Effects of Multi User MIMO Scheduling Freedom on Cellular Downlink System Throughput

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Abstract— **This paper studies different degrees of channel quality-based scheduling freedom for the downlink of a DS-CDMA system where the *base station* (BS) and each *mobile station* (MS) have 2 antennas. The system combines opportunistic user time slot scheduling, opportunistic spatial multiplexing, and *adaptive modulation and coding* (AMC) with either limited or unlimited constellation sizes. System performance is investigated under propagation environments varying in time dispersion and transmit antenna correlation. Three transmission schemes with increasing degrees of resource allocation freedom are identified. The full freedom scheme allows for time slots and transmit antennas to be independently allocated to different users and is compared to two schemes of more limited flexibility in the antenna allocation. For a system with little multi user diversity, the option of single antenna selection transmit diversity is favorable, while dual antenna transmission with independent antenna-to-user allocation becomes increasingly important when a higher degree of multi user diversity can be exploited in weakly correlated environments.**

Keywords- MIMO, proportional fair scheduling, spatial multiplexing, AMC

I. INTRODUCTION

Since the revolutionary publication by Telatar [1], the idea of *multiple input multiple output* (MIMO) antenna systems has been the topic of extensive research activity worldwide because of their potential to achieve high spectral efficiencies, and therefore high data rates. Different open [2] and closed loop [3] strategies have since been proposed to enable the transmission of parallel data streams over the MIMO radio channel. These techniques discuss the single user capacity of MIMO systems, i.e. they assume that the multiple transmitted data streams are destined to a single user, that is equipped with a multiple antenna enabled terminal.

As data traffic becomes more important, the focus shifts from delay stringent circuit switched communication to delay tolerant packet data communication. In this context, opportunistic transmission has been proposed as a way to exploit multi-user selection diversity. Using channel aware scheduling [4], opportunistic transmission techniques grant different users access to the system resources when their instantaneous channel conditions are favorable, thus enhancing the overall multi user system throughput [5], [6]. Only a limited amount of channel quality information per user is required at the transmitter side and due to its computationally practical nature and its enormous potential, channel quality based scheduling has recently been introduced to the downlink packet data transmission of emerging 3G evolution systems, i.e. 1xEV-DV [7], and HSDPA [8].

In the context of multi-user MIMO systems, the concept of spatial multiplexing to different users has been introduced among others in [9]. Here one can think of a system where different antennas of the same transmit array are sending independent data streams for different users and potentially more than one BS antenna can be used for the same user.

In this paper, we combine the concepts of MIMO transmission and opportunistic scheduling, and investigate the effects of increasing the scheduling freedom on the system throughput. Section II describes the simulations at link and system levels and states its main assumptions, while Sections III and IV illustrate the results and give the conclusions, respectively.

II. SYSTEM MODEL

We have simulated a MIMO downlink DS-CDMA system, where independent data streams are sent through different antennas, potentially to different users.

In conventional orthogonal spread DS-CDMA systems like WCDMA and CDMA2000 the downlink data destined for any user is spread by a Walsh-Hadamard code unique to this particular user and scrambled by a sequence unique to the cell. Since the number of orthogonal spreading codes is limited, codes might become a scarce resource within a cell and it would be desirable to have the option of reusing them for simultaneous data transmission from different antennas. Therefore, the studied system simulates transmissions where the total available data channel power is used to target a group of users that time share a single spreading code.

Within this group, multiple access is achieved via

a) opportunistic spatial multiplexing, i.e. separate data streams are transmitted simultaneously from different antennas, therefore using different propagation channels, and/or

b) opportunistic time scheduling, i.e. different time-slots are allocated to different (sets of) users within this group.

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Opportunistic spatial multiplexing enables simultaneous transmissions using the same spreading code, and opportunistic time scheduling takes advantage of the independence of the user fading statistics to provide multi user diversity [9].

A. Link level description

This section includes the transmission (spreading, scrambling and modulation), the propagation through a MIMO channel, the reception, and the CQI feedback.

At the BS, the data streams for all users are assumed to be *independent identically distributed* (iid). They are assumed to be spread using a Walsh-Hadamard code with spreading factor 16 and scrambled using an iid pseudo random noise sequence. *Quadrature amplitude modulation* (QAM) is used with a constellation size dependent on the feedback from the MSs, as will be explained in section II.B. Link adaptation and scheduling operations are performed anew for every 2 ms *transmit time interval* (TTI). The MIMO channel model employed is of the correlation-based stochastic type, as described in [10] and uses either the ITU-Pedestrian A or the ITU-Vehicular A *power delay profiles* (PDPs). In order to illustrate the effect of the channel characteristics, low (0.3) and high (0.7) transmit antenna correlation levels were considered. Path loss, shadowing and other cell interference modeled as additive white Gaussian noise are determined by the cell *geometry* (G)-factor, which is randomly selected according to the probability distribution function over the cell area given by [11]. A fraction of the total transmit power (70%) is allocated to data transmission, while the rest is used for pilot and control signaling. We use a quasi static system simulation approach keeping a user's G-factor and a user's transmit and receive correlation constant during its entire session. We investigate a low mobility scenario (user speed of 3km/hr), and we can therefore safely assume that the shadow fading parameters do not change during the session.

Each MS estimates the channel transfer characteristics with the help of pilot signals (such as in UMTS), and, for the purpose of this analysis, we assume perfect channel estimation. The MS receiver can then use this knowledge to decode the originally transmitted data streams. Each user is equipped with a space-time *minimum mean square error* (MMSE) receiver [12]. The symbol level SINR is determined using the average MMSE implementation from [12], with an extension of the average received signal covariance matrix to account for co-stream interference.

The MSs feed *channel quality indication* (CQI) values on every possible antenna allocation option back to the BS. The CQI is the predicted average SINR per TTI for each case of concurrent activity of the transmit antennas. Alternatively, the MSs could have fed back the wideband complex transfer matrix of the channel. However, feeding back only CQI limits the amount of feedback data and is less sensitive to errors and/or channel variations. It is assumed that the feedback link is error free and that the channel does not change significantly within the scheduling delay (which includes data reception and feedback of CQI from the MS, antenna and constellation size selection at the BS). This assumption is reasonable for slowly moving MSs, such as the ones in our simulated scenario.

B. System level description

A smart packet scheduler located at the BS uses the CQI feedbacks (combined with knowledge about past transmissions) to allocate the BS's antenna resources to the MSs dynamically on a TTI basis. To model the link adaptation mechanism, the SINR is mapped to throughput using an 8 dB shifted version of the Shannon capacity bound as suggested as an approximation in [13] and indicated in Figure 1. In case of limited modulation constellation size, the throughput is upper bounded by 4 b/s/Hz (16 QAM), with the consequence that any SINR increase above 20dB does not improve system throughput performance.

The throughput is determined independently for each of the BS transmit antennas similar to per antenna rate control (PARC) [14]. The total transmit power is kept constant independently of the modulation size used and of the number of active transmitting antennas. In case of dual stream transmission, the total transmit power is split evenly between the transmit antennas, to facilitate SINR prediction.

In systems with opportunistic scheduling, the user is selected dynamically based on a scheduling algorithm. We have selected the *Proportional-Fair Resource algorithm* (P-FR) [7], because it achieves an appealing balance between cell through-put and user fairness [15]. The priority of user j to be scheduled at TTI n, denoted $\Pr(j,n)$, is determined by

$$\Pr(j,n)=\frac{R_j(n)}{\overline{R_j}(n)}, \tag{1}$$

where $R_j(n)$ stands for the potentially achievable throughput of the channel between the BS and the MS j at TTI n, and $\overline{R_j}(n)$ is the mean allocated data to user j from the beginning of the transmission until TTI n. $\overline{R_j}(n)$ is given by

$$\overline{R_j}(n)=\left(1-\frac{1}{t_c}\right)\overline{R_j}(n-1)+\frac{1}{t_c}R_j(n-1). \tag{2}$$

$R_j(n-1)$ equals the allocated data rate to user j at TTI n-1 if he was scheduled and 0 otherwise, as described in [7]. The parameter $t_c \in [1,+\infty)$ tunes the scheduler between a stringent ($t_c \to \infty$) and a delay-tolerant ($t_c \to 1$) behavior. Based on [7] we have chosen 10^3. At any TTI n, the scheduler selects to transmit to the user j with the maximum priority ($\max_j \{\Pr(j,n)\}$).

Specifically for MIMO systems with independent stream transmission and antenna allocation, (1) can be generalized to express the priority of a scheduling option, which now includes the selection of a subset of users J and a subset of antennas I:

$$\Pr(I,J,n)=\sum_{(i,j)}\frac{R_{ij}(n)}{\overline{R_j}(n)}, \tag{3}$$

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where $R_{ij}(n)$ is the achievable data rate of the channel between the BS antenna $i \in I$, and MS $j \in J$ at TTI n and (i,j) stands for each of the BS antenna-user links that define the particular scheduling option.

The scheduler selects the subset of users and antennas (I, J) that have the maximum priority ($\max_{(I,J)}\left\{\Pr(I,J,n)\right\}$). In this paper, we consider offered services that are equally delay tolerant. If not, advanced scheduling algorithms can take into account the quality of service requirements of each user by modifying their priorities, e.g. through the variation of t_c. Such investigations are however beyond the scope of this paper.

The transmitting BS and the receiving MSs were equipped with 2-element antenna arrays. The array size was kept small to simulate a realistic configuration. In a cell, the number of users sharing a code ranges from 1 to 10. The scheduling techniques have shown stable performance for this number of simultaneous active users.

Under these conditions, there are three transmission options:

- SMP-D1: Dual stream to one user. Here, I={ant.1 and ant.2} and $J=\{j\}, j \in [1,10]$; then (3) becomes

$$\Pr(I,J,n) = \frac{R_{ant.1,j}(n)}{\overline{R}_j(n)} + \frac{R_{ant.2,j}(n)}{\overline{R}_j(n)}. \tag{4}$$

- SMP-D2: Dual stream to two users, one stream per user (spatial stream- and user- multiplexing). Here, I={ant.1 and ant.2} and $J=\{j_1, j_2\}$, $j_1 \neq j_2$; $j_1, j_2 \in [1,10]$; (3) becomes

$$\Pr(I,J,n) = \frac{R_{ant1,j_1}(n)}{\overline{R}_{j_1}(n)} + \frac{R_{ant2,j_2}(n)}{\overline{R}_{j_2}(n)}. \tag{5}$$

- SMP-S: Single stream to one user. Here, $I=\{i\}$, $i \in [1,10]$ and $J=\{j\}$, $j \in [1,10]$; (3) becomes

$$\Pr(I,J,n) = \frac{R_{i,j}(n)}{\overline{R}_j(n)}. \tag{6}$$

Each MS feeds back a total of 4 CQI values, i.e. the predicted SINR for a data stream transmission from antenna one and two when either the other antenna is silent or when both antennas are transmitting. We study three transmission schemes that progressively allow more transmission options.

- Scheme 1 only allows SMP-D1.
- Scheme 2 allows SMP-D1 and SMP-D2.
- Scheme 3 allows SMO-D1, SMP-D2, and SMP-S.

As we allow more and more options, we increase the scheduling freedom in our system. An overview of the parameter settings employed in the link and system level simulations is given in TABLE I.

TABLE I. OVERALL PARAMETER SETTINGS.

Parameter	Setting
Link Level	
Carrier frequency	2 GHz
Spreading factor	16
Modulation	QAM
Maximum constellation size	Unlimited or limited to 16
Time Unit	TTI (2 ms)
Other cell interference model	AWGN model based on G-factor distribution from [11]
MS speed	3 km/h
Receiver	MMSE [12]
Channel model	Correlation-based stochastic type
PDP	ITU Vehicular A (Environments 1 and 2)
	ITU Pedestrian A (Environment 3)
Tx. power correlation coefficient	0.3 (Environment 1)
	0.7 (Environment 2)
	0.3 (Environment 3)
Rx. power correlation coefficient	0.3
Power allocated to data transmission	70 % of total transmit power
Channel Estimation	Ideal
CQI	Predicted SINR
Feedback Link	Error and delay free
System Level	
Link Adaptation	AMC, user and antenna selection
Packet scheduler	Generalized P-FR
Time constant, t_c	10^3
Number of BS and MS antennas	2
Number of users	[1,10]

III. RESULTS

A. SINR probability distribution and AMC

Figure 1. shows how the post-detection SINR is mapped to a given throughput. The derivation of the throughput curves for each modulation is explained in [13]. The envelope shown is the mapping function between the fed back SINRs and the rate (section II.B). Moreover, Figure 1. shows the *probability density function* (PDF) of the observed SINRs in several environments and for several transmit options, which will be used later to explain the effects of limited maximum modulation size, correlation and time dispersion. The selection transmit diversity gain obtained by selecting the antenna to transmit within SMP-S or the user in SMD-Dx is not included in this plot.

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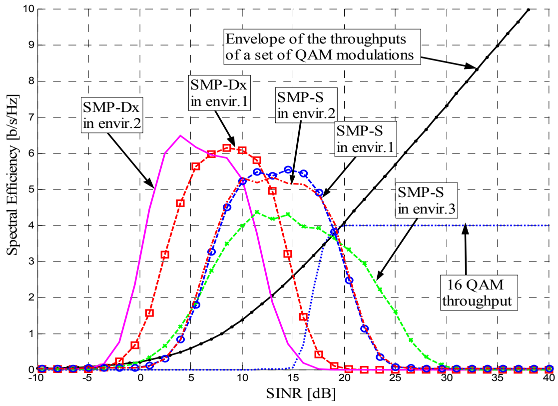

Figure 1. QAM constellation sizes throughputs and SINR dynamic range.

B. *Scheduling freedom*

The cellular throughput achieved by each scheme (for limited and unlimited modulation) was investigated in environment 1. Figure 2. shows the spectral efficiency increase when multi user diversity can be exploited: the more users there are in the cell, the higher the probability of encountering one in favorable channel conditions. For a large number of users, the largest gain is obtained by allowing independent antenna allocation because the event of two favorable channels being destined for two different users becomes more likely. When there are a small number of users, multi-user diversity does not gain as much as the freedom to switch off one antenna and reduce stream interference.

Figure 3. shows the cell throughput when the maximum constellation size is set to 16 QAM. The differences are not significant because the number of high SINR users that have now an upper bound on their data rate (SINR > 20 dB) are negligible under environment 1 (Figure 1.).

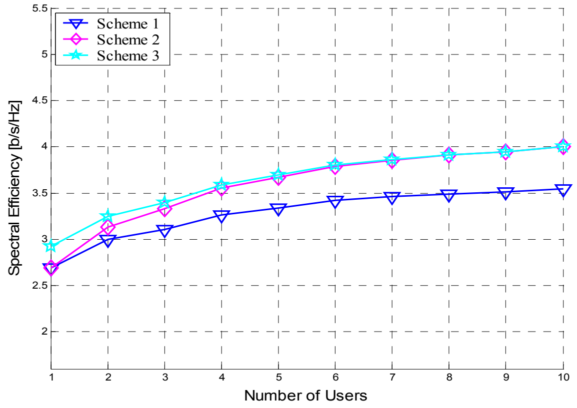

Figure 2. Cell throughput for unlimited constellation sizes.

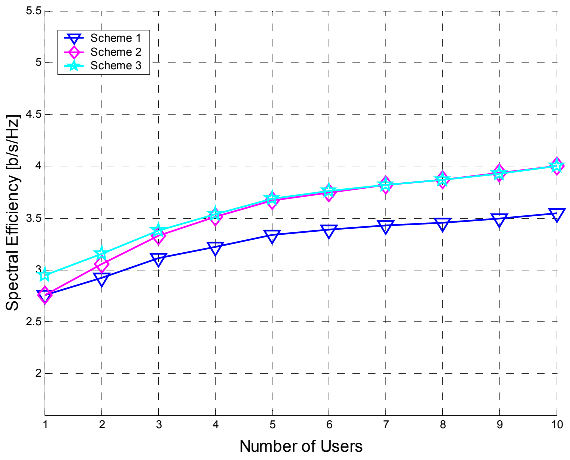

Figure 3. Cell througput when M_{MAX}=16.

C. *Effect of channel transmit correlation and time dispersion*

Figures 3-5 show the probability of selection of each transmission option in different correlation environments. For this set of curves, we have unlimited constellation sizes.

Figure 4. shows that if the transmit and receive correlations are low (environment 2), dual stream transmission is preferred: the sum of the probabilities of selection of SMP-D1 and SMP-D2 are much higher than the probability of selection of SMP-S. This happens despite the advantages of transmitting with only one antenna: no co-stream interference, receive diversity gain (1×2 SIMO) and double transmit power for that stream. As the number of users increases, SMP-D2 is more likely than SMP-D1 because the probability that the two best spatial channels aim at the same user decreases.

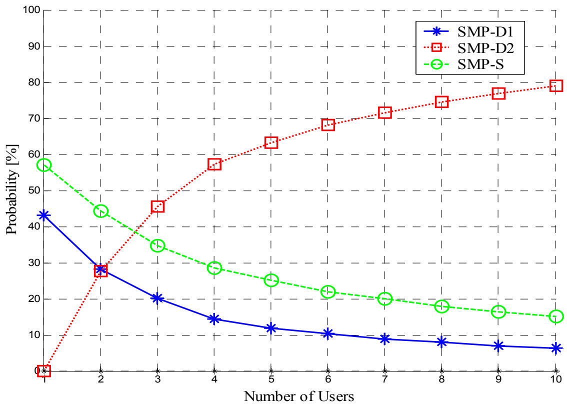

Figure 4. Probabilility of selection of each option in environment 1.

Figure 5. shows that when the correlation at the transmitter is high (environment 2), the scheduler is more likely to select the option with the lowest stream interference (SMP-S) than any other option. This is expected considering the reduced mean SMP-Dx SINR as shown in the pdf of Figure 1. The SINR PDF for single stream transmission is the same for both environments as it is immune to the transmit correlation. The

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radical change of the scheduler's preferences expresses the importance of dynamic link adaptation through antenna selection in MIMO systems.

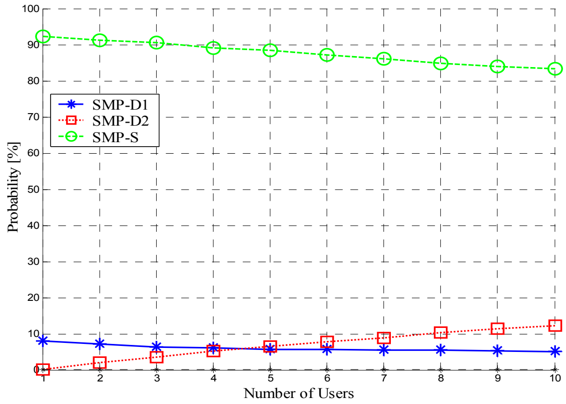

Figure 5. Probability of selection of each option in environment 2.

Figure 6. shows a transitional behavior due to the PDP of environment 3. Environment 3 is a less time dispersive environment, and therefore the own cell interference is reduced. The contribution of other stream interference is now dominant. Therefore, SMP-Dx is not selected as frequently as in environment 1, where the own cell interference makes the presence of another stream less of an issue. Again, the link level results indicated so: the mean SMP-S SINR in environment 3 is larger than in environment 1 (Figure 5.).

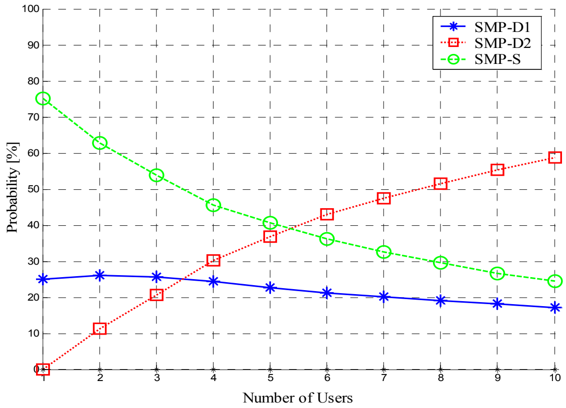

Figure 6. Probability of selection of each option in environment 3.

IV. CONCLUSIONS

This paper has studied the behavior of a proposed MIMO downlink scheduling algorithm based on the P-FR algorithm. Link and system level simulations have been performed for a 2×2 MIMO configuration. The link level simulation includes channel and reception effects while the system level simulation includes the scheduling itself under various degrees of antenna allocation freedom. For a reasonable number of users, switching one antenna off is not profitable and independent antenna allocation achieves the higher gain.

Furthermore, the probabilities of selection to transmit with each scheduling option for the full freedom scheme have been shown. These probabilities are very dependent on the spatial correlation and on the number of users in the cell.

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