Combined Opportunistic Beamforming and Receive Antenna Selection

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***Abstract*— Opportunistic beamforming with proportional fair scheduling is a very promising technique that exploits multiuser diversity to achieve high data rates on the downlink while ensuring a certain level of fairness. However, it greatly improves system performance only for sufficiently large mobile user population. This paper proposes a technique enhancing opportunistic beamforming at the transmitter with antenna selection at each mobile receiver to overcome this limitation. Significant performance improvement is achieved especially for small number of users. The simplicity and inexpensive deployment of this technique make it a highly desirable enhancement to opportunistic beamforming.**

I. INTRODUCTION

Achieving high data rates on the cellular downlink is a challenging problem that has attracted much research activity recently. The increasing interest in the downlink is motivated by the growing demand for wireless Internet access and the asymmetric nature of Internet traffic, where the download requests significantly outnumber the uploads. Supporting high data rates is especially challenging because of the bottleneck presented by the bandwidth and power limited wireless channel. A useful technique to overcome these limitations is to use multiple antennas. Multiple antenna wireless systems are becoming increasingly popular due to their remarkable potential to increase channel capacity. The capacity benefits of multiple antennas have been explored for the single user point-to-point communications scenario [1], [2], as well as multiuser, many-to-one (uplink) [3] and one-to-many (downlink) [4], [5] scenarios.

For the multiple antenna downlink the multiplicity of mobile users and base station antennas offers additional spatial degrees of freedom that can translate into tremendous throughput gains. However, an intriguing aspect of the multiple antenna downlink is that the ability to exploit these additional degrees of freedom depends strongly on the amount of channel knowledge available not only at the receiver but also at the transmitter [6]–[8]. With insufficient channel knowledge the ability to resolve these dimensions is lost and the throughput gains quickly disappear. The reason for the sharp decrease in the throughput with channel state information at the transmitter (CSIT) is that with no CSIT the transmitter is unable to resolve the user's channels in space. Thus the transmitter can not selectively beamform to any user's channel vector. Moreover, with no CSIT, the transmitter can not exploit multiuser diversity, i.e., the transmitter can not distinguish stronger users from the weaker users for each channel realization.

A. Multiuser Diversity

In this paper our focus is on techniques to exploit multiuser diversity on the multiple antenna downlink. Best motivated by Knopp and Humblet in [9], the notion of multiuser diversity is now well-recognized and much research has been directed toward exploiting channel fading by transmitting signals opportunistically to the users when their channel is good. The diversity gain is achieved from the fact that with many users who experience independent fading, there is a high possibility that a user has good channel condition.

B. Opportunistic Beamforming

Since perfect CSIT is impractical, techniques that exploit multiuser diversity with minimal CSIT are especially desirable. One such scheme is the idea of opportunistic beamforming [10]. Opportunistic beamforming [10] in combination with proportional fair scheduling is a recently proposed technique to exploit multiuser diversity subject to fairness constraints. The basic idea of opportunistic beamforming is to use multiple transmit antennas at the base station and to arbitrarily vary the beamforming vector. With a sufficiently large user population, there exists with high likelihood a user whose instantaneous channel vector matches the beamforming vector and who can thus benefit from the array gain to maximize the received SNR. Varying the beamforming weights with time increases the dynamic fluctuations of the users' channels and ensures fairness as the beamforming vector aligns with various users' channels at different time instants. An enhancement of this opportunistic beamforming scheme is proposed in [11], where pipe selection is combined with multiuser diversity to solve the scheduling latency issue for delay sensitive traffic.

While opportunistic beamforming is a powerful technique, its performance depends on the likelihood that an arbitrary choice of a beamforming vector will be close to an active users' channel vector. The more active users there are, the more likely it is that one of them will have a channel vector aligned to the beamforming vector. Therefore, it is observed that the benefits of opportunistic beamforming are limited for small user populations and improve rapidly as the number of users increases. In this paper we are concerned with scenarios where the user population is not sufficiently large for opportunistic beamforming to perform well. This limits the implementation of this promising technique. We show that this limitation can be greatly overcome by combining opportunistic beamforming at the base station transmitter with a powerful technique at the mobile receivers- antenna selection.

C. Receive Antenna Selection

Multiple receive antennas require multiple RF chains, usually composed of low-noise amplifiers, mixers that are very expensive. In practical system design, higher capacity is expected, but high hardware complexity is not desired and the cost needs to be reduced. One approach, called antenna selection, which can achieve high capacity and low hardware complexity, is to maintain a reduced number of RF chains and employ multiple antennas which are usually much cheaper, and to allocate the RF chains to the best set of antennas.

Several criteria have been considered in literature for selecting the subset of transmit or receive antennas. In [12], the criterion of selecting the subset of transmit or receive antennas is based on Shannon capacity. For a coherent receiver, minimum error rate is used as the criterion to select the best antenna subset in [13]. [14] relaxes the perfect channel knowledge assumption and proposes an interesting discrete stochastic approximation algorithm when only a noisy estimate of the channel is available. In [15], a signal strength based selection criterion is explored.

The remainder of the paper is organized as follows. In Section II, the basic opportunistic beamforming scheme is summarized. The proposed enhancement of combined opportunistic beamforming with antenna selection is described in Section III. Section IV demonstrates the throughput improvements of our enhanced scheme over basic opportunistic beamforming. Conclusions and directions for future work are presented in Section V.

II. System Model

The downlink scenario of a wireless communication system is considered here. Suppose the base station has M transmit antennas and can communicate with K mobile users. Conventional opportunistic beamforming (a single receive antenna at each user) is explained first, followed by the proposed enhancement.

A. Conventional Opportunistic Beamforming

Let the complex vector $X = [x_1, x_2, \cdots, x_M]$ denote the symbols transmitted from the M antennas at the base station. Transmit power is constrained as $\mathrm{E}\left[||X||^2\right] \leq P$. The complex channel gain vector from the M transmit antennas to user k is denoted as $H^{[k]} = [h_1^{[k]}, h_2^{[k]}, \cdots, h_M^{[k]}]$. The zero mean additive white Gaussian noise (AWGN) for user k is $n^{[k]} \sim \mathcal{N}(0,1)$.

With downlink beamforming, one symbol is transmitted through multiple transmit antennas to all the active users. Thus, the transmitted vector can be represented as $X = Wx$, where x is a scalar symbol and the vector $W = [w_1, w_2, \cdots, w_M]$ represents the beamforming vector for the M transmit antennas. The coefficient for transmit antenna m is a complex number $w_m = \sqrt{a_m}e^{j\theta_m}$, where a_m is the fraction of power allocated to antenna m and θ_m is the phase shift for antenna m. According to [5], a_m and θ_m are determined in a pseudo-random manner.

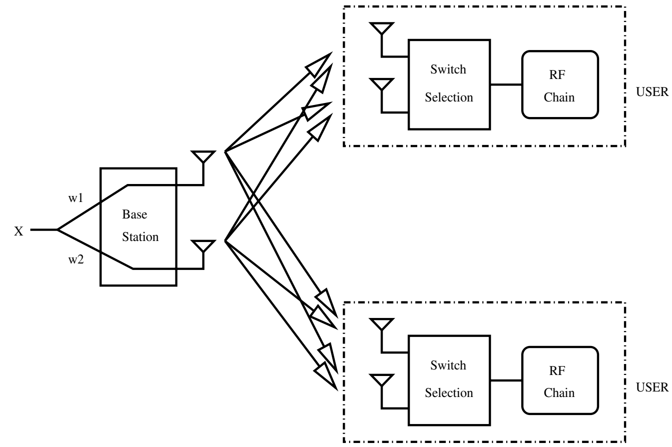

Fig. 1. System Model

Each user measures his received SNR $|| < H^{[k]}, W > ||^2 P$ and feeds it back to the base station transmitter. Here $< \cdot, \cdot >$ stands for vector dot-product. Assuming that the objective is to maximize throughput without additional fairness constraints, the base station selects the mobile user with the maximum received SNR. For a user with a given channel vector $H^{[k]}$, the maximum received SNR is achieved when the beamforming vector W is parallel to $H^{k]}$. This is called the beamforming configuration. With opportunistic beamforming, when the number of users is large enough, it is likely that for each random choice of W, there exists a user such that W is close to that user's beamforming configuration. It is desirable to transmit to such a user at each time instant to maximize the throughput. However, if the number of users is not large enough, the chances of a user approaching beamforming configuration become much lower. In this case, the performance can be greatly improved through receive antenna selection diversity.

III. Proposed Scheme: Combined Opportunistic Beamforming and Receive Antenna Selection

We propose an enhancement to the opportunistic beamforming scheme by adding receive antenna selection diversity to improve performance, especially for small user populations. According to the proposed scheme, each mobile receiver has one RF chain and multiple antennas. Based on the size constraints for the mobile receivers the number of antennas R maybe limited to 2 or 3. We assume that the receive antennas are spaced such that they experience independent fading. The R receive antennas are connected to a switch selection component and only one antenna is connected to the RF chain at any time. Fig. 1 shows the system model. The channel vector to the r^{th} receive antenna belonging to user k is denoted as $H^{[k,r]} = [h_1^{[k,r]}, h_2^{[k,r]}, \cdots, h_M^{[k,r]}]$ and the corresponding AWGN is $n^{[k,r]} \sim \mathcal{N}(0,1)$. The received signal at antenna r for user k is

$$y^{[k,r]} = < H^{[k,r]}, W > x + n^{[k,r]}. \quad (1)$$

We assume that each mobile is able to track its own relevant channel state information. User k's receiver only needs to monitor the overall received SNR at each of his R receive antennas. The antenna with the highest signal strength is selected to receive the signal for user k. Once each mobile user selects the best receive antenna and feeds back the SNR for that antenna, the base station can perform opportunistic beamforming as in the conventional case. In this manner, both antenna selection diversity and multiuser diversity are utilized to enhance system performance.

Intuitively, it is easy to understand why receive antenna selection is particularly useful in combination with opportunistic beamforming. Employing additional receive antennas at the mobile users can be viewed as increasing the effective number of users on the downlink. For example, even with only two antennas at each mobile, the effective number of users is doubled. Since the gains of opportunistic beamforming depend strongly on the number of users and antenna selection at the receiver increases the number of effective users, the cumulative impact of the two techniques leads to remarkable throughput enhancements.

If the mobile users experience i.i.d. fading statistics, receive antenna selection diversity is equivalent to multi-user diversity. In effect, the system with both receive antenna diversity and multiuser diversity is equivalent to a system simply with multiuser diversity which has an expanded user space - the product of the number of real mobile users and the number of receive antenna for each user. This significantly helps to relax the large user population requirement for opportunistic beamforming to perform well.

In practice, the channel statistics different mobile users experience are not identical. Even in this asymmetric channel case, performance is still expected to improve greatly. Ensuring fairness becomes crucial in this case and a fair scheduling algorithm is required. To estimate the performance benefits of enhanced opportunistic beamforming with fairness constraints, we use the proportional fair scheduling algorithm [16].

A. *Proportional Fair Scheduling*

Latency and fairness are important issues for practical system design. The proportional fair scheduling [16] scheme is popular as it allows a better trade off among the performance metrics of interest, namely diversity, fairness and delay. Time is divided into slots. At each time slot, each mobile user sends data rate information to base station, denoted by $R^{[k]}(t)$. This data rate is a time-varying variable based on the channel quality perceived by user k. The base station keeps track of the average throughput $T^{[k]}(t)$ for each user. At each time slot, the scheduler selects to transmit to user $k^\star$ with the largest $R^{[k]}(t)/T^{[k]}(t)$ among all the active users in the system. This scheduling algorithm tends to favor either high instantaneous data rate user or the user who has low throughput and has not been served recently.

The average throughput $T^{[k]}(t)$ is updated according to the following exponentially weighted low-pass filter:

$$T^{[k]}(t+1) = (1-\tau)T^{[k]}(t) + \tau R^{[k]}(t) 1(k^\star(t) = k) \quad (2)$$

where τ is a weighted factor providing the tradeoff between the multiuser diversity and latency. When τ is close to zero, the throughput is averaged over a long time scale, the user who hits its own peak rate is more likely to be selected. When τ is close to one, the average throughput decreases quickly if users are not scheduled. So a user does not need to wait too long to get selected even though his channel may not be strong.

IV. Numerical Results

The improvement of enhanced opportunistic beamforming with antenna selection is demonstrated through simulation results. The simulation is conducted for $M = 16$ transmit antennas and $R = 1, 2, 3$ receive antennas. The performance of basic opportunistic beamforming with one receive antenna is considered as the baseline. The throughput for $R = 2, 3$ is normalized by this baseline and their improvement is represented in percentage of this baseline in the following figures. The performance is evaluated for both symmetric and asymmetric user channel statistics, whereas results for Rayleigh and Rician fading channels are provided for each case. For the asymmetric case the users average SNR is generated according to the empirical distribution shown in Fig. 4. For the symmetric case all users have the same average SNR, equal to the mean value of the distribution shown in Fig. 4.

A. *Symmetric Users*

Suppose users experience independent and identically distributed (i.i.d.) average SNR and the only channel difference among users is caused by multi-path fading. This leads to the same long-term average throughput $T^{[k]}(t)$ for each user. Since fairness is not an issue in the symmetric case, we try to maximize throughput at each time slot. Thus the scheduling decision depends only on current data rate $R^{[k]}(t)$, which is directly determined by SNR. In Fig. 3 and 4, the performance improvement of enhanced scheme over basic scheme for both Rayleigh fading and Rician fading is demonstrated.

From Fig. 2, significant improvement in throughput can be observed, especially for small number of users, when antenna selection is used at the receiver side. For example, when there is only one mobile user in the system, there is no multiuser diversity to be exploited by basic opportunistic beamforming. However, if two or three receive antennas are deployed at the receiver side, antenna selection diversity can enhance the throughput by about 32% for two receive antennas and 48% for three receive antennas case. As the number of users increases, the improvement tends to be stabilize at about 6% for two receive antennas and 10% for three receive antennas.

Similar simulations are also conducted for Rician fading channel. In this case also, substantial performance improvement is observed. Results for two different κ factors are illustrated in Fig. 3. Here the κ factor determines the ratio of energy between the line of sight (LOS) signal and diffused

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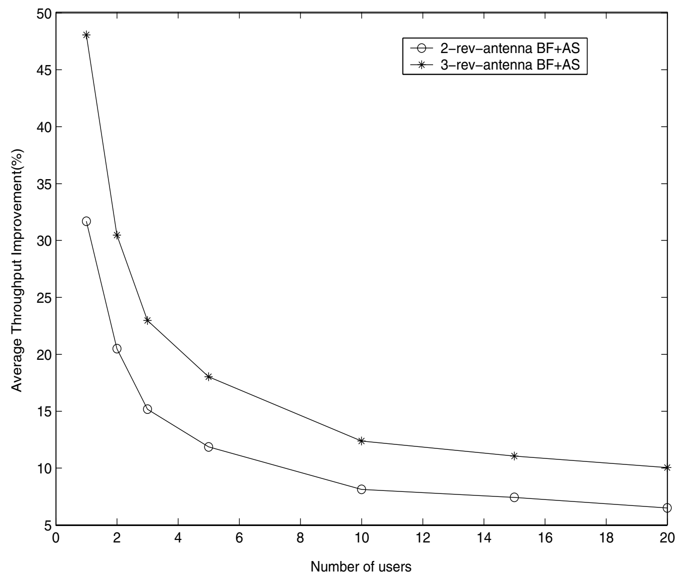

Fig. 2. Performance of Rayleigh Fading with Symmetric Users

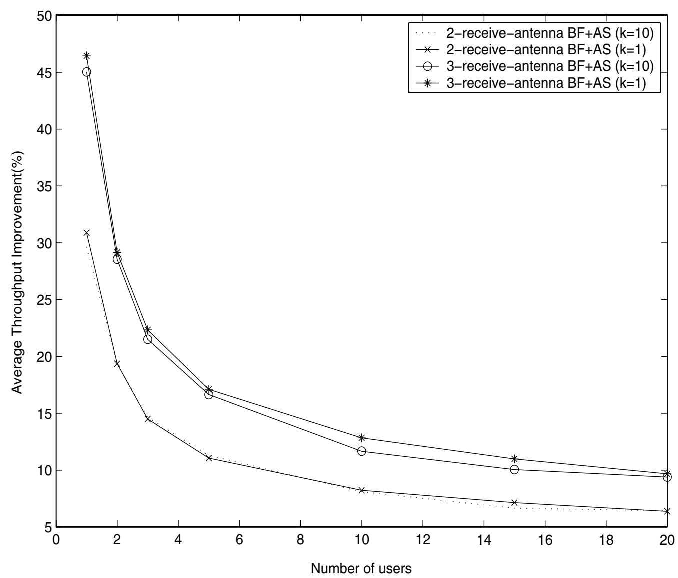

Fig. 3. Performance of Ricean Fading for Symmetric User Channel

signal. The performance difference between two different κ factors is not very distinguishable. So with symmetric users, the impact of average SNR outweighs the impact of κ factors. The dependence on κ factor is stronger for the asymmetric users case considered next.

B. Asymmetric Users

In a cellular system users experience different channel fade statistics based on their respective propagation path loss, scattering and shadowing effects. To model the typical asymmetries among users, we use empirical data to simulate the average SNR. In our simulation, the average SNR is independently assigned to each user according to the distribution in Fig. 4. The distribution shown in Fig. 4 is based on field measurements in a cellular environment and has been used previously for numerical results with rate allocation [17].

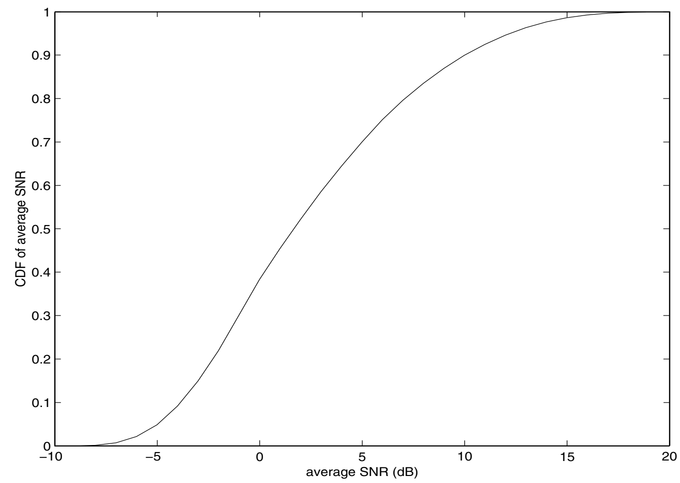

Fig. 4. CDF of Average Received SNR

Fig. 5 shows significant throughput improvement with the enhanced opportunistic beamforming scheme for the Rayleigh fading channel with asymmetric users. Results for two different κ factors are illustrated in Fig. 6 for the Rician fading channel. Excellent improvement for each κ can be observed, particularly for small number of active users. For larger κ, it means the LOS signal is stronger than the diffused component, correspondingly, the dynamic fluctuation range of the composite channels becomes smaller. Therefore, performance for large κ is degraded due to the fact that diversity cannot be fully explored if channels perceived by different users or antennas are not as distinguishable. This is confirmed by the simulation results in Fig. 6, where performance for $\kappa = 1$ is better than that for $\kappa = 10$ for very small number of users. When the number of users increases, the impact of both multiuser diversity and antenna selection diversity on channel fluctuations compensates the influence of the κ factor. Therefore, the difference for $\kappa = 1$ and $\kappa = 10$ is less significant for larger user population.

Comparing the symmetric and asymmetric user channels, the performance improvement achieved is similar for asymmetric situation for Rayleigh fading channel. However, for Rician fading channel, the performance difference between different κ factors is more noticeable than symmetric user channel statistics. It is due to the fact that different average SNR for users plays an important role, along with the impact of κ factors, to differentiate channels perceived by different users. This leads to much larger range of channel fluctuations among users and diversity can be well exploited.

V. Conclusion

We propose a combination of opportunistic beamforming and receive antenna selection to achieve high data rates, particularly for small user populations. This enhanced scheme overcomes the limitations of the conventional opportunistic

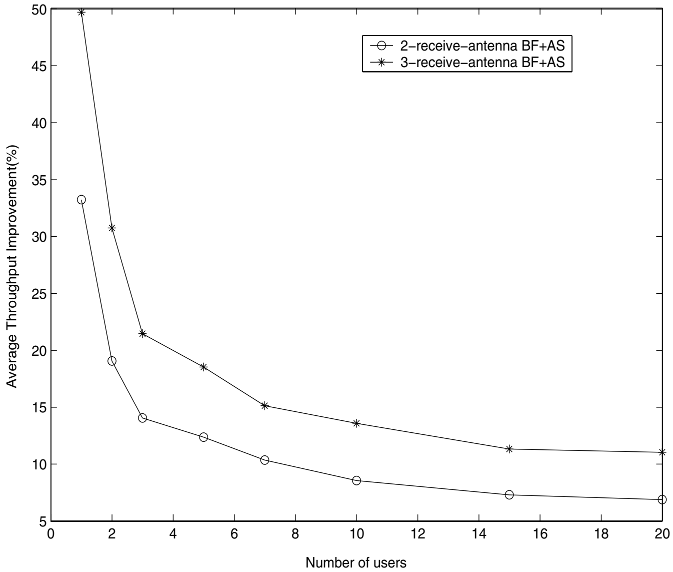

Fig. 5. Performance of Rayleigh Fading for Asymmetric Users

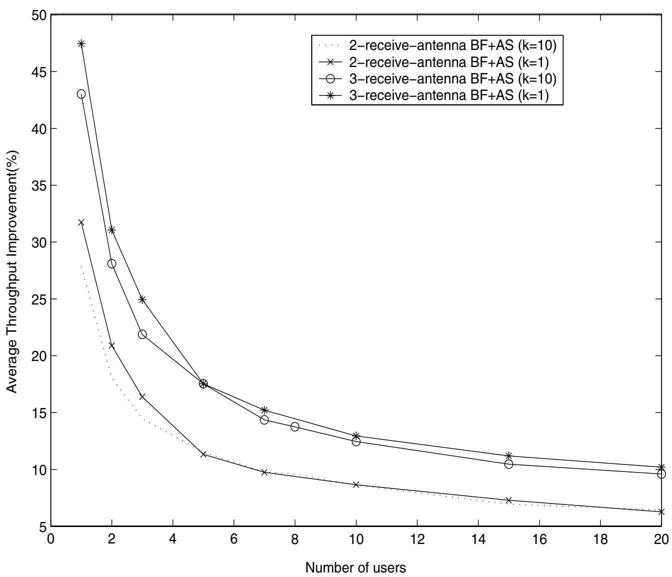

Fig. 6. Performance of Rician Fading for Asymmetric Users

beamforming technique when the user population is small. Without increasing the number of RF chains, antenna selection has the effect of increasing the number of users in the system. Numerical results indicate that significantly higher throughputs are achieved through this scheme. Along with the throughput benefits the relatively inexpensive deployment of this scheme makes it promising and practical.

Further investigations on this topic could take several directions. Antenna selection requires a comparison between all R received signals simultaneously. While the number of antennas at the mobile is usually small, it may be desirable to avoid the comparisons through simpler techniques such as threshold combining. Even with threshold combining and $R = 2$ the design of the switching scheme involves tradeoffs between simplicity and performance. *Switch-and-stay* is known to be easier to implement than *switch-and-examine* scheme [18]. The choice of the switching scheme also affects the training scheme. Since only one RF chain is available, examining all the R SNRs requires a training interval proportional to R. Therefore switch-and-examine schemes will require training intervals proportional to the number of receive antennas R while switch-and-stay schemes will need smaller training intervals. Besides these tradeoffs, a combination of antenna selection, opportunistic beamforming and the enhanced opportunistic beamforming scheme in [11] is of interest. The benefits of antenna selection when multiple beams are transmitted [6] are not known. A comprehensive theoretical analysis of the rate of growth of throughput with users, transmit antennas, number of beams, and the order of selection diversity per user is also of great interest as a direction for future work.

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