2005 IEEE 6th Workshop on Signal Processing Advances in Wireless Communications

Performance of the MIMO Downlink Channel with Multi-Mode Adaptation and Scheduling

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Abstract— **This paper presents an algorithm for switching transmission methods (whether for diversity or data rate maximization) over a multiple antenna broadcast channel. The proposed approach exploits long-term spatial selectivity of the user channels to decide between different diversity and multiplexing modes. We investigate the performance of this adaptive transmission method with different scheduling polices (both sensitive to user queue sizes and independent of user queue sizes). While the methods outlined in this paper are general, we present our results in the context of a broadcast channel with four transmit antennas at the central transmitter, and four antennas at each receiver. Our results indicate a gain of approximately 20% in average system throughput with the proposed algorithm over realistic channel models.**[1]

I. INTRODUCTION

Transmission over a broadcast channel in multiple-input multiple-output (MIMO) systems, such as the downlink of a wireless cellular system, can be tailored for either diversity or data rate maximization. The choice of transmission method, whether for diversity or data rate maximization, depends upon the channel state of each user. In a multi-user cellular scenario, with channel state information at the central transmitter, the scheduler can decide the transmission method appropriate for each user, constrained by the resulting error probability, and in addition, make transmission allocations that are sensitive to individual user queue sizes to ensure “fair” bandwidth sharing. This target error rate represents a threshold on acceptable air interface performance for each user and the notion of “fairness” represents an attempt to provide uniform bandwidth allocation to users with dissimilar channels.

An overview on the design challenges of physical (PHY) and medium access control (MAC) layers, employing adaptive transmission techniques in MIMO systems, was presented in [1]. In [1] it was shown that cross-layer PHY and MAC design may yield significant range and spectral efficiency enhancement in typical cellular systems employing MIMO technology, in comparison to single-input single-output (SISO) systems. In this contribution, we aim to compare the following two MAC-PHY co-design options: i) a MIMO system using a fixed beamforming transmission scheme at the PHY layer with a sophisticated MAC design (i.e., opportunistic scheduler) and ii) a MIMO system employing adaptive multi-mode PHY transmission with a simple MAC design (i.e., round robin scheduler). We show that these two methods yield similar system performance. Our simulations and comparisons are in the context of realistic indoor channel models as being proposed for IEEE802.11n.

At the PHY layer, our proposed method employs adaptive modulation/coding and MIMO transmission schemes. The switching criterion employed in this paper is novel compared to existing adaptive transmission methods presented in [2], [3] in that it exploits the long-term statistics of the wireless channel and estimates the channel spatial selectivity (defined as in [4]) based on the spatial correlation matrices. More details on the specific implementation of this algorithm for single-link transmissions are provided in [5]. In the context of multi-user MIMO we allow different users to communicate with the central transmitter using different schemes. The choice of available transmission methods is assumed to be beamforming (BF), double space-time transmit diversity (D-STTD), and spatial multiplexing (SM). The key insight of this switching criterion is to evaluate the link quality based on signal-to-noise ratio (SNR) and spatial selectivity information. Then, the transmission scheme (i.e., BF, D-STTD or SM) that provides the highest throughput for the predefined fixed error rate is selected for a given link.

At the MAC layer, the scheduler (with a knowledge of the long-term spatial selectivity of each user channel and instantaneous user queue sizes) determines the best transmission mode (and hence the rate allocation) for each user. We

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[1] This material is based in part upon work supported by the Texas Advanced Technology Program under Grant No. 003658-0380-2003 and by the National Science Foundation under grant numbers 0322957 and 0435307.

consider two different scheduling polices: simple round robin and the throughput optimal c-μ scheduler [6]. We evaluate the average throughput in the context of the downlink of an infrastructure 802.11 network. We show that the adaptive PHY transmission method provides significant gains in throughput or reduced per-user packet delays over conventional fixed scheme transmissions. We also compare the benefit of the c-μ scheduler over a simple round robin scheduler.

This paper is organized as follows. In Section II we describe the system model. In Section III we provide a detailed description of the PHY and MAC system specifications and present our adaptive transmission technique. In Section IV we provide simulation results on the gains in average throughput delay achievable with our method. Finally, we draw some conclusions in Section V.

II. SYSTEM MODEL

We consider transmission over a wireless broadcast channel with M_T antennas at the central transmitter and M_R receive antennas for each of the K users in the system. We assume a narrowband quasi-static channel, i.e. the $M_R \times M_T$ channel matrix $\mathbf{H}_k(t_s)$ is constant for user k over the symbol t_s duration, but may vary from symbol to symbol.

The discrete-time model on the downlink where the signal received by user k at symbol duration t_s is given by

$$\mathbf{y}_k(t_s) = \mathbf{H}_k(t_s)\mathbf{s}_k(t_s) + \mathbf{v}_k(t_s),$$

where $\mathbf{s}_k(t_s)$ is the $M_T \times 1$ transmitted signal to user k, $\mathbf{v}_k(t_s)$ is independent identically distributed (i.i.d.) circularly symmetric complex Gaussian noise vector at receiver k during symbol t_s with distribution $\mathcal{CN}(0, \sigma^2\mathbf{I}_{M_R})$ and $\mathbf{y}_k(t_s)$ is the $M_R \times 1$ received signal for user k during that interval. The transmit power is constrained to P_T. The path-loss model is given in [7].

The central transmitter decides among BF, D-STTD, and SM modes for transmission over different users. Each user k tracks the channel quality via a common downlink pilot symbol and accumulates these channel quality measurements over several channel coherence times. The long-term average of these channel quality measurements is sent back to the transmitter over a low-rate feedback channel to enable adaptation across different MIMO schemes.

The scheduler operates at the resolution of a time-slot of duration t. A time-slot consists of a large enough number of symbols to allow practical coding and modulation methods to approach a data rate that is arbitrarily close to the Shannon capacity over the time-slot, i.e. $t \gg t_s$. During every time-slot the scheduler assigns transmission opportunities to a single user according to different scheduling rules.

A scheduling decision at time-slot t, conditioned on known long-term-averaged user channels and the queue length, is the rate assigned to a user and the best MIMO scheme suited to the long-term-averaged channel for that user. Then, based on the chosen MIMO scheme, the central transmitter constructs an appropriate signal vector by combining one or more data streams for each single user.

We consider a workload arrival process of $a_k(t)$ bits (where $k = 1, 2, \cdots, K$ and $t = 1, 2, \cdots$) for each user k at the central transmitter, corresponding to variable length user data. Each user has a dedicated queue at the central transmitter. We assume that $a_k(t)$, $t = 0, 1, 2, \cdots$ are i.i.d. random variables with a finite second moment, i.e., $\mathbb{E}[a_k(t)^2] < \infty$. We denote the backlog queue vector at time t by $\mathbf{Q}(t) = [\{q_1(t), q_2(t), \cdots, q_K(t)\}]$, where the queue length for user k at the start of time slot t is given by $q_k(t)$ bits. The average arrival rate of bits intended for user k is denoted by $A_k = \mathbb{E}[a_k(t)]$. We call $\mathbf{A} = (A_1, A_2, \cdots, A_K)^T$ an arrival vector. Each transmission opportunity to a given user necessarily results in a decrease in the corresponding queue size of that user.

The capacity of the broadcast channel with K users is a K-dimensional vector. The set of all feasible K-dimensional rate vectors is called the *capacity region*. At time slot t, conditioned on the known channels, the capacity region is denoted by $\mathcal{C}\left(\{\mathbf{H}_k(t)\}_{k=1}^{K}\right)$. Since we consider single-user scheduling, the capacity region has a polymatroid structure, i.e. it is bounded by hyperplanes. An important characteristic of this polymatroid structure is that any point in the interior of the capacity region may be achieved by an appropriate weighted linear sum of the extreme points [6].

III. MULTI-USER ADAPTIVE ALGORITHM

In this section we describe our proposed multi-user transmission adaptive technique, providing details on the system specifications at the PHY and MAC layers.

To gain intuition on the potential benefits of our adaptive method as a function of the channel model, we present the following example. We consider three different channel scenarios in the context of cellular systems. The first scenario is defined by line-of-sight (LOS) and/or user at the edge of the cell. In this case, since the channel has rank 1 and/or low SNR, a beamforming scheme would be selected by the adaptive algorithm as a means to increase the robustness of the link. The second channel scenario is poor scattering environment (i.e., low angular spread) and medium SNR, in which few channel eigen-modes are available to transmit parallel streams over the wireless link. In this case, the user would be starved of diversity and would require schemes like double space-time transmit diversity (D-STTD) [8] for additional diversity gain, which results in throughput enhancement. The third channel scenario is rich scattering environment (i.e, high angular spread) and/or user close to the base station (high SNR), for which our adaptive algorithm would switch to multiplexing schemes in order to increase spectral efficiency.

A. PHY Layer Adaptive Algorithm

The performance of the MIMO system depends on the characteristics of the propagation environment, as already acknowledged in [9]–[12]. Particularly, it has been proved that capacity [12, p.77] and error rate performance [11] depend on the eigenvalues of transmit/receive spatial correlation matrices, which are a measure of the spatial selectivity of the MIMO channel, defined as in [4]. In our proposed method, we exploit the knowledge of the eigenvalues of the transmit/receive spatial correlation matrices to define a criterion to switch across different MIMO transmission schemes, hereby maximizing the spectral efficiency for a predefined error rate performance.

We characterize four "typical" channel models, with different degrees of spatial selectivity, based on the IEEE 802.11n standard channel models described in [7]. A complete description of these models is provided in [5]. Due to space constraints, in this paper we only present the results for channel "Model 1". This model is defined as a zero-mean (i.e., K-factor of 0) correlated Rayleigh fading model, with angular spread in the range $[28°, 55°]$ and 6 clusters (consistent with "Model F, NLOS" in [7]).

The combination of these models with different values of SNR thresholds defines the *link-quality regions*. To predict the link-quality region for a given transmission, we employ two *link-quality metrics*: the average SNR and the relative condition number of the eigenvalues of the spatial correlation matrices. More details on these metrics are provided in [5].

To enable transmissions over the wireless link, we use a combination of modulation/coding schemes (MCS) and practical MIMO transmit/receive techniques. We consider three common MIMO transmission schemes:

- **Beamforming** (BF): with MRC receiver
- **Double space-time transmit diversity** (D-STTD): with minimum mean squared error (MMSE) receiver
- **Spatial multiplexing** (SM): with equal power allocation across the transmit antennas and MMSE receiver

We chose these schemes since they provide increasing data rates for a fixed error rate performance and for a fixed number of transmit/receive antennas. Moreover, they are being actively considered by different standards bodies such as 3GPP and IEEE 802.11n, as reported in [8], [13]–[15]. We defined eight combinations of modulation/coding schemes, according to the standard IEEE 802.11a [16]. The combination of the three MIMO schemes with these eight MCSs results in a total of 24 different transmission modes. We selected a subset of 12 modes, according to the criterion of minimizing the SNR requirement for a given transmission rate.

The spectral efficiency and error rate performance of these MIMO transmission modes is a function of the characteristics of the propagation environment, as was already acknowledged in [11], [12]. Unfortunately, it is not possible to derive in closed-form the error rate performance of these transmission modes as a function of the SNR, for different Rician channel models. Therefore, we simulate the error rate performance for all the feasible link-quality regions previously defined and built up a look-up table (LUT). This LUT maps the channel quality information (i.e., SNR and spatial selectivity) into error rate performance.

Our proposed method adaptively selects the optimal transmission mode, which maximizes the throughput (or spectral efficiency) for a predefined target error rate, depending on the current channel condition. To enable this mode adaptation, the proposed algorithm estimates the link-quality for the current transmission based on the average SNR information and the spatial selectivity indicator. These metrics are the inputs to the LUT, used to select the mode providing the highest throughput for the predefined target error rate.

Figure 1 illustrates the resulting spectral efficiency for each of the transmit modes over a given range of SNRs. We employed channel Model 1, as described above. Observe that for high SNR, a system employing the proposed adaptive algorithm would produce a gain in spectral efficiency of 13.5 bps/Hz, compared to a system using fixed BF transmission with adaptive MCS.

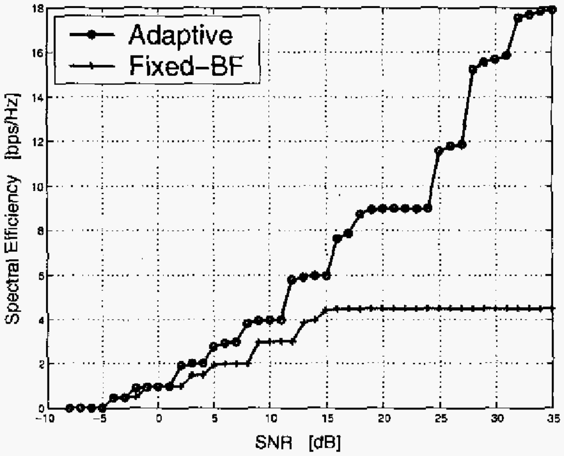

Fig. 1. Spectral efficiency for a single link with adaptive and fixed BF transmission techniques using channel Model 1.

B. MAC Layer Scheduler

For the downlink channel, signal propagation attenuates with distance. The path-loss exponent characterizes the rate of signal strength decay with distance. Assuming that users are distributed uniformly over the area of the cell, the propagation path-loss induces a spatial SNR distribution. The primary objective of the scheduler is to ensure "fair" allocation of transmission opportunities to all users and maintain acceptable (bounded) per-user packet delays, regardless of user SNR.

From a system perspective, the average long-term throughput is given by a weighted average of the spectral efficiency versus SNR curve, where the weights correspond to the probability measure induced by spatial distribution of the user population over the cell area, and the scheduling decisions, which may be a function of the instantaneous queue sizes of each user. Next we define the "round-robin" scheduler (where scheduling decisions are made independent of the queue sizes) and the throughput optimal c-μ scheduler (which makes scheduling decisions based on both the channel state and the instantaneous queue sizes). We will compare both the system throughput and the per-user packet delay for these two scheduling rules.

1) Round-Robin (RR) Scheduler: Suppose we separate users into N classes according to their SNR levels (and hence the corresponding supported rates). A user in class n receives data at rate R_n bps, where $n = 1, 2, \cdots, N$. Also we assume all users request statistically identical traffic. Then, the relative frequency of occurrence of packets of class n, denoted by P_n, is proportional to the number of users in that class. Assume infinite traffic backlog of each class and a round-robin scheduling policy where slots are assigned one at a time sequentially to each user. Then the bandwidth share of a given class is proportional to the class size and the average system throughput is given by

$$\bar{R} = \sum_{n=1}^{N} R_n P_n \text{ bps.} \tag{1}$$

This implies that fixed size packets of lower data rate users will have proportionally higher latencies. That is, if latency of a B-bit packet is considered, the number of slots consumed by each user in class n will be B/R_n, and hence the latency is inversely proportional to rate R_n.

Now, on the other hand, if we require that all users have essentially the same packet delay irrespective of the R_n they can support, and that a finite amount of traffic is requested by each user within a certain time window. Then, each class will consume bandwidth directly proportional to its size and inversely proportional to its rate. Consequently, the achieved system throughput differs from (1) due to multiplexing of users with different SNRs. Assume that each user requests B bits and that users of class n require $S_n = k/R_n$, k being a constant, slots to transmit B bits. We define effective throughput as [1]

$$\bar{R} = \frac{\sum_{n=1}^{N} S_n R_n P_n}{\sum_{n=1}^{N} S_n P_n} = \frac{1}{\sum_{n=1}^{N} P_n / R_n} \text{ bps.} \tag{2}$$

This discussion indicates the price paid in throughput for packet delay equalization. Allocation that is less bandwidth unfair can be made if delay guarantees are relaxed for the user with worst link conditions. Note that (2) is the maximum input (symmetric) traffic that the system can sustain for stability of user queues with the round-robin scheduler.

2) Throughput Optimal c-μ Scheduler: Unlike the round-robin scheduler, if scheduling decisions are made based on the channel state (hence rate allocated) and the current queue size, overall system throughput may be increased. The c-μ scheduler identifies a class of optimal scheduling policies that ensure the largest throughput region among all scheduling policies.

An arrival vector $\mathbf{A}$ is said to be stable if there exists a scheduling policy such that [17]

$$\limsup_{t \to \infty} \Pr\{q_k(t) > c\} = 0, \quad \forall c > 0 \tag{3}$$

$\forall k = 1, 2, \cdots, K$, where $q_k(t)$ is the length of the queue, in bits, for user k at the start of timeslot t. If a scheduling policy Θ satisfies (3) then we say that $\mathbf{A}$ is *stable* under Θ. The set of *all* stable arrival vectors is called the *throughput region*, denoted by $\mathcal{A}$. In other words, if $\mathbf{A} \in \mathcal{A}$, then $\exists \Theta_A$ such that $\mathbf{A}$ is *stable* under Θ. The following result establishing the throughput optimality of the c-μ rule is well known [6].

Theorem 1: Consider a scheduling policy that selects a rate vector according to

$$\mathbf{R}(t) = \arg \max_{(r_1, r_2, \cdots, r_K) \in \mathcal{C}(\{\mathbf{H}_k(t)\}_{k=1}^{K})} q_k(t) r_k \tag{4}$$

at every time-slot t. Then, for every $\mathbf{A} \in \mathcal{A}$, (3) is satisfied.

IV. SIMULATION RESULTS

We compute the downlink spectral efficiency for both adaptive and fixed BF schemes. We derive the SNR distribution in the cell using the path-loss model described in [7]. We assume the users are located uniformly over the cell area, with an area coverage of 90%. Note that the resulting size of the cell area is the same for both adaptive and fixed BF schemes.

In Fig. 2 we show the distribution of the downlink spectral efficiency for both adaptive and fixed BF transmission techniques. Numerical evaluation of the average throughput, using (1), for a single isolated cell and channel Model 1 yields the following result. The adaptive switching scheme results in an average throughput increase of approximately 50% over that of the fixed BF. Thus, fixed BF transmission strategy suffers an average throughput loss. Note that the throughput gain of the proposed adaptive technique versus fixed transmission schemes is a function of the channel model.

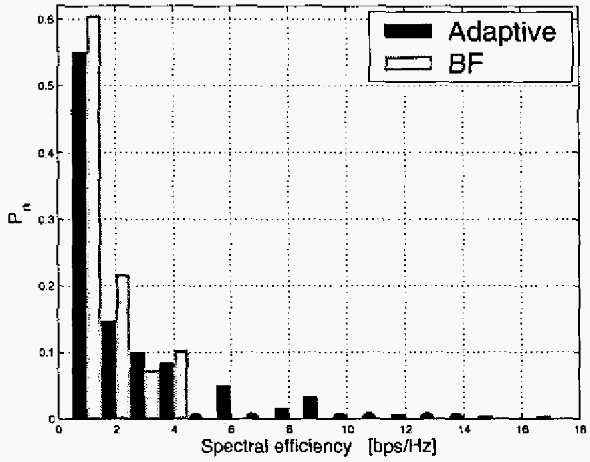

Fig. 2. Distribution of the downlink spectral efficiency for adaptive and fixed BF transmission techniques in channel Model 1.

Averaging the spectral efficiency as above yields one measure of performance benefit. However, we wish to evaluate the performance of the proposed adaptive transmission method in the presence of delay constrained MAC layer scheduling. In Fig. 3 we show the average packet delay versus system throughput for the adaptive and fixed BF transmission methods with round-robin and c-μ scheduling. This plot is derived assuming $K = 50$ users in the system, each with Poisson packet arrivals with exponentially distributed packet lengths and mean 1 Mb. The input traffic workload is uniform across users. Simulations indicate that the round-robin (RR) scheduler, with the adaptive transmission technique implemented at the PHY layer, provides average throughput similar that of the fixed BF scheme with c-μ scheduler, at an average user delay of 1 sec. Moreover, at the same average user delay, the adaptive PHY with c-μ scheduler results in an average throughput increase of 20% over fixed BF with RR scheduler.

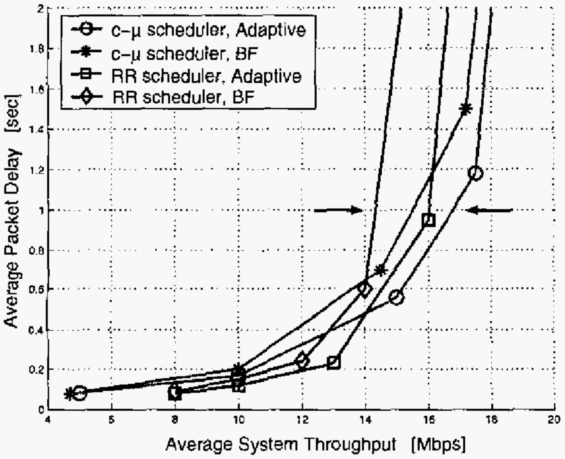

Fig. 3. Average delay versus system throughput for different PHY transmission techniques and MAC schedulers in channel Model 1.

From our simulation results, we make one important observation. The adaptive transmission method with simple round-robin scheduling performs comparably as well as BF with c-μ scheduling. For the adaptive method, since the transmission scheme is decided based on a long-term average of channel quality, clearly the channel feedback requirements are lower than for the c-μ scheduler. Note that the c-μ rule requires a linear search of complexity $O(K)$ every time-slot, compared to the $O(1)$ complexity of the round-robin scheduler. This observation suggests an interesting design tradeoff. System performance may be enhanced at either the MAC layer by exploiting opportunism inherent in diversity of user channel realizations, or at the PHY layer by increasing the spectral efficiency of the air interface design. An efficient system design is one where the PHY and MAC layers are designed to jointly maximize system performance.

V. CONCLUSIONS

In this paper we presented an adaptive transmission strategy for MIMO systems, exploiting the long-term statistics of the channel. We showed that this algorithm combined with a simple round-robin scheduler provides performance similar that to a fixed beamforming transmission scheme with opportunistic scheduler, thereby reducing feedback requirements. We also described the benefits of joint design of PHY and MAC layers in MIMO systems.

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