Multiuser Extensions for Closed Loop Transmit Diversity in HSDPA

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Abstract—Closed loop transmit diversity has already been adopted by 3GPP for MIMO HSDPA in the form of TxAA and its dual stream counterpart, D-TxAA. While both these transmission techniques provide performance gains for single user (SU) scenarios, they both introduce multi-user interference in the downlink in multi-user(MU) scenarios. In this paper, we study the extension of these transmission techniques to the multi-user case which entail minimal changes to the existing standard. To this end, we consider the classical MMSE chip equalizer receivers that feed back beamforming weights so as to maximize the receive SINR at each user equipment (UE). Given that the base station (BS) has to use these weights to transmit data to the UEs, we compare practical and realistic strategies that BS can employ in order to maximize downlink capacity. We derive the SINR expression for MMSE chip equalizer receivers for the general case of MU-TxAA which is used at the receivers to select optimum feedback weights. We investigate different multiuser schemes for HSDPA in the downlink (DL), compare their performance and suggest optimal strategies for single and dual stream transmission for both single and multi-antenna receivers and corroborate our arguments with simulation results. We show that for the case of single antenna receivers, scheduling users with same beamforming weights maximizes downlink capacity in TxAA. For the D-TxAA with multiple antennas at receivers (MIMO) we show that SDMA outperforms spatial multiplexing in terms of maximizing DL capacity.

I. INTRODUCTION

Advanced cellular systems deploy some kind of antenna diversity at the base station to exploit transmit and/or receive diversity not just in the interest of enhancing link quality but also to increase total system capacity. While, the same arguments are true for the user equipment (UE), multiple antennas at the UE, may not be desirable for any number of practical reasons. Regardless, it is true that there exist possible use cases where multiple antennas at UE are advantageous. For the former case, the problem is elegantly solved by using transmit diversity schemes at the base station while the latter situation provides opportunities for both enhanced link throughput using spatial multiplexing and increased spectral efficiency using SDMA.

Both transmit diversity and spatial multiplexing has been incorporated by 3GPP as standard in the form of TxAA and its dual stream counterpart D-TxAA for MIMO HSDPA. HSDPA supports two modes (mode-1 and mode-2) of the closed loop transmit diversity technique called transmit adaptive array (TxAA). In the 2 transmit-1 receive (2×1) antenna configuration of TxAA, the UE and feeds back optimum beamforming weights that the BS uses while transmitting data to UE. In mode-1, UE chooses one of 4 beamforming weights that control the antenna phase at BS. The BS fixes the phase of its primary (reference) antenna and alters the phase of the secondary antenna accordingly. In mode-2, UE is also able to control relative amplitudes of the antenna output based on a 1-bit feedback scheme. In addition, mode-2 has a finer phase control which together lead to a total of 16 beamforming weights to choose from. D-TxAA is an extension of TxAA where two separately encoded, interleaved and spread transport blocks are transmitted in parallel. In its present form however, the standard only supports SU scenarios in D-TxAA when UE is equipped with multiple receive antennas and both transport blocks are allocated to the same user (in other words MIMO for spatial multiplexing). For SDMA in HSDPA, the limitation of 2 transmit antennas implies that a maximum of 2 spatially separated users can be simultaneously served by the BS with the same code. In general, MU extensions for these closed loop transmit diversity schemes introduce multi-user interference in downlink since there exists the possibility of different users feeding back different beamforming vectors (or in the case of D-TxAA precoding matrices).

There is a large amount of literature available for multiuser MIMO communication in the general case. It has been studied previously in [1] and more recently in [2] where multiuser transmission techniques are classified into linear and non-linear transmission algorithms. Non-linear algorithms involving multiuser signal designs that avoid interference generation to other users based on dirty paper coding techniques remain currently impractical due to the requirement of perfect channel state information at the transmitter (CSIT). They also suffer from all the drawbacks associated with outdated CSIT due to scheduling delays at the base station and/or rapidly changing downlink channels. Linear processing of transmitted signals like multiuser beamforming remain by far the most practical solution for multiuser transmission. Theoretical research in multiuser communications tends to consider frequency-flat channels. In reality most mobile communication channels are frequency selective. There exists some literature on multiuser extension of HSDPA. In [3] the authors propose code reuse in D-TxAA based on a multi-user beamforming (MUB) scheme which schedules users with orthogonal weight vectors to sep-

arate them in space. They however limit their analysis to flat-channels. In [4], the authors consider MU-TxAA for frequency selective channels and propose the so-called "interference-aware" receiver which in addition to requiring multiple antennas at the receiver also assumes knowledge of beamforming weight vectors of all the users at the receiver. On the other hand, in this paper, we look at the problem of maximizing system capacity in the frequency selective MISO/MIMO downlink channels assuming the receivers select weights that maximize receive SINR (and thus increase their individual data rates). In the HSDPA context, the BS is equipped with 2 transmit antennas i.e. $N_{tx} = 2$. In our treatment, we do not assume any explicit knowledge of beamforming weight vectors of other users, for single stream transmission we consider single antenna UE and study different beamforming strategies that can be adopted by the BS and for dual stream transmission we consider UE with two antennas and compare the performance of SDMA against spatial multiplexing to a single user by extending D-TxAA to a MU configuration where at most N_{tx} users can be synchronously served by the BS. Each transmit stream is assigned to a different user. This rules out simultaneously serving any two users that feed back the same beamforming weight vector. Users that request linearly independent weight vectors can however be served simultaneously.

The paper is organized as follows. In section II we introduce the transmit signal model for TxAA. After a brief primer on MMSE chip-equalization in section III, we derive the SINR expression for LMMSE receivers for the general case of multiuser TxAA and propose extensions of TxAA for the multiuser case in section IV. In section V we explain the signal model for MU-D-TxAA and devote section VI to the multiuser extension of D-TxAA. Finally in section VII we present simulation results for different multiuser schemes proposed in this paper and draw our conclusions in section VIII based on simulation results.

II. TRANSMIT SIGNAL MODEL FOR MU-TxAA

We consider a 2-transmit, 1-receive antenna configuration for TxAA. For the rest of the paper, whenever we refer to a MU-TxAA system, we consider U seperate UEs each having a single receive antenna. The number of codes assigned to each user is denoted by $K_1, K_2, \ldots, K_U$ and $K = \sum_{u=1}^{U} K_u$. Then, for TxAA, from Fig. 1 the transmit and beamformed chip sequence is given by

$$\boldsymbol{x}[j] = \sum_{u=1}^{U} \boldsymbol{w}_u \cdot s_n[j \mod G] \sum_{k \in K_u} c_k[j \mod G] a_{u,k}[\lfloor \frac{j}{G} \rfloor n],$$
(1)

where j is the chip index, n is the symbol index, u is the user index, k is the code index, G is the spreading gain, s_n denotes the scrambler for the nth symbol, c_k denotes the kth spreading code, $\boldsymbol{w}_u = [w_{u,1} w_{u,2}]^T$ is the weight vector corresponding to u^{th} user and finally $a_{u,k}$ is the uth user's symbol on code index k given that $k \in K_u$. The transmitted signal propagates through a multipath channel which we denote here
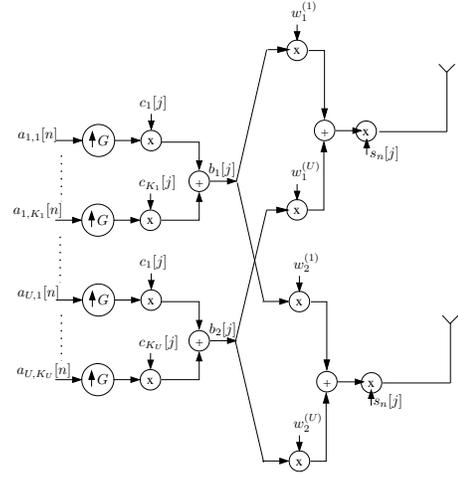
Fig. 1.   Multiuser TxAA transmit signal model.

by $\mathcal{H}_u^0, \mathcal{H}_u^1, \ldots, \mathcal{H}_u^{L-1}$. For an oversampling factor of m at the receiver, each $\mathcal{H}_u^l$ matrix is a $m \times 2$ matrix corresponding to the lth tap of the uth user's multipath channel. For simplicity we assume that all UEs see a channel with a maximum delay spread of L chips and employ an equalizer of length E (in chips). The chip-rate received signal at each UE is given by

$$\boldsymbol{y_u} = \boldsymbol{H_u} \boldsymbol{x} + \eta$$
(2)

where $\boldsymbol{H}_u$ is the channel convolution matrix for the uth user given by

$$\boldsymbol{H}_u = \begin{bmatrix} \mathcal{H}_u^0 & \mathcal{H}_u^1 & \cdots & \mathcal{H}_u^{L-1} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \mathcal{H}_u^0 & \cdots & \cdots & \mathcal{H}_u^{L-1} & \vdots \\ \boldsymbol{0} & \boldsymbol{0} & \ddots & \ddots & \ddots & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \ddots & \mathcal{H}_u^0 & \ddots & \mathcal{H}_u^{L-1} \end{bmatrix},$$
(3)

$\boldsymbol{x}$ is the transmit chip-vector formed by stacking $L + E - 1$ vectors and can be expressed as

$$\boldsymbol{x} = [\boldsymbol{x}^T[j], \boldsymbol{x}^T[j-1], \ldots, \boldsymbol{x}^T[j - L - E + 2]],$$
(4)

and η is zero mean, circularly symmetric, Gaussian distributed, additive white noise of variance σ_η^2. In addition, we also define the $m \times 1$ vector $\boldsymbol{r}_{u,v}^l = \mathcal{H}_u^l \boldsymbol{w}_v$, $v \in 1, 2, \ldots, U$ and use this to define the lth beamformed channel tap of user u, due to beamforming weight of another synchronous DL user v. We denote this by $\boldsymbol{R}_{u,v}$ and express this as

$$\boldsymbol{R}_{u,v} = \begin{bmatrix} \boldsymbol{r}_{u,v}^0 & \boldsymbol{r}_{u,v}^1 & \cdots & \boldsymbol{r}_{u,v}^{L-1} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{r}_{u,v}^0 & \cdots & \cdots & \boldsymbol{r}_{u,v}^{L-1} & \vdots \\ \boldsymbol{0} & \boldsymbol{0} & \ddots & \ddots & \ddots & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \ddots & \boldsymbol{r}_{u,v}^0 & \ddots & \boldsymbol{r}_{u,v}^{L-1} \end{bmatrix},$$
(5)

III. MMSE Chip Equalization

Consider the case where the base station serves U simultaneous users in the downlink. We assume standard MMSE chip equalizer-correlator receivers. Let $\boldsymbol{f}_u$ represent the MMSE filter of length E applied at user u, then the equivalent channel-equalizer cascade at the output of the chip equalizer for user u is given by

$$\boldsymbol{\alpha}^{(u)} = \boldsymbol{f}_u \boldsymbol{R}_{u,u} + \boldsymbol{f}_u \sum_{v \neq u}^{U} \boldsymbol{R}_{u,v}, \tag{6}$$

which can be represented by

$$\boldsymbol{\alpha}^{(u)} = \boldsymbol{\alpha}_{u,u} + \sum_{v \neq u}^{U} \boldsymbol{\alpha}_{u,v}, \tag{7}$$

where $\boldsymbol{\alpha}_{u,u}$, is the channel-equalizer cascade for codes assigned to user u and $\boldsymbol{\alpha}_{u,v}$ is the channel-equalizer cascade for codes assigned to user v at user u. $\boldsymbol{\alpha}_{u,u}$ can in turn be split into the desired equalizer response and the residual inter-chip-interference and represented as

$$\boldsymbol{\alpha}_{u,u} = \boldsymbol{\alpha}_{u,u}^d + \overline{\boldsymbol{\alpha}}_{u,u} \tag{8}$$

$$\boldsymbol{\alpha}_{u,u}^d = \left[\overbrace{0 \ldots 0}^{d-1} \; \alpha_{u,u}^d \; \overbrace{0 \ldots 0}^{L+E-2-d} \right] \tag{9}$$

where d is the equalizer delay. The LMMSE equalizer is considered to be followed by a stacking operation allowing despreading and symbol decision.

IV. Multiuser Beamforming For TxAA

A. Simple multiuser beamforming

To understand the effect of multiple-users with distinct beamforming weights in DL, it is insightful to derive the per-code SINR at the receiver for the case where multiple users are served in the downlink with different beamforming weights. When the BS employs different user-defined beamforming weights in downlink for MU transmission, at each receiver, codes assigned to different users propagate through U distinct *beamformed channels* even though the physical channel through which they propagate is the same. Without explicit knowledge of all beamforming weights used in the downlink, which is the so called interference aware [4] receiver, the receiver will not be able to effectively mitigate the effect of MUI. Since each user is aware only of beamforming weights that will be applied for codes assigned to itself and not of other users, the equalizer at each user is only matched to the beamformed channel seen by the codes assigned to this user. In computing the ideal beamforming weights for itself, a UE has to make some hypothesis on the beamforming weight vectors of other users in DL and choose the weight vector that maximizes the SINR corresponding to that hypothesis. For the general case where there exist U different users, defining K_u as the index set containing code indices of the uth user, the

SINR per-code $SINR_{k \in K_u}$ that is seen by the code assigned to the user is given by

$$\frac{\sigma_k^2 |\alpha_{u,u}^d|^2}{\frac{1}{G} \sum_{k \in K_u} \sigma_k^2 \|\overline{\boldsymbol{\alpha}}_{u,u}\|^2 + \sum_{v \neq u} \frac{1}{G} \sum_{k \in K_v} \sigma_k^2 \|\boldsymbol{\alpha}_{u,v}\|^2 + \sigma_\eta^2 \boldsymbol{f}_u \boldsymbol{f}_u^H} \tag{10}$$

Where σ_k^2 denotes the chip variance of the kth code. In a simple extension of beamforming with multiple users with different beamforming weight vectors, each UE makes the assumption that all users in DL have the same beamforming weight vectors and computes the ideal beamforming weight vector under this assumption. The BS however makes no attempt to group users with same beamforming weights. As a result, it is expected that the downlink capacity drops significantly

B. Weight optimization by average interference criterion

Alternatively UE can anticipate that in reality, any of the four weights by be chosen by the other users in DL. Assuming that other users choose one of four beamforming weights with equal likelihood, it is reasonable to choose that beamforming weight which has the maximum SINR when averaged over all four hypothesis for the other users weights. Each UE computes the ideal beamforming weight by plugging into (10), the all possible combinations of weight vectors and feeds back the weight vector with the best average SINR over all the hypothesis for all the other users in DL. The true SINR at the receiver may still not be the same as expected SINR but it is higher that that of simple multiuser beamforming case thus corresponding to an increase in data rate per user when compared to the simple multiuser beamforming.

C. Co-operative beamforming

If the BS were to have the knowledge of the SINR seen by a particular user for all possible combinations of weight vectors applied at the base station, then, the BS can choose the combination of weights that maximizes the downlink capacity. We call this co-operative beamforming because, in this case, all the users compute all possible SINRs corresponding to the weight vectors in the codebook. From (10) we see that for a given weight-vector, the SINR is highest when all other users also have the same beamforming weight-vector. Each user therefore feeds back as many SINRs as the codebook size. Thus it is a form of co-operation between the users and BS to maximize system capacity. In practice, this involves considerable amount of receiver processing and also a lot of feedback to the BS. Nonetheless, the gains in such a case is worth investigating.

D. Scheduled beamforming

The practical and indeed the best solution to this problem with least complexity is for the BS to schedule in the DL, only those users that request the same beamforming weights. Each user assumes that same weights are applied to all codes in DL and computes the weight vector that maximizes the per code

SINR. For this case, the user can then restore the orthogonality of all codes with the MMSE chip equalizer-correlator receiver. The per-code SINR for the uth user is then given by

$$\frac{\sigma_k^2 |\alpha_{u,u}^d|^2}{\frac{K}{G}\sigma_k^2 \|\overline{\boldsymbol{\alpha}}_{u,u}\|^2 + \sigma_\eta^2 \boldsymbol{f}_u \boldsymbol{f}_u^H} \quad (11)$$

The combination of scheduling at BS and the choice of weight vector that maximizes the individual SINR at the receiver results in maximization of DL capacity.

V. Transmit Signal Model for Multiuser D-TxAA

For MU-D-TxAA system, we consider 2 separate UEs with N_{rx} receive antennas each. In a MU-D-TxAA system, the BS transmits 2 transport blocks for as many users scheduled in DL. All codes of a single stream are assigned to one user and re-used across the two streams. From Fig. 2, we see that the transmit signal vector in downlink can be modeled as

$$\boldsymbol{x}[j] = \underbrace{\boldsymbol{W}}_{2\times 2} \boldsymbol{b}[j] = \boldsymbol{W} \cdot \sum_{k=1}^{K} s[j]c_k[j \mod G]\boldsymbol{a}_k[n] \quad (12)$$

$\boldsymbol{W} = [\boldsymbol{w}_1 \ \boldsymbol{w}_2]$ is the 2×2 unitary precoding matrix. The columns of $\boldsymbol{W}$ are made up of the beamforming weight vectors corresponding to the two downlink users. The symbol vector $\boldsymbol{a}_k[n] = [a_{1k}[n] \ a_{2k}[n]]^T$ represents two independent symbol streams belonging to two different users. The spreading codes are common to the two streams and so is the scrambling sequence $s[j]$.
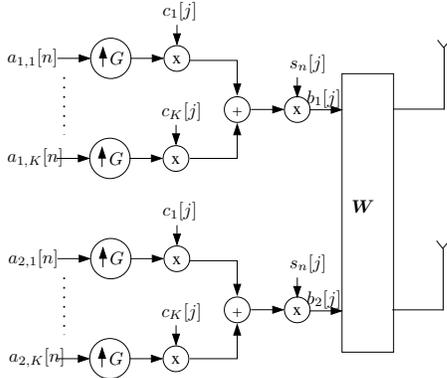
Fig. 2. Multiuser D-TxAA transmit signal model.

VI. Spatial Multiplexing vs. SDMA

In the spatial multiplexing context, there is only a single user in downlink and the precoding matrix corresponds to the weight vectors applied to the two separate streams transmitted to the same user. For such a case, we can write the equalizer output as the sum of an arbitrarily scaled desired term and an error term

$$\widehat{\boldsymbol{x}}[j] = \boldsymbol{x}[j] - \widetilde{\boldsymbol{x}}[j]. \quad (13)$$

The error $\widetilde{\boldsymbol{x}}[j]$ is a zero-mean complex normal random variable. The error covariance matrix is denoted by $\boldsymbol{\mathcal{R}}_{\widetilde{x}\widetilde{x}}$.

In (13), an estimate of the chip sequence can be obtained after a further stage of processing where the precoding is undone to separate streams. The latter represented by $\boldsymbol{W}^H$ is a linear operation and can be carried out before or after despreading. Under the assumption of a FIR signal model, the estimation error covariance matrices $\boldsymbol{\mathcal{R}}_{\widetilde{x}\widetilde{x}}$ (chip-level) and $\boldsymbol{\mathcal{R}}_{\widetilde{z}\widetilde{z}}$ (symbol-level) are derived in [5]. It can be shown that the SINR for the qth stream at the output of the output of the LMMSE chip equalizer/correlator is given by [5]

$$SINR_q = \frac{\sigma_a^2}{\left(\boldsymbol{W}^H \boldsymbol{\mathcal{R}}_{\widetilde{z}\widetilde{z}} \boldsymbol{W}\right)_{qq}} - 1. \quad (14)$$

where σ_a^2 corresponds to the symbol variance.

In the SDMA context, the BS transmits a single stream for each of the two downlink users. The BS applies the precoding matrix $\boldsymbol{W}$ whose columns correspond to the weight vectors fed back by the two users. It is obvious that two users who feedback the same weight-vector cannot be scheduled simultaneously for transmission in the downlink. At the receiver, each UE receives both the streams but processes only the stream assigned to itself. In HSDPA, 2×2 unitary precoding is used, this implies that the two columns of the precoding matrix are orthogonal. Moreover, knowledge of a single column automatically fixes the other column of $\boldsymbol{W}$. Thus, the BS does not have to explicitly inform one UE of the weight vector applied for the other UE. The SINR for the stream assigned to the user in question is therefore the same as in (14)

VII. Simulation Results

In this section, we present Monte-Carlo simulation results and performance comparison of different beamforming strategies proposed in the paper. We consider a multipath channel with a maximum delay spread L of 10-chips with uniform power in all channel taps. At any given time BS simultaneously serves 2 users. The beamforming weights are calculated to maximize the per-code SINR at the output of the equalizer correlator combination. Simulations were carried out for a fixed SNR at each receive antenna while keeping the total transmit power is normalized to 1. The cumulative distribution function of the sum-capacity upper-bound in DL is then used as a performance metric to compare different strategies. Depending on the number of independent transport blocks at the transmitter the other simulation parameters are given as below

A. TxAA

Each UE is assumed to have single receive antenna. Normally, each UE feeds back only its preferred weight vector index, only in case of co-operative beamforming, it feeds back SINR values to the BS. For the sake of simplicity we assume that each UE is allocated 7 of the 15 codes in the DL all with the same power.

B. D-TxAA

Each independent transport block is assumed to be allocated to a different user. Thus all codes of a stream are allocated to one user. For SDMA with single antenna receivers, we assume users with orthogonal weights are scheduled together. For SDMA with 2-antenna receivers, users with different beamforming weight vectors are assumed to be scheduled together. In the SM case, a 2×2 MIMO system is assumed with all codes and both streams transmitted to a single user. Fig.3 compares the sum-capacity in the DL for the case of
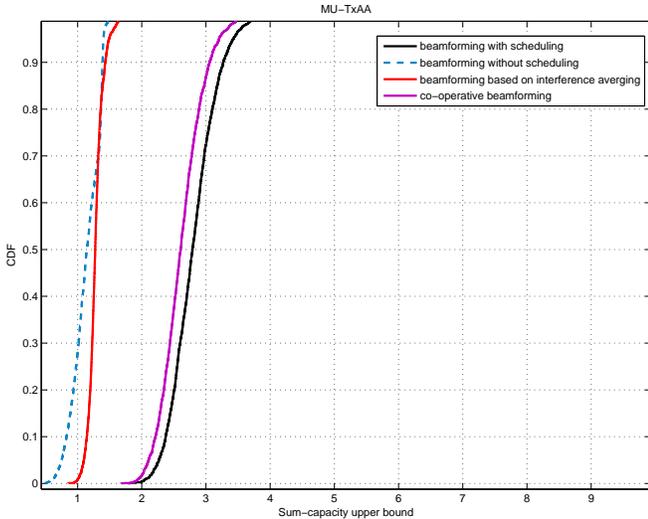
Fig. 3. Performance of different beamforming schemes for MU-TxAA.
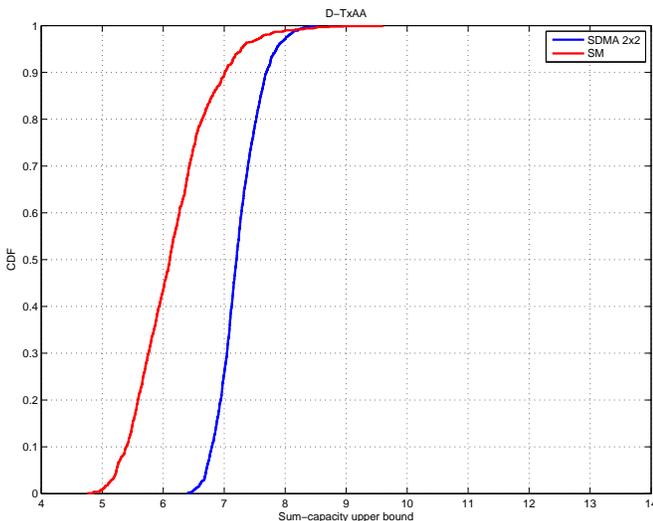
Fig. 4. DL sum-capacity for MU-D-TxAA.

TxAA. The DL capacity is worst for the case of beamforming without scheduling. This is because of the inability of the receivers to effectively restore orthogonality for all codes and hence effectively mitigate MUI since they do not know the actual beamforming weight of the other user. When the

beamforming weight is optimized by the average interference criterion, the weights are not just chosen based on the channel seen by each user, but also based on the capability of these weights to reduce the average multi user interference due to different beamforming weights of the other user.the downlink capacity is thus better than that in the case of simple multiuser beamforming. At the cost of an increase in complexity and feedback, co-operative beamforming performs better than that of the earlier schemes, even so, it is does not do better than the scheduled beamforming because the UEs need not necessarily be assigned the weight vector that maximizes their individual SINR. Scheduled beamforming thus outperforms all the other schemes since in this case each user is able to effectively mitigate MUI due to the same beamformed channel seen by all codes in downlink. It should be noted that for the case where the total number of users in DL far exceed the number of users actually scheduled in the DL, the performance of co-operative beamforming is expected to improve. In Fig.4, we compare the performance of D-TxAA in spatial multiplexing mode with that of the multiuser (SDMA) mode. Simulation results show that the DL sum-capacity is greater for the case of SDMA with single stream transmission to both users.

VIII. CONCLUSIONS

In this contribution we derived an SINR expression for MMSE receivers for the case of multiuser single stream transmission that uses closed loop transmit diversity at the base station. Using this SINR expression we proposed and studied beamforming strategies that can be employed at the BS and compared the performance of these strategies in terms of sum-capacity in downlink. Simulation results show that for receivers that are not interference aware, simple multiuser extension of single-user TxAA incurs a DL capacity loss due to imperfect restoration of orthogonality at the receivers which leads to increased MUI. We showed here that downlink capacity is maximized when users feed back weights that maximize their individual SINR and BS combines beamforming with scheduling users with the same weight vector. When UEs are equipped with multiple receive antennas, we see that DL capacity is maximized if BS prefers SDMA to two users instead of spatial multiplexing to a single user.

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