CSI Acquisition Concepts for Advanced Antenna Schemes in the WINNER+ Project

Petri Komulainen¹, Antti Tölli¹, Bin Song², Florian Roemer², Emil Björnson³, Mats Bengtsson³

¹Centre for Wireless Communications, PO Box 4500, 90014 University of Oulu, Finland
Fax: +358 8 5532845, Email: petri.komulainen@ee.oulu.fi, antti.tolli@ee.oulu.fi

²Ilmenau University of Technology, PO Box 10 05 65, 98684 Ilmenau, Germany
Fax: +49 3677 691195, Email: bin.song@tu-ilmenau.de, florian.roemer@tu-ilmenau.de

³KTH Royal Institute of Technology, Ösquadas väg 10, SE-100 44 Stockholm, Sweden
Fax: +46 8 7907260, Email: emil björnson@ee.kth.se, mats.bengtsson@ee.kth.se

Abstract: This paper summarizes four novel advanced antenna concepts explored in the framework of the WINNER+ project. The concepts are related to multiuser MIMO communication in cellular networks, focusing on the acquisition and application of channel state information (CSI) at the transmitter in time-division-duplex (TDD) mode. The concepts include new ideas for CSI modeling and sounding for the purposes of multiuser precoding, and methods for pilot signal design with the aim to support the estimation of different CSI quantities. Furthermore, a new relaying strategy for terminal-to-terminal communication is described. All the ideas are feasible for adoption into practical upcoming communication systems such as LTE-Advanced, and most of the proposed concepts have only a minor impact on standards. Our study indicates that the CSI at its best is not only about estimating the channel responses between different antenna pairs. What counts is the nature of the intended communication link as well as the form in which CSI is applied.

Keywords: channel state information, MIMO, precoding, SDMA, pilot signal, CSI sounding, two-way relaying, WINNER+, LTE-Advanced

1. Introduction

One of the principal techniques for future radio systems is MIMO communication, employing multiple antennas both at the transmitters and the receivers. In cellular systems, MIMO transmission may be combined with user scheduling or multiuser precoding to facilitate space division multiple access (SDMA). Efficient MIMO transmission requires the availability of channel state information (CSI) at the transmitter, allowing the system to effectively adapt to the radio channel and take full advantage of the available spectrum. The main challenge is in the acquisition of CSI. In the time division duplex (TDD) mode, the CSI can be tracked at the transmitter during receive periods, provided that the radio chains are well calibrated. For the base station (BS), CSI can be provided via antenna-specific non-precoded uplink sounding signals [1].

In heavily frequency- or time-variant channels, short-term CSI may not be easily available. In this case long-term CSI, i.e. second-order spatial channel statistics averaged over some finite time period or frequency bandwidth, can still be utilized. Long-term CSI can be acquired in frequency division duplex (FDD) mode as well, either via feedback signaling or frequency transformation of uplink measurements.

This paper summarizes four innovative concepts studied in the framework of the WINNER+ project. The concepts are related to multiuser MIMO communication in cellular networks by means of linear transmit precoding, focusing on the acquisition...
and application of transmitter CSI. The problem of acquiring the CSI consists of multiple tasks, such as pilot signal design, channel state and quality estimation, as well as feedback signal design. All these aspects are addressed in order to enhance the system capacity.

Section 2 presents a method for low-rank modeling of the long-term CSI in order to improve the precoding performance in time or frequency selective fading. Section 3 describes a novel signaling concept for reducing the extensive overhead caused by the uplink CSI sounding. In Section 4, a pilot signal design technique is introduced for exploiting the knowledge of long-term statistics to improve the estimation accuracy of different CSI quantities. Finally, in Section 5, a novel two-way MIMO amplify-and-forward (AF) relaying strategy for terminal-to-terminal communication is presented.

2. Long-term CSI modeling for linear precoding

In a MIMO communication system, multiple antennas at both ends of the link offer us the benefit of using SDMA to simultaneously transmit multiple data streams to a group of users. Obviously, this benefit comes from the awareness of CSI at the transmitter. Linear precoding, as a sub-optimal SDMA strategy, has attracted much attention due to its lower complexity compared to dirty paper coding (DPC). By exploiting perfect short-term CSI at the transmitter, the capacity of a multi-user MIMO system with linear precoding can be significantly improved. If the channel varies too rapidly to obtain short-term CSI, in order to perform precoding a new approach called rank-one approximated long-term CSI (ROLT-CSI) is proposed [2] to effectively exploit the knowledge of the spatial correlation. Based on ROLT-CSI, any linear precoding technique designed for perfect CSI at the transmitter, can be used with long-term CSI.

From the system model point of view, we consider a $K$ user MIMO downlink system. The base station (BS) is equipped with $M_T$ transmit antennas and the $i$th user has $M_{R_i}$ receive antennas. We use $\mathbf{H}_i(m, n) \in \mathbb{C}^{M_{R_i} \times M_T}$ to denote the propagation channel between the BS and the user $i$ at subcarrier $m$ and OFDM symbol $n$. One chunk is defined as the basic resource element, which contains $N_T$ consecutive OFDM symbols in the time direction and $N_F$ subcarriers in the frequency direction. Therefore, $N_{\text{chunk}} = N_T \cdot N_F$ symbols are available within each chunk. Chunk-wise precoding and decoding are performed. The proposed ROLT-CSI method is briefly described as follows.

For each receive antenna $l = 1, \ldots, M_{R_i}$ of user $i$, we estimate the spatial correlation matrix by averaging over chunk $b$. We have the estimate and its SVD as

$$
\hat{\mathbf{R}}_{i,b,l} = \frac{1}{N_{\text{chunk}}} \sum_{m=1}^{N_F} \sum_{n=1}^{N_T} \mathbf{h}_{i,l}(m,n)\mathbf{h}_{i,l}^H(m,n) = \mathbf{V}_{i,b,l}\mathbf{\Lambda}_{i,b,l}\mathbf{V}_{i,b,l}^H,
$$

where $\mathbf{h}_{i,l}^H(m,n)$ denotes the $l$th row of the channel matrix $\mathbf{H}_i(m, n) \in \mathbb{C}^{M_{R_i} \times M_T}$.

When only second-order channel statistics are available at the transmitter, the optimum strategy is to transmit along the dominant eigenmode of the matrix $\hat{\mathbf{R}}_{i,b,l}$. Therefore, we do a rank-one approximation for each $\hat{\mathbf{R}}_{i,b,l}$ of user $i$ and define the equivalent channel matrix of user $i$ in chunk $b$ as

$$
\hat{\mathbf{H}}_{i,b} = \mathbf{A}_{i,b}\mathbf{B}_{i,b} \in \mathbb{C}^{M_{R_i} \times M_T},
$$

where

$$
\mathbf{A}_{i,b} = \text{diag} \left( \sqrt{\Lambda_{i,b,1}(1,1)}, \sqrt{\Lambda_{i,b,2}(1,1)}, \ldots, \sqrt{\Lambda_{i,b,M_{R_i}}(1,1)} \right)
$$
Figure 1: Comparison between ROLT-CSI based and previous long-term CSI based (p. method) linear precoding: (a) Sum rates for BD and RBD precoding (b) Individual user throughput for RBD precoding.

and

\[ B_{i,b} = [V_{i,b,1}(;1), V_{i,b,2}(;1), \ldots, V_{i,b,M_{R_i}}(;1)]^H. \]

Here \( \Lambda_{i,b,l}(1,1) \) indicates the largest eigenvalue of \( \hat{R}_{i,b,l} \) and \( V_{i,b,l}(;1) \) denotes the corresponding eigenvector. The multi-user MIMO precoding can now be performed on the equivalent channel as defined in equation (2).

To evaluate the proposed ROLT-CSI method we present simulation results in Figure 1. A MIMO downlink time variant frequency selective scenario with 3 users is considered. The system bandwidth is 128.5 MHz. There are 8 transmit antennas at the BS and each user is equipped with 2 receive antennas. User 1 and user 2 always have non-line of sight (NLOS) channels and user 3 always has a line of sight (LOS) channel. We compare the throughput performance of block diagonalization (BD) and regularized block diagonalization (RBD) precoding techniques based on the proposed ROLT-CSI method to the previous long-term CSI method proposed in [3, 4]. It can be shown that the significant performance gain can be achieved by our new approach relative to the previous long-term CSI method. Figure 1(b) shows that the ROLT-CSI approach is particularly efficient for the user who has the LOS channel. Even for the users who only have NLOS channels, which means that the spatial correlation matrices of these user channels have a high rank, relative to the previous long-term CSI method there are still some performance gains available for the presented ROLT-CSI approach.

### 3. CSI sounding pilot overhead reduction

Multiuser precoding in the downlink requires centralized CSI of all the terminals at the BS. In the TDD mode, CSI for the BS is provided by means of uplink CSI sounding pilot signals. However, antenna-specific uplink pilot streams cause an extensive overhead that restricts the size of the practical user group and the terminal antenna setup that can be handled within the same time-frequency slot. Conventionally, the number of the required mutually orthogonal CSI sounding pilot streams corresponds to the aggregate number of terminal antennas that are simultaneously active. Let there be \( K \) user terminals in the spatial signal processing group, each with \( M_{R_k} \) antennas, \( k = 1, \ldots, K \), and let the BS have \( M_T \) antennas. In practice, \( \sum_k M_{R_k} \) mutually orthogonal - in time and/or frequency domain - pilot sequences are needed.

This concept reduces the required CSI sounding overhead by letting the terminals form \( J_k < M_{R_k} \) uplink pilot beams by transmit precoding instead of transmitting...
antenna-specific pilots [5]. As a result, the number of required pilot resources reduces to \( \sum_k J_k \). Consequently, terminal \( k \) appears as a \( J_k \)-antenna device to the BS. The number \( J_k \) can be imposed either statically by a standard or dynamically by the BS. The CSI sounding beams are formed based on the knowledge of the user-specific MIMO channels, obtained via a downlink common pilot signal. This way part of the signaling overhead is moved to the downlink. The common pilot signal is resource efficient since only \( M_T \) orthogonal pilot sequences are needed. The concept also allows the use of advanced terminals or relay stations that have a different or higher number of antenna elements than supported by the system standard, as they can hide their true number of antennas from the BS.

The proposed signaling stages are depicted in Figure 3. The terminals estimate their individual \( M_{R_k} \times M_T \) MIMO channels based on a transmit-antenna-specific downlink common pilot signal before performing CSI sounding. The best choice for the sounding beamformers is then based on the strongest spatial eigenmodes-specific downlink so that the precoding matrix contains the corresponding \( J_k \) left singular vectors of the estimated channel. As a result, the BS cannot determine the full channel matrices but only the \( J_k \) best eigenmodes per user. From the system sum rate point of view, the optimal number \( L_k \) of data streams to be allocated per user is usually less than \( M_{R_k} \), especially when either \( K \) or \( M_{R_k} \) is large. Therefore, the weak eigenmodes, neglected in the reduced overhead sounding concept, would rarely be utilized.

The performance of the strategy in terms of achievable sum rate in the context of greedy beam selection and multiuser zero-forcing by coordinated transmit-receive processing [6] in uncorrelated fading channel is depicted in Figure 2. Here, all the users are equipped with identical antenna arrays, i.e. \( M_{R_k} = M_R \) for all \( k \), and they employ the same overhead reduction so that \( J_k = J \). In the case of noise-free pilot reception (Figure 2(a)), the performance loss induced by the incomplete sounding is minor, as the beamforming gain provided by multiple terminal antennas, and the multiuser diversity are retained. As shown in Figure 2(b), when taking into account the estimation noise, the overhead reduction turns out to improve robustness and even increase the average system capacity. This is due to the power efficiency of the CSI sounding concept: Uplink transmit power is not wasted on the weak eigenmodes that are unlikely to be utilized.
4. Pilot optimization for CSI estimation

Practical channels are often spatially correlated due to low antenna spacing and multipath propagation. This long-term statistics of the Rayleigh fading depends on large-scale properties in the environment and can therefore be assumed known both at the transmitter and receiver with only a minor overhead and can be exploited for improved acquisition of short-term CSI. Thus, the limited pilot resources can be focused on acquiring CSI for statistically strong spatial “directions”, while the impact of weak directions often can be ignored.

In mathematical terms, let $H \in \mathbb{C}^{M_R \times M_T}$ be a Rician fading channel matrix from an $M_T$ antenna transmitter to an $M_R$ antenna receiver (either downlink or uplink). Let the long-term statistics be defined on the column stacked version of $H$: $\text{vec}(H) \in \mathcal{CN}(\text{vec}(\bar{H}), R)$, where the covariance matrix $R = (R_T^T \otimes R_R)$ is assumed to be Kronecker-structured to clarify the impact of transmit-side and receive-side correlation in $R_T$ and $R_R$, respectively. Then, the MSE minimizing pilot sequence (under a total pilot power constraint) results in a pilot with different power along the different eigenvectors of $R_T$. The optimal power allocation is given by a convex optimization problem and has a waterfilling structure that allocates more power to strong directions [7]. If the long-term interference statistics are known, then pilot signaling along strong channel eigendirections should be performed when the interference is as weak as possible.

The optimal pilot power allocation also depends on what kind of CSI should be acquired at the receiver; different CSI quantities are used for different purposes. Estimation of the channel matrix $H$ is useful for precoding design, while for example the squared Frobenius norm $\|H\|_F^2$ is useful for scheduling and feedback [8]. It is of great importance to always estimate each quantity directly from the received pilot signal, as illustrated in Figure 5 for a spatially correlated channel. Here, the MMSE estimator of $\|H\|_F^2$ in [7] is compared with an indirect scheme that first estimates the full channel matrix $H$ and then calculates the norm of that estimate. It is clear that indirect estimation yields bad performance, in many cases even worse than completely ignoring the training data and just using the statistical mean as the estimate. Pilot optimization gives a clear performance gain compared with uniform pilot power allocation, and channel matrix optimized pilot signaling works well even for channel norm estimation.

To summarize, spatial correlation can be used to improve the channel estimates using adaptively optimized pilot sequences. In contrast to Section 3, we here considered a single link and designed the pilot based on long-term statistics instead of instantaneous channel estimates in the reverse link. The same pilot signal can be used to acquire different CSI quantities, but different estimators should be used for each of them and the optimal choice of pilot sequence will also differ.
5. Two-way relaying with MIMO-AF-relays

Relaying is one of the key candidate technologies to achieve the ubiquitous demand of high data rate traffic which is expected for next generation mobile radio systems. Relays can be used in many different ways, e.g., to enhance the coverage of a radio cell (as in relay enhanced cells), to extract spatial diversity (using cooperative relaying), or to enhance the feasible sum rates in the cell by playing the role of a direct communication partner (as in one-way or two-way relaying).

The two-way relaying (TWR) scheme is a very promising candidate among the relaying protocols, since it uses the radio resources particularly efficiently [9]. In TWR, two communication partners (which can be terminals or access points and will be referred to as ”nodes” in the sequel) that need to exchange data are supported by a single relay in a two-step procedure: In the first step both nodes transmit their data to the relay where their transmissions interfere, in the second step the relay transmits back to both nodes. The corresponding system model is depicted in Figure 4: the relay is equipped with $M_R$ antennas and the nodes possess $M_1$ and $M_2$ antennas, respectively.

We focus on Amplify and Forward (AF) relays operating in TDD mode, i.e., the relay processes the received superposition of the users’ transmissions by amplifying the signal and retransmitting it in the second time slot. Consequently, the signal received by each node comprises four terms: (1) the “self-interference”, which is the echo of the node’s own transmission amplified by the relay and received through its reverse channel; (2) the desired signal of the other node, received via the other node’s forward channel, the relay amplification matrix, and the node’s own reverse channel; (3) the relay’s additive noise contribution, amplified by the relay and transmitted through the node’s reverse channels; (4) the node’s own additive noise component. Since each node knows its own transmitted signal, the first term can be canceled, provided that channel knowledge is available. This step is usually referred to as Analogue Network Coding (ANC). ANC decouples the TWR channel into two parallel single-user MIMO channels, where the effective channel matrices are given by the product of one node’s reverse channel, the relay amplification matrix, and the other node’s forward channel. The single-user MIMO transmissions are superimposed by an effective noise contribution which comprises the node’s own noise and the forwarded relay noise.

Therefore, two aspects are of crucial importance to the TWR system: The estimation of the channels to facilitate the ANC and the choice of the relay amplification matrix during the data transmission phase. Firstly, for the channel estimation, we have proposed the purely algebraic Tensor-Based Channel Estimation (TENCE) algorithm in [10] and the Structured Least Squares (SLS) based iterative refinement for TENCE in [11]. Both schemes provide both nodes and the relay with all relevant channel param-
eters based on a training phase, where at least $M_1 + M_2$ pilots are repeated by the nodes in $M_R$ subsequent frames, changing the relay amplification matrix from frame to frame. We also develop design rules and recommendations on the choice of the pilot symbols and the relay amplification matrix during the training phase in [10]. As we show, the nodes should use mutually orthogonal sequences. The nodes use their CSI twofold: (a) The subtraction of self-interference via ANC and (b) the pre- and decoding to transmit data over the effective single-user MIMO links, e.g., via Dominant Eigenmode Transmission (DET) or Spatial Multiplexing. The relay station uses its CSI to influence the effective single-user MIMO channel matrices via a proper choice of the relay amplification matrix. Thereby, the link quality can be further improved. Note that CSI at the relay is optional whereas CSI at the nodes is crucial for the TWR system due to the required ANC step.

Secondly, for the choice of the relay amplification matrix, we have proposed the Algebraic Norm-Maximizing (ANOMAX) transmit strategy in [12]. ANOMAX maximizes the weighted sum of the squared Frobenius norms of the effective channel matrices and thereby enhances the energy of the desired signals at the nodes compared to alternative strategies. This promises a good bit error rate performance for single-stream transmission, which we have verified numerically in [12].

Summarizing, we have shown that a two-way relaying (TWR) system with AF relays is feasible even under real-world conditions where the channels have to be estimated. The main benefit of the TWR system is that a bidirectional transmission is achieved in only two time slots while the nodes and the relay can operate in half-duplex mode. The channel estimation schemes TENCE and its SLS-based refinement as well as the ANOMAX scheme feature a very low computational complexity which allows to build low-cost relays nodes that implement the TWR protocol. This renders their deployment in larger quantities economically feasible.

6. Conclusions

This paper summarized multiple novel concepts related to multiuser MIMO communication in cellular networks, focusing on the acquisition and application of CSI. The first concept presented a method for low-rank modeling of the long-term CSI, estimated over a finite time and frequency bandwidth. Compared to the conventional direct averaging, the low-rank modeling provides a more useful reference for precoding, especially when the directional components are dominating in the spatial channel. The concept can be directly employed in any system allowing sounding-based precoding, such as LTE-Advanced. Furthermore, the computational complexity is low, since the BS computes matrix decompositions only per relatively long channel averaging periods.

The second proposal introduced a novel signaling concept for reducing the overhead caused by uplink CSI sounding. According to the simulation results, reducing of the pilot overhead actually improves the performance of the precoded transmission, due to the increased sounding power efficiency. The concept requires the existence of a down-link common pilot. The complexity of the scheme depends on the number of terminal antennas, as each terminal performs decompositions on its own channel matrices.

The third concept proposed to optimize the CSI estimation performance by exploiting long-term statistics in the pilot signal design, and showed how different CSI quantities require different estimators. Finally, the fourth concept proposed a new two-way
MIMO amplify-and-forward relaying strategy for terminal-to-terminal communication. Here, a bidirectional exchange of information is achieved in just two time slots even though both terminals as well as the relay operate in half-duplex mode. The computational burden of these two concepts is moderate, as the optimization tasks are performed over long-term channel statistics.

The results of the research indicate that the CSI at its best is not only about estimating the channel responses between different antenna pairs. What counts is the nature of the intended communication link as well as the form in which CSI is applied. On the other hand, the availability, form, and quality of the CSI affect the design of the communication strategies themselves.

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