Closed-Loop CSI Feedback with Co-operative Feedback Design for use in MIMO/MISO systems

FIELD OF INVENTION

The invention relates to methods and apparatuses, in particular user terminals and base stations, for implementing a three-phase closed-loop feedback of instantaneous channel state information from a group of user terminals. Aspects of the invention can also be implemented in hardware, software or a combination thereof.

TECHNICAL BACKGROUND

Interference management is recognized as a key enabler to improve spectral and power efficiency in current and future wireless communication systems. In contrast to legacy systems where a cautious network planning avoided interference, in advanced wireless networks, a very intensive use of the available frequency band is allowed at the expenses of a dynamic interference management based on instantaneous and/or statistical knowledge of the channel conditions between each transmit and receive node.

Estimation of the channel parameters and exchange of such information among nodes involved in the interference management play a crucial role in the design of such wireless networks. The estimation of the channel between a node S and a node R requires transmission of a signal from node S to receiver node R, which performs channel estimation based on the received signal. In TDD based communication systems, such channel state information (CSI), usually referred to as local CSI, can be used locally at the receiver as an eventually rough knowledge on the link between node R and node S to manage interference when node R is transmitting. This CSI acquisition scheme is usually referred to as open loop feedback. It is a very simple scheme but often it is inadequate to support effective interference mitigation techniques.

In the article "Noncooperative cellular wireless with unlimited numbers of base station antennas," IEEE Transactions on Wireless Communications, vol. 9, no. 11, pp. 3590–3600, Nov. 2010, Marzetta suggests an open loop feedback scheme for interference control, which however limits the applicability of massive MIMO networks to time division duplex (TDD) mode. By appealing to the reciprocity principle, TDD mode enables the acquisition of the CSI for down-link by channel estimation in the uplink, i.e. in the time slot when the access point with large antenna array plays the role of a receiver. This is an open loop feedback scheme that avoids costly feedback. Although the reuse of the same set of pilot sequences in adjacent cells, usually referred to as pilot contamination, seems to have severe detrimental effects on the spectral and power efficiency of the massive MIMO networks compared to ideal CSI knowledge, nevertheless the promised gains are still of several orders of magnitude and fueled intensive research activities on massive MIMO networks in TDD mode (see also H. Q. Ngo, E. G. Larsson, and T. L. Marzetta, "Energy and spectral efficiency of very large multiuser MIMO systems," IEEE Transactions on Communications, vol. 61, no. 4, pp. 1436–1449, Apr. 2013).

In frequency division duplex (FDD) mode, the open loop feedback is not an option since channel reciprocity does not hold and closed loop feedback is required. In closed loop schemes, receiver nodes R transmit their channel estimates to the transmitter node S such that the transmitter node S can adopt interference management techniques based on a global CSI to optimize the communication performance. Such two-phase scheme is illustrated in Fig. 1. In phase 1, the base station broadcasts a sounding signal 101 which is received by the user terminals. Fig. 1 illustrates three user terminals for exemplary purposes. The user terminals perform 102, 103, 104 channel estimation based on the sounding signal to obtain channel state information, which is sent 105, 106, 107 as feedback in phase 2.

The amount of CSI feedback required from the receiving nodes R in order to allow a transmitter node S to acquire "global" estimation of the channel state can be very large or even prohibitive compared to the coherence time of the channel. In fact, adopting traditional closed loop approaches, the required closed loop feedback for large antenna arrays becomes prohibitive and massive MIMO networks in FDD mode appeared unfeasible.

However, the large majority of currently deployed cellular networks is based on FDD mode. Very recently, promising schemes have been proposed also for FDD mode . In J. Nam, J.-Y. Ahn, A. Adhikary, and G. Caire, "Joint spatial division and multiplexing: Realizing massive MIMO gains with limited channel state information," in 46th Annual Conference on Information Sciences and Systems (CISS), 2012, pp. 1–6; A. Adhikary, J. Nam, J.-Y. Ahn, and G. Caire, "Joint spatial division and multiplexing – the large-scale array regime," IEEE Transactions on Information Theory, vol. 59, no. 10, pp. 6441–6463, Oct 2013 and A. Adhikary and G. Caire, "Joint spatial division and multiplexing: Opportunistic beamforming and user grouping," arXiv preprint arXiv:1305.7252, 2013, the effective channel dimensions are further reduced by a pre-beamforming designed using only second order channel statistics. Then, a reduced amount of feedback is required to design the precoder on the reduced-dimension effective channel. In X. Rao, V. K. Lau, and X. Kong, “CSIT estimation and feedback for FDD multi-user massive MIMO systems,” in Acoustics, IEEE International Conference on Speech and Signal Processing (ICASSP), 2014, pp. 3157–3161 and X. Rao and V. K. Lau, “Distributed compressive CSIT estimation and feedback for FDD multi-user massive MIMO systems,” IEEE Transactions on Signal Processing, vol. 62, no. 12, pp. 3261–3271, 2014, the authors exploit the hidden joint sparsity of the channel for clusters of UTs to reduce both training and feedback by applying compressed sensing techniques.

In the article by A. Adhikary and G. Caire a drastic reduction of the required CSI is obtained in the ideal case as the access point is equipped with a large - theoretically infinite - uniform linear antenna array and each cluster consists of UTs located on a ray with origin at the access point. Those ideal conditions imply a common channel covariance matrix to all UTs in the cluster with a Fourier matrix as eigen-basis. Thus, the selection of a reduced effective channel with negligible performance loss is strongly simplified, since the dominant eigenvectors are common to all UTs, and the required training length and CSI is drastically reduced. The low-rankness of UT channel covariance matrices for more general antenna array settings has been studied for example in in H. Yin, D. Gesbert, M. Filippou, and Y. Liu, “A coordinated approach to channel estimation in large-scale multiple-antenna systems,” IEEE Journal on Selected Areas in Communications, vol. 31, no. 2, pp. 264–273, Feb. 2013 and H. Yin, D. Gesbert, and L. Cottatellucci, “Dealing with interference in distributed large-scale mimo systems: A statistical approach,” IEEE Journal of Selected Topics in Signal Processing, vol. 8, no. 5, pp. 942–953, Oct 2014: under more realistic conditions, with UTs of a cluster randomly located in a given sector and arbitrary topology of large antenna array, the dimensions of the effective channel subspace, defined as the rank of the joint channel covariance, might be still too large. The selection of a reduced effective subspace is not obvious and an arbitrary subspace selection can severely impair the system performance.

In other words, a feedback based on the effective channel is still too demanding, while a choice of the reduced-dimension effective channel based on statistical CSI can be heavily suboptimal.

SUMMARY

One object of the invention is to suggest a new scheme of sending closed-loop feedback on the instantaneous channel state in systems where one or more transmission stations (bases stations, access points) transmit signals to receiver stations (user terminals, user equipments) via an antenna array. The invention aims to suggest a feedback scheme that can improve the system performance (e.g. in terms of a given optimization criterion and/or interference) with the same amount or a lower amount of control plane overhead for sending the feedback in comparison to conventional systems, as exemplarily discussed in the sections herein above.

One aspect of the invention relates to what can be circumscribed as a three-phase closed loop feedback as alternative to the traditional feedback loop in two phases. This scheme exploits a synergy between multiuser networks with stations (e.g. base stations or user terminals) equipped with multiple antenna arrays and device to device (D2D) communications. The proposed scheme can thus be dubbed closed loop feedback with cooperative feedback design.

One of the main ideas underlying the proposed feedback scheme is that, once the channel parameters are estimated by receiver stations, e.g. in form of local CSI, the receiver stations exchange the channel estimation results such that the global channel estimate is available to at least one of them for processing the global channel estimate. The expression global channel estimate may also be denoted global channel state and should be understood as a set of local channel state information from different receiver stations, for example, of a group or cluster or receiver stations. This one receiver station that obtains the global channel state from a group of receiver stations available can also be denoted a master station for simplicity, in case of centralized processing of the global channel state.

Alternatively, distributed processing can be used. In this latter case, the receiver stations (e.g. of a given group or cluster) may also share their local channel state information amongst each other, so that each receiver station (in the group or cluster) is aware of the global channel state and each receiver station may thus determine its own feedback based on the global channel state.

The availability of the global channel state enables a joint optimized selection of channel state information that is to be fed back to the transmitting station. For example, when assuming that the number of bits that can be sent as feedback to the transmitting station is limited/predefined and thus a compression of channel states is required for feedback, the processing of the global channel state (vs. the local channel state) allows an optimized selection of the channel state parameters of the local channel states that are communicated back to the transmitting station which yields a drastic performance improvement compared to the selection of channel state parameters for feedback based only the local channel state information or based on statistical channel state information as proposed by A. Adhikary and G. Caire in their article "Joint spatial division and multiplexing: Opportunistic beamforming and user grouping".

Alternatively, instead of optimizing the selection of feedback on the instantaneous channel state as observed by the receiver stations, a dedicated receiver station (e.g. the master station) may also determine the optimal transmission scheme for the receiver stations of the group or cluster based on the global channel state information. The selected transmission scheme (e.g. a modulation and coding scheme and/or a beamformer configuration, or only a part of the parameters thereof) may be fed back to the transmitting station and the transmitting station may adopt the signaled parameter(s) of the transmission scheme for transmissions to the group or cluster of receiver stations. For example, the transmission scheme could be communicated by means of a codeword selected from a transmission scheme codebook known to the transmitting station and the receiver station(s).

The selection of the channel state parameters for feedback or the transmission scheme based on the global channel state information may be for example implemented such that some optimization criterion (or criteria) is (are) fulfilled. Exemplary criteria are for example – and without loss of generality – minimization of interference of transmissions to the group of receiver stations (with or without additional consideration of a fairness constraint), maximization of the data rate for transmissions to the group of receiver stations (with or without additional consideration of a fairness constraint), minimization of some bit error or frame error rate for transmissions to the group of receiver stations (with or without additional consideration of a fairness constraint), etc. Note that one or more of these criteria may be applied taking into account the limitations on the amount of feedback information (e.g. in terms of a number of bits) that can be communicated to the transmitting station.

One exemplary embodiment of the invention relates to a method ("feedback method") for use in communication system using an antenna array, such as a MISO or MIMO communication system. In this method one or more of the transmitting stations transmits a sounding signal to a group of receiver stations via a channel using an antenna array. Each of the receiver stations of the group receives the sounding signal from one or more of the transmitting stations via a channel, and performs a channel estimation based on the sounding signal. Each of the receiver stations of the group thereby obtains respective channel state information characterizing the instantaneous channel state.

At least one of the receiver stations of the group receives the channel state information obtained by the other receiver stations of the group, and processes the channel state information jointly to obtain optimized feedback on the channel that allows one or more of the transmitting stations to select a transmission scheme for transmitting signals via the channel to the group of receiver stations. The optimized feedback on the channel is transmitted to one or more of the transmitting stations.

In several embodiments of the invention, the transmission scheme is a modulation and coding scheme or a beamformer configuration (beamforming pattern), or a combination of both. The transmission scheme may also denote only a subset of the parameters that are configurable within the given transmission scheme.

In an example implementation of the embodiment, the sounding signal is for example formed by a plurality of pilot symbols or preambles exciting a set of orthogonal beamformer configurations.

According to a further exemplary embodiment of the invention, the channel state information of the respective receiver stations of the group each comprises a set of channel coefficients and the processing of the channel state information is based on an algorithm selecting a sub-set of the channel coefficients in each channel state information according to some optimization criterion, wherein the selected sub-set of the channel coefficients in each channel state information is transmitted to one or more of the transmitting stations within the optimized feedback. For example, in some implementations, the channel state information forms a vector of dimension d and the joint processing selects a sub-set of $s < d$ indices within the vector identifying the channel coefficients to be fed back from each channel state information vector.

In some embodiments, the sounding signal may sound the channel with different orthogonal beamformer configurations. The channel coefficients of each channel state information of the receiver stations may thus represent a channel estimate of the channel for the respective different beamformers represented by respective beamformer configurations.

Further optionally, the respective beamformer configurations could correspond to respective eigenvectors of a covariance matrix describing the channel. Accordingly, sounding signal as received via the channel by the receiver stations can be viewed as a projection of the channel onto a given eigenvector of a covariance matrix describing the channel.

In another embodiment of the invention, one or more of the transmitting stations reconstructs the instantaneous channel state observed by each of the receiver stations of the group based on the optimized feedback, and selects a transmission scheme for transmitting signals to the group of receiver stations based on the reconstructed instantaneous channel state.

In a further embodiment of the invention, the at least one of the receiver stations of the group which performs the processing of the channel station information of the receiver stations transmits the information on the selected sub-set of channel coefficients to the other receiver stations of the group. Each of the receiver stations of the group transmits the sub-set of channel coefficients of the respective receiver station's channel state information to one or more of the transmitting stations. As noted above, for example, in case the indices within the channel state information vectors are selected, the s selected indices are communicated to the other receiver stations of the group and each receiver station of the group will send s channel coefficients of its local channel state information vector at the selected indices together with an information on the selected indices to one or more of the transmitting station.

When not using the centralized processing approach, in an alternative embodiment of the invention, each receiver station of the group may receive the channel state information from the respective other receiver stations of the group and selects the sub-set of the channel coefficients for transmission to one or more of the transmitting stations. As the receiver stations may use the same optimization criterion for the joint processing of the global channel state information, the receiver stations of the group will select the same subset of channel coefficients from the local channel state information and will feed them back to one or more of the transmitting stations.

Irrespective of whether centralized or distributed processing of the global channel state is used, optionally, in embodiments of the invention, the respective sub-sets of channel coefficients of the respective receiver station's channel state information are transmitted by the receiver stations of the group in parallel, so as to arrive at one or more of the transmitting stations with the same timing. This may be ensured for example by using mechanisms similar to timing advance to coordinate uplink reception timing of the receiver stations.

In another embodiment of the invention, a receiver station may directly determine the transmission scheme based on the global channel state information. In this embodiment, the at least one of the receiver stations of the group selects a transmission scheme for transmitting signals from one or more of the transmitting stations to the group of receiver station via the channel. According to this embodiment, the optimized feedback indicates the selected transmission scheme to one or more of the transmitting stations. For example, the selected transmission scheme could be communicated by means of a codeword of a codebook known to one or more of the transmitting stations and the group of receiver stations.

In some embodiments of the invention, the selected transmission scheme consists of or comprises a beamformer configuration to be used for transmitting signals to the receiver stations of said group.

In a further embodiment of the invention, one or more of the transmitting stations selects the transmission scheme indicated in the optimized feedback for transmitting signals to the group of receiver stations.

In another embodiment of the invention, the at least one of the receiver stations of the group transmits the selected transmission scheme to the other receiver stations of the group, and each of the receiver stations of the group transmits at least a portion of the optimized feedback to one or more of the transmitting stations in parallel.

In a further embodiment of the invention, the at least one of the receiver stations of the group receives the channels state information from the other receiver station of the group using device-to-device communication.

Another exemplary embodiment of the invention relates to a receiver station for use in a communication system. The receiver station comprises a receiver unit adapted to receive a sounding signal from one or more of the transmitting stations via a channel, wherein the sounding signal has been transmitted from one or more of the transmitting stations using an antenna array. The receiver unit is further adapted to receive channel state information obtained by the other receiver stations by channel estimation based on the sounding signal. The receiver station further comprises a processing unit adapted to perform a channel estimation based on the sounding signal to thereby obtain channel state information characterizing the instantaneous channel state. The processing unit is further adapted process the channel state information of the receiver station and the other receiver stations jointly to obtain optimized feedback on the channel that allows one or more of the transmitting stations to select a transmission scheme for transmitting signals via the channel to the receiver stations. The receiver station also comprises a transmitter unit adapted to transmit the optimized feedback on the channel to one or more of the transmitting stations.

A further embodiment of the invention relates to another receiver station that comprises a receiver unit adapted to receive a sounding signal from one or more of the transmitting stations via a channel, wherein the sounding signal has been transmitted from one or more of the transmitting stations using an antenna array, a processing unit adapted to perform a channel estimation based on the sounding signal to thereby obtain a set of channel coefficients forming channel state information characterizing the instantaneous channel state, and a transmitter unit adapted to send the channel state information to another receiver station. The receiver unit is further adapted to receive from the other receiver station an information indicating a sub-set of the channel coefficients forming the channel state information, and the transmitter unit is further adapted to transmit the indicated sub-set of channel coefficients to one or more of the transmitting stations.

Another embodiment of the invention relates to a transmitting station for use in a MISO or MIMO communication system comprising an antenna array, a transmitter unit adapted to transit a sounding signal via a channel using the antenna array, and a receiver unit adapted to receive optimized feedback on the channel from at least one of a plurality of receiver stations. The optimized feedback is based on the instantaneous channel state observed by the plurality of users receiving the sounding signal and allows one or more of the transmitting stations to select a transmission scheme for transmitting signals via the channel to the receiver stations. The transmitter unit of the transmitting station is further adapted to use the transmission scheme indicated in the optimized feedback for transmitting signals to the plurality of receiver stations.

In another exemplary embodiment, the processing unit of the transmitting station is further adapted to reconstruct the instantaneous channel state observed by each of the plurality of receiver stations based on the optimized feedback, and to select the transmission scheme for transmitting signals to the plurality of receiver stations based on the reconstructed instantaneous channel state.

Alternatively, in other embodiments, the antenna array may be a distributed antenna array, that is for example formed by the antennas of several transmitting stations. Such MISO or MIMO communication system may thus comprise a plurality of transmitting stations, wherein each transmitting station comprises at least one antenna, a transmitter unit adapted to transmit a sounding signal via a channel using the at least one antenna, a receiver unit adapted to receive optimized feedback on the channel from at least one of a plurality of receiver stations, wherein the optimized feedback is based on an instantaneous channel state observed by the plurality of users receiving the sounding signal from the plurality of transmitting stations and allows one or more of the transmitting stations to select a transmission scheme for transmitting signals via said channel to the receiver stations. The transmitter unit of the transmitting stations is adapted to use the transmission scheme configuration indicated in the optimized feedback for transmitting signals to said plurality of receiver stations. The antennas of the transmitting stations form an antenna array for transmitting said signals to the group of receiver stations.

Further embodiments of the invention relate to a receiver station and a transmitting station, each of which comprises components formed in hardware and/or software for performing the feedback method according to one of the various embodiments discussed herein.

In addition, the individual method steps performed by a receiver station in one of the various embodiments of the feedback method described herein may also be implemented by means of computer-executable instructions that are stored on a computer readable storage medium. When executing those stored instructions on the computer readable storage medium by a processor of the receiver station, the receiver station would thus perform individual method steps performed by a receiver station in one of the various embodiments of the feedback method described herein. Similarly, the individual method steps performed by one or more of the transmitting stations in one of the various embodiments of the feedback method described herein may also be implemented by means of computer-executable instructions that are stored on a computer readable storage medium. When executing those stored instructions on the computer readable storage medium by a processor of one or more of the transmitting stations, one or more of the transmitting stations would thus perform individual method steps performed by one or more of the transmitting stations in one of the various embodiments of the feedback method described herein.

In case of embodiments where there are plural transmitting stations, transmission to “one or more of the transmitting stations” means that the information is transmitted to one of the transmitting stations, to a subset of the transmitting stations or to all of transmitting stations. If the feedback is sent to only one or a subset of the transmitting stations in this scenario, the one transmitting station or the subset transmissions receiving the feedback may optionally provide the feedback to the other transmitting stations. In another alternative embodiment of the invention, where feedback is sent to one of the plural transmitting stations, the one transmitting station may optionally either share the feedback with the other transmitting stations, or may select a transmissions scheme for all transmitting stations and may inform the other transmitting stations on the selected transmission scheme.

BRIEF DESCRIPTION OF FIGURES

In the following embodiments of the invention are described in more detail in reference to the attached figures and drawings. Similar or corresponding details in the figures are marked with the same reference numerals.

Fig. 1 shows a conventional two-phase channel state information feedback scheme,

Fig. 2 shows an exemplary three-phase channel state information feedback scheme according to an embodiment of the invention,

Fig. 3, 4 & 5 highlight the three phases of the channel state information feedback scheme of Fig. 2,

Fig. 6 & 7 show simulation results comparing an exemplary three-phase channel state information feedback schemes according to embodiments of the invention with an exemplary reference two-phase channel state information feedback scheme of the state of the art,

Fig. 8 shows an exemplary embodiment of a user terminal according to an embodiment of the invention, and

Fig. 9 shows an exemplary embodiment of a base station according to an embodiment of the invention.

DETAILED DESCRIPTION

The following paragraphs will describe various embodiments of the different aspects. For exemplary purposes only, most of the embodiments are outlined in relation to massive MIMO/MISO communication systems in FDD mode using beamforming for building clusters of user terminals. However, the invention can also be readily applied generally to MIMO/MISO systems with beamforming which could be operated in FDD or TDD mode.

It is noted that the invention can be applied in uplink and downlink. The transmitting station may be for example a base station (sometimes also denoted access point or NodeB), and the receiver station may be a user terminal (sometimes also denoted mobile terminal or user equipment) when a downlink scenario is considered. The receiver station may be for example a base station, and the transmitting station may be a user terminal (sometimes also denoted mobile terminal or user equipment) when an uplink scenario is considered. Furthermore, besides providing an antenna array on a single station, the principles of the invention may be also practiced using a distributed antenna array, where the antennas of the array are provided by multiple stations.

Notably, the following description focuses on a downlink scenario with a single base station that has an antenna array. Furthermore, the following description also focuses on beamformer configurations as an example of a transmission scheme or part of a transmission scheme. However, as noted above, this is not to be considered limiting the applicability of the principles of the invention to such systems.

As noted herein above, one aspect of the invention relates to a three-phase closed loop feedback as alternative to the traditional feedback loop in two phases. Fig. 2 shows an exemplary three-phase channel state information feedback scheme according to an embodiment of the invention practiced in the downlink. This scheme exploits a synergy between multiuser networks with base stations (access points, Node Bs) equipped with multiple antenna arrays and device to device (D2D) communications. The proposed scheme can thus be dubbed closed loop feedback with cooperative feedback design. Similar to phase 1 in Fig. 2, the base station broadcasts 101 a sounding signal which is received by a group of user terminals. The user terminal perform 102, 103, 104 channel estimation based on the sounding signal, and thereby obtain local channel state information describing the instantaneous channel state. Unlike Fig. 2, in phase 2, the user terminals share 201 the channel state information amongst each other or report them to a master terminal. Accordingly, at least the master terminal thus becomes aware of the local channel state information of the other user terminals and therefore has information on the instantaneous global channel state available as observed by all user terminals of the group. Based on this instantaneous global channel state, the feedback information that is to be sent back to the base station is designed 202 as will be explained below in further detail. The feedback is then sent 203 back from the user terminals (or the master terminal only) to the base station. The base station can use this feedback to select the beamformer for transmissions to the user terminals of the given group.

To better understand the theoretic principles underlying the feedback scheme discussed herein, the theoretic basis is elaborated in more detail herein below. For simplicity and for exemplary purposes only, but without losing generality, the following description focuses on a multiuser single-cell system with a base station that serves K single-antenna users. The base station is equipped with an antenna array and uses a beamformer to direct transmissions on downlink to one or more groups of user terminals, which define a “cluster”. It is worth noticing that clustering is not an essential requirement for the applicability of the proposed closed-loop feedback scheme. The user terminals (in a group) may have a single antenna (MISO case) or multiple antennas (MIMO case). The described principles can be extended to a more general setting with multiple base stations (access points, Node Bs), which are not necessarily organized by a cellular planning and user terminals equipped with multiple antennas. For example, as noted above the principles of the invention may also be applied to systems, where the antenna array is formed by the antennas of different base stations. In another example a mobile terminal transmits signals via an antenna array and received feedback on the instantaneous channel quality using the principles of the invention herein.

The base station has *M* antennas and operates in FDD mode. Again, the operation in FDD mode as well as the application of the principles to downlink transmissions is only exemplary, as it is a mode of operation where the principles of the invention can be advantageously used. The downlink channel between the base station and the k^{th} user terminal is denoted by the vector $h_k^H \in \mathbb{C}^{1\times M}$. The full downlink channel can therefore be represented by the matrix:

$$\mathbf{H}^H = \begin{bmatrix} \mathbf{h}_1^H \\ \vdots \\ \mathbf{h}_K^H \end{bmatrix}_{\in \mathbb{C}^{K\times M}} \qquad (1)$$

Additionally, the base station uses a linear precoder or beamformer for downlink transmissions. Different precoding schemes (beamformer configuration) may be used by the base station. Then, the downlink transmission is modeled by:

$$\mathbf{y} = \mathbf{H}^H\mathbf{B}\mathbf{s} + \mathbf{n} \qquad (2)$$

where $y \in \mathbb{C}^{K\times 1}$ represents the signal received by all the user terminals, $s \in \mathbb{C}^{K\times 1}$ denotes the vector of i.i.d. Gaussian signals transmitted by the base station with zero-mean and unit-variance, and n represents the spatially and temporally white additive Gaussian noise (AWGN) with zero-mean and element-wise variance σ_n^2. B represents the downlink beamformer with total power P.

In an embodiment, in a first phase (phase 1 as shown in Fig. 2) of the closed-loop feedback scheme, the downlink channel is sounded for channel estimation by the user terminals. Without loss of generality, it can be assumed that the base station has statistical knowledge of each channel, i.e. it knows the covariance matrix $E\{h_k h_k^H\} = R_k, \forall k$. As discussed in more detail below, in case the bases station selects the beamformer configuration, the user terminals do not need to have statistical knowledge of their respective observed channel, i.e. do not necessarily know the covariance matrix R_k.

Generally, this statistical information and thus long term knowledge on the channel may be for example acquired by the user terminals from the preamble(s) sent during channel sounding. The possibility to track the channel covariance matrix is based on the assumption that each channel is locally stationary with respect to the coherence time of the instantaneous channel vector h_k. Channel covariance tracking is a well established field in signal processing and several techniques are available both for low dimension antenna array channel vector and for very large antenna arrays. An overview on recent techniques, mostly developed for large antenna arrays is presented by A. Adhikary, J. Nam, J.-Y. Ahn, and G. Caire, in their article "Joint spatial division and multiplexing – the large-scale array regime" mentioned previously herein.

The assumption of statistical channel knowledge at the base station (and depending on the implementation, also at one or more of the user terminals) is for example relevant in systems where the transmitters are equipped with a large number of antennas, as for example in FDD massive MIMO systems. In general, the channel estimation at the user terminals is typically based on training sequences (sounding signal) of length proportional to the number of antennas M at the base station and designing training sequences for antenna array with a very high number of antennas (e.g. $M >> 50$) could be very expensive in terms of utilization of transmission resources or even unaffordable in the coherence time of the system. However, in these cases, the channel covariance matrices R_k exhibits a low-rank property that depends on the scattering environments. In example implementations of the proposed feedback scheme, clusters of user terminals whose covariance matrices span vector subspaces almost overlapping are built, and further simultaneous transmissions may be scheduled only for clusters of user terminals whose subspaces are mutually orthogonal.

The set $\{c_1, c_2, \dots, c_\ell\}$ defines a group or cluster of ℓ user terminals whose covariance matrices are similar in terms of spanning almost the same subspace. Spanning almost the same subspace means that none of the considered covariance matrices has an effective space rank d that differs from the effective rank d_C of the cluster covariance matrix $R_C = E\{\sum_{k\in C} h_k h_k^H\}$ by not more than a threshold value T. For example and in more detail, let $\lambda_m(R)$ denote the m^{th} eigenvalue of the covariance matrix R_{c_i} where the eigenvalues of R are ordered in decreasing order, i.e. $\lambda_1(\mathrm{R}) \geq \lambda_2(\mathrm{R}) \geq \lambda_3(\mathrm{R}) \geq \cdots$. The effective space rank d of the matrix R is defined such that $\lambda_d(R) \geq \epsilon$ while $\lambda_{d+1}(R) < \epsilon$ with ϵ being a given nonnegative real. The covariance matrices $R_{c_1}, R_{c_2}, \ldots, R_{c_\ell}$ span almost the same subspace if, given a threshold $T > 0$, the following inequation is fulfilled:

$$\frac{d_C - \max_{k\in C} d_k}{d_C} \leq T$$

where d_C is the effective rank of the cluster covariance matrix $R_C = E\{\sum_{k\in C} h_k h_k^H\}$

The cluster $C = \{c_1, c_2, \ldots c_\ell\}$ is characterized by a covariance matrix $R_C = E\{\sum_{k\in C} h_k h_k^H\}$. By construction, R_c spans a vector subspace that contains the vector subspaces spanned by the individual covariance matrices R_c, for $k \in C$. The rank of the covariance matrix R_c is denoted d. Applying an eigen-value decomposition (EVD) to the covariance matrix R_c gives:

$$\mathbf{R}_C = \mathbf{U}_C \mathbf{\Sigma}_C \mathbf{U}_C^H \tag{3}$$

Without loss of generality, the eigenvalues in Σ_c are assumed to be in descending order, so that the first d eigen-values are non-negligible, while the others can be neglected. We extract the first d columns of U_c in order to form a sub-matrix $\widetilde{U}_C \in \mathbb{C}^{M\times d}$. Now the instantaneous channel vector h_k, for $k \in C$, is in the column space of $\widetilde{U}_C$, e.g., $\forall k \in C$, $h_k$is a linear combination of the columns of $\widetilde{U}_C$. The vector space spanned by $\widetilde{U}_C$ identifies the effective channel space of cluster C. Note that clusters of user terminals spanning orthogonal subspaces have eigen-bases $\widetilde{U}_C$ which are also orthogonal each other. Then, by designing the precoder for cluster C in the effective channel subspace $\widetilde{U}_C$, the transmitted signal will be orthogonal to the signals of all the user terminals belonging to other clusters and it will not cause interference. Thus, without loss of generality we can focus on a cluster and write its instantaneous channel as

$$\mathbf{H}_C = \begin{bmatrix} \mathbf{h}_{C_1} & \mathbf{h}_{C_2} & \cdots & \mathbf{h}_{C_\ell} \end{bmatrix} = \widetilde{\mathbf{U}}_C \mathbf{A}_C \tag{4}$$

where $A_c \in \mathbb{C}^{d\times \ell}$ is defined as:

$$\mathbf{A}_c \triangleq \begin{bmatrix} \mathbf{a}_1 & \mathbf{a}_2 & \cdots & \mathbf{a}_\ell \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1\ell} \\ a_{21} & a_{22} & \cdots & a_{2\ell} \\ \vdots & \vdots & \cdots & \vdots \\ a_{d1} & a_{d2} & \cdots & a_{d\ell} \end{bmatrix} \quad (5)$$

In an example embodiment of the three-phase closed-loop feedback scheme proposed herein, the base station forms clusters of user terminals and announces the cluster composition to the user terminals in the downlink. This announcement may also provide the information to enable device-to-device (or peer-to-peer) communications among user terminals belonging to the same clusters. The device-to-device communications between user terminals of a cluster can be supported by protocols in the suite of protocols for 5G which, according to the declared intentions of the 5G Public Private Partnership, should support device-to-device communications and massive MIMO technologies or by existing wireless local area network (W-LAN) technologies. It is apparent that the user terminals that share close to identical channel covariance matrices R_k are user terminals located close to each other and sharing similar/identical scattering environments. Therefore, local area device-to-device communication technologies can be employed for enabling device-to-device communication between user terminals in a group/cluster.

As noted previously, one exemplary embodiment of the closed-loop feedback scheme proposed herein uses centralized feedback design. In this case, a master terminal is selected among the user terminals of each cluster and performs the feedback design considering the global channel state. The master terminal may be for example selected by the base station. Optionally, in cases where the (at least) the master terminal needs to have knowledge of the eigen-basis $\widetilde{U}_C$ is relevant, for example, for selecting an optimal beamformer configuration for the cluster, the other user terminals of the cluster need to signal their individual covariance matrices R_k to the master terminal to allow the master terminal to construct eigen-basis $\widetilde{U}_C$.

In more complex scenarios, e.g. in ad hoc networks, user terminals may be self-organizing and could autonomously select their clusters, e.g. according to cooperative games, and the base station is informed of the clustering. Further or alternatively, the user terminals of a cluster may (also) autonomously select a master terminal that performed the centralized processing of the global channel state.

An exemplary channel sounding scenario with user clustering is illustrated in Fig. 3. The base station transmits training sequences to each cluster. The training sequences are expressed by a matrix S of sounding symbols, and the columns of may be orthogonal to each other. Further, the training sequences S are distributed to the transmit antennas by means of the beamformer $B = \widetilde{U}_C$. For example and in further detail, if the matrix of training sequences S is a $d \times d$ matrix whose rows are the orthogonal training sequences, the transmitted beamformed signal for cluster C is $X = \widetilde{U}_C S$ and the signal received jointly by all terminals in the cluster is the $\ell \times d$ matrix $Y = A_c^T X + N$, where N is the $\ell \times d$ matrix of the additive white Gaussian noise. In other words, the individual training sequences of the sounding signal sent by the base station correspond to the respective eigenvectors of eigen-basis $\widetilde{U}_C$ or a linear combination of the eigenvectors.

The sounding signal is received by the user terminals in the cluster and each of the user terminals performs a channel estimation to produce instantaneous channel state information (CSI) characterizing the channel as observed for the different beamformers of the training sequences. The channel estimation result may be for example represented as a vector of channel coefficients for the different beamformers. Assuming that the rank of eigen-basis $\widetilde{U}_C$. is d, the local CSI of a respective user terminal k would thus correspond to a column vector a_k, which holds d channel coefficients characterizing the instantaneous channel state.

Following channel sounding and channel estimation by the user terminals (of a cluster) to obtain local CSI, in phase 2 of the three-phase closed-loop feedback scheme according to an embodiment, the local CSI is shared amongst the user terminals (of the cluster). As noted this is advantageously implemented using direct device-to-device communication techniques and protocols. The sharing of CSI is exemplarily illustrated in Fig. 4. In case of centralized processing, the master terminal receives the local CSI from the other user terminals in the cluster. The master terminal can reconstruct the instantaneous global channel state observed by the user terminals of the cluster. The instantaneous global channel state can be represented as matrix A_c which is reconstructed by the master terminal based on the column vectors a_k received from the other user terminals. Note that strictly speaking, since the channel coefficients of the column vectors a_k of the user terminals may need to be compressed (quantized and/or encoded to a given number of bits) the reconstructed matrix A_c may not be a perfect reconstruction of the local CSIs of the user terminals of the cluster.

In an alternative implementation and in a distributed processing scenario, all the user terminals in a cluster transmit their local CSI to the other user terminals of the cluster, so that each user terminal can reconstruct matrix A_c and design feedback on the instantaneous global channel state observed by the user terminals of the cluster.

Once the global instantaneous global channel state (global CSI) is reconstructed it can be processed for optimum design of the feedback under some optimization constraint. This optimization constraint may require fulfillment of one or more criteria. For example, the total amount of information to be fed back may be predefined, so that the available information for feedback may need compression. In the above example, this may require the selection of only a sub-set of the channel coefficients of the column vectors a_k for feedback and/or selecting according quantization and/or encoding schemes. In addition to compression or independently therefrom, the criterion/criteria considered in processing the instantaneous global channel state represented by the reconstructed matrix A_c are criteria that do not optimize the feedback for a single user terminal only (as it would be the case for conventional feedback schemes, where each user terminal sends its individual compressed local CSI), but the criteria should take into account the overall cluster of terminals, for example by including fairness constraints that ensure fairness of the processing algorithm amongst the user terminals. For example, the joint processing of the instantaneous global channel state represented by the reconstructed matrix A_c could for example yield maximizing the sum data rate of transmissions to all user terminals of the cluster for a given amount of feedback (in terms of bits). This example is however not to be considered limiting, and other criteria, e.g. minimization of the interference and/or bit error rate of transmissions to all user terminals of the cluster for a given amount of feedback with or without considering fairness constrained could be also considered.

In the following two optimal design techniques aiming at maximizing the sum rate under constraint on the feedback amount are considered for exemplary purposes only.

Optimal Reduced Effective Subspace Design

In this section a first exemplary implementation to optimally reduce the channel subspace utilized for transmission based on the knowledge of instantaneous global CSI available at the master terminal. It is worth noticing that this method does not require the user terminals to have knowledge of the cluster covariance matrix R_c and the common eigen-basis $\widetilde{U}_C$. Once the feedback has been optimally designed by the master user terminal the feedback is sent to the base station. Feedback transmission may be distributed in the sense that all cluster user terminals send feedback in a coordinated manner. In this first exemplary implementation, as noted above, the master terminal receives the local CSI from the other user terminals in the cluster and builds the instantaneous global channel state represented by reconstructing matrix A_c from the local CSI. As will be outlined below, the master terminal may determine the feedback based on the instantaneous global channel state represented by matrix A_c according to some optimization criterion, without knowledge of the cluster covariance matrix R_c and the common eigen-basis $\widetilde{U}_C$, since the signal-to-noise ratio (SNR) experiences by the user terminals for a beamformer B is independent on the eigen-basis $\widetilde{U}_C$ and cluster covariance matrix R_c. This will be explained in the following.

Extracting N $(\ell \leq N \leq d)$ rows from matrix A_c, one can form a new matrix $A_s \in \mathbb{C}^{N \times K}$; and by extracting the corresponding N columns of the eigen-basis $\widetilde{U}_C$, one can form a matrix $U_s \in \mathbb{C}^{M \times N}$. The channel matrix H_s using incomplete CSI represented by matrix A_s can thus be represented as follows:

$$\mathbf{H}_s \triangleq \mathbf{U}_s \mathbf{A}_s \tag{6}$$

Based on the incomplete CSI of matrix A_s a zero-forcing (ZF) beamformer with power P can be written as:

$$\mathbf{B} = \frac{\sqrt{P}\mathbf{H}_s^{\dagger}}{||\mathbf{H}_s^{\dagger}||_{\mathrm{F}}} \tag{7}$$

where $||\cdot||F$ denotes the Frobenius norm. $\mathbf{H}_s^{\dagger}$ is the Moore- Penrose pseudoinverse:

$$\mathbf{H}_s^{\dagger} = \mathbf{H}_s^H (\mathbf{H}_s \mathbf{H}_s^H)^{-1}$$

The ZF beamformer B as defined in equation (7) is able to eliminate inter-user interference completely. We may rewrite $\mathbf{H}_s^{\dagger}$ as follows:

$$\mathbf{H}_s^{\dagger} = \mathbf{U}_s \mathbf{A}_s (\mathbf{A}_s^H \mathbf{A}_s)^{-1} \tag{8}$$

The channel model can be thus rewritten as

$$\mathbf{y} = \mathbf{A}_c^H \widetilde{\mathbf{U}}_c^H \mathbf{U}_s \mathbf{A}_s (\mathbf{A}_s^H \mathbf{A}_s)^{-1} \frac{\sqrt{P}}{||\mathbf{H}_s^{\dagger}||_{\mathrm{F}}} \mathbf{s} + \mathbf{n} \tag{9}$$

Since the following equation holds:

$$\mathbf{A}_c^H \widetilde{\mathbf{U}}_c^H \mathbf{U}_s = \mathbf{A}_s^H, \tag{10}$$

the received signal vector *y* is

$$\mathbf{y} = \frac{\sqrt{P}}{||\mathbf{H}_s^{\dagger}||_{\mathrm{F}}} \mathbf{s} + \mathbf{n} \tag{11}$$

As one can readily observe, interference does not exist in this expression.

The SNR at each user terminal side can thus be expressed as

$$\mathrm{SNR} = \frac{P}{||\mathbf{H}_s^{\dagger}||_{\mathrm{F}}^2} = \frac{P}{\mathrm{tr}(\mathbf{A}_s^H \mathbf{A}_s)^{-1}} \tag{12}$$

Interesting, the SNR is independent of the common eigen-basis $\widetilde{U}_C$, which is also why the common eigen-basis $\widetilde{U}_C$ does not need to be available at the user terminals in this implementation example.

The master terminal takes a decision on the channel coefficients of which rows of matrix A_c to extract and feed back to the base station based on some optimization criterion. The base station can reconstruct matrix A_s based on the fed back sub-set of channel coefficients and their indices, and may use the reconstructed matrix A_s to select an optimal beamformer configuration.

Under the assumption that the sounding signal represents the common eigen-basis $\widetilde{U}_C$, the individual rows of the global instantaneous channel state in matrix A_c correspond to the eigenvectors in common eigen-basis $\widetilde{U}_C$. An element of the matrix A_c can be considered a projection of the channel onto the subspace of the related eigenvector. The linear combination of the eigenvectors $\widetilde{U}_C$ with coefficient given by the columns of A_c respresents the channel between the base base station and the user terminal. The base station thus (only) determines the weighting of the eigenvector contributions to the beamformer so as to configure the beamformer for transmissions to the user terminals of the cluster.

Denoting the index of the i^{th} selected eigenvector as e_i, and defining the set of chosen indices as $\mathcal{G} \triangleq \{e_1, e_2, \dots, e_N\}$ so that $\forall i, 1 \leq e_i \leq d$, and that $\forall i \neq j, e_i \neq e_j$, the feedback to be transmitted to the base station may thus correspond to the respective channel coefficients in the matrix A_c within the given rows at indices of $\mathcal{G}$. In one example implementation the master terminal could send the selected rows of coefficients together with an indication of the row indices to which they belong, respectively. Alternatively, master terminal may send the selected indices $\mathcal{G} \triangleq \{e_1, e_2, \dots, e_N\}$ to the other user terminals, so that all user terminals can individually send the channel coefficients in the rows of the local channel state vector a_k corresponding to the selected indices $\mathcal{G} \triangleq \{e_1, e_2, \dots, e_N\}$ as feedback to the base station along with the indices (each user terminal sends a disjoint subset of indices).

As a simple example, consider the SNR is defined in equation (12) and choosing, as an optimization criterion, that $N \geq \ell$ out of dd eigenvectors from U_c are to be chosen (i.e. their corresponding $N \geq \ell$ rows in matrix A_c) for feedback so that the SNR is maximized:

$$\mathcal{G}^{(1)} = \underset{N=K}{\arg} \min \mathrm{tr}(\mathbf{A}_s^H \mathbf{A}_s)^{-1} \tag{13}$$

The master terminal may for example employ an algorithm that finds the optimal combination of N eigenvectors (respectively, selects the optimum sub-set of N rows in matrix A_c). The result of the optimization may be denoted $\mathcal{G}^{(1)}$ and may, for example, be a sub-set of channel coefficients of ℓ rows in matrix A_c that forms the feedback information that is fed back to the base station along with the indices in of the selected rows.

As noted above, one possibility is that the master terminal provides the entire feedback on behalf of the user terminal cluster, or alternatively, the master terminal may send the the row indices of the selected eigenvectors, to the other user terminals in the cluster to indicate to the other user terminals the channel coefficients at which indicates of their local CSI vector they should transmit to the base station.

The base station receives the selected sub-set of channel estimates and the corresponding row indices and can thus reconstruct a matrix A_s. Based on this matrix A_s the base station may then determine the optimal beamformer configuration that is used for beamforming of the transmissions to the cluster of user terminals.

Next, the above described closed-loop feedback scheme reporting the channel coefficients of ℓ rows in matrix A_c selected based on the global channel state is compared in terms of performance with a reference system based on classical closed loop feedback, where CSI exchange between users is not possible. It is assumed that in this reference system the choice of eigenvectors is based on the statistical global CSI in terms of selecting the first ℓ rows in U_c, as they are the strongest ℓ eigen-modes. The decision criterion for eigenvector selection is in this reference system is:

$$\mathcal{G}^{(2)} = \{1, \cdots, \ell\} \tag{14}$$

which is known by the base station by default. In this reference system, the user terminals will thus only feed back the channel coefficients of the first ℓ rows of their local CSI vector $\mathcal{G}^{(1)}\ a_k$.

To assess the performance by numerical simulations, a cluster of 3 single-antenna user terminals being served by a base station equipped with 50 antennas is simulated. Due to limited angle spread (30 degrees), the rank of the channel covariance R_c is around $d = 15$. Since channel covariance is assumed known by the users for exemplary purposes, one can consider only the reduced-dimension subspace or effective subspace, where the 50×1 channel vector a_k can be effectively represented by a linear combination of 15 eigenvectors of the channel covariance matrix R_c. Two different feedback schemes are evaluated and the sum-rate performances are given in Fig. 5. For the sake of fairness, it has been assumed the same amount of quantization bits is available in both feedback schemes. The curve “Use strongest ℓ eigen-modes, no D2D” shows the performance when each user feeds back the channel coefficients corresponding to the ℓ dominant eigenvectors of the channel covariance matrix R_c, as described in the reference system $\mathcal{G}^{(2)}$ defined in (14). The curve "Exhaustive, D2D" refers to the proposed closed-loop feedback scheme where the users exchange their local CSI and search exhaustively for the best 3 eigen-modes which minimize the SNR at user side. The users need to feed back the quantized channel coefficients and the indices of the three eigenvectors (rows of matrix A_c) that are chosen. The number of possible combinations that the users need to search is $\binom{15}{3}$, or 15 choose 3. Despite the fact that this method has fewer quantization bits available for transmitting the channel coefficients (as some bits are needed for feeding back the indices), this method still has better performance.

Joint Precoder Selection

While in the previous exemplary implementation, the user terminals of a cluster feedback an optimized selection of channel coefficients, based on which the base station determines the beamformer configuration. In this alternative implementation, the precoder is selected by the user terminals instead of the base station and the selected beamformer configuration is sent as feedback to the base station. In response to the feedback the base station uses the indicated beamformer configuration for transmissions to the user terminals. In order to facilitate the signaling of the user terminal selected beamformer configuration, a precoder codebook is may be used which is composed of a finite set of precoding matrices (beamformer configurations) predetermined a priori. After local CSI exchange, the master terminal selects the best precoding matrix according an optimization criterion (as in the previous exemplary implementation) and based on the available instantaneous global channel state (represented by matrix A_c). As in the previous implementation, one could for example adopt as optimality criterion the maximization of the downlink sum-rate of transmissions to the cluster of user terminals. The codebook may be generated according to the statistics of the precoder. In this case, the master terminal requires some knowledge of the reduced effective eigen-basis $\widetilde{U}_C$. Under this assumption, one also assumes that the codebook is known to both, the base station and the master terminal. Then, the master terminal may search in the codebook and selects the precoder configuration that maximizes the sumrate based on the instantaneous global channel state information.

In the following we will evaluate the performance of the aforementioned joint precoder selection implementation and the reference system under the same assumptions also made in the previous performance assessment with respect to Fig. 5. In the reference system, where CSI exchange is not possible between users, the traditional approach is that each user quantizes its own channel and sends back the quantized CSI to the base station. Then the base station designs a precoder based on the quantized CSI. In the proposed implementation, once the local CSI is exchanged between user terminals, the master terminal knows the interference channels as well as its own channel. It can compute the system performance, e.g., the sum-rates, when different precoders in the codebook are used, and finally pick the best precoder. Note that in simulation, the random codebook has been generated as follows: 1) generate a fixed number of realizations of A_c according to its distribution; 2) compute the normalized Moore-Penrose pseudoinverse of A_c for each realization. The simulation result of the two methods is shown in Fig. 6. A ZF downlink precoder is used in the reference system, where each user quantizes its CSI into 4 bits. The total amount of feedback overhead of all three users is 12 bits. For the sake of fairness, the joint precoder selection scheme proposed herein also has 12 bits of feedback overhead available. Looking at Fig. 6 one can observe significant gain of proposed joint precoder selection scheme over the traditional feedback scheme.

The last phase of the closed loop feedback according to the implementations discussed herein above is illustrated in Fig. 7. At the end of the phase of cooperative feedback design the optimally designed feedback is either sent to the base station from the master terminal, or it may be distributed to all the user terminals of the cluster who then send (a part of) the feedback. In this latter approach, all the user terminals retransmit simultaneously the optimized feedback.

A further embodiment provides a terminal 800 as exemplarily shown in Fig. 8. The terminal 800 may be configured to implement the embodiments of the invention described herein. The user terminal 800 may be a mobile terminal, e.g. a cellular phone, a PDC, smart-phone, tablet computer etc. The terminal comprises a transceiver 810, which has a transmitter 811 and a receiver 812. The receiver 812 is comprises receiver circuitry and is configured to receive signals over the air. As explained, the receiver 812 could receive a sounding signal via antenna(s) 805 on. Furthermore, the receiver 812 may provide demodulation and decoding functionality to terminal 800. The receiver 812 may also be used to receive local CSI from other user terminals.

Transmitter 811 may provide encoder and modulation functionality to the terminal 800 for sending signals to a base station, e.g. feedback information on the instantaneous channel state. Additionally, the terminal 800 could be equipped with a display 802 and a keyboard 803 to facilitate control of the terminal 800 by a user.

The terminal 800 further comprises a processor 801 configured to perform channel estimation to derive the local CSI based on a sounding signal that is received with receiver 812. The processor 801 may also be used process the local CSI of the user terminal and the local CSI received from other user terminals jointly to select the optimized feedback to be fed back to the base station. The terminal 800 may also comprise a memory 804 for storing the CSI information and intermediate results of the optimization processing.

Another embodiment relates to a base station 900 as exemplarily shown in Fig. 9. Base station 900 is configured to implement the embodiments of the invention described herein. The base station has a processor 901 that select a beamformer configuration for transmissions the clusters of user terminals 800. The memory 902 may store multiple beamformer configurations, statistical channel state information, e.g. in form of a covariance matrix of the channel, and/or the feedback information provided by the user terminal(s) 800. The memory 902 may also store a codebook the codewords of which indicate different beamforming configurations. The base station 900 may optionally have further wired or wireless network interfaces 903 to support e.g. alternative wireless or wired access technologies, or to connect the base station 900 to the core network of the communication system.

The base station 900 comprises a transceiver 910, which has a transmitter 911 and a receiver 912. The transceiver 910 is coupled to and antennas 905 forming an antenna array for reception and transmission of signals via an air interface. Further, using antenna array 905, the transmitter 911 can transmits sounding signals on the downlink to facilitate channel estimation by the user terminals 800. The receiver 912 may receive the feedback on the instantaneous channel state reported by the user terminal(s) 800.

It should be further noted that the individual features of the different implementations and embodiments of the aspects discussed herein may individually or in arbitrary combination be subject matter to another invention.

Although some aspects have been described in the context of a method, it is clear that these aspects also represent a description of the corresponding apparatus suitably adapted to perform such method. In such apparatus a (functional or tangible) block or device may correspond to one or more method step or a feature of a method step. Analogously, aspects described in the context of a corresponding block or item or feature of a corresponding apparatus may also correspond to individual method steps of a corresponding method.

Furthermore, the methods described herein may also be executed by (or using) a hardware apparatus, like a processor, microprocessor, a programmable computer or an electronic circuit.

Some one or more of the most important method steps may be executed by such an apparatus. Where an apparatus has been described herein in terms of functional elements, e.g. processing unit, receiving unit, transmitter unit, or the like, it should be further understood that those elements of the apparatus may be fully or partly implemented in hardware elements/circuitry. Individual hardware, like a processor or microprocessor, a transmitter circuitry, receiver circuitry, etc., may be used to implement the functionality of one or more elements of the apparatus.

In addition, where information or data is to be stored in the process of implementing a method step of functional element of an apparatus in hardware, the apparatus may comprise memory or storage medium, which may be communicatively coupled to one or more hardware elements/circuitry of the apparatus.

It is also contemplated implementing the aspects of the invention in hardware or in software or a combination thereof. This may be using a digital storage medium, for example a floppy disk, a DVD, a Blu-Ray, a CD, a ROM, a PROM, an EPROM, an EEPROM or a FLASH memory, having electronically readable control signals or instructions stored thereon, which cooperate (or are capable of cooperating) with a programmable computer system such that the respective method is performed. A data carrier may be provided which has electronically readable control signals or instructions, which are capable of cooperating with a programmable computer system, such that the method described herein is performed.

It is also contemplated implementing the aspects of the invention in the form of a computer program product with a program code, the program code being operative for performing the method when the computer program product runs on a computer. The program code may be stored on a machine readable carrier.

The above described is merely illustrative, and it is understood that modifications and variations of the arrangements and the details described herein will be apparent to others skilled in the art. It is the intent, therefore, to be limited only by the scope of the impending claims and not by the specific details presented by way of description and explanation above.

CLAIMS

1. A method for use in a MISO or MIMO communication system, the method comprising the steps of:

transmitting a sounding signal from one or more transmitting stations to a group of receiver stations via a channel using an antenna array,

receiving, by each receiver station of said group, the sounding signal from the one or more transmitting stations via a channel,

performing, by each of the receiver stations of said group, a channel estimation based on said sounding signal to thereby obtain, by each of the receiver stations of said group, a respective channel state information characterizing an instantaneous channel state,

receiving, by at least one of the receiver stations of said group, the channel state information obtained by the other receiver stations of said group by said channel estimation,

processing the channel state information of the receiver stations of said group by said at least one of the receiver stations of said group to obtain optimized feedback on the channel that allows one or more of the transmitting stations to select a transmission scheme for transmitting signals via said channel to the group of receiver stations, and

transmitting the optimized feedback on the channel to one or more of the transmitting stations.

2. The method according to claim 1, wherein the transmission scheme is a modulation and coding scheme and/or a beamformer configuration.

3. The method according to claim 1 or 2, wherein the channel state information of the respective receiver stations of said group each comprises a set of channel coefficients and the processing the channel state information is based on an algorithm selecting a sub-set of the channel coefficients in each channel state information according to some optimization criterion, wherein the selected sub-set

of the channel coefficients in each channel state information is transmitted to one or more of the transmitting stations within the optimized feedback.

4. The method according to claim 3, wherein the sounding signal sounds the channel with different beamformer configurations and the channel coefficients of each channel state information represent a channel estimate of the channel for the respective different beamformer configurations.

5. The method according to one of claims 3 or 4, wherein the respective beamformer configurations correspond to respective eigenvectors of a covariance matrix describing the channel.

6. The method according to one of claims 3 to 5, further comprising the steps of:

reconstructing, by one or more of the transmitting stations, the instantaneous channel state observed by each of the receiver stations of said group based on the optimized feedback, and

selecting a transmission scheme for transmitting signals to the group of receiver stations based on the reconstructed instantaneous channel state.

7. The method according to one of claims 3 to 6, wherein the method further comprises:

transmitting, by said at least one of the receiver stations of said group, information on the selected sub-set of channel coefficients to the other receiver stations of said group, and

transmitting, by each of the receiver stations of said group, the sub-set of channel coefficients of the respective receiver station's channel state information to one or more of the transmitting stations.

8. The method according to one of claims 3 to 6, wherein each receiver station of said group received the channel state information from the respective other receiver stations of said group and selects said sub-set of the channel coefficients for transmission to one or more of the transmitting stations.

9. The method according to claim 7 or 8, wherein respective sub-sets of channel coefficients of the respective receiver station's channel state information are transmitted by the receiver stations of said group in parallel.

10. The method according to claim 1 or 2, wherein the method further comprises:

selecting, by the at least one of the receiver stations of said group a transmission scheme for transmitting signals from one or more of the transmitting stations to the group of receiver station via said channel, and wherein the optimized feedback indicates the selected transmission scheme to one or more of the transmitting stations.

11. The method according to claim 10, wherein the selected transmission scheme consists of or comprises a beamformer configuration to be used for transmitting signals to the receiver stations of said group.

12. The method according to claim 10 or 11, wherein the selected transmission scheme is communicated by means of a codeword of a codebook known to the one or more of the transmitting stations and the group of receiver stations.

13. The method according to one of claims 10 to 12, wherein the method further comprises:

selecting, by one or more of the transmitting stations, the transmission scheme configuration indicated in the optimized feedback for transmitting signals to the group of receiver stations.

14. The method according to one of claims 10 to 13, wherein the method further comprises:

transmitting, by said at least one of the receiver stations of said group, the selected transmission scheme to the other receiver stations of said group, and

transmitting, by each of the receiver stations of said group, at least a portion of the optimized feedback to one or more of the transmitting stations in parallel.

15. The method according to one of claims 1 to 14, wherein the said at least one of the receiver stations of said group receives the channels state information from the other receiver station of said group using device-to-device communication.

16. The method according to one of claims 1 to 15, wherein the sounding signal is formed by a plurality of pilot symbols or a preambles corresponding to respective beamformer.

17. The method according to one of claims 1 to 16, wherein the MIMO or MISO communication system operates in FDD mode.

18. The method according to one of claims 1 to 17, wherein the MIMO or MISO communication system is a massive MIMO or massive MISO system.

19. A receiver station for use in a MISO or MIMO communication system, the receiver station comprising:

a receiver unit adapted to receive a sounding signal from one or more of the transmitting stations via a channel, wherein the sounding signal has been transmitted from one or more of the transmitting stations using an antenna array,

wherein the receiver unit is further adapted to receive channel state information obtained by the other receiver stations by channel estimation based on said sounding signal,

a processing unit adapted to perform a channel estimation based on said sounding signal to thereby obtain channel state information characterizing an instantaneous channel state,

wherein the processing unit is further adapted to process the channel state information of the receiver station and said other receiver stations to obtain optimized feedback on the channel that allows one or more of the transmitting stations to select a transmission scheme for transmitting signals via said channel to the receiver stations, and

a transmitter unit adapted to transmit the optimized feedback on the channel to one or more of the transmitting stations.

20. A receiver station for use in a MISO or MIMO communication system, the receiver station comprising:

a receiver unit adapted to receive a sounding signal from one or more of the transmitting stations via a channel, wherein the sounding signal has been transmitted from one or more of the transmitting stations using an antenna array,

a processing unit adapted to perform a channel estimation based on said sounding signal to thereby obtain a set of channel coefficients forming channel state information characterizing an instantaneous channel state, and

a transmitter unit adapted to send the channel state information to another receiver station,

wherein the receiver unit is further adapted to receive from said other receiver station an information indicating a sub-set of the channel coefficients forming the channel state information, and

wherein the transmitter unit is further adapted to transmit the indicated sub-set of channel coefficients to one or more of the transmitting stations.

21. A transmitting station for use in a MISO or MIMO communication system, the transmitting station comprising:

an antenna array,

a transmitter unit adapted to transit a sounding signal via a channel using the antenna array,

a receiver unit adapted to receive optimized feedback on the channel from at least one of a plurality of receiver stations, wherein the optimized feedback is based on an instantaneous channel state observed by the plurality of users receiving the sounding signal and allows one or more of the transmitting stations to select a transmission scheme for transmitting signals via said channel to the receiver stations, and

wherein the transmitter unit is further adapted to use the transmission scheme configuration indicated in the optimized feedback for transmitting signals to said plurality of receiver stations.

22. The transmitting station according to claim 21, wherein the processing unit is further adapted to reconstruct the instantaneous channel state observed by each of

the plurality of receiver stations based on the optimized feedback, and to select the transmission scheme for transmitting signals to the plurality of receiver stations based on the reconstructed instantaneous channel state.

23. A MISO or MIMO communication system comprising:

a plurality of transmitting stations, wherein each transmitting station comprises:

at least one antenna,

a transmitter unit adapted to transit a sounding signal via a channel using the at least one antenna, and

a receiver unit adapted to receive optimized feedback on the channel from at least one of a plurality of receiver stations, wherein the optimized feedback is based on an instantaneous channel state observed by the plurality of users receiving the sounding signal from the plurality of transmitting station and allows one or more of the transmitting stations to select a transmission scheme for transmitting signals via said channel to the receiver stations, and

wherein the transmitter unit is further adapted to use the transmission scheme configuration indicated in the optimized feedback for transmitting signals to said plurality of receiver stations,

wherein the antennas of the transmitting stations form an antenna array for transmitting said signals to the group of receiver stations.

ABSTRACT

The invention relates to methods and apparatuses implementing a novel three-phase closed-loop CSI feedback scheme, in which receiver stations exchange local channel state information for optimal feedback design. One or more transmission stations transmit a sounding signal to a group of receiver stations via a channel using an antenna array, so as to enable the receiver stations to obtain local channel state information representing the instantaneous channel state. The channel state information of the receiver stations is shared so that at least one master station has the global channel state and can obtain based on the knowledge of the instantaneous global channel state and on some given optimization criterion an optimum feedback on the channel that allows one or more of the transmitting stations to select a transmission scheme for transmitting signals to the receiver stations. The optimized feedback is sent back to one or more of the transmission stations.

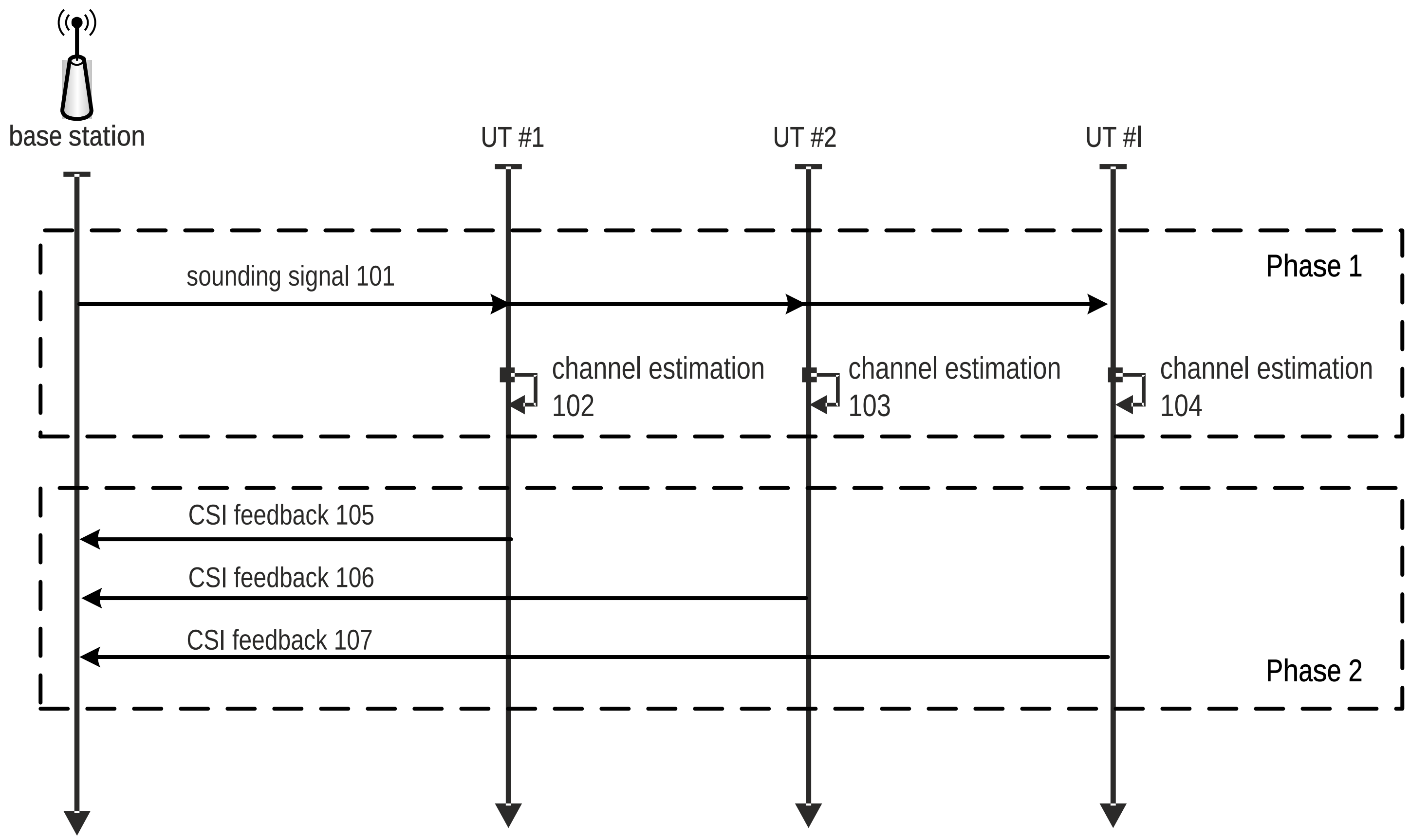
base station
UT #1
UT #2
UT #l
Phase 1
sounding signal 101
channel estimation 102
channel estimation 103
channel estimation 104
CSI feedback 105
CSI feedback 106
CSI feedback 107
Phase 2

Fig. 1

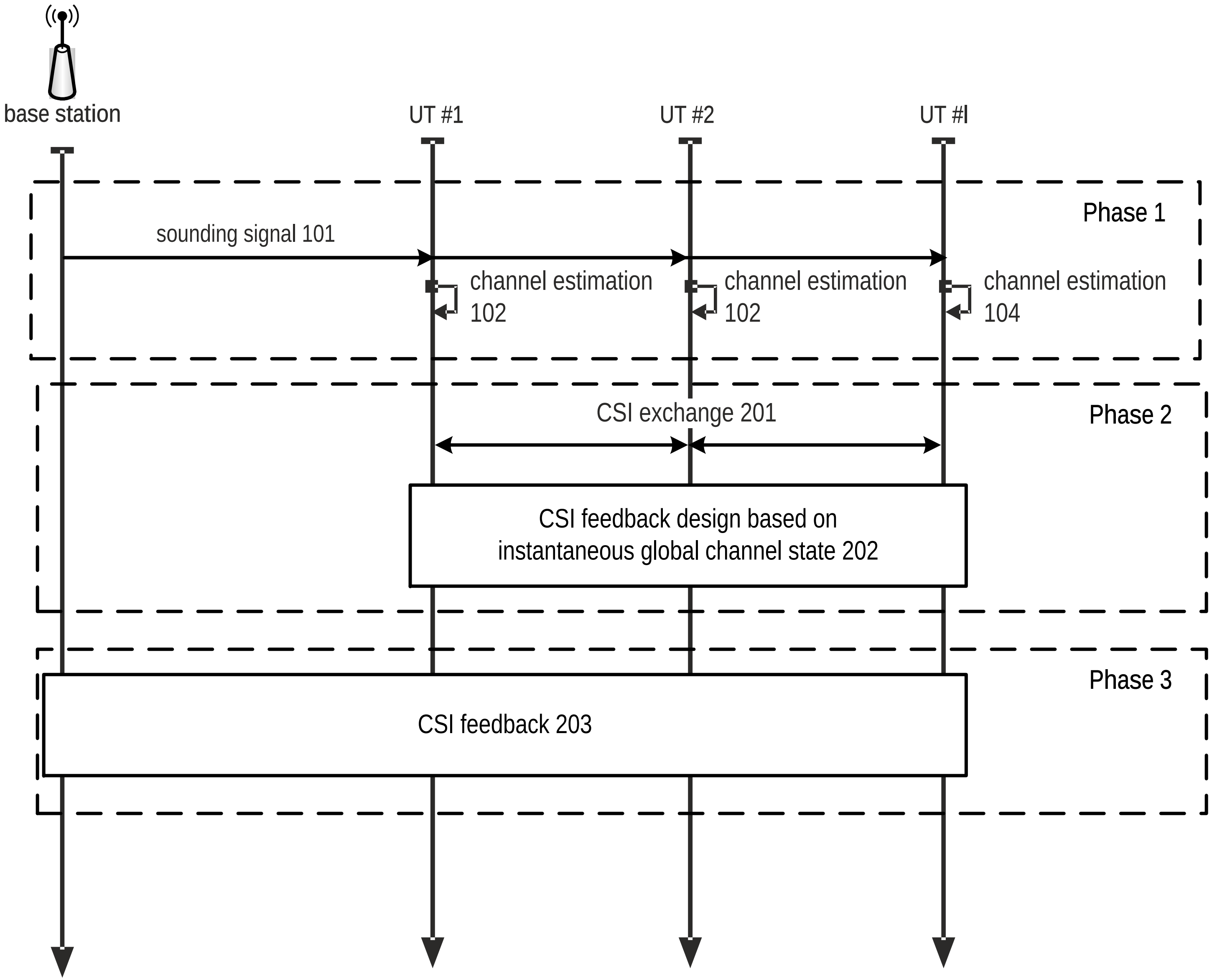
base station
UT #1
UT #2
UT #I
Phase 1
sounding signal 101
channel estimation 102
channel estimation 102
channel estimation 104
Phase 2
CSI exchange 201
CSI feedback design based on instantaneous global channel state 202
Phase 3
CSI feedback 203

Fig. 2

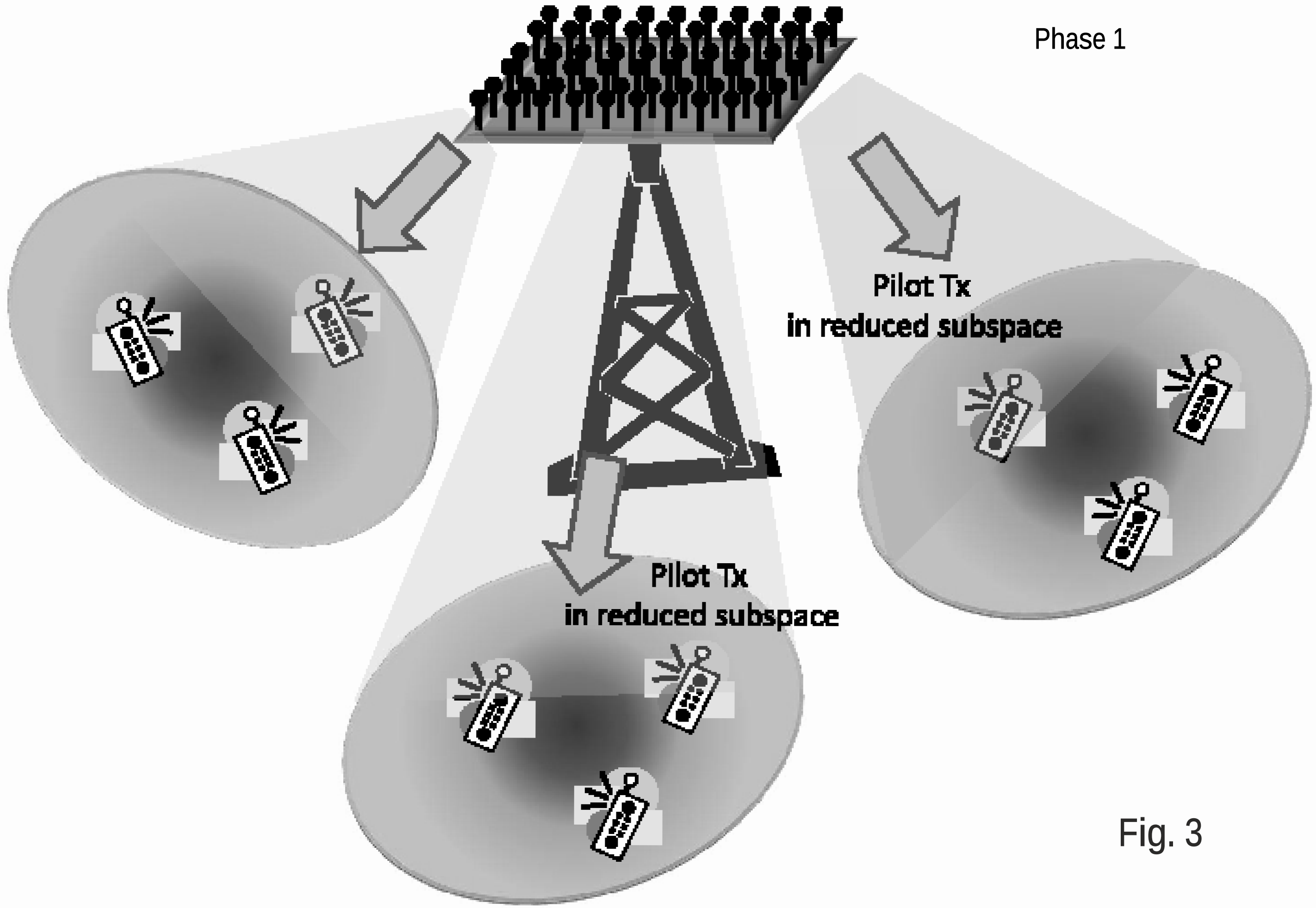
Phase 1
Pilot Tx
in reduced subspace
Pilot Tx
in reduced subspace

Fig. 3

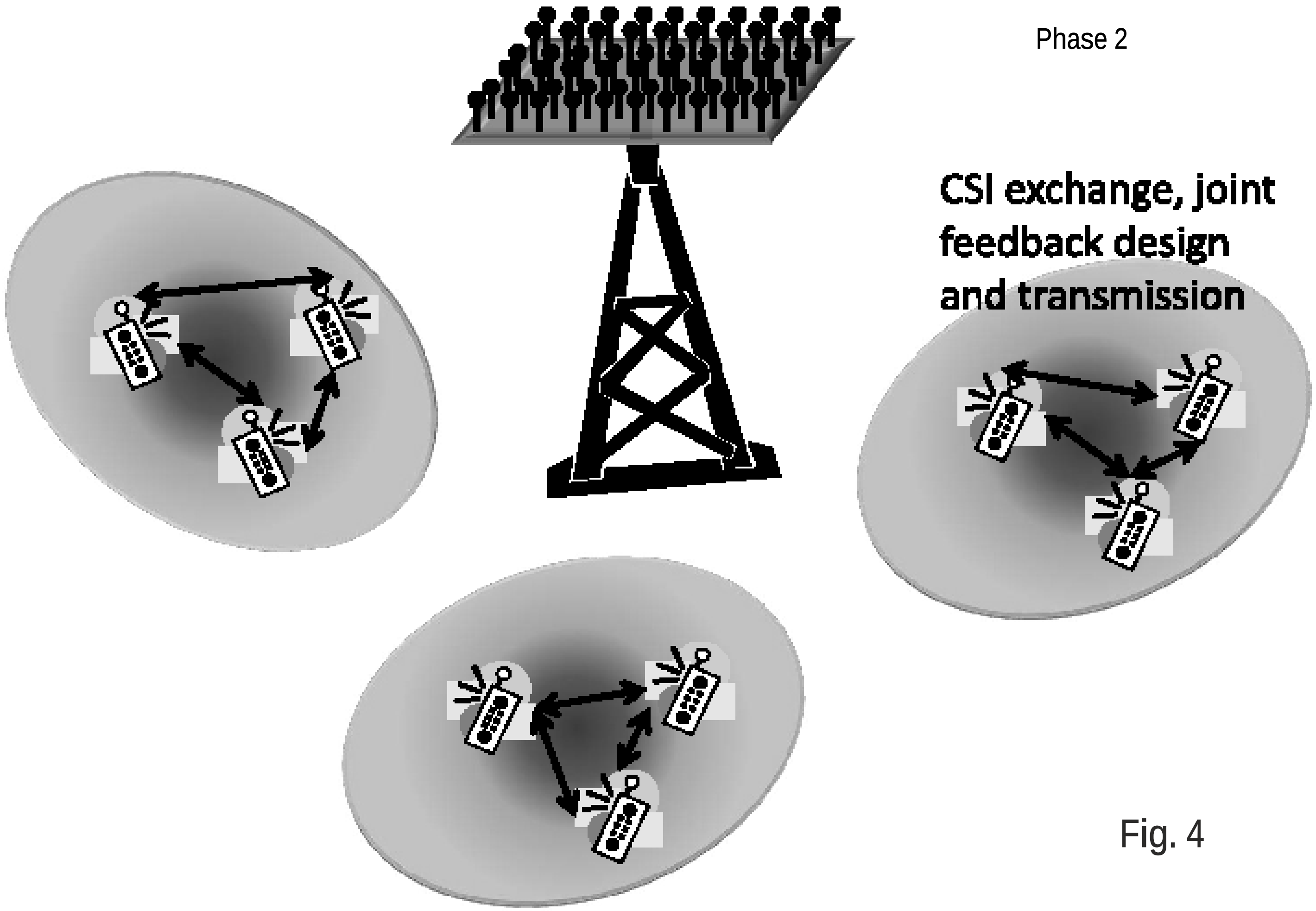
Phase 2
CSI exchange, joint
feedback design
and transmission

Fig. 4

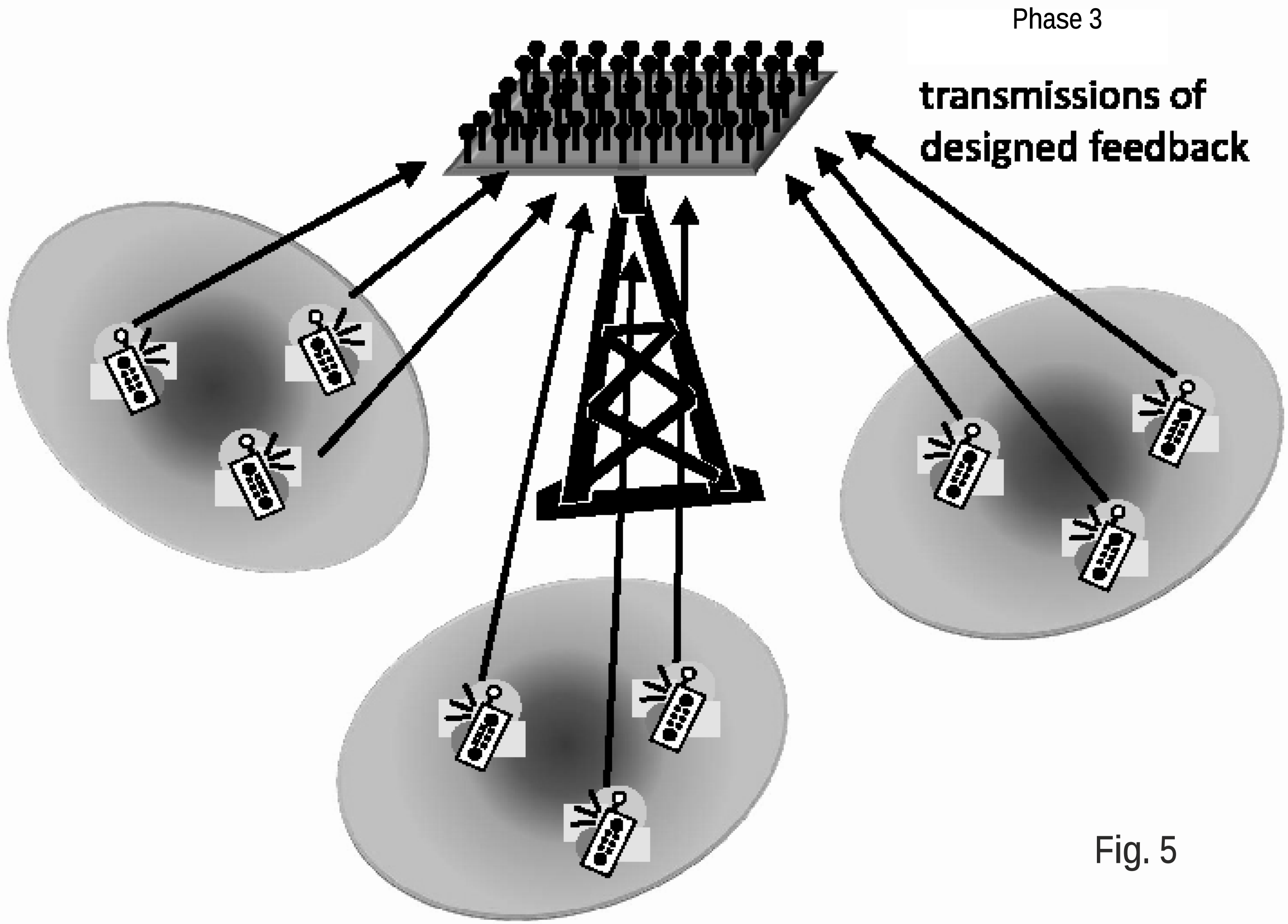

Fig. 5

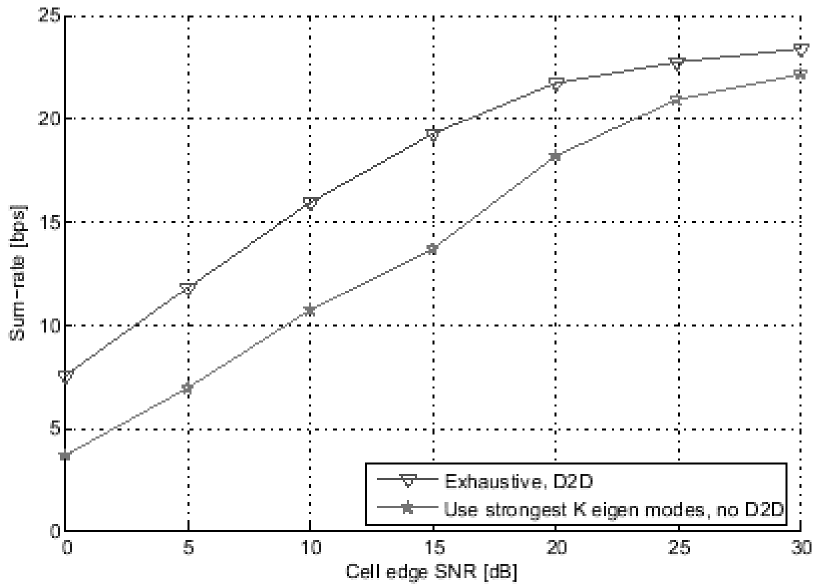
Sum−rate [bps]
Cell edge SNR [dB]
Exhaustive, D2D
Use strongest K eigen modes, no D2D
0
5
10
15
20
25
30

Fig. 6

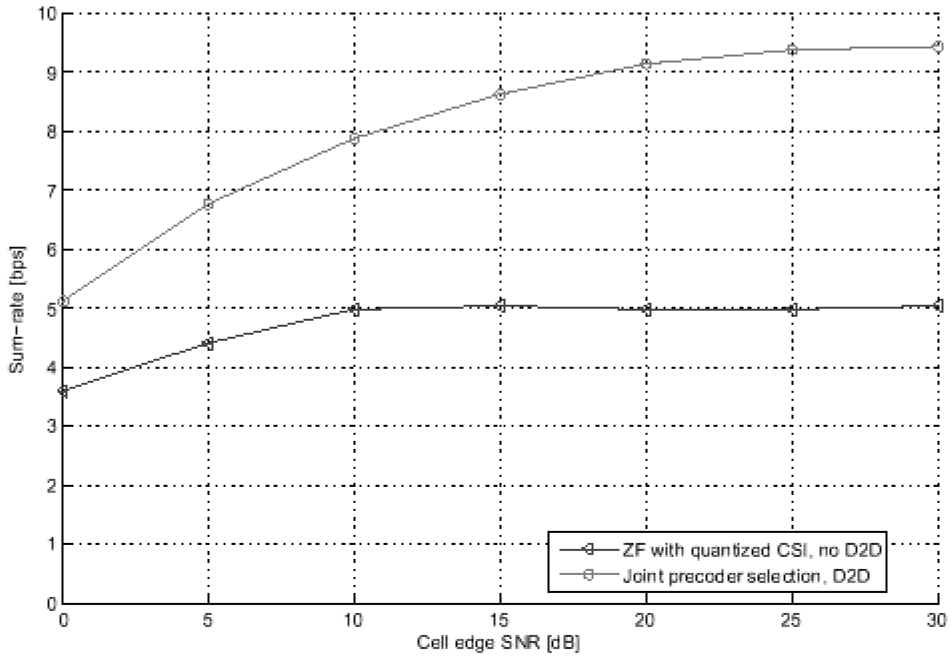
Sum-rate [bps]
Cell edge SNR [dB]
0
1
2
3
4
5
6
7
8
9
10
0
5
10
15
20
25
30
ZF with quantized CSI, no D2D
Joint precoder selection, D2D

Fig. 7

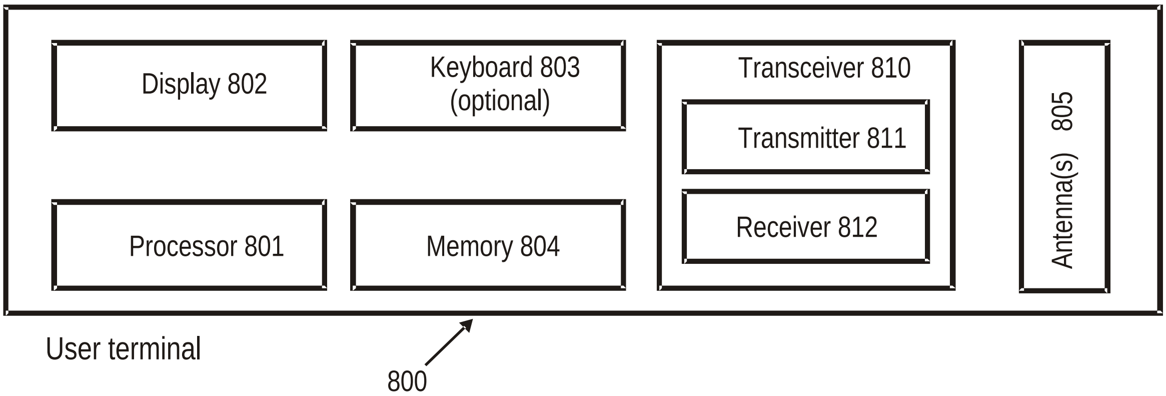
Display 802
Keyboard 803 (optional)
Transceiver 810
Transmitter 811
Receiver 812
Antenna(s) 805
Processor 801
Memory 804
User terminal
800

Fig. 8

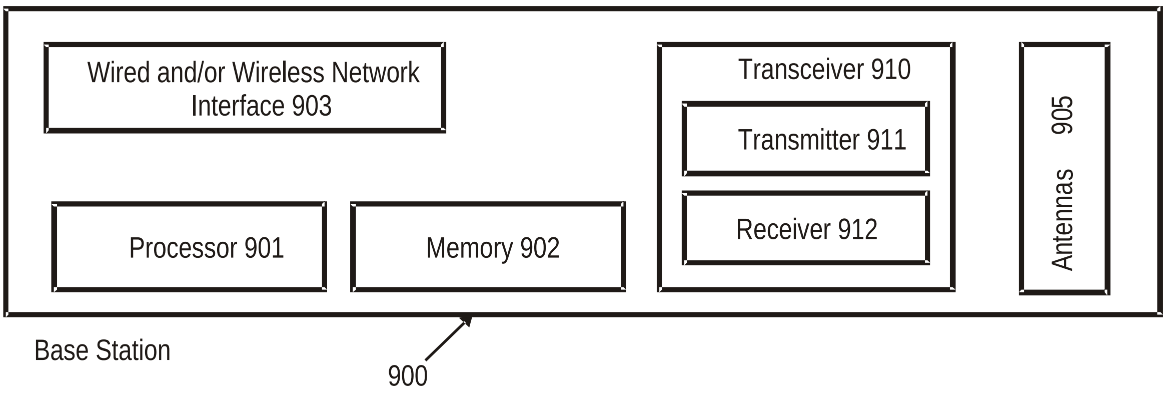
Wired and/or Wireless Network Interface 903
Transceiver 910
Transmitter 911
Receiver 912
Antennas 905
Processor 901
Memory 902
Base Station
900

Fig. 9