Achievable Data Rates for Two Transmit Antenna Broadcast Channels with WCDMA HSDPA Feedback Information

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I. INTRODUCTION

Wireless communications are currently facing an enormous growth on the advent of the worldwide introduction of 3G mobile cellular standards. With both the amount of internet traffic and cellular wireless communications exploding in the past few years, a huge market is being created for high speed wireless access. However, it is already clear that the promise of significantly higher data rate wireless services and applications can only be met if the available frequency resources are used in a much more efficient manner than today, utilizing all available forms of diversity.

It has been known for quite some time that in order to communicate efficiently over the wireless channel, one should exploit spatial diversity by benefitting from independent fading propagation paths. This led to the development of efficient open-loop (OL) and closed-loop (CL) transmit diversity (TD) solutions with the idea of enhancing capacity by means of taking advantage of the spatial diversity available in the channel. When the number of users is large, another form of diversity called multiuser diversity can be exploited to increase the system throughput in delay tolerant data applications. Pioneering studies have demonstrated that the system capacity in a single transmit antenna system can be maximized by employing a scheduling scheme that allocates all the channel resources to the user experiencing the most favorable channel condition [3].

The option of devoting the majority of system resources to a single user at a time was extended in [4] for multiple-input multiple-output (MIMO) systems, and has recently been adopted to the downlink of cdma2000 [5] and WCDMA systems [6] (i.e., 1xEV-DO and HSDPA). For multiple transmit antennas it has been shown that higher rates can be achieved by using linear spatial prefiltering (SP) and multiuser scheduling (MS) to simultaneously transmit to several users [1], [2]. The behaviour of these strategies has been analyzed assuming full channel state information at the transmitter (CSIT); under partial CSIT, the performance of these schemes is still an open problem. We put great emphasis on the fact that when uplink and downlink utilize different frequency bands as in case of, e.g., FDD WCDMA mode, CSIT is mandatory partial due to the limited capacity of the feedback channel.

In this work, we propose new transmission schemes for multiuser environments that combine SP and MS concepts, assuming partial CSIT based on the closed-loop transmit diversity (CLTD) and channel quality indicator (CQI) feedback mechanisms available in WCDMA HSDPA [7], [6]. Considerable gains in the order of 40% can be achieved if we properly use the available channel state information, compared to the scheme which only transmits to the user with the best channel condition in each particular transmission time interval (TTI). We also compare the performance loss of these partial CSIT schemes with respect to linear SP schemes with full CSIT.

We emphasize that the proposed partial CSIT schemes can be implemented within FDD WCDMA mode with small modification, or even without changes to the specifications and legacy terminals, while SP with full CSIT cannot be used in practice within FDD WCDMA. Instead of utilizing CLTD and partial instantaneous CSIT together with MS, the authors of [8] have proposed to make use of long-term channel state information within WCDMA to perform downlink beamforming. The fundamental difference from system design point of view is that CLTD can use the common omnidirectional
pilot channels present in WCDMA downlink, while user specific beamforming requires dedicated pilot channels for channel estimation in mobile stations and therefore increases the overhead of control signaling. Finally, another motivation for studying this simple two transmit antenna system is to provide insights on the achievable sum-rate capacity of more complex broadcast channels that need feedback information to estimate the channel.

The rest of the paper is organized as follows. Section II introduces the system model, and Section III presents the different SP schemes with full CSIT. The analyzed scheduling strategies are deployed in Section IV, while Section V studies the performance loss when only partial CSIT is available. Finally, Section VI draws the conclusions.

II. SYSTEM MODEL

We begin with a simple model of the downlink of a wireless communication system. Consider a multiuser system consisting of 2 transmit antennas and $K \geq 2$ active user equipments (UEs) with single-element antenna. This channel will be referred to as $2 \times 1 \cdots K$ BC to be read 2 times 1 to $K$ broadcast channel, in order to stress the fact that the receivers must process their signals separately [1]. In case of flat fading, the channel gain from a transmit antenna $t$ to a UE $k$ is described by a zero-mean circularly symmetric complex Gaussian (ZMCSG) random variable $h_{k,t}$, for $t = 1, 2$ and $k = 1, \ldots, K$. For simplicity we assume that all the UE are homogeneous and experience independent fading. The signal received by user $k$, $y_k$, may be written as

$$y_k = h_k x + z_k,$$

(1)

where $x \in \mathbb{C}^{2 \times 1}$ is the transmitted signal vector from the BS antennas, $h_k \in \mathbb{C}^{1 \times 2}$ is the channel gain vector to the $k$th user, and $z_k$ is additive white Gaussian noise (AWGN) at the $k$th user. We normalize the channel and noise such that the entries of $h_k$ and $z_k$ have unit variance. Furthermore, the average power constraint of the input signal implies that

$$\text{trace} \left\{ E(x x^H) \right\} \leq A,$$

(2)

where $A$ is the maximum allowed total transmit energy per channel use and $(.)^H$ denotes conjugate transposition. We further assume that the BS is subject to short term power constraint (i.e., the BS should satisfy the power constraint for each fading state). Since the noise has unitary variance, $A$ takes on the meaning of total transmit signal-to-noise ratio (SNR).

III. REVIEW OF MIMO DOWNLINK STRATEGIES

In the conventional time-division multiple-access (TDMA) downlink scheme, the BS transmits to only a single user at a time. In this case, the maximum sum-rate is achieved by allocating all the resources to the user with largest channel gain. Herein, this strategy is referred to as maximum ratio combining (MRC) beamforming and its sum-rate is given by

$$R_{TDMA\text{-}MRC} = \max_{k \in \{1, \ldots, K\}} \log(1 + A \|h_k\|^2),$$

(3)

where the logarithm is taken in base two.

TDMA achieves the sum-rate capacity when the BS has only one transmit antenna; however, it becomes more and more suboptimal as the number of transmit antennas grows [9]. Under this situation, the BS can transmit to multiple users simultaneously to achieve a higher rate when channel state information (CSI) is available at the transmitter. In this context, dirty-paper coding (DPC) [10] allows the BS to transmit to multiple users at the same time avoiding the impact of multiuser interference by joint encoding of the transmitted signals. It has recently been shown that the combination of linear SP and DPC achieves the sum-rate capacity of the multiple-antenna broadcast channel [1], [11], [12], but it is difficult to implement in practical systems due to high computational burden of successive encoding and decodings, especially when the number of users is large.

A reduced-complexity suboptimal choice of the prefiltering matrix is proposed in [1]. It suggests to use QR decomposition, obtained by applying Gram-Schmidt orthogonalization to the rows of the channel matrix, combined with DPC at the transmitter to optimize the sum-rate for channel matrices with full row rank (i.e., with as many transmit antennas as users). This scheme is referred as zero-forcing dirty-paper (ZFDP) coding and is proven to be asymptotically optimal both at low and high SNR in full row rank channel matrices. When there are more users than transmit antennas, the random selection of users incurs in throughput loss. However, the authors of [13] propose a selection algorithm that capitalizes on multiuser diversity narrowing the gap between ZFDP and capacity.

A linear suboptimal strategy that can serve multiple users at a time like DPC, but with much reduced complexity, is Beamforming (BF). In this case, each user stream is coded independently and multiplied by a beamforming weight vector for transmission through multiple antennas. Despite its reduced complexity, BF has been shown to achieve a fairly large fraction of capacity when the BS has multiple antennas and each user has a single antenna [1], [2], [12]. Finding the optimal beamforming weight vector is a difficult non-convex optimization problem. In [14], the authors consider the suboptimal zero-forcing beamforming (ZFBF) strategy, where the channel matrix is inverted at the BS to create orthogonal channels between transmitter and receivers. Let $u_k$, $w_k$, $P_k$ be a data symbol, a beamforming weight vector, and a transmit power scaling factor for user $k$, respectively. In ZFBF, beamforming vectors are selected such that $h_k u_j = 0$ for $j \neq k$. Let $S \subset \{1, \ldots, K\}$, $|S| = 2$, $S = \{s_1, s_2\}$ be a subset of user indices that the BS intends to transmit to, and $H(S)$ and $W(S)$ be the corresponding submatrices of $H = [h_1 \cdots h_K]^T$ and $W = [w_1 \cdots w_K]$, respectively. $(.)^T$ denotes transposition. The ZFBF matrix is

$$W(S) = H(S)^+ = H(S)^H (H(S) H(S)^H)^{-1},$$

(4)

where $H(S)^+$ is the Moore-Penrose pseudoinverse of $H(S)$. The transmitted vector is obtained as $x = H(S)^+ u$, $u = (u_{s_1}, u_{s_2})^T$, and yields the set of parallel channels $y_i = u_i + z_i$ for $i \in S$, while no information is sent to users $i \notin S$. For a
given $S$, the throughput of ZFBF is easily found to be
\[
R_{ZFBF}(S) = \max_{P_i} \frac{P_i}{\gamma_i} \sum_{i \in S} \log(1 + P_i),
\]
where
\[
\gamma_i = \frac{1}{\|H(S)H(S)^H\|_{i,i}},
\]
is the effective channel gain to the $i^{th}$ user. The optimal $P_i$ in (5) is given by waterfilling, $P_i = [\xi_i - 1]_+$, where the waterfilling level $\xi$ is chosen to satisfy $\sum_{i \in S}[\xi_i - 1]_+ = A$. The operator $[x]_+$ is defined as $[x]_+ = \max(x, 0)$. Finally, the achievable sum-rate of ZFBF is found by considering every possible choice of unordered active user set \[ R_{ZFBF} = \max_{S \subset \{1, \ldots, K\} : |S|=2} R_{ZFBF}(S). \] (7)

The authors of [14] show that ZFBF is also asymptotically optimal and can achieve an expected sum-rate equal to that of DPC when $K$ is large.

IV. Multiuser Scheduling with Full Channel State Information

Using multiple transmit antennas at BS with full CSIT increase the system capacity of the broadcast channel. Besides the spatial multiplexing gain, the appropriate selection of the scheduled set of users in each time instant boosts the multiuser diversity gain that can be reached through multiuser selection. For the maximization of (7), the authors of [14] propose a suboptimal MS scheme that obtains a nearly optimal average sum-rate using optimal power allocation. However, optimal waterfilling power allocation puts a high demand on the linear range of transmit power amplifiers, which is extremely costly from a practical point of view if not impossible. Moreover, spatial power allocation does not provide a significant capacity enhancement for moderate to high transmit power regimes, and this gain is even lower when the number of active users $K$ is sufficient large. Therefore, the MS algorithms that we present perform an equal power allocation to all selected users. It is interesting to note that because of the assumption of independent and identically distributed (i.i.d.) fading statistics of the users, the strategy of communicating with the set of UEs that maximizes the achievable sum rate in each TTI will grant an equitave utilization of the resources.

The scheduler that maximizes the sum-rate for each different fading state, referred to as a greedy scheduler, requires $\binom{K}{2}$ computations of the achievable sum-rate metric (5) in order to detect the best combination of active users. Under this situation, the greedy algorithm searches the set of users $S$ that maximizes
\[
\max_{S \subset \{1, \ldots, K\} : |S|=2} \left\{ \log(1 + P_{s_1}) + \log(1 + P_{s_2}) \right\}.
\]
Assuming equal power allocation in the high throughput region, i.e.,
\[
P_{s_1} = \frac{A}{2} \gamma_{s_1} \gg 1 \quad P_{s_2} = \frac{A}{2} \gamma_{s_2} \gg 1,
\]
the maximization (8) becomes
\[
\max_{S \subset \{1, \ldots, K\} : |S|=2} \left\{ \frac{|\det(H(S))|^2}{\|H_{s_1}\| \|H_{s_2}\|} \right\}.
\]
(10)

Having introduced the new metric, we now consider the following scheduling strategies in addition to the greedy scheduler.

**Smart joint selection (SJS) algorithm**: In order to reduce the number iterations, this algorithm always selects as user 1 the index $s_1$ that maximizes \[
\max_{s_1 \in \{1, \ldots, K\}} \left( |h_{s_1,1}|^2 + |h_{s_2,2}|^2 \right),
\]
and as user 2 the one that maximizes metric (10), conditioned on the previously selected user. Notice that metric (11) is proportional to the individual channel gain of the user. This algorithm requires $K$ computations of (11) to select user 1, and $(K - 1)$ computations of (10) to select user 2.

**Best users’ (BUs) selection**: This scheduling strategy chooses the pair of users $s_1$ and $s_2$ with largest individual channel indicator (11), without taking into account the potential level of interference between them. This algorithm only requires $K$ computations of metric (11).

**Round robin set (RRS) selection**: This is the simplest strategy that schedules the set of users in a deterministic fashion.

Fig. 1 shows the performance of joint ZFBF and different MS algorithms for the $2 \times 1 \cdot \cdot \cdot 16$ and $2 \times 1 \cdot \cdot \cdot 64$ BCs, along with two schemes that schedule only one user at a time: TDMA round robin (RR) and MRC. The ZFDP plot with optimal power allocation and maximization over all ordered user sets $S$ also included as an upper bound.
The achievable throughput of ZFBF grows linearly with the increase of the transmit power, and the grow rate achieves the expected scaling factor at high power regimes (i.e., two times faster with respect to TDMA strategies). The deterministic policy of the RRS algorithm is the worst of all MS strategies; however, the throughput is enhanced at high power regimes with respect to TDMA-MRC due to the multiplexing gain. The performance curves of ZFBF with non deterministic schedulers have the same slope as ZFBF-RSS selection, and the gap between both curves gives the multiuser diversity gain. ZFBF-BU selection reaps a multiuser diversity gain in the order of 5 (7) dB for 16 (64) users. Meanwhile the ZFBF-SJS algorithm achieves a multiuser diversity gain in the order of 8 (9) dB for 16 (64) users. Note that this gain is significantly higher than the 5 (7) dB for 16 (64) users obtained with single-user scheduling (i.e., TDMA-MRC over TDMA-RR). It is interesting to note that the performance of the ZFBF-SJS algorithm is almost identical to the ZFBF-Greedy and ZFDPEGreedy one (upper bound). To sum up, we can conclude that the combination of a practical linear BF scheme (ZFBF) along with a relative simple MS algorithm (SJS) can achieve a sum-rate very close to channel capacity assuming full CSIT.

V. MULTIUSER SCHEDULING WITH PARTIAL CHANNEL STATE INFORMATION

In many applications, it is not reasonable to assume that the BS perfectly knows the channel coefficients to every UE. This is especially true in FDD systems, where CSIT has to be provided by a separate feedback mechanisms. Since full CSIT is impractical, it is very important to devise and study schemes that use partial CSIT. For example, the authors of [15] propose an orthogonal random beamforming (RBF) scheme for wireless systems with \( M \) transmit antennas that requires very little feedback. In RBF, each user only reports to the BS a single vector \( w \) for wireless systems with \( W \) transmit antennas that requires very little feedback. In RBF, each user only reports to the BS a single vector \( w \) that is simultaneously complementary in amplitude and phase to its maximum signal-to-noise-plus-interference ratio (SNIR) along with the index number of the beam in which the SNIR is maximized. The information in each of the \( M \) random beams is transmitted to the user with maximum SNIR. For a large number of users, RBF asymptotically achieves the optimal sum-rate of DPC; however, for a moderate number of users (i.e., no more than 64), its performance is slightly superior to that of TDMA-MRC. In this section we devise an scheme that use the feedback information available in FDD WCDMA; i.e., the reported beam weight of the CLTD feedback information and the CQI. Using this partial CSIT, we will analyze the sum-rate gain that this new scheme can achieve over TDMA-MRC. Moreover, we also compare the throughput of RBF with respect to TDMA-MRC and the performance loss of the proposed scheme with respect to the scheme that can count on full CSIT.

A. Achievable Data Rates for FDD WCDMA Modes

In the CLTD system [7], the selection of transmit weights at the BS is based on partial CSIT that is signalled by the UE. The mathematical formulation of the problem of finding the best possible transmit weight \( w_{0k} \) at each user can be written as

\[
\text{Find } w_{0k} \in W : \quad |h_k w_{0k}| = \max_{w \in W} |h_k w|, \tag{12}
\]

where \( h_k = (h_{k,1}, h_{k,2}) \) and \( W = \{ w = (w_1, w_2)^T : ||w|| = 1 \text{ and } w_1, w_2 \in \mathbb{C} \} \). For the one-by-one transmission strategy, it can be assumed without loss of generality that \( w_1 \) is real. Therefore, the solution can be characterized by a single complex coefficient, i.e.,

\[
w_2 = z e^{j\phi} \tag{13}
\]

where \( z, \phi \) are orthogonal. Now CSIT for user \( k \) is achieved with the channel estimation for user \( k \) at BS becomes

\[
h_k = \sqrt{\alpha_k} w_{0k}. \tag{14}
\]

This estimation does not take into account possible intra-cell interference due to simultaneous transmission to the other scheduled users. Therefore, in order to anticipate the real achievable rate, the UEs should report a new indicator that takes into account this phenomenon. If we want to analyze all possible combinations of beamforming weights at BS, each particular UE would have to report one SNIR indicator for each transmit weight that the other simultaneous scheduled user could take. Fortunately, the combination of users at high power regimes, that yields the higher throughput, tends to be one with users reporting beamforming weights \( w_{0s} \) and \( w_{0s-s} \) that are simultaneously complementary in amplitude (i.e., \( |w_{0s}^2| + |w_{0s-s}^2| = 1 \) and opposite in phase, i.e., weight vectors \( w_{0s} \) and \( w_{0s-s} \) are orthogonal. This situation is valid with probability one for large \( K \). Keeping this in mind we assume that each UE reports

\[
\alpha_k = \frac{A |h_k w_{0k}|^2}{\sigma^2}, \tag{15}
\]

where \( \sigma^2 \) refers to instantaneous noise power, is used to determine the CQI that indicates to the BS the data rate that the UE can currently support. With these two parameters \( \alpha_k \) and \( w_{0k} \), the channel estimation for user \( k \) at BS becomes

\[
h_k = \sqrt{\alpha_k} w_{0k}. \tag{16}
\]

which is a more representative estimation of the current channel condition under MS. It is worth noticing that there is no way to get information about the relative phase between the two selected users in 3GPP WCDMA CLTD systems [7], because the weight \( w_1 \) is assumed to be a real scalar.
Fig. 2. Achievable throughput of the $2 \times 1 \cdots 16$ (above) and $2 \times 1 \cdots 64$ BCs (below) with Mode 1 CLTD and $\alpha^k$ feedback. The scheduling algorithms are TDMA-RR (dashed curve), TDMA-MRC (dash-dot curve), ZFBF-RRS (solid curve), ZFBF-BUs (−−−), ZFBF-SJS (−−−), and upper bound (−−−−).

Fig. 3. Achievable throughput of the $2 \times 1 \cdots 16$ (above) and $2 \times 1 \cdots 64$ BCs (below) with Mode 1 CLTD and $\alpha^k$ feedback. The scheduling algorithms are TDMA-RR (dashed curve), TDMA-MRC (dash-dot curve), ZFBF-RRS (solid curve), ZFBF-BUs (−−−), ZFBF-SJS (−−−), and upper bound (−−−−).

Fig. 4. Achievable throughput of the $2 \times 1 \cdots 16$ (above) and $2 \times 1 \cdots 64$ BCs (below) with Mode 2 CLTD and $\alpha^k$ feedback. The scheduling algorithms are TDMA-RR (dashed curve), TDMA-MRC (dash-dot curve), ZFBF-RRS (solid curve), ZFBF-BUs (−−−), ZFBF-SJS (−−−), and upper bound (−−−−).

Mode 1 and 256 for Mode 2) before selecting the particular one that maximizes the instantaneous throughput. Notice that the upper bound of Mode 2 is higher than that of Mode 1 because of the larger number of weights the BS has to choose from in order to maximize the sum-rate capacity under CLTD feedback. This is not the case for TDMA schemes that show a robust behavior under partial CSIT; even under Mode 1, the performance loss with respect to full CSIT case is negligible. Therefore, we conclude that high channel accuracy at the transmitter is required for schemes that schedules multiple users at the same time.

There is practically no difference between the ZFBF-SJS algorithm and the upper-bound when we apply the new proposed indicator (17) under both CLTD feedback modes. However, this behavior cannot be extended when the CQI parameter based on (15) is employed (see Fig. 2). It is worth noticing that even though all these schemes are asymptotically interference limited, we observe that at medium SNR values the simultaneous transmission to two users achieves a significant capacity gain over TDMA-MRC.

Fig. 5 shows the MS gain of ZFBF-SJS algorithm and RBF with respect to TDMA-MRC, and the performance loss of ZFBF-SJS under partial CSIT. This figure shows that with Mode 1 CLTD and the new CQI, the ZFBF-SJS scheme achieves a gain of almost 10% (30%) for 16 (64) participating users when compared to the achievable throughput with TDMA-MRC strategy. With Mode 2, the achievable gain is in the order of 30% (40%) for 16 (64) participating users. RBF does not provide any capacity gain over TDMA-MRC at 16 users; however, it can provide 20% more sum-rate than TDMA-MRC strategy for 64 users.

Finally, it is interesting to evaluate the performance loss of the ZFBF-SJS scheme when the BS has only partial CSIT. For that purpose, we do comparisons near the 15 dB region, which
is the area of the plots in which the analyzed schemes achieve the best performance over the TDMA-MRC counterpart. With Mode 1 and 16 (64) users, ZFBF-SJS with partial CSIT can achieved 70 % (80 %) of the sum-rate capacity of the full CSIT case. In the same way, more than 80 % of the capacity with full CSIT can be achieved by ZFBF-SJS with partial CSIT provided by Mode 2.

VI. CONCLUSIONS

We considered different MS algorithms and a practical SP scheme in order to combine the multiuser diversity gain along with the possibility of simultaneous transmission to more than one UE per TTI. We proposed a simple algorithm that is able to capture almost all the sum-rate capacity of the broadcast channel when full CSI is available at the BS. We also studied the performance loss in the achievable sum-rate when the CSI is estimated at the BS by means of the feedback information of FDD WCDMA CLTD modes and a modified CQI that takes into account the intra-cell interference level. We observed that even though the behavior of the achievable throughput in the absence of full CSIT is always interference limited at high power regimes, considerable gains in the order of 40 % can be achieved if we properly use the available CSIT.

REFERENCES


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