Improved Round Robin Scheduling for MIMO Cellular Systems

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Abstract—Packet scheduling is investigated for the downlink of a multiple-input multiple-output (MIMO) cellular system. The conventional round robin scheduling (RRS) scheme does not utilize the benefits of multiuser environments, although it provides fair channel access chance to users. We propose an antenna-assisted round robin scheduling (AA-RRS) scheme to improve the conventional RRS scheme. The AA-RRS scheme provides fair channel access chance to users as the RRS scheme, whereas it increases the system capacity through the effective use of multiple antennas in achieving a diversity effect from multiple users. Computer simulations are conducted to compare the RRS and AA-RRS schemes in terms of the expected and outage capacities. It is shown that the AA-RRS scheme provides significant capacity gain over the RRS scheme, especially in terms of the outage capacity. We also discuss the effects of power control, signal-to-noise ratio (SNR), and spatial correlation on the system capacities.

I. INTRODUCTION

Multiple-input multiple-output (MIMO) communication system has received considerable attention as a means for achieving high capacity over wireless links [1]. Various space-time processing techniques have been proposed to approach the theoretical capacity limit of MIMO systems [1]-[3], amongst which is spatial multiplexing architecture [2]. In MIMO systems based on spatial multiplexing, a single data stream is split into multiple parallel substreams, and each of these substreams is transmitted through one of the transmit antennas [2]. There have been intensive research efforts to increase the capacity of spatial multiplexing systems. However, most of the previous works have focused on a single user system, although multiuser scenarios are popular in real systems. In multiuser environments, independence of fading for different users, called as multiuser diversity [4], can be exploited to increase the system capacity.

To benefit from multiuser diversity in cellular packet transmission systems, a packet scheduler should effectively allocate radio resources to users in different channel conditions. Two essential goals of packet scheduling are to maximize the system capacity and to provide fairness among users. Recently, packet scheduling for MIMO cellular systems has been investigated [4], [5]. A channel state dependent scheduling scheme in [4] maximizes the system capacity through the use of multiuser diversity. Specifically, every or each spatial channel is allocated to a user with the best channel condition for each time slot. Therefore, some users in adverse channel conditions may not be served, causing unfairness problem. In [5], the round robin scheduling (RRS) scheme has been studied for MIMO cellular systems. The RRS scheme serves users in a cyclic fashion regardless of channel conditions, and thus achieves fair sharing of channel access chance among users [5]. The RRS scheme, however, cannot take advantage of inherent multiuser diversity, resulting in the same capacity as a single user system.

In this paper, we propose an effective packet scheduling scheme, referred to as antenna-assisted round robin scheduling (AA-RRS) scheme, for the downlink of a MIMO cellular system based on spatial multiplexing. The AA-RRS scheme is an improved RRS scheme that exploits multiple antennas to achieve a diversity effect from multiple users. Active users are initially listed in some fashion, and a group of users are selected from all active users at each time slot. To guarantee equal channel access chance to users as in the RRS scheme, the selection of users is made in a round robin fashion, and each selected user is restricted to use one and only one spatial channel. An appropriate mapping between selected users and spatial channels can achieve a diversity effect from selected users. An exhaustive search is shown to accomplish the mapping that maximizes the system capacity. To reduce the computational requirements of the exhaustive search, we propose a simple mapping scheme that performs close to the exhaustive search. The expected and outage capacities of the RRS and AA-RRS schemes are evaluated by computer simulations, and compared with each other. Simulation results show that the proposed AA-RRS scheme achieves significant capacity gain over the RRS scheme, especially in terms of the outage capacity. We also discuss the effects of long-term power control, signal-to-noise ratio (SNR), and spatial correlation on the system capacities.
II. SYSTEM AND CHANNEL MODELS

We consider the downlink of a single cell MIMO cellular system. As depicted in Fig. 1, the base station is equipped with a uniform linear array with $N_T$ antenna elements, and each user terminal is equipped with a uniform linear array with $N_K (\geq N_T)$ antenna elements. It is assumed that the base station serves a total of $K$ active users in a time division fashion, and that the $K$ users are distributed uniformly over the cell area. At the transmitter, the transmit power is equally divided into transmit antennas, and the receiver of each user estimates transmit symbols destined for the user using a zero-forcing (ZF) or minimum mean square error (MMSE) linear detector. In MIMO systems with these configurations, each transmit antenna creates a spatial channel [4], resulting in total $N_T$ spatial channels for each time slot. The receiver also estimates the post-detection signal-to-interference-plus-noise ratio (SINR) for each transmit antenna, and passes the SINR information to the base station through an uplink feedback channel, as shown in Fig. 1. The packet scheduler at the base station determines which packet to transmit through each transmit antenna.

The transmit signals from the base station are assumed to experience path loss, log-normal shadow fading, and multi-path fading. The channel is assumed to be fixed during a time slot, and to vary independently over time slots. The channel matrix $H_k(t)$ between the base station and the user $k$ for a time slot $t$ may be expressed as

$$H_k(t) = \sqrt{\text{SNR}_0} (r_k / R)^{-\alpha \cdot 10^S_t/10} \cdot G_k(t)$$

where $\text{SNR}_0$ denotes the median SNR at the cell boundary, $r_k$ is the distance between the base station and the user $k$, $\alpha$ is the path loss exponent, and $S_t(t)$ is a real Gaussian random variable with zero mean and variance of $\sigma_r^2$. An $N_K \times N_T$ matrix $G_k(t)$ represents Rayleigh-distributed multipath fading. The user terminals are assumed to be surrounded by sufficient local scatters so that fading at the receive antennas is spatially uncorrelated. However, the fading at the transmit antennas are spatially correlated, and the degree of correlation depends on the antenna spacing and scattering environments around the base station. Assuming that there exist $L$ significant scattering path clusters around the base station, and that all the signal paths experience the same delay, $G_k(t)$ in (1) may be expressed as [6]

$$G_k(t) = G_{w,k}(t) \sum_{l=1}^{L} \rho_l \Phi_{l}$$

where elements of $G_{w,k}(t)$ are independent complex Gaussian random variables with zero mean and unit variance, and $\rho_l$ is the portion of power emanating from the $l$th scattering path cluster with the constraint $\sum_{l=1}^{L} \rho_l = 1$. Under the assumption that the angle of departure for each path cluster is Gaussian distributed, the element of the correlation matrix $\Phi_l$ in the $m$th row and $n$th column is given as [6]

$$[\Phi_l]_{mn} = e^{-j2\pi(m-n)D\cos(\phi_l)/\lambda}, e^{-j2\pi(m-n)D\sin(\phi_l)/\delta}$$

where $D$ is antenna spacing between adjacent antennas, $\lambda$ is the carrier wavelength, and $\phi_l$ and $\delta_l$ are, respectively, the mean angle of departure and angular spread for the $l$th path cluster.

III. PACKET SCHEDULING AND SYSTEM CAPACITY

In this section, we investigate packet scheduling schemes and corresponding system capacities for the MIMO cellular system described in Section II. In Section III-A, we briefly discuss the conventional RRS scheme. In Section III-B, we propose the AA-RRS scheme and describe two mapping schemes between selected users and transmit antennas.

A. Round Robin Scheduling (RRS)

In the conventional RRS scheme [5], one among $K$ active users is selected at each time slot in a round robin fashion, and all the $N_T$ spatial channels or $N_T$ transmit antennas are assigned to the selected user for the time slot. This scheduling scheme provides equal channel access chance to users, since every users use $N_T$ spatial channels every $K$ time slots. When the $k$th user is selected at the time slot $t$, the system capacity $C_{RRS}(t)$ for the given time slot may be expressed as

$$C_{RRS}(t) = \sum_{n=1}^{N_s} \log_2 (1 + \gamma_{k,n}(t))$$

where $\gamma_{k,n}(t)$ denotes the post-detection SINR for the channel corresponding to the $n$th transmit antenna and the $k$th user. The post-detection SINR is defined as the SINR of a transmit symbol after ZF or MMSE nulling, and it may be expressed as [7]

$$\gamma_{k,n}(t) = \frac{P_R \|W_k(t)H_k(t)\|_2^2}{\sigma^2 \sum_{m=1}^{N_s} \|W_k(t)\|_2^2 + P_R \sum_{n=1, n \neq n} \|W_k(t)H_k(t)\|_2^2}$$
where $P_N$ is the total received signal power, and $\sigma_{kn}^2$ is the noise power per receive antenna. The nulling weight matrix \( \mathbf{W}_k(t) \) for the ZF and MMSE cases is given as [7]

\[
\mathbf{W}_k(t) = \begin{cases} 
\mathbf{H}_k^H(t) \mathbf{H}_k^H(t) + \sigma_{kn}^2, & \text{ZF} \\
\mathbf{H}_k^H(t) \mathbf{H}_k^H(t) + \sigma_{kn}^2 \mathbf{I}_{N_k}, & \text{MMSE} 
\end{cases}
\]

(6)

where \( \cdot^H \) denotes the conjugate transpose, and \( \mathbf{I}_{N_k} \) is the \( N_k \times N_k \) identity matrix. It can be seen that the system capacity does not depend on the number of users, and thus the RRS scheme provides the same system capacity as the single user system.

### B. Antenna-Assisted Round Robin Scheduling (AA-RRS)

The RRS scheme does not exploit multiuser diversity at all, although it provides equal channel access chance to users. As discussed in Section II, there are \( N_R \) spatial channels at each time slot in MIMO systems, contrary to single antenna systems. The proposed AA-RRS scheme exploits this multiple spatial channels of MIMO to achieve a diversity effect from multiple users. Specifically, \( K \) active users are initially listed in such a way that each user is identified with a unique user index \( k \) (\( k = 1, 2, \cdots, K \)). At each time slot, \( N_T \) users are selected from \( K \) users, and the selected users form a scheduled user group (SUG) at the time slot. The selection of users for an SUG is made in a round robin fashion. For example, in the case of \( K = 5 \) and \( N_T = 3 \), the SUGs for subsequent time slots are \{1, 2, 3\}, \{4, 5, 1\}, \{2, 3, 4\}, and so forth, where the numbers denote user indices. In the special cases of \( K < N_T \), users are allowed to participate in the SUG more than once in a time slot. Once an SUG is formed, the spatial channels or transmit antennas should be assigned to users in the SUG. To guarantee equal channel access chance as the RRS scheme, we restrict each scheduled user to use one and only one transmit antenna. Consequently, every user can use one spatial channel every \( K/N_T \) time slots, or equivalently \( N_T \) channels every \( K \) time slots, as in the RRS scheme. There are \( N_T! \) possible one-to-one mappings between \( N_T \) scheduled users and \( N_T \) transmit antennas, and an appropriate choice of mapping may realize a diversity effect.

We utilize the post-detection SINR information for determining an effective mapping. The post-detection SINR can be calculated at the receiver, and should be fed back from each user to the base station, as illustrated in Fig. 1. The post-detection SINR information for the users in the SUG at time slot \( t \) may be integrated into a matrix \( \mathbf{Y}(t) \), whose \((k, n)\) element \( y_{kn}(t) \) equals the post-detection SINR for the channel between the \( n \)th transmit antenna and the \( k \)th user in the SUG, as expressed in (5). A mapping between transmit antennas and users may be represented as a sequence \( \{k_1, k_2, \cdots, k_{N_T}\} \), with \( k_n \) denoting the user index assigned to the \( n \)th transmit antenna. For a given sequence of \( k_n \)'s, the system capacity for the time slot \( t \) may be calculated as

\[
C_{AA-RRS}(t|\{k_1, k_2, \cdots, k_{N_T}\}) = \sum_{n=1}^{N_T} \log_2(1 + y_{kn}(t)).
\]

(7)

The sequence of \( k_n \)'s that maximizes the system capacity may be found using an exhaustive search (EXS) over all possible sequences, and the corresponding capacity can be expressed as

\[
C_{AA-RRS,EXS}(t) = \max_{\{k_1, k_2, \cdots, k_{N_T}\}} C_{AA-RRS}(t|\{k_1, k_2, \cdots, k_{N_T}\}).
\]

(8)

Exhaustive search in (8) requires \( N_T! \) computations of (7), and this overhead may be excessively large for large \( N_T \). To reduce computational requirements, we propose a simple heuristic mapping scheme, which is described as follows: 1) Select the largest post-detection SINR value among all the elements of \( \mathbf{Y}(t) \). Assume that \( y_{m,n} \) is the largest one, then set \( k_n \) to the user index corresponding to the \( m \)th row of \( \mathbf{Y}(t) \). 2) Repeat the same operations \((N_T-1)\) more times for a modified \( \mathbf{Y}(t) \), where columns and rows associated with the selected post-detection SINR are deleted. We call this mapping scheme max-delete search (MDS). If \( \{m_1, m_2, \cdots, m_{N_T}\} \) is the resulting mapping sequence of the MDS, the system capacity may be expressed as

\[
C_{AA-RRS,MDS}(t) = C_{AA-RRS}(t|\{m_1, m_2, \cdots, m_{N_T}\}).
\]

(9)

Note that the max-delete search selects the best channel at each stage.

### IV. Simulation Results

In this section, the system capacities for the RRS and AA-RRS schemes described in Section III are evaluated and compared. The capacity for the RRS scheme is calculated from (4) for 20,000 random realizations of the channel matrix in (1). To evaluate (4) for each channel matrix, the weight matrix of the receiver and the corresponding SINR values are computed using (6) and (5), respectively, under the assumption that the MMSE detection is employed. Similarly, the capacity for the AA-RRS scheme is calculated from (8) for the exhaustive search and from (9) for the max-delete search. The expected capacity is defined as the capacity averaged over all possible channel realizations, and the $x \%$ outage capacity is defined such that the probability of the capacity at a time slot being less than the value is $x \%$ [6]. The path loss exponent $\alpha$ and log standard deviation of shadow fading $\sigma_5$ in (1) are assumed to be 3.7 and 8 dB, respectively. In the subsequent results, the channel is assumed to be spatially uncorrelated, i.e., \( \mathbf{G}_t(t) = \mathbf{G}_R(t) \) in (2), unless explicitly specified. We use \( \{N_{R_1}, N_{R_2}\} \) to denote a MIMO system with \( N_R \) transmit antennas and \( N_R \) receive antennas.

Figs. 2 and 3 show the system capacities for (4, 4) and (8, 8) MIMO systems, respectively, when power control is not employed. The transmit power is fixed to give \( SNR_0 = 10 \text{ dB} \).
As predicted, the RRS scheme provides the same capacity independent of the number of users $K$. On the contrary, the capacity for the AA-RRS scheme increases with $K$ until $K$ approaches the number of transmit antennas $N_T$. This is because the AA-RRS scheme achieves a diversity effect from different users in the SUG of each time slot. Since the maximum number of different users in an SUG is $N_T$, more than $N_T$ users do not increase the capacity any more. For the AA-RRS scheme, capacity difference between the exhaustive search and max-delete search is shown to be not significant, which verifies the effectiveness of the max-delete search.

We define the capacity gain of the AA-RRS scheme over the RRS scheme as the ratio of the capacity for the AA-RRS scheme with max-delete search to that for the RRS scheme. For a $(4, 4)$ system in Fig. 2, the gains in the case of $K \geq N_T$ are found to be 1.1 in terms of the expected capacity, 2.9 in terms of the 10% outage capacity, and 5.8 in terms of the 1% outage capacity. For a $(8, 8)$ system in Fig. 3, these capacity gains are 1.2, 3.1, and 6.0, respectively. As expected, the capacity gains are shown to be larger for a $(8, 8)$ system than for a $(4, 4)$ system due to greater multiuser diversity. These results also indicate that improvement of the AA-RRS scheme is more substantial in terms of the outage capacity, especially for a low outage probability, than in terms of the expected capacity. The reason for this is that the AA-RRS scheme allows selecting a mapping between users in different conditions and transmit antennas, and this selection may reduce the low-tail probabilities of post-detection SINR rather than increase the average post-detection SINR. It should be noted that the outage capacity is a more important performance measure than the expected capacity for applications with delay constraint [6].

Fig. 4 shows the system capacities for a $(4, 4)$ MIMO system, when the perfect long-term power control is employed. The long-term power control makes the received signal power constant independently of mobile positions and shadow fading. For comparison with the case of no power control in Fig. 2, we make the average transmit power become the same as the transmit power in the case of no power control. Comparing Figs. 2 and 4, it is found that the long-term power control decreases the expected capacities but increases the outage capacities, for both the RRS and AA-RRS schemes. This implies that a long-term power control is an effective means for reducing the probability of bad channel states that lead to outage situations. Another benefit of long-term power control is a guarantee of fair long-term throughput as well as fair channel access chance. The effects of $SNR_0$ on the system capacities are depicted in Fig. 5, when power control is not employed. For the given $SNR_0$ range, the AA-RRS scheme is shown to provide significant capacity.
Fig. 5. System capacities for a (4, 4) MIMO system for various values of SNR₀ without power control.

The effects of antenna spacing and angular spread at the base station on the expected and 1 % outage capacities are shown in Fig. 6, when the power control is not employed, SNR₀ = 10 dB, and the number of path clusters L is 1 and 2. The mean angle of departure for a path cluster is set to 45° for L = 1, and the angles are set to −60° and 45° for L = 2. For L = 2, two clusters are assumed to emanate the same power (ρ₁ = ρ₂ = 0.5), and the angular spreads of both clusters are set to the same value. When the antenna spacing or angular spread is small, a significant capacity loss is observed for both the RRS and AA-RRS schemes due to high spatial correlation. When the angular spread is 5°, the antenna spacing D should be as large as 5λ for L = 1 and 2λ for L = 2 to achieve the full system capacities. In any cases, however, the AA-RRS scheme is shown to achieve the larger capacities than the RRS scheme.

V. CONCLUSIONS

We have proposed an improved RRS scheme for the downlink of a MIMO cellular system. The proposed AA-RRS scheme provides fair channel access chance to users as the conventional RRS scheme, whereas it increases the system capacity through grouping of users and an effective mapping between the grouped users and transmit antennas. The costs of capacity gain are feedback signaling overhead and selection processing for mappings. Simulation results have shown that the AA-RRS scheme provides significant capacity gain over the RRS scheme.

to decrease the expected capacity but to increase the outage capacities. We have also discussed the effects of SNR, and capacity loss due to spatial correlations.

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