Performance Evaluation of Opportunistic Round Robin Scheduling for V-BLAST Users over MIMO Channels

Samir Al-Ghadhban
KFUPM, EE Department
Dhahran, 31261, Saudi Arabia
E-Mail: samir@kfupm.edu.sa

Abstract: In this paper, **we compare and evaluate several opportunistic round robin (ORR) scheduling for V-BLAST users over uplink MIMO channels. Each user spatially multiplexes his data over multiple transmit antennas. This spatial multiplexing scheme provides high data rates while multi-user diversity obtained from scheduling improves the performance of the uplink system. The opportunistic round robin scheduler is totally fair and it allows all users to access the channel. In the same time it captures part of the available multiuser diversity. The main results of this study show the performance gains of using ORR compared to RR scheduling. In addition, we compare the performance to the greedy and proportional fair algorithms in term of BER and supported capacity at different number of users.**

Keywords: *MIMO Scheduling, V-BLAST, Opportunistic Round Robin, Uplink Scheduling*

I. INTRODUCTION

Most of the studies on MIMO techniques were focused on optimizing the physical layer. However, in a multiuser environment, optimizing the physical layer for each user doesn't necessary optimize the system performance nor does it take advantage of the statistical independence of the fading channels among the users in a typical mobile environment. Furthermore, different users have different needs in terms of data rates, power limits and Quality of Service (QoS). These requirements make scheduling an important technique for optimizing the performance of a communication system and utilizing the system resources efficiently. Scheduling transmission to the best user leads to a form of selection diversity known as multiuser diversity [1].

In single-input single-output (SISO) systems, where each mobile and the base station have one antenna, it was shown that selecting the user that has the maximum signal to noise ratio (MaxSNR) maximizes the total information capacity of the uplink system [2]. This scheduler is known as MaxSNR scheduling. Over MIMO channels, most of the studies are based on theoretical information capacity [3-5] and on the downlink, which is the broadcast channel from the base station to the mobile unit. It has been shown in [6] that space time block coding (STBC) and scheduling aren't a good match. In fact, scheduling to a user with a single antenna can outperform scheduling using STBC. The reason is that STBC averages the fades while the scheduler tends to benefit from high peaks in the fading channel. In addition, the multiuser diversity obtained from scheduling is much higher than the spatial diversity of STBC, so STBC diversity doesn't add much benefit. On the other hand, spatial multiplexing (SM) schemes are more synergistic with scheduling. This is because they provide high data rates while the scheduler provides multiuser selection diversity.

In a MIMO system, scheduling can be done to a single user or multiple users. Scheduling to multiple users, i.e allowing more than one user to transmit or receive at the same time, is shown to be optimal in terms of maximizing system capacity and throughput. In [3], downlink scheduling to multiple users improved the average throughput compared to single user scheduling. Furthermore, the optimal uplink MIMO scheduling based on an information theoretical approach was considered in [7]. They showed that the scheduler should allocate all the power to at most M_R users, where M_R is the number of receive antennas at the base station. Also, they found that the optimal power resource allocation is water-filling in space and time. In [4], the authors found that multiuser scheduling reduces the average delay experienced by the users compared to single-user scheduling.

The authors in [10] investigated scheduling for uplink V-BLAST users. V-BLAST [8] is a practical spatial multiplexing MIMO system. The focus was on single-user scheduling. Although it is not optimal, it is more practical and easily implemented. The search space for best transmission is much less than the multiuser case and a multiuser diversity of order K, where K is the number of users, can be achieved. The scheduler selects one user at a time based on a criterion that minimizes the aggregate error rate of the uplink MIMO system. Each user spatially multiplexes his data over the transmit antennas to provide high data rates while the multiuser diversity obtained from scheduling improves the performance of the uplink system. The main contribution of that work was finding the capacity maximization scheduling criteria for V-BLAST uplink users. Also, the results show that the scheduler that maximizes optimal MIMO capacity doesn't work well for V-BLAST. The V-BLAST maximum capacity scheduler is derived specifically from its detection algorithm.

The scheduling algorithms in [10] were all greedy in the sense that they select the best user without providing any fairness to other users. In this paper, we extend our previous study in [10] to provide fairness for uplink MIMO systems. We propose using opportunistic round robin (ORR) [11] and proportional fair (PF) scheduling algorithms. The ORR algorithm selects the best user first based on a scheduling criteria then this selected user will be excluded from the search in the next round until all users are served. The result of this work shows that this algorithm captures part of the available multiuser diversity. In addition, we estimate the loss compared to the greedy and proportional fair algorithms.

II. SYSTEM MODEL

We consider multiuser uplink MIMO systems where there are K users and each user transmits through M_T transmit antennas and the receiver has M_R receive antennas. The scheduling algorithm selects a single user at a time. The average SNR is assumed to be the same for all users; they are either at a similar distance or strict power control is applied. However, the instantaneous SNR is different and based on that, the scheduling algorithm is implemented. A block diagram of the uplink system is shown in Figure 1. The MIMO channel is assumed to be an independent Rayleigh flat fading MIMO channel where each coefficient is an i.i.d complex Gaussian random variable with zero mean and unit variance. The received signal form user k is:

$$\mathbf{y}_k = \mathbf{H}_k \mathbf{x}_k + \boldsymbol{\eta}_k \quad (1)$$

where $\mathbf{y}_k$ is an $M_R \times 1$ received vector, $\mathbf{H}_k$ is an $M_R \times M_T$ MIMO channel matrix for the k^{th} user, $\mathbf{x}_k$ is an $M_T \times 1$ transmitted symbols from user k, and $\boldsymbol{\eta}_k$ is an $M_R \times 1$ i.i.d complex AWGN vector of zero mean and variance $N_0/2$ per dimension.

III. SCHEDULING CRITERIA

This section describes the MIMO scheduling criteria used in our study.

Assuming that an optimal MIMO encoder and decoder are available, the first criterion is to maximize the optimal MIMO capacity. This scheduler is called MaxMIMOCap and it selects a user k such that:

$$k = \arg \max_{n=1,2,\cdots,K} \{C_n\} \text{ ; where}$$

$$C_n = \log_2\left(\det\left(\mathbf{I}_{M_R} + \frac{SNR}{M_T}\mathbf{H}_n\mathbf{H}_n^H\right)\right) \quad (2)$$

where $\mathbf{I}_{M_R}$ is the identity matrix and $\mathbf{A}^H$ is the conjugate-transpose (Hermitian) of $\mathbf{A}$.

For V-BLAST users, unlike the criterion proposed in [2] for SISO systems, selecting the user who has the maximum SNR (MaxSNR) is not optimal. In the same time, scheduling based on maximum MIMO channel capacity as in equation (2) is also not optimal for V-BLAST, as we will see from simulation results.

Since V-BLAST is an open loop system and all layers have the same rate, an outage in capacity will occur if an outage happens in at least one layer. Therefore, the V-BLAST capacity is dominated by the weakest layer and it is given by [9]:

$$C_{VBLAST}^{ZF} = M_T \cdot \min_{i=1,2,\ldots,M_T}\left\{\log_2\left(1+\frac{SNR}{M_T\left\|\mathrm{W}_{ZF,i}\right\|^2}\right)\right\} \quad (3)$$

where $\mathrm{W}_{ZF,i}$ is the ZF projection row for the i^{th} layer and M_T is the number of layers (transmit antennas).

V-BLAST detector performs a series of interference nulling and cancellation operations. At the n^{th} stage, the ZF nulling matrix is:

$$\mathrm{W}_{ZF} = \left(\mathcal{H}_n^H \mathcal{H}_n\right)^{-1} \mathcal{H}_n^H \quad (4)$$

where $\mathcal{H}_n$ is the MIMO channel matrix after canceling the n-1 detected layers.
The detected layer at this stage, assume it is the i^{th} layer, is the strongest layer which has:

$$\left\|\mathrm{W}_{ZF,i}\right\|^2 = \min\left(diag\left(\left[\mathcal{H}_n^H \mathcal{H}_n\right]^{-1}\right)\right) \quad (5)$$

and its post-processing SNR is:

$$SNR_i^{ZF} = \frac{SNR}{M_T\left\|\mathrm{W}_{ZF,i}\right\|^2} \quad (6)$$

Where diag(A) is the vector of diagonal elements of matrix A.

After detecting all layers, the capacity of V-BLAST is determined by the weakest layer as in (3). The norm of the ZF projection row of the weakest layer for user k is:

$$w_k = \max_{i=1,2,\ldots,M_T}\left\{\left\|\mathrm{W}_{ZF,i}^k\right\|^2\right\} \quad (7)$$

where $\mathrm{W}_{ZF,i}^k$ is the ZF projection row for the i^{th} layer of user k.
Based on this analysis, the scheduler that maximizes V-BLAST capacity, called "*MaxVBLASTCapc*", selects user k such that:

$$k = \arg \min_{k=1,2,\cdots,K}\{w_k\} \quad (8)$$

To reduce the computations needed to perform the above scheduler, we propose suboptimal schedulers that are based on the received MIMO channels before V-BLAST processing. The first one chooses the user with the largest MIMO channel power $\left(trace(\mathbf{H}_k\mathbf{H}_k^H)\right)$ and we refer to it as *MaxSNR* scheduler, which mimics the optimal scheduler for single antenna systems [2].

The other scheduler considered in this study measures the eigenspread of the MIMO correlation channel matrix $\left(\mathbf{H}_k\mathbf{H}_k^H\right)$. This scheduler is called *MinES* and it selects the user k such that:

$$\min_{k=1,\ldots,K}\left\{s\left(\mathbf{H}_k\mathbf{H}_k^H\right)\right\} \quad (9)$$

The eigenspread is defined as $s\left(\mathbf{H}_k\mathbf{H}_k^H\right) = \lambda_{\max}/\lambda_{\min}$ where $\lambda_{\max}$ and $\lambda_{\min}$ are the largest and smallest eigenvalues of $\mathbf{H}_k\mathbf{H}_k^H$. The eigenspread gives insight into the orthogonality of the channels. The smaller the value of s, the closer the matrix is to be orthogonal. The minimum value of s is one, and it occurs when the channel matrix is orthogonal.

The last criterion considered in this study is based on the singular values of the MIMO channel. Let $\rho_{\max}$ and $\rho_{\min}$ be the largest and smallest singular values of $\mathbf{H}_k$, then we have the following relation:

$$\rho_{\min} = \frac{\rho_{\max}}{\sqrt{s}} \quad (10)$$

Thus, selecting the user that has the largest minimum singular value of $\mathbf{H}_k$ takes into account both the channel power and the eigenspread of $\mathbf{H}_k$. We refer to this scheduler as *MaxMinSV* and it selects user k such that his MIMO channel is:

$$\max_{k=1,\ldots,K} \left\{ \rho_{\min}\left(\mathbf{H}_k\right) \right\} \tag{11}$$

The performance of these algorithms are compared to round-robin (RR) scheduling which is a passive algorithm that cycles equally through all users irrespective of their channel status and it doesn't obtain any multiuser diversity.

IV. SCHEDULING ALGORITHMS

We compare in this study three algorithms. They are greedy, opportunistic round robin and proportional fair scheduling algorithms.

The greedy algorithm selects the best user at a time based on one of the scheduling criteria discussed in section III. This algorithm is not fair in the sense that users with weak channel conditions will not be served. However, if all users have same channel statistics and strict power control is applied, then the greedy algorithm will be fair on average.

On the other hand, the ORR algorithm guarantees fair scheduling to all users. It selects the best user first based on one of the scheduling criteria. In the next round, this selected user is excluded from the search and one of the other users is selected. This procedure is repeated until all users are served.

The third scheduling algorithm considers for comparison is proportional fair scheduling [12]. In this scheduler, the selection criteria are weighted by the throughput or data rate sent by each user. Therefore, users who access the channel more frequently than others will be penalized by this weight. Unlike ORR, this scheduler doesn't guarantee an access for all users but it is proportionally fair.

Let Ψ be one of the scheduling selection criteria as described in previous sections, the new PF criteria will be:

$PF(\Psi) = \dfrac{\Psi}{T_k}$; where T_k is the total data sent by user k.

V. SIMULATION RESULTS

The first part of the simulation results evaluate the aggregate BER performance of the uplink multiuser MIMO system with ORR scheduling. The number of users is ten and the result is shown in Figure 2 at 8bps/Hz and over 4×4 iid complex Gaussian MIMO channels. The MaxSNR scheduler captures very little multiuser diversity and it gains around 1dB compared to the RR algorithm. The other scheduling criteria perform very close to each other and they gained around 12dB compared to RR at BER=10^{-3}. This suggests that for ORR scheduling, it is sufficient to use suboptimal less complex scheduling criteria such as MaxMinSV.

The study also evaluates the performance of proportional fair scheduling and the BER result is plotted in Figure 3. The relative performance among different scheduling criteria is different from ORR scheduler. The best scheduler in this case is the one that maximizes V-BLAST capacity (MaxVBLASTCapc). The MinES and the MaxMinSV schedulers capture most of the multiuser diversity but MaxMinSV provides more gain since it takes into account the power of the MIMO channel. They perform very close to MaxVBLASTCapc, which has more diversity at high SNR (sharper slope). The results in this figure also show that using maximum MIMO capacity as the scheduling criterion is not optimal for V-BLAST. The reason is the suboptimality of the V-BLAST detection algorithm.

In Figure 4, the study compares between the greedy, ORR and PF scheduling using MaxVBLASTCapc criterion. The ORR scheduler doesn't capture the whole multiuser diversity since it lies between the greedy algorithm and round robin. A loss in multiuser diversity is apparent from the slope of the BER curve. This is a tradeoff that the system pays for achieving total fairness. However, the system still gains around 12dB compared to RR scheduler at ten users. The PF algorithm is better than ORR in terms of BER performance but it doesn't guarantee fairness for all users. It performs very close to the greedy algorithm. However, it is clear that the slope of the BER curve for the greedy algorithm is sharper than PF. Therefore, at high SNR, we expect that the difference will significantly increase

The scheduling gains of ORR algorithm as a function of users are shown in Figure 5. This indicates that the scheduling gain increases with increasing number of users, unlike the RR algorithm, which is a significant advantage for this scheduler.

The capacity gains of uplink ORR MIMO scheduling criteria at 10% outage versus the number of users are shown in Figure 6. Optimal MIMO capacity scheduling, as defined in (2) , is estimated by assuming the availability of optimal MIMO modems. Therefore, it provides an upper bound for the V-BLAST scheduling algorithms. The MaxVBLASTCapc scheduler approaches optimal MIMO scheduling at a large number of users. The capacity gain is around 9 bps/Hz compared to RR scheduling at 100 users. In addition, the supported rates of MaxMinSV and MinES criteria are close to MaxVBLASTCapc scheduling at large number of users, the difference is within 2 bps/Hz. This greatly improves the information capacity of the uplink system with much less processing. The results in this figure also illustrate the poor performance of MaxSNR scheduling. It has very little gains even at high number of users.

In addition, a capacity comparison of the ORR and greedy algorithms is shown in Figure 7. The result shows a loss in capacity of 2 bps/Hz. This is a tradeoff for total fairness achieved by the ORR algorithm.

VI. CONCLUSION

This paper proposed and compared several opportunistic round robin scheduling criteria for V-BLAST users over MIMO uplink systems. The performance of ORR is also compared to greedy and proportional fair algorithms. The main result of this paper shows a fundamental tradeoff between performance and fairness. The ORR doesn't capture the whole multiuser diversity advantage. However, it provides total fairness to all users while in the same time it enhances the system performance compared to round robin algorithm. Thus, it is an excellent candidate for next generation high data rate system and it can provide full fairness and provide scheduling gains to the multiuser uplink MIMO system.

ACKNOWLEDGMENT

The authors like to thank King Fahd University of Petroleum and Minerals (KFUPM) for their support.

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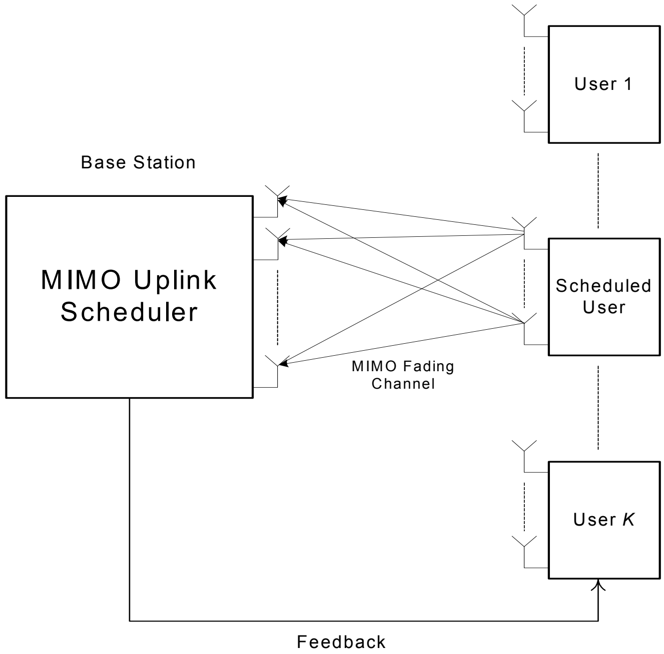

Figure 1: Block Diagram of Uplink MIMO Scheduling

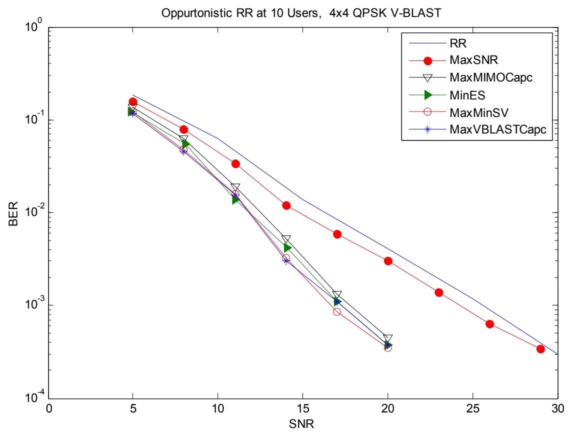

Figure 2: ORR scheduling aggregate BER of 4x4 QPSK V-BLAST users

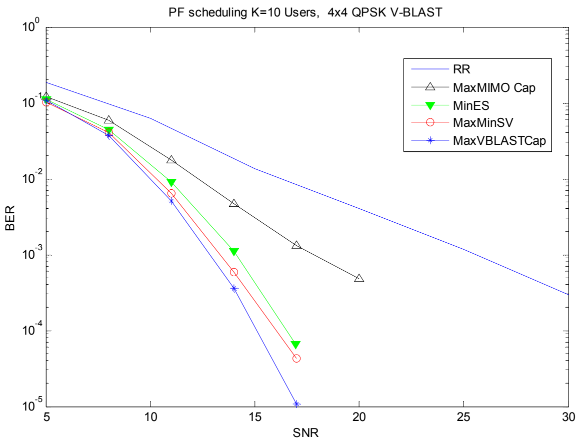

Figure 3: BER Performance of Proportional Fair Scheduling Algorithms over 4x4 MIMO Channels at 8 bps/Hz efficiency

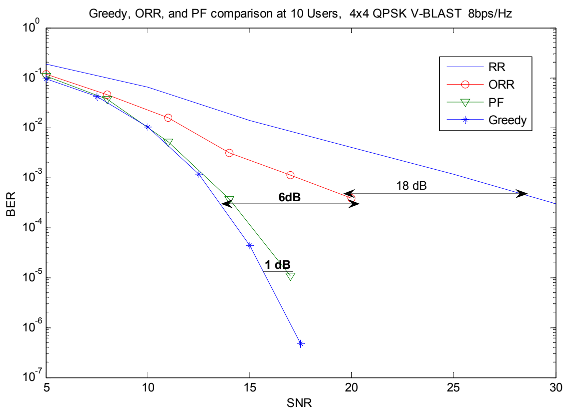

Figure 4: Greedy, PF and ORR at 10 users and over 4x4 MIMO Channels using MaxVBLASTCapc scheduler

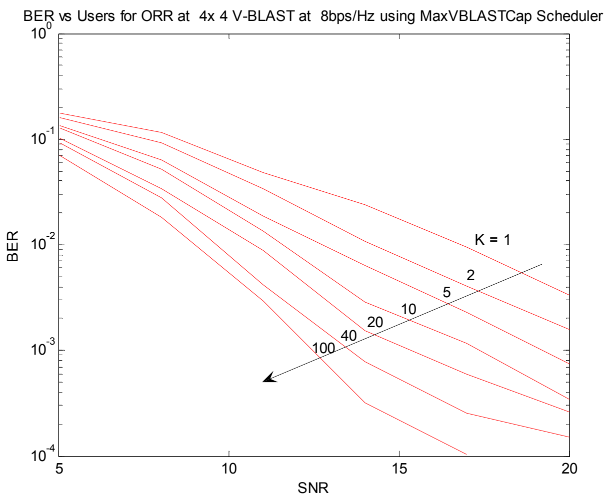

Figure 5: Effect of Multi-user diversity of ORR scheduling algorithm over 4x4 MIMO channels. Number of users (K) is set from 1 to 100.

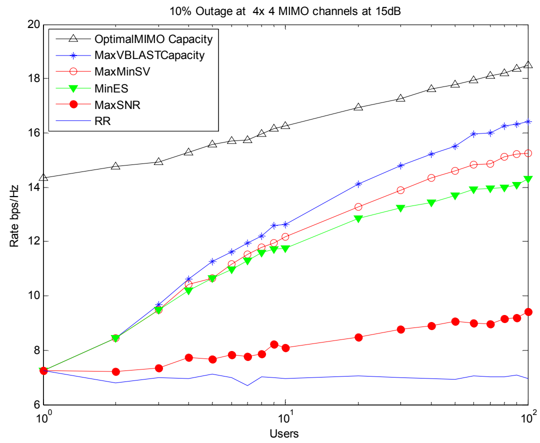

Figure 6: ORR 10% outage capacity versus number of users over 4x4 MIMO channels and at 15dB.

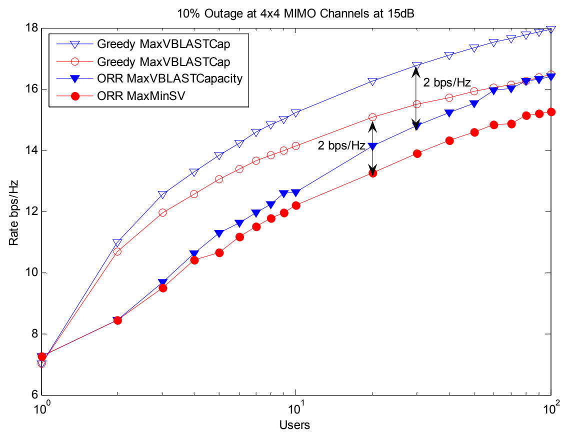

Figure 7: 10% outage capacity comparison of Greedy and ORR schedulers over 4x4 MIMO channels and at SNR=15dB.