Variable Overhead Effective CSI Signaling for Coordinated Beamforming in TDD MIMO Systems

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***Abstract*—We propose signaling concepts with variable pilot overhead to provide effective channel state information (CSI) to support decentralized coordinated beamforming for multi-antenna terminals in the time division duplex (TDD) mode. The focus is on linear downlink multi-cell transmit-receive processing with underlay device-to-device connections in the context of an iterative weighted sum rate (WSR) maximization algorithm that consists of optimization steps carried out locally by the transmitters. Arbitrary numbers of antennas in the terminals are supported. However, the channel sounding overhead is kept low as each terminal transmits only a few or just one precoded pilot beam in the channel sounding phase, regardless of how many antennas it employs. The overhead reduction hides the weak eigenmodes of the whitened channels, but at the same time the signal-to-noise-ratio of the channel estimation improves as the limited sounding energy is concentrated on the strong eigenmodes.**

I. Introduction

We consider a multi-antenna interfering broadcast channel (IBC), formed by a cellular network comprising multiple multi-antenna base stations (BSs) that share the same frequency band for their downlink transmissions. Here, each BS serves its own set of user terminals (UTs), and the co-channel transmissions from each BS cause interference to the UTs of other cells. Furthermore, we assume that the data streams are transmitted via linear spatial precoding (beamforming) and that each UT treats the signals intended to other UTs, i.e., both intra-cell and inter-cell interference, as colored noise. In order to mitigate or avoid the inter-cell interference problem, the BSs employ *coordinated beamforming* [1]–[4] where the transmissions within a coordinating set of cells are jointly designed in terms of transmit beamforming and user scheduling.

The system model is further extended by employing spatial underlay device-to-device (D2D) communication, where some UT pairs are allowed to directly transmit to each other. Here, the transmitting UT assumes the role of a small BS and takes part in the beam coordination protocol accordingly. Compared to the case where the UT pair communicates via the BS, direct D2D connection has multiple benefits [5], [6]. *Proximity gain* is obtained when the D2D UTs are close to each other so that the channel between them is strong. This translates to very low transmit powers or alternatively to high data rates. On the other hand, the duplexing loss and delay caused by multi-hop transmission is avoided, and resources are saved for other cellular users. Thus, from the network perspective, it is beneficial to allow direct D2D communication.

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Beam coordination is practical in the sense that the transmitters do not need to share user payload data, and carrier phase coherence between the transmitters is not required since each data stream is precoded by a single transmitter. The approach is in line with the architecture of modern wireless cellular networks such as 3GPP LTE (Long Term Evolution), where the data traffic of all services is packet switched, and where the BSs locally carry out fast dynamic user and packet scheduling [7].

II. WSR Maximization

When accompanied with just transmit power constraints, the WSR maximization problem is always feasible. Furthermore, the WSR criterion can be directly linked to the multi-user scheduling problem, and the priority weights of different users may be adaptively adjusted to match their services or to ensure fairness between the users. Beam coordination based on WSR maximization carries out spatial user and beam scheduling implicitly. However, in the context of interference channels, WSR maximization is not a convex problem with respect to the transmit covariance matrices [8], and, therefore, only local optima can be found via practical methods.

A connection between the weighted sum mean-squared-error (WSMSE) minimization and the WSR maximization problems in the MIMO broadcast channel was established in [9]. In this approach, a local WSR optimum is found via alternating optimization of the transmit and receive filters, and by iteratively updating the MSE weights. The same approach was taken in [10] and [11] in order to solve the WSR problem for the MIMO interference channel (IFC) consisting of a set of transmitter and receiver pairs. Finally, [4] generalized the treatment for MIMO IBC, and formulated a new joint optimization problem of all three variables (transmitters, receivers, weights) that was shown to be equivalent to the WSR maximization problem.

III. CSI Acquisition and Information Exchange

Coordinated beamforming requires information of the channels or effective channels between each BS and all active terminals within the coordinating group of cells. A simple approach applicable in the time-division-duplex (TDD) mode is channel sounding (CS) that relies on the reciprocity of the uplink and downlink radio channels. Compared to the quantized or analog CSI feedback that are applicable in the frequency-division-duplex (FDD) mode as well, channel sounding is more resource efficient [12]. The TDD mode is best applicable to local area deployments and small cells, where the transmit powers, mobile speeds, and the channel propagation delays are relatively low. In uplink sounding, the terminals transmit known pilot (training) signals that are observed by the BSs. In the case of single-cell designs, sounding overhead reduction for multi-antenna UTs has been proposed in [13], [14].

The usual assumption for the decentralized algorithms presented in the literature is that each BS acquires the knowledge of the channel matrices at least between itself and all the terminals [1]–[4], [15]. In case of single-antenna terminals, the sounding responses are all that is needed for each BS to perform straightforward multi-cell MMSE-precoding via decentralized processing [3]. However, when the UTs are equipped with multiple receive antennas or when only a subset of the sounding terminals may be simultaneously receiving, the problem becomes more elaborate. Now, the information needed by a BS, in order to avoid interfering a given UT, is the *effective channel*, i.e., the channel matrix multiplied by the active receiver. One way to construct the effective channels is to share information of the receiver filters between the cells [15]. However, in TDD mode, as proposed in [16], the effective channels can be indicated by specific uplink training signals called busy bursts (BB).

In our earlier work, we proposed decentralized algorithms and corresponding signaling concepts of effective CSI for WSR maximization via linear downlink transmit-receive processing in multi-cell multi-user MIMO systems operating specifically in the TDD mode [17], [18]. In one strategy, the coordinating cells update their transmit precoders and receivers one cell at a time, which guarantees monotonic convergence of the network-wide WSR in static channel conditions. This strategy employs separate uplink CS signaling that essentially provides the CSI of a UT to its own serving BS, whitened with respect to inter-cell interference and noise [19], and BB signaling to indicate the effective channels to the neighboring BSs. The strategy requires almost negligible backhaul traffic. In another strategy, the monotonic convergence was sacrificed to devise a faster scheme where the BSs are allowed to optimize their variables in parallel. Here, separate BB signaling is not needed as the effective channels are constructed based on just the CS responses and additional backhaul information. In [17], full-rank channel sounding was assumed, while in [18], pilot overhead reduction was sought by employing just one sounding beam per UT regardless of the number of the UT antennas.

IV. Contributions

In this work, we generalize the channel sounding strategy so that any number between one and N (where N is the number of UT antenna elements) of sounding beams can be formed by each UT. The overhead reduction hides the weak eigenmodes of the effective channels, but at the same time the signal-to-noise-ratio of the channel estimation improves as the limited sounding energy is concentrated on the strong eigenmodes. It is noticed that there is a trade-off between the gain obtained by observing a multiplicity of vector channels and the gain due to the accuracy of those observations. In the presence of channel estimation noise, and when adjusting the number of sounding beams, this trade-off can be seen in the system sum-rate performance. The framework is further applied in the context of underlay D2D communication so that the transmitting UT assumes the role of a small BS and takes part in the beam coordination protocol. Here, the coordination employs BB signaling in order to avoid continuous backhaul signaling between the BSs and the transmitting UT.

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