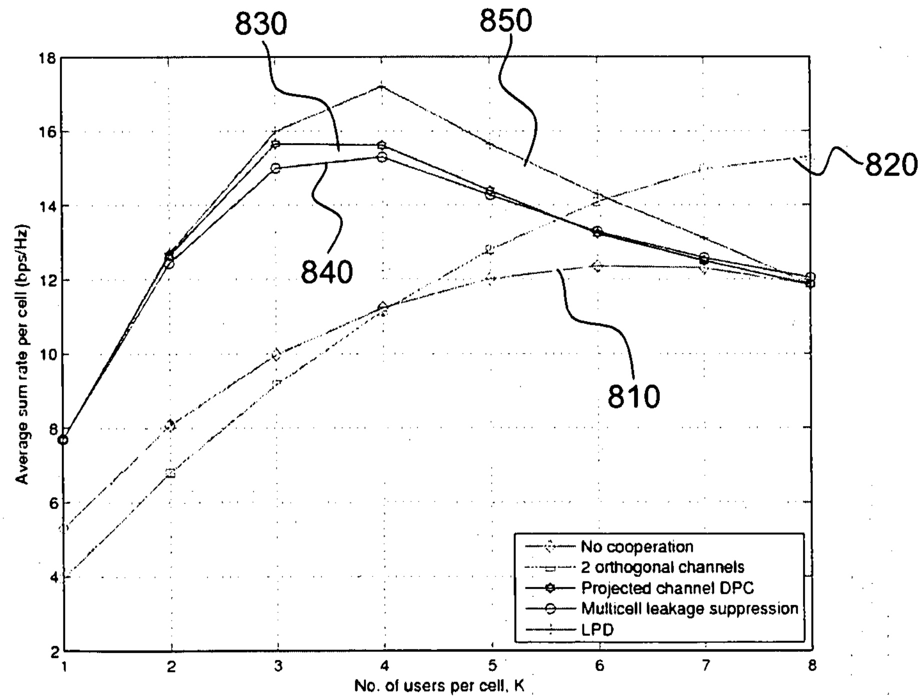


Figure 8

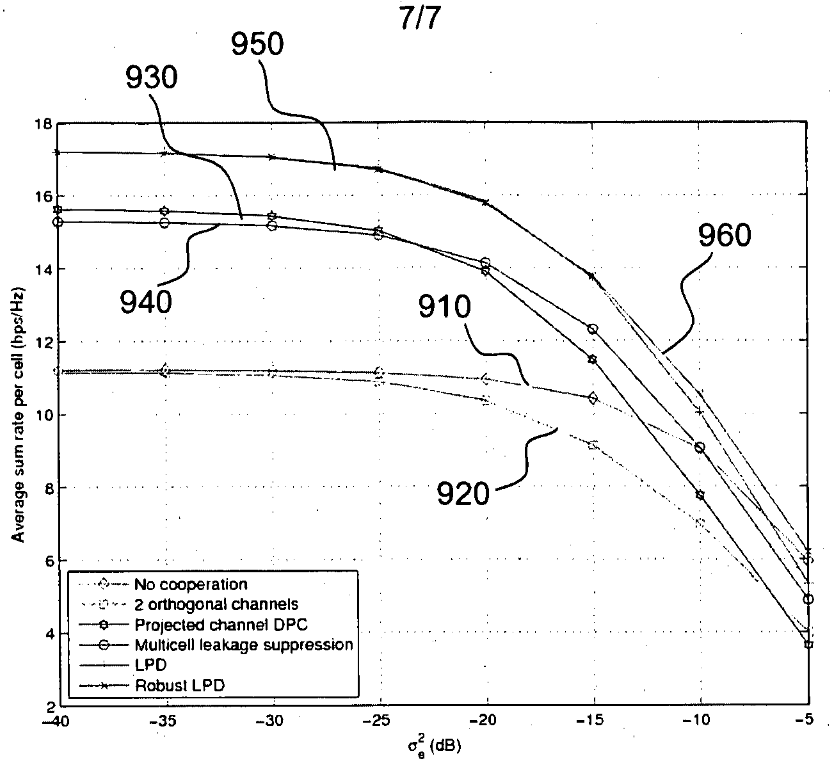


Figure 9

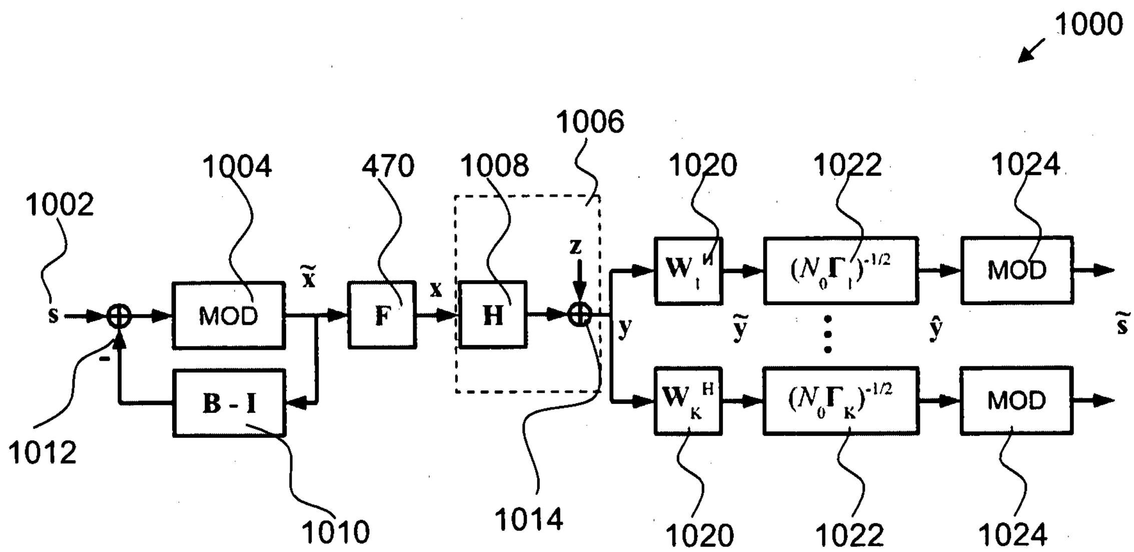


Figure 10

INTERNATIONAL SEARCH REPORT

International application No.
PCT/SG2010/000358

A. CLASSIFICATION OF SUBJECT MATTER

Int. Cl.

H04L 27/28 (2006.01) ***H04M 1/00*** (2006.01) ***H04W 72/04*** (2009.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPODOC, WPI and **INTERNET**: H04L, MIMO, CSI, precoder, plural+, base station, mobile station, interference, minimi+, inter, intra, cell, covariance matrix, linear, non-linear and similar keywords.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	US 2009/0215480 A1 (KIM et al.) 27 August 2009	
Y	Abstract; Fig. 1; paragraphs [0041], [0042], [0097]	1
A		2 – 41
	US 2007/0189151 A1 (PAN et al.) 16 august 2007	
Y	paragraphs [0015], [0034] – [0035]	1
A		2 – 41

[X] Further documents are listed in the continuation of Box C [X] See patent family annex

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
16 December 2010	21 DEC 2010

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/SG2010/000358

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	US 2008/0159425 A1 (KHOJASTEPOUR et al.) 03 July 2008	
A	See Whole Document	
	US 2007/0254607 A1 (BANDEMER et al.) 01 November 2007	
A	See Whole Document	

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.
PCT/SG2010/000358

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report.. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report		Patent Family Member					
US	2009215480	CN	101911529	CN	101911539	CN	101911540
		EP	2227867	EP	2227868	EP	2227869
		KR	20090073973	KR	20090073974	KR	20090073975
		US	2009181708	US	2009207822	WO	2009084904
		WO	2009084905	WO	2009084921		
US	2007189151	AR	059420	AU	2007215314	CA	2641973
		CN	101379748	EP	1994665	KR	20080091398
		KR	20080094935	RU	2008136372	WO	2007095102
US	2008159425	NONE					
US	2007254607	CN	101467362	EP	2013986	KR	20080111147
		US	7706469	WO	2007125169		

Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.

END OF ANNEX