Multiuser MIMO Transmission in Distributed Antenna Systems with Heterogeneous User Traffic

Long Gao, Sudhanshu Gaur and Joydeep Acharya
Wireless Systems Research Lab
Hitachi America, Ltd
Santa Clara, California, 95050, USA
Email: {long.gao, sudhanshu.gaur, joydeep.acharya@hal.hitachi.com}

***Abstract*—In this paper, we consider multiuser transmission in the downlink of a distributed antenna system with two types of users: i) the real-time users that require a minimum instantaneous rate and ii) the best-effort users that try to maximize their rates. We start with a two-user system consisting of one real-time user and one best-effort user, in which the optimal beamforming scheme is proposed to maximize the instantaneous rate of the best-effort user under the rate constraint of the real-time user and per-antenna-power constraint. Two suboptimal transmission schemes are then proposed to reduce the computational complexity and feedback overhead, respectively. Furthermore, we propose a round-robin based scheduler to extend the proposed schemes to a general multiuser system, such that the outage probability of the real-time users is minimized. System-level simulation results show that the proposed schemes have better performance than two reference schemes.**

I. INTRODUCTION

A distributed antenna system (DAS) consists of multiple distributed antennas and a centralized base station (CBS), which performs the baseband processing and coordinates the data transmissions of the multiple antennas. DASs were originally introduced to cover the indoor dead spots of traditional cellular systems [1]. In addition to improving coverage, it has been shown that DASs can increase system capacity by reducing transmit power and thus co-channel interference [2].

In a DAS with a large number of antennas, the antennas are usually grouped into clusters to facilitate data transmissions and reduce signaling overhead. The users are jointly served by the antennas within a cluster, which can be formulated as a distributed multiple-input-multiple-output (MIMO) system [3]. The transmission schemes for a cluster can be roughly divided into two categories, i.e., single-user MIMO (SU-MIMO) schemes [4] [5] and multiuser MIMO (MU-MIMO) schemes [6]-[9], depending on the number of the users being served simultaneously at each time within the cluster. Specifically, for the MU-MIMO transmission, a rate-profile based scheme was proposed in [6] to characterize the achievable rate region under a sum-power constraint. Several zero-forcing (ZF) based schemes were proposed to maximize the sum rate (or weighted sum rate) under a sum-power constraint [7] or per-antenna-power constraint [8]-[9]. However, most existing schemes were proposed for homogeneous user traffic. In practice, the users with heterogenous traffic, e.g., packet-based traffic and circuit-based traffic [10], may coexist in a DAS and share common resource blocks (RBs) such as frequency bands and time slots.

In this paper, we consider multiuser transmission in the DAS downlink with heterogenous user traffic, where we have real-time users that require a minimum instantaneous rate and best-effort users that do not have any rate requirement. To make the problem tractable, we start with a two-user system consisting of one real-time user and one best-effort user, where the optimal beamforming scheme is proposed to maximize the instantaneous rate of the best-effort user under the rate constraint of the real-time user and per-antenna-power constraint (the latter of which is required especially in DASs). Two suboptimal schemes based on ZF beamforming and antenna selection (AS) are then proposed to reduce the computational complexity and feedback overhead, respectively. Furthermore, we propose a round-robin based scheduler to extend the proposed schemes to a general multiuser system, such that the outage probability of the real-time users is minimized. System-level simulation results show that the proposed schemes have better performance than two reference schemes.

The rest of the paper is organized as follows. The model for the two-user system is described in Section II. The optimal beamforming scheme is proposed in Section III. The two suboptimal schemes are described in Section IV. In Section V, we discuss the extension of the proposed schemes to a general multiuser system. Simulation results are provided in Section VI. Finally, Section VII summarizes our conclusions.

II. SYSTEM MODEL

We consider the downlink of a DAS as shown in Fig. 1 with multiple hexagonal cells, each of them has one omni-directional antenna in its center. All antennas are connected to a CBS via wired lines or dedicated wireless links, which performs baseband signal processing and coordinates the data transmissions for users. The cells are grouped into clusters for the ease of management and the reduction of signaling overhead. As an example in Fig. 1, every seven cells are grouped into a cluster and the users in the central cluster experience interference from the cells out of the cluster. For simplicity, we only consider the interference from the first-tier interfering cells (the dark cells as shown in Fig. 1) when modeling the outer cluster interference (OCI).

Users are dropped randomly and uniformly in the network, each of them employs one receive antenna. The users that dropped in a cluster are jointly served by C antennas within the cluster, where C is the cluster size. In the example as shown in Fig. 1, we have $C = 7$. We assume that there are two types of users with different traffic and quality-of-service (QoS) requirements: the real-time users (e.g., voice users) who

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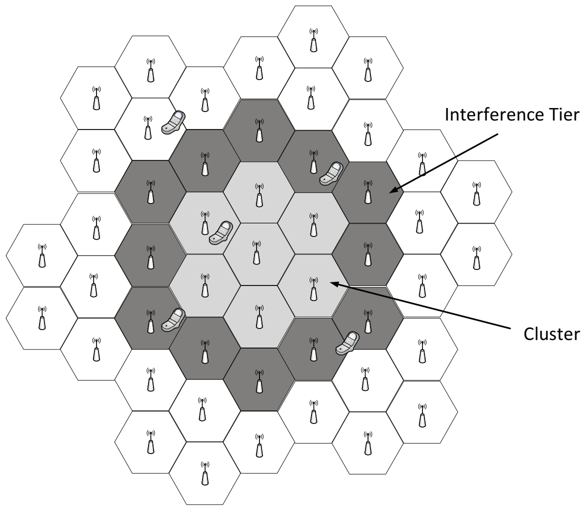

Fig. 1. Illustration of 7-cell clusters in DASs.

have a minimum instantaneous rate requirement at each time slot and the best-effort users (e.g., data users) who just do their best to maximize their own rates. In a particular cluster, the time-frequency resource is divided into small resource blocks (RBs), which are further assigned to the users within the cluster. In traditional systems, each RB is exclusively assigned to one user for SU-MIMO transmission. Given the fact that the real-time users are satisfied as long as their minimum rate requirements are met and any further rate improvement does not increase their satisfaction, we argue that the RBs assigned to the real-time users may not be efficiently used, which could be shared and utilized by the best-effort users. To reduce the signalling overhead and algorithm complexity, a RB assigned to a real-time user could be shared with only one best-effort user. Note that a RB can be shared by different real-time and best-effort user pairs at different time slots, which is controlled by a scheduler as will be discussed in Section V.

Consider a RB shared by a real-time user, denoted as user 1, and a best-effort user, denoted as user 2, at a particular time slot. The received signal of user k, y_k, can be expressed as

$$y_k = \mathbf{h}_k^H \mathbf{x}_k + \mathbf{h}_k^H \mathbf{x}_j + I_k + n_k, \text{ for } j,k = 1,2, \text{ and } j \neq k, \quad (1)$$

where $(\bullet)^H$ denotes the conjugate transpose operation, $\mathbf{h}_k^H$ is $1 \times C$ complex channel matrix between the cluster and user k, $\mathbf{x}_k$ is the transmitted signal for user k, I_k is the OCI, and n_k is the Gaussian noise with zero mean and variance σ^2.

The transmitted signal $\mathbf{x}_k$ for user k is given by

$$\mathbf{x}_k = \mathbf{w}_k s_k, \quad (2)$$

where s_k is the transmitted symbol for user k and $\mathbf{w}_k$ is the beamforming vector for user k. Note that the average power of s_k is assumed to be one.

Our objective is to maximize the instantaneous rate of the best-effort user under the rate constraint of the real-time user, i.e., to solve the following optimization problem,

$$\max \quad \log\left(1 + \frac{|\mathbf{h}_2^H \mathbf{w}_2|^2}{|\mathbf{h}_2^H \mathbf{w}_1|^2 + I_2 + \sigma^2}\right) \quad (3a)$$

$$\text{s.t.} \quad \log\left(1 + \frac{|\mathbf{h}_1^H \mathbf{w}_1|^2}{|\mathbf{h}_1^H \mathbf{w}_2|^2 + I_1 + \sigma^2}\right) \geq R_1 \quad (3b)$$

$$\left(\mathbf{w}_1 \mathbf{w}_1^H + \mathbf{w}_2 \mathbf{w}_2^H\right)_{ii} \leq P, i = 1, \cdots, C, \quad (3c)$$

where $| \bullet |$ denotes the absolute value, $\mathbf{A}_{ii}$ represents the ith diagonal element of matrix $\mathbf{A}$, the design variables are the beamforming vectors $\mathbf{w}_1$ and $\mathbf{w}_2$ for the two users, respectively, R_1 is the minimum rate requirement for user 1, and P is the per-antenna-power constraint. We see that generally speaking, the above optimization problem is not convex problem given the fact that the object function is not concave. In the next section, we will solve this problem by transforming it into a sequential convex optimization problem.

We want to point out that for given $\mathbf{h}_1$ and R_1, there may be no feasible $\mathbf{w}_1$ for the constraint (3b) even if we set $\mathbf{w}_2$ to be a all-zero vector. We call this as an *outage event*. The outage probability of the real-time users will be discussed in Section V and evaluated in Section VI.

III. Optimal beamforming Scheme

In this section, we present the optimal solution to optimization problem (3) formulated in Section II. Problem (3) is equivalent to the following problem by introducing a new design variable R_2.

$$\max \quad R_2 \quad (4a)$$

$$\text{s.t.} \quad \log\left(1 + \frac{|\mathbf{h}_2^H \mathbf{w}_2|^2}{|\mathbf{h}_2^H \mathbf{w}_1|^2 + I_2 + \sigma^2}\right) \geq R_2 \quad (4b)$$

$$\log\left(1 + \frac{|\mathbf{h}_1^H \mathbf{w}_1|^2}{|\mathbf{h}_1^H \mathbf{w}_2|^2 + I_1 + \sigma^2}\right) \geq R_1 \quad (4c)$$

$$\left(\mathbf{w}_1 \mathbf{w}_1^H + \mathbf{w}_2 \mathbf{w}_2^H\right)_{ii} \leq P, i = 1, \cdots, C. \quad (4d)$$

As such, the object function becomes linear. However, optimization problem (4) is still not a convex problem due to the non-convexity of the first two constraints. In the following, we show that problem (4) can be solved by solving a sequence of feasibility problems with a fixed R_2, which are given by

$$\text{Find} \quad \mathbf{w}_1, \mathbf{w}_2 \quad (5a)$$

$$\text{s.t.} \quad \log\left(1 + \frac{|\mathbf{h}_1^H \mathbf{w}_1|^2}{|\mathbf{h}_1^H \mathbf{w}_2|^2 + I_1 + \sigma^2}\right) \geq R_1 \quad (5b)$$

$$\log\left(1 + \frac{|\mathbf{h}_2^H \mathbf{w}_2|^2}{|\mathbf{h}_2^H \mathbf{w}_1|^2 + I_2 + \sigma^2}\right) \geq R_2 \quad (5c)$$

$$\left(\mathbf{w}_1 \mathbf{w}_1^H + \mathbf{w}_2 \mathbf{w}_2^H\right)_{ii} \leq P, i = 1, \cdots, C. \quad (5d)$$

Let $\mathbf{w}_1^*$, $\mathbf{w}_2^*$, and R_2^* denote the optimal solution to the problem (4). If problem (5) is feasible for a given R_2, it means that $R_2^* > R_2$; if infeasible, then $R_2^* < R_2$. Thus, by solving feasibility problem (5) with different R_2's and applying the simple bisection method [12] over R_2, $\mathbf{w}_1^*$, $\mathbf{w}_2^*$, and R_2^* can be obtained for problem (4), where $\mathbf{w}_1$ and $\mathbf{w}_2$ are also the optimal solution to the original problem (3).

Unfortunately, it is difficult to solve the feasibility problem (5) due to the non-convexity of (5b) and (5c). However, problem (5) can be transformed into the following equivalent problem, in which $\mathbf{w}_1$ and $\mathbf{w}_2$ are rotated such that $\mathbf{h}_1^H\mathbf{w}_1$ and $\mathbf{h}_2^H\mathbf{w}_2$ are non-negative real numbers [11], i.e.,

$$
\begin{aligned}
\text{Find} \quad & \mathbf{w}_1, \mathbf{w}_2 && \text{(6a)}\\
\text{s.t.} \quad & (2^{R_1}-1)(|\mathbf{h}_1^H\mathbf{w}_2|^2 + I_1 + \sigma^2) \le (\mathbf{h}_1^H\mathbf{w}_1)^2, && \text{(6b)}\\
& (2^{R_2}-1)(|\mathbf{h}_2^H\mathbf{w}_1|^2 + I_2 + \sigma^2) \le (\mathbf{h}_2^H\mathbf{w}_2)^2, && \text{(6c)}\\
& \mathbf{h}_i^H\mathbf{w}_i \ge 0, \quad i = 1, 2, && \text{(6d)}\\
& \left(\mathbf{w}_1\mathbf{w}_1^H + \mathbf{w}_2\mathbf{w}_2^H\right)_{ii} \le P, i = 1, \cdots, C, && \text{(6e)}
\end{aligned}
$$

The reasons why problems (5) and (6) are equivalent are the following: If $(\mathbf{w}_1^*, \mathbf{w}_2^*)$ a feasible solution for problem (6), it will automatically satisfy (5b)-(5d). Conversely, if $(\mathbf{w}_1^*, \mathbf{w}_2^*)$ is a feasible solution for problem (5), the solution $(\mathbf{w}_1^* e^{j\phi_1}, \mathbf{w}_2^* e^{j\phi_2})$ is also feasible for problem (5) and (ϕ_1, ϕ_2) can be chosen such that (6b)-(6e) are satisfied. Note that (6d) - (6e) are convex constraints while (6b) and (6c) are not. By introducing two new variables z_1 and z_2, we can transform problem (6) into the following problem, where (7b) - (7e) are equivalent to (6b) and (6c) in problem (6).

$$
\begin{aligned}
\text{Find} \quad & \mathbf{w}_1, \mathbf{w}_2 && \text{(7a)}\\
\text{s.t.} \quad & \mathbf{h}_i^H\mathbf{w}_i = z_i, \quad i = 1, 2, && \text{(7b)}\\
& \sqrt{(2^{R_i}-1)}||\mathbf{A}_i\mathbf{w}_i + \sqrt{(I_i+\sigma^2)}\mathbf{b}_i|| \le z_i, \quad i = 1, 2, && \text{(7c)}\\
& z_i \ge 0, \quad i = 1, 2, && \text{(7d)}\\
& \left(\mathbf{w}_1\mathbf{w}_1^H + \mathbf{w}_2\mathbf{w}_2^H\right)_{ii} \le P, i = 1, \cdots, C, && \text{(7e)}
\end{aligned}
$$

where $|| \bullet ||$ denotes the norm of a vector, $\mathbf{A}_i$ is chosen such that $\mathbf{A}_i^H\mathbf{A}_i = \mathbf{h}_i\mathbf{h}_i^H$, and $\mathbf{b}_i$ is a null vector of $\mathbf{A}_i^H$. Obviously, (7b) - (7e) are convex constraints and thus problem (7) is a convex problem, which can be easily solved by some existing optimization algorithms such as interior-point method [12]. As such, we can perform bisectional search over R_2 and thus problem (3) can be solved.

IV. Suboptimal Beamforming Schemes

As we can see from Section III, the optimal solution for the original problem (3) can be obtained by solving a sequence of convex optimization problems, which requires high computational complexity. In this section, we propose a suboptimal solution based on ZF beamforming to reduce the complexity. In addition, in order to run the optimal scheme for a particularly user pair, the CBS has to know the channel vectors of the two users, which incurs a high feedback overhead especially in FDD systems. In order to reduce the feedback overhead, we propose a suboptimal scheme based on antenna selection (AS), in which each user only feedbacks the channel gain for its closest antenna (i.e., the one with the highest received signal strength). In the following, we first describe the proposed ZF scheme and then present the proposed AS scheme.

A. Zero-forcing beamforming scheme

Problem (3) can be simplified to the following problem by adding two ZF constraints given in (8c) and (8d).

$$
\begin{aligned}
\max \quad & \log\left(1 + \frac{|\mathbf{h}_2^H\mathbf{w}_2|^2}{I_2+\sigma^2}\right) && \text{(8a)}\\
\text{s.t.} \quad & \log\left(1 + \frac{|\mathbf{h}_1^H\mathbf{w}_1|^2}{I_1+\sigma^2}\right) \ge R_1, && \text{(8b)}\\
& \mathbf{h}_1^H\mathbf{w}_2 = 0, && \text{(8c)}\\
& \mathbf{h}_2^H\mathbf{w}_1 = 0, && \text{(8d)}\\
& \left(\mathbf{w}_1\mathbf{w}_1^H + \mathbf{w}_2\mathbf{w}_2^H\right)_{ii} \le P, i = 1, \cdots, C, && \text{(8e)}
\end{aligned}
$$

where we see that the ZF constraints simplify the interference terms in (8a) and (8b). Unfortunately, problem (8) is still not convex. With the similar transformation as from problem (5) to problem (7), we transform problem (8) into the following problem by introducing a new variable z_1

$$
\begin{aligned}
\max \quad & \mathbf{h}_2^H\mathbf{w}_2 && \text{(9a)}\\
\text{s.t.} \quad & \mathbf{h}_1^H\mathbf{w}_1 = z_1 && \text{(9b)}\\
& z_1 \ge \sqrt{(2^{R_1}-1)(I_1+\sigma^2)}, && \text{(9c)}\\
& \mathbf{h}_1^H\mathbf{w}_2 = 0, && \text{(9d)}\\
& \mathbf{h}_2^H\mathbf{w}_1 = 0, && \text{(9e)}\\
& z_1 \ge 0, && \text{(9f)}\\
& \left(\mathbf{w}_1\mathbf{w}_1^H + \mathbf{w}_2\mathbf{w}_2^H\right)_{ii} \le P, i = 1, \cdots, C. && \text{(9g)}
\end{aligned}
$$

The above problem is a convex optimization problem, which can be easily solved. Compared with the optimal beamforming scheme in Section III, the proposed ZF beamforming scheme only needs to solve one convex optimization problem and thus significantly reduces the computational complexity.

B. Antenna-selection scheme

In the proposed AS scheme, each user only receives packets from its closest antenna. One advantage of the AS scheme is the feedback overhead reduction since each user only feeds back the channel gain for its closed antenna. Generally speaking, the amount of the CSI feedback in the AS scheme is $1/C$ times less than that in the beamforming schemes, where C is the cluster size.

Similar as the original problem (3) formulated for the beamforming transmission, the optimization problem for the AS transmission when two users (i.e., one real-time user and one best-effort user) drop in different cells (but still in the same cluster) is given by

$$
\begin{aligned}
\max \quad & \log\left(1 + \frac{|h_2 w_2|^2}{|h_2 w_1|^2 + I_2 + \sigma^2}\right) && \text{(10a)}\\
\text{s.t.} \quad & \log\left(1 + \frac{|h_1 w_1|^2}{|h_1 w_2|^2 + I_1 + \sigma^2}\right) \ge R_1 && \text{(10b)}\\
& |w_i|^2 \le P, \quad i = 1, 2, && \text{(10c)}
\end{aligned}
$$

where h_k is the channel between user k and its closest antenna, w_k is the transmit signal power and phase control parameter for user k, and P is the per-antenna power constraint. In the case where the two users drop in the same cell, the optimization problem is given by

$$\max \quad \log\left(1+\frac{|h_2 w_2|^2}{|h_2 w_1|^2+I_2+\sigma^2}\right) \tag{11a}$$

$$\text{s.t.} \quad \log\left(1+\frac{|h_1 w_1|^2}{|h_1 w_2|^2+I_1+\sigma^2}\right) \geq R_1 \tag{11b}$$

$$|w_1|^2+|w_2|^2 \leq P. \tag{11c}$$

We see that optimization problems (10) and (11) are the scaler versions of problem (3), which can be solved by a similar sequential optimization scheme as described in Section III.

V. General Multiuser Case

So far, we only consider the two-user case where a RB is shared by a real-time user and a best-effort user. In general multiuser case where there are multiple RBs available for multiple users in a cluster, a scheduler is required to assign the available RBs to different users such that the outage probability of the real-time users is minimized and the sum rate of the best-effort users is maximized[1]. However, the optimal scheduler requires performing exhaustive search over all possible user and RB combinations, which cannot be implemented in practical systems due to its high complexity. In this section, we propose a round-robin based scheduler with relatively low complexity, which can minimize the outage probability of the real-time users and achieve a reasonable sum rate of the best-effort users.

Let K_1, K_2, and K denote the numbers of the real-time users, the best-effort users, and all users in a cluster, respectively, where $K = K_1 + K_2$. We assume that there are N available RBs for the cluster at a particular time slot. Since upcoming cellular networks are mostly data based, we assume that $N \geq K_1$ and $N < K_2$. The proposed scheduler assigns the N RBs to the K users in two stages, which is explained as follows.

Stage 1: We give top priority to the real-time users and want to minimize their outage. In this stage, we perform exhaustive search over all possible pairs of RBs and real-time users by running (5) with $R_2 = 0$ in order to find the optimal combination. This stage has the complexity of $O\left(\binom{N}{K_1}K_1!\right)$, where $O(\cdot)$ denotes the order. Since the number of real-time users, K_1, is assumed to be low, the complexity of this step is not high. Note that since the total number of outage events at each time slot is minimized, the outage probability of the real-time users over all time slots is thus minimized.

Stage 2: Schedule N best-effort users according to round-robin order and then randomly assign one RB to each scheduled best-effort user. The complexity of this stage is of $O(1)$, which is negligible compared to that of the first stage.

We can see that the proposed scheduler, which has the complexity of $O\left(\binom{N}{K_1}K_1!\right)$, can reduce the scheduling complexity by a factor of K_2^N compared to the optimal scheduler, which has the complexity of $O\left(\binom{N}{K_1}K_1!K_2^N\right)$. After the scheduling process, if a RB is assigned to a real-time user and a best-effort user simultaneously, the proposed schemes in Sections III and IV can be utilized. Otherwise, the proposed scheme in [4] can be used to maximize the instantaneous rate of the best-effort user.

[1]We assume that a best-effort user could either share a RB with a real-time user or use the RB exclusively, since how to maximize the sum rate of multiple best-effort users sharing the same RB is still an open problem.

VI. Simulation Results

In this section, we evaluate the performance of the proposed schemes in terms of the outage probability for the real-time users and the sum rate for the best-effort users. We consider a DAS as shown in Fig. 1, where the $C = 7$. We assume that there are 10 users (which includes 3 real-time users and 7 best-effort users) uniformly distributed within each cluster and 5 RBs available for each cluster at each time slot.

In the simulation, the inter-site distance of the DAS is 50m. For the channel model, we use the path loss model for indoor hotspots in [13] and we assume complex Gaussian distribution with zero mean and unity variance for the small-scale fading. For the interference model, we only take one-tier interfering cells into account when calculating the interference from the neighboring clusters for a user, which is the same as in [2]. Two reference schemes are also evaluated for comparison purpose, which use the same scheduler proposed in this paper (such that they have the same outage probability for the real-time users) but the following different transmission schemes for the RBs assigned to two users (i.e., one real-time user and one best-effort user).

Reference Scheme 1: In the case where one real-time user and one best-effort user share the same RB, the cluster uses the optimal SU-MIMO beamforming vector given by [4] for both users, with a appropriate power allocation between the two users to guarantee the rate requirement of the real-time user.

Reference Scheme 2: In the case where one real-time user and one best-effort user share the same RB, the cluster uses the optimal SU-MIMO beamforming vector given by [4] for the real-time user and does not transmit any data for the best-effort user, i.e., this scheme is actually a SU-MIMO transmission scheme.

In Fig. 2, we plot the outage probability of the real-time users with the proposed scheduler for different values of transmit SNRs. The transmit SNRs are chosen such that the received SNR at the cell users are roughly in the range from -10 dB to 20dB. We see that for a given transmit SNR, the outage probability increases with a larger value of R_1. Furthermore, for each value of R_1, the outage probability decreases with a growing SNR and finally achieves a certain "floor" value, which means increasing transmit power cannot reduce the outage probability in the high SNR regime (i.e., the interference limit regime). The reason is that the SINRs for the cluster-edge users do not increase with a higher transmit power in this regime since the OCI also increases at the same time.

In Fig. 3, we plot the sum rates of the best-effort users in different schemes over different values of transmit SNRs, where $R_1 = 2$ bits/s/Hz. The transmit SNRs are chosen such that the received SNR at the cell users are roughly in the range from -10 dB to 10 dB, which is the normal operation range for the receivers. We see that all MU-MIMO schemes have better

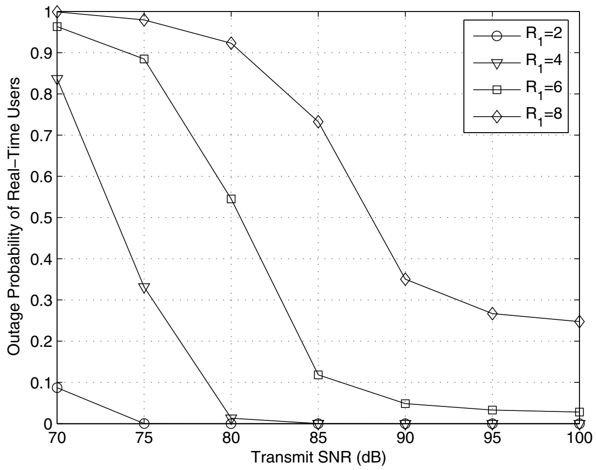

Fig. 2. Outage probability for the real-time users.

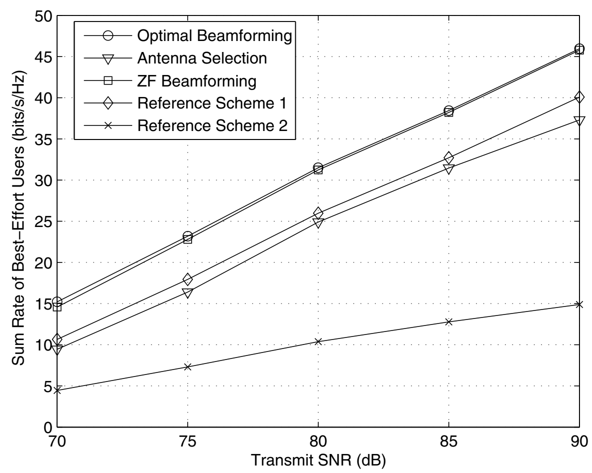

Fig. 3. Sum rate for the best-effort users with $R_1 = 2$ bits/s/Hz.

performance than *reference scheme 2* (i.e., the SU-MIMO scheme). The proposed optimal beamforming and ZF schemes have better performance than that of *reference scheme 1*. Furthermore, the performance gap between the optimal scheme and the ZF scheme is negligible for all SNR values. This is because the number of antennas in a cluster (C=7) is much larger than that of the co-scheduled users (only 2) for a RB, such that there is enough degree of freedom for the transmitter to mitigate the intra-cluster interference with the ZF beamforming scheme.

In Fig. 4, we plot the sum rates of the best-effort users in different schemes over different values of transmit SNRs, where $R_1 = 8$ bits/s/Hz. We see that all schemes achieve less sum rate compared to the case with $R_1 = 2$. The performance gap between the optimal scheme and the ZF scheme is still negligible. Furthermore, these two beamforming schemes outperform *reference scheme 1* in the high SNR regime.

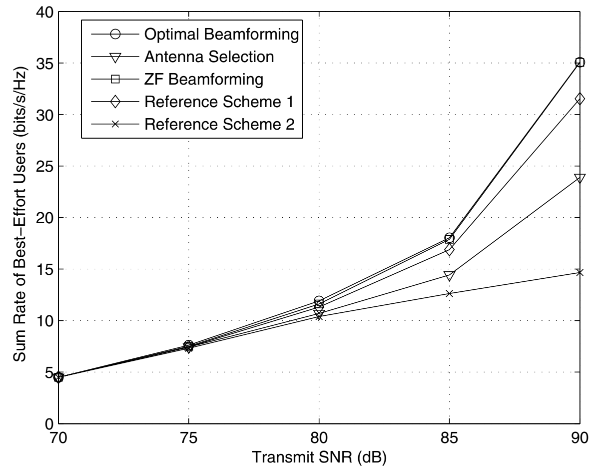

Fig. 4. Sum rate for the best-effort users with $R_1 = 8$ bits/s/Hz.

VII. Conclusion

We proposed several multiuser MIMO transmission schemes for the downlink of a DAS with heterogenous user traffic. Some practical constraints such as implementation complexity and feedback overhead were considered in this paper. From the simulation results, we see that the proposed ZF scheme has low complexity and near-optimal performance especially for a DAS with large cluster size, which could be a good candidate in such a heterogenous scenario.

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