Adaptive Multiuser MIMO-OFDM QoS-Based Scheduler Using Virtual Channel State Information

Khaled Hassan[1,2], Alexandra Filip[1], and Werner Henkel[1]

[1]Transmission Systems Group (TrSyS),
Center for Advanced Systems Engineering,
Jacobs University Bremen, 28759 Bremen, Germany
Email: {a.filip, w.henkel, a.wakeel}@jacobs-university.de
[2]Information Engineering and Technology, German University in Cairo, New Cairo, Egypt
Email: khaled.shawky@guc.edu.eg (since 2012)

***Abstract*—We propose an adaptive multiuser QoS-based scheduler based on the users' channel measurements. In order to mitigate the complexity that results from computing non-codebook based beamformers for possibly infeasible users, we propose to preselect the optimal users using a virtual signal-to-noise ratio (vSNR). This is computed assuming non-interfering users and a total power constraint. Solely depending on vSNR, we obtain thresholds that fulfill the equivalent SINR constraints for a different number of users. In this paper, vSNR thresholds are utilized to develop a fast adaptive multiuser scheduling routine. Finally, a performance comparison to the unscheduled case will be demonstrated in the presence of channel state information uncertainty as well as with perfect channel information.**

***Index Terms*—QoS, MU-MIMO, OFDM, Non-orthogonal SDMA, SNR, SINR, SINR/Rate Outage probability**

I. INTRODUCTION

Efficient multiuser (MU) transmission succeeds in minimizing the MU interference, which is dependent on two factors: the channel state information (CSI) and the number of users joining the same base station (BS). Assuming a priori knowledge of CSI at the transmitter, the power allocation across users and their transceiver filters need to be jointly adapted. In [3] the authors suggest to use an iterative approach that succeeds in diminishing the complexity compared to the convex optimization approach propose in [4]. In this case, the sum mean-squared error (SMSE) between the transmitted and the received signals is iteratively minimized, i.e., for all data streams, with a total transmit power constraint. The algorithm in [3] has been modified to realize different QoS with SDMA in [1], however, without user selection. In [2], a greedy user selection is proposed using zero-forcing and dirty-paper (gZF-DP) with a non-linear combination, which results in quite high complexity.

In this paper, we study a non-orthogonal SDMA MU-MIMO downlink channel using OFDM to exploit both spatial and spectral domains for allocating users. In this suboptimal scheme, the SINR can be computed using an iterative approach, using the scaled gradient projection method, as in [5]. This mechanism is selected as a non-codebook based beamforming, where only feasible users, on a certain subcarrier, are the only users who fulfil a given target SINR.

To reduce the complexity of solving a non-orthogonal SDMA scheme with probably non-feasible users (i.e., some users may be not suitable for obtaining the target SINR; however, performing complex computations, iterations, and inappropriate space division among the feasible users) we propose to reduce the number of users, to the feasible ones only, before starting the computations of the beamformers. This can be easily achieved by considering a measured vSNR of each user assuming a virtual uplink channel similar to the channel setup in [1]. In this virtual uplink channel, the total power is divided equally among users, assuming that each user solely transmits to the BS in a dual uplink.

In order to analyze the system performance, we obtained the cumulative density function (CDF) curves for both vSNR and its equivalent SINR, i.e., illustrating the outage probabilities for different SINR/vSNR constraints [8]. We consider the vSNR to be an upper bound to the prospective SINR (relying on the outage analysis of vSNR) with a level of reliability. Nevertheless, this can be an indication to the corresponding SINR worst case scenario.

Based on the vSNR read from the CDF curves (for different channel situations which can be generalized to any real channel conditions), our scheduler devotes different number of users to different subcarriers. This is done in greedy fashion, i.e., the stronger subcarriers accommodate more users than the weaker ones. Additionally, the algorithm is capable of grouping different users and devoting a unique quality-of-service (QoS) to each group.

We also investigate the performance of this scheduling algorithm in case of channel-state information (CSI) errors at the BS. To compensate for these CSI errors, we adapt the vSNR-threshold gain to control the number of simultaneous users, i.e., reducing the probability of multiplexing a high number of users when the CSI error increases. Finally, to evaluate the overall performance of SDMA, we compare our results to an orthogonal frequency-division multiple access (OFDMA) transmission scheme, where every subcarrier is devoted to a single user.

The rest of this paper is organized as follows: in Section II, our system model is introduced. Section III, describes

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our proposed multiuser scheduling algorithm based on the proposed vSNR. Section IV, discusses the results. Finally, Section V, summarizes and concludes this paper.

II. SYSTEM MODEL

We consider a MU-MIMO downlink transmission scenario with, in total, N_T transmit antennas distributed at N_{BS} coordinated base stations (BSs), D user clusters where each cluster contains U non-cooperative users and each user is equipped with N_u receive antennas. $N_R = \sum_{u=0}^{U-1} N_u$ represents the total number of receive antennas at all users within a certain cluster. The BS attempts to transmit M_u symbol streams to user u, where the sum of data streams is $M = \sum_{u=0}^{U-1} M_u$. Figure 1 shows four coordinated access points and a few mobile sets (MSs). These MSs are divided into two clusters, a high quality of service (QoS) cluster (QoS A) and a less quality set (QoS B); some of the MSs are not transmitting.

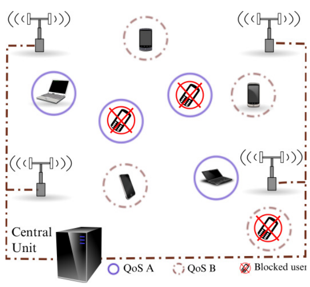

Fig. 1. Coordinated BSs with non-cooperative users with 2 QoSs, QoS A (low SER) and QoS B (high SER)

The frequency band is divided into N subcarriers using OFDM, i.e., N MIMO-OFDM channels. Assuming a MIMO channel $\mathbf{H}_{k,u} \in \mathcal{C}\mathcal{N}(0, \sigma^2_{\mathbf{H}} \mathbf{I}_{N_u} \otimes \mathbf{I}_{N_T})$ where u is the user index and k is the subcarrier index of the OFDMA frame as in [1], i.e., $\mathbf{H}_u \in \mathbb{C}^{N_u \times N_T}$ (uncorrelated zero mean circularly symmetric complex Gaussian (ZMCSCG)). This is modeled as independent Rayleigh fading blocks with exponential decaying. We assume a partial CSI with a quantized/outdated channel $\overline{\mathbf{H}}_{k,u}$ which deviates from the instantaneous channel $\mathbf{H}_{k,u}$ by a total error $\mathbf{\Xi}_{k,u}$. This error is simply defined as $\mathbf{\Xi}_{k,u} = \mathbf{H}_{k,u} - \overline{\mathbf{H}}_{k,u}$, where $\sigma^2_{\mathbf{\Xi}}$ is the variance of the channel error and $\mathbf{\Xi} \in \mathcal{C}\mathcal{N}(0, \sigma^2_{\mathbf{\Xi}} \mathbf{I}_{N_u} \otimes \mathbf{I}_{N_T})$ [6].

Since we are targeting a down-link (DL) scenario, the users symbols are beamformed together at the BS using the following beamformer $\mathbf{F} = [\mathbf{F}_0 \mathbf{F}_1 \cdots \mathbf{F}_U]$, where $\mathbf{F}$ is the overall pre-coding matrix and $\mathbf{F}_u \in \mathbb{C}^{N_T \times M_u}$. Thus, multiplexing the base-band output at each MS u, we obtain (after receiver equalization)

$$\mathbf{W}_u \mathbf{r}_u = \mathbf{W}_u \left(\mathbf{H}_u \mathbf{F} \mathbf{x} + \mathbf{n} \right) , \quad (1)$$

where $\mathbf{x} = [\mathbf{x}_1^T \mathbf{x}_2^T \cdots \mathbf{x}_U^T]^T$ is the aggregated multiuser quadrature amplitude modulated symbol (QAM), such that $\mathbf{x}_u \in \mathbb{C}^{M_u \times 1}$. $\mathbf{W}_u \in \mathbb{C}^{M_u \times N_u}$ is the user's individual post-processing matrix. $\mathbf{n} \in \mathbb{C}^{N_u \times 1}$ is the zero mean Gaussian noise vector with a variance σ_n^2 per component.

In order to find the minimum sum-MSE, the following optimization problem must be solved

$$\begin{aligned} \underset{\mathbf{F},\mathbf{W}}{\text{minimize}} \quad & \textstyle\sum_{u=0}^{U-1} E_u^{\text{DL}} \\ \text{subject to} \quad & \text{Tr}\left(\mathbf{F}^H \mathbf{F}\right) \le P_m , \end{aligned} \quad (2)$$

where E_u denotes the mean-squared error of the u^{th} user's symbols and P_m is the maximum transmit power. This optimization problem can be solved utilizing the MAC-BC duality using the same iterative gradient projection method proposed in [3] and modified in [1]. For simplicity, we assumed that the channel is perfectly known at the coordinated transmitters and at the individual users. Reader is referred to [1, Algorithm 1] for more details.

III. MULTIUSER ADAPTIVE SCHEDULING BASED ON VSNR

In this paper, our aim is to assign users to the appropriate subcarriers and offer a fast solution to the complex Multiuser MIMO-OFDM system. This is achieved by classifying each subcarrier into one of the three cases presented below (based only on the measured received SNR values at each subcarrier) and decide for the appropriate users on each subcarrier:

1) fully loaded subcarriers - shared by all users,
2) partially used subcarriers - only the strong users are allowed to be multiplexed, and
3) unused subcarriers that show weak signals for many users can be utilized by only one of them, i.e., traditional frequency division multiple access (FDMA) technique.

A. Computing the vSNR

We propose to compute a kind of virtual SNR (vSNR), which can be used to estimate the quality of each subcarrier simpler than computing the actual SINR. Since the SINR is mostly equal or less than any single-user SNR (before prober beamforming), then the user's SNR itself can be used as a good metric for channel qualities. Thus, we assumed that vSNR is computed as if the BS is transmitting to a single user, however, with the power scaled by the total number of users U. We decompose the channel of each user (for each subcarrier) using eigenvalue decomposition as follows

$$\mathbf{H}_{k,u}^H \mathbf{H}_{k,u} = \mathbf{V}_{k,u} \mathbf{D}_{k,u} \mathbf{V}_{k,u}^H , \quad (3)$$

where k is the subcarrier index and $\mathbf{D}_{k,u} = \text{diag}\left(\lambda_1, \lambda_2, \cdots, \lambda_{M_u}\right)$ with $\lambda_{k,l,u}$ as the eigenvalue of the l^{th} stream of the Hermitian matrix $\mathbf{H}_{k,u}^H \mathbf{H}_{k,u}$. Hence, the SNR of the u^{th} user's l^{th} stream is

$$\text{SNR}_{k,l,u} = \frac{\lambda_{k,l,u} p_{k,l,u}}{U \sigma_n^2} , \quad (4)$$

where U is the total number of users in each cluster and $p_{k,l,u}$ is the power of the l^{th} stream. For simplicity, we assume that the power is allocated equally to each stream, i.e., $p_{k,l,u} = \frac{1}{M_u}$.

To achieve the channel capacity, the authors in [6] showed that the multiuser throughput is easily maximized (assuming

FDMA transmission) by maximizing the product $\prod_{l=1}^{M_u} \lambda_{k,l,u}$. In other words, select the user with the maximum geometric mean of the eigenvalues $g_{u,k}$, such that

$$g_{u,k} = \sqrt[M_u]{\prod_{l=1}^{M_u} \lambda_{k,l,u}} \ , \tag{5}$$

where M_u is the number of streams. The equivalent (virtual) SNR for every user u (β_u) is given by

$$\beta_{k,u} = \frac{g_{u,k}}{M_u U \sigma_n^2} \ , \tag{6}$$

which is directly computed using the geometric mean in (5). Thus, it is necessary that all the users feedback their $\beta_{k,u}$ to the BS. These $\beta_{u,k}$ $\forall$ $u = 1..U$ have to be sorted in descending order. This sorting is repeated for the given N subcarriers. Hence, the user(s) with the strongest $\beta_{k,u}$ $\forall$ $k = 1..N$ can only be scheduled for transmission using either FDMA or SDMA (simultaneous users share the same subcarrier). For each multiuser scenario, i.e., $\mu = 1, 2, \cdots, U$, we have to find the geometric mean of the vSNR for the μ users as follows

$$\Upsilon_{k,\mu} = \sqrt[\mu]{\prod_{v=1}^{\mu} \overleftarrow{\beta}_{k,v}} \ , \ \forall \ \mu = 1..U \ \& \ k = 1..N \ , \tag{7}$$

where $\overleftarrow{\beta}_{k,v}$ are the users' vSNR sorted in descending order, i.e., $\overleftarrow{\beta}(1) > \overleftarrow{\beta}(2) > \cdots > \overleftarrow{\beta}(U)$. To compute the equivalent SINR$_{u,k}$, similar to the computation of vSNR in (6) and (7), one has to find the eigenvalue of the Hermitian channel $\mathbf{F}_u^H \mathbf{H}_u^H \mathbf{H}_u \mathbf{F}_u$, i.e., $\hat{\lambda}_l$, using eigenvalue decomposition. Hence, the equivalent SINR for each user ($\nu_{k,u}$) is

$$\nu_{k,u} = \frac{\prod_{l=1}^{M_u} \hat{\lambda}_{l,i}}{\sum_{u=1, u\neq i}^{U} \prod_{l=1}^{M_u} \hat{\lambda}_{l,i} + \sigma_n^2} \tag{8}$$

and the geometric mean of the SINR ($\Gamma_{k,\mu}$) for μ users can be computed similar to (7) as follows

$$\Gamma_{k,\mu} = \sqrt[\mu]{\prod_{v=1}^{\mu} \overleftarrow{\nu}_{k,v}} \ , \ \forall \ \mu = 1..U \ \& \ k = 1..N \ . \tag{9}$$

Note: although vSNR is computed whithout the knowledge of the beamforming matrix F, it can only be greater than or equal the equivalent SINR. Thus, vSNR is selected to evaluate the quality of subcarriers/user.

B. Scheduler Design

In this paper, we design a sub-optimal SDMA multiuser scheduler. To simplify our computations, we proposed to set a few vSNR thresholds (vSNR$_T$) off-line, i.e., to forecast the quality of each individual subcarrier. To find the appropriate thresholds that guarantee specific QoSs, it is required to find the CDF curves of both Υ (vSNR) and Γ (equivalent SINR) for all possible multiuser scenarios, i.e., for $\mu = 1, 2, \cdots, U$. Based on these curves, we can easily find the appropriate percentage (1− the outage probability P_T) of the subcarriers which exceed a certain quality vSNR$_T$ (or its equivalent SINR$_T$), i.e., where the outage probability here is definded as the percentage of subcarriers with vSNR/SINR < vSNR$_T$/SINR$_T$ Hereby, we allow multiple users to share a percentage $(1 - P_T)$ of the subcarriers that exceed the corresponding vSNR$_T$ on the CDF curves. Those thresholds should be computed during system initialization based on U.

We divided the users into **five** different QoS groups with five different percentages: **10%** (the strongest 10% of the subcarriers are multiplexed; or $P_T = 90\%$), **30%**, **50%**, **70%**, and **80%** (80% of the subcarriers can be multiplexed with higher SER (higher multiplexing gain); or $P_T = 20\%$).

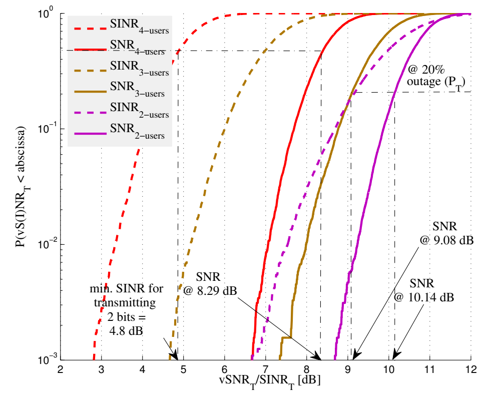

Fig. 2. Outage probability for different vSNR$_T$ and SINR$_T$ for 2, 3, and 4 users with a minimum SINR$_T$ = 4.8 dB and a maximum outage probability $P_T = 20\%$ (80% of the subcarriers can be multiplexed)

Fig. 2 depicts the CDF curves of both SINR and vSNR for different multiuser scenarios: 4, 3, and 2-user cases. The average signal to background white Gaussian noise ratio is set to 9 dB. The x-axis shows the different vSNR$_T$/SINR$_T$ (the subcarriers quality); these are computed considering the geometric mean in (7) and (9). The outage probability $P_T = 20\%$ (80% of the subcarriers exceed vSNR$_T$) works perfectly for the 3 and 2 case. At this outage, the equivalent SINR$_T$ (for the 3-user case) is 6 dB, which is enough to transmit 2 bits (≡ 4.8 dB). However, for 4 users at $P_T = 20\%$, the minimum SINR$_T$ (4.8 dB) is not achieved, i.e., transmitting 2 bits is not feasible. However, the 4.8 dB rather results in an outage of 50% (transmitting only on the strongest 50% of the subcarriers), which means a vSNR ≥ 8.29 dB. Decreasing the noise variance will shift these curves to the right. Table I lists the vSNR threshold equivalent to the outage probabilities 20%, 50%, and 90%. This is listed for μ = 4, 3, and 2 users at an average SNR of 9 dB and 15 dB. We should notice that the granularity between the vSNR of the different percentages is not high enough to be quantized in real systems, i.e., only 1.1 dB between 20% and 50%. However, this can be scaled and quantized inside the feedback channel quality indicator (CQI).

In the following (Algorithm 1), we discuss the detailed steps of our multiuser scheduling based on the offline-computed vSNR.

TABLE I
P_T AND VSNR/USER THRESHOLDS IN DB

$1/\sigma_n^2$	9 dB			15 dB		
Outage	20%	50%	90%	20%	50%	90%
4 users	8.29	8.49	9.33	16.91	17.49	18.33
3 users	9.08	9.73	10.74	18.08	18.77	19.73
2 users	10.14	10.72	11.48	19.14	19.69	20.52

Algorithm 1 Multiuser adaptive scheduling using vSNR

Initialize: the maximum number of users U, the scheduling table $\mathbf{S} = \mathbf{0}^{N\times 1}$, and compute $g_{u,k}$ for all users
Input: the required $b_{\mu,k}$ bit/stream/user for each individual scenario, a gain to compensate the CSI error A_g (initially set to 1), and Table I with all the vSNR$_\mu$
Output: the sorted indices $\mathbf{S}$

```
compute Υ_{k,μ} ∀ k = 1..K for each individual scenario, i.e., μ = 1···U, where μ is the number of users allowed to be multiplexed
μ ⇐ 1 (start with 1 user)
repeat
   repeat
      if Υ_{k,μ} ≥ vSNR_μ × A_g then
         S(k) ⇐ μ (overwrite the current number of users)
      end if
      μ ⇐ μ + 1 (increment the number of users)
   until μ > U
   k ⇐ k + 1 (go to the next subcarrier)
until k > N
allocate b_{μ,k} bits/stream/user (for each individual scenario μ) to all users in S for every subcarrier k
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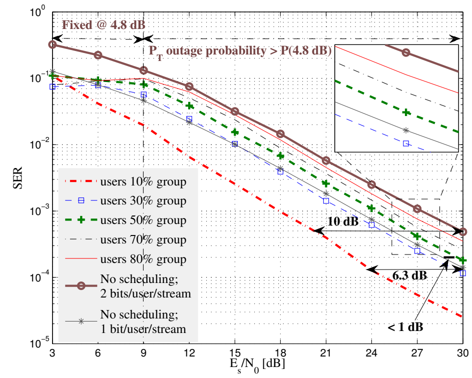

Fig. 3. SER for 10%, 30%, 50%, 70%, and 80% QoS groups. Below 9 dB shows the performance of 20% outage probability (not transmitting 2 bits).

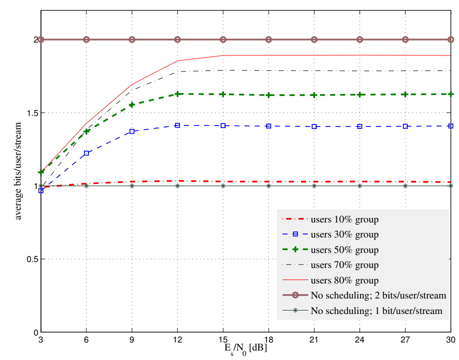

Fig. 4. Number of bits/user/stream for the 5-QoS groups with a comparison to the unscheduled cases using 1 and 2 bits/user/stream

IV. SIMULATION RESULTS AND ANALYSIS

In our simulation, we model a MU MIMO-OFDM transmission system to have a total number of subcarriers of 1024, where 5 clusters of 128 subcarriers are dedicated for 5 groups of users. The remaining subcarriers can be used for signaling, pilots, and other services. Four access points are assumed with 8 antennas in total. The number of the receive antennas at each MS is assumed to be 2. For simplicity, let the number of streams dedicated to each user, M_u, be equal to the number of antennas per user N_u, i.e., 2 as well. Figure 3 depicts the symbol-error ratio (SER) for the different multiuser groups, i.e., $1 - P_T = 10\%, 30\%, 50\%,$ 70%, and 80%. It is clear that the group of users which is allowed to be simultaneously multiplex over 10% of the given subcarriers are performing the best. It achieves **10 dB** better error performance than the unscheduled approach with **2 bits/stream/user**. However, from Fig. 4, we can see that the 10% group achieves only 1.1 bits/stream/user (on average). Nevertheless, it is still outperforming the unscheduled scheme, with 1 bit/stream/user, by **6.3 dB** (Fig. 3).

Another interesting result in Fig. 3 is the performance of the 50% group; it is only 1 dB less than the unscheduled scheme with **1 bit/stream/user**. However, from Fig. 4, it gains **63%** more throughput compared to that of the unscheduled scheme with 1 bits/stream/user, i.e., $> \mathbf{1.63}$ bits/stream/user. It is also important to mention that the 70% group outperforms the unscheduled scheme with **2 bits/stream/user** by more than **2.7 dB** (at 5×10^{-4} in Fig. 3) and looses only 0.23 bits compared to the same case (Fig. 4). Figure 5 shows a comparison between the unscheduled SDMA, scheduled SDMA, unscheduled OFDMA, and scheduled OFDMA. For SDMA transmission, we have adapted different bit rates on different subcarriers based on the number of multiplexed users such that

- $b_{4,k} = 2$, $b_{3,k} = 4$, $b_{2,k} = 6$, and $b_{1,k} = 8$, i.e., 2.78 bits/stream/user on average,
- $b_{4,k} = 1$, $b_{3,k} = 2$, $b_{2,k} = 4$, and $b_{1,k} = 6$, i.e., 1.75 bits/stream/user on average, and
- $b_{4,k} = 2$, $b_{3,k} = 2$, $b_{2,k} = 4$, and $b_{1,k} = 8$, i.e., 1.91 bits/stream/user on average,

which is equivalent to 15.28 bits/BS transmission. In the scheduled OFDMA transmission, the user with the strongest received SNR (geometric mean) of each subacrrier is scheduled for transmission. However, for unscheduled OFDMA, an arbitrary user is selected on each subcarrier. One can notice a

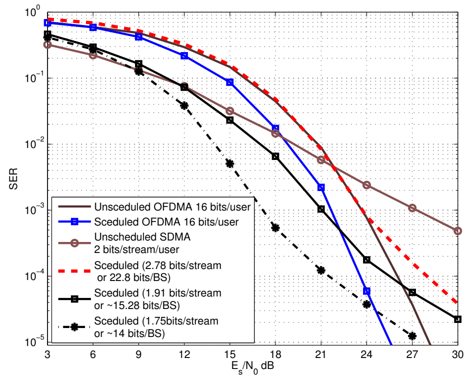

Fig. 5. Comparison between scheduled multiuser MIMO SDMA (for 10% QoS) and OFDMA cases to the unscheduled ones

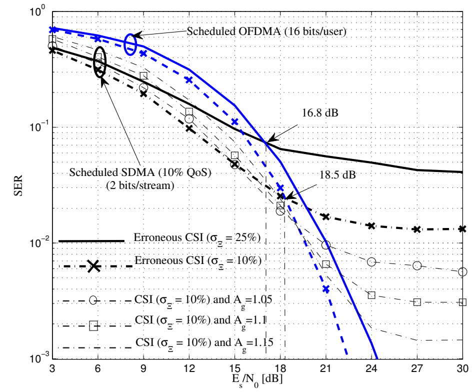

Fig. 7. Comparison between scheduled SDMA and OFDMA transmission under 25 % of CSI errors and different threshold compensation gain

difference of 3 dB between the scheduled and unscheduled OFDMA. Comparing scheduled SDMA to both OFDMA cases, we can see that the SDMA performs better than the OFDMA at low-to-moderate SNR. Mainly, this is due to the sub-optimality of the selected SDMA algorithm.

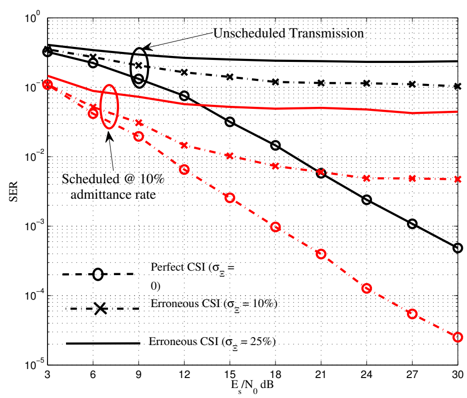

Fig. 6. Comparison between unscheduled and scheduled (for 10% QoS) transmission under different CSI qualities

Figure 6 evaluates the performance for different CSI qualities, i.e., $\sigma_{\Xi}^2 = 0$ (perfect CSI), $\sigma_{\Xi}^2 = 10\%$, and $\sigma_{\Xi}^2 = 25\%$. It is clear that the performance of the scheduled SDMA, although very low, is much better than the unscheduled one.

Finally, Fig. 7 shows the performance under CSI error equal 25%. It is clear that increasing the threshold gain, i.e., reducing the probability of multiplexing high number of users, would enhance the performance. However, an obvious error floor remains, which can be mitigated by a channel coding.

V. Conclusion

Instead of selecting the users after computing their optimum beamformers, we opt for a simpler multiuser scheduler. Hereto, we forecast the quality of each individual subcarrier and the maximum number of users it can accommodate using a simple virtual SNR computation. This makes our solution faster than unscheduled multiuser MIMO-OFDM. This is due to minimizing the simultaneous computations of the optimum beamformers. Additionally, we successfully devoted different QoSs by just changing the number of subcarriers utilized for multiuser transmission. Furthermore, utilizing only 50% of the subcarriers for multiuser SDMA transmission results in 63% more throughput compared to the unscheduled scheme with 1 bit/user/stream. Finally, the comparison of the scheduled SDMA and the scheduled OFDMA shows that the OFDMA outperforms the SDMA at high SNR.

VI. Acknowledgment

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