Transmit Diversity Techniques for Multicasting over Wireless Networks

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Abstract— **Transmit diversity (TD) is one of the key technologies to achieve high data rate communications in wireless fading environments. While transmit diversity techniques have been extensively studied for point-to-point communications, their applications in wireless multicast scenario have not been fully exploited. In this paper, we first design an adaptive transmit antenna array for multicasting, with the assumption of perfect channel information at the transmitter and the performance criteria as maximizing the worst signal-to-noise ratio (SNR) among all receivers. Compared with the existing beamforming scheme that aims to maximize the average SNR, a performance gain in decoding bit error rate is obtained. Then, the proposed close-loop scheme is compared with space-time block coding that does not require feedback of channel information. When the number of multicast receivers is below a certain threshold, the proposed close-loop scheme outperforms the space-time codes. When the multicast group size is large, the space-time codes have better performance. Finally, jointly considering close loop and open loop techniques based on group size and availability of channel information feedback is suggested.**

I. Introduction

Multicast is known for its efficiency in supporting group-oriented applications, such as video conferencing and communal gaming. In the wireline Internet environment, multicast communications have been supported for more than ten years. With the widespread deployment of wireless networks, supporting multicast over wireless networks is recently attracting increasing interests [1] [2].

Wireless multicast will support a variety of applications such as group-oriented mobile commerce, distance education, and military command and control systems [1]. These applications often require reliable, continuous and secure connections, which are more difficult to achieve in wireless networks with mobile users than in conventional wireline environments [1]. For wireless multicast, reliability is the fundamental challenge that often serves as a prerequisite for achieving security and continuity in large-scale group communications.

Although a variety of schemes have been proposed for reliable multicast [3]–[6], the studies on physical layer techniques for multicasting is still limited. Previously, the broadcast nature of the wireless media, which enables efficient implementation of multicast, has been utilized in establishing multicast routing trees in ad-hoc networks [7] and improving power control strategies in cellular networks [8]. However, one important physical layer technique, *transmit diversity* (TD), which could significantly improve link quality in wireless fading channel, has not been fully exploited for multicasting.

Transmit diversity techniques can be categorized into *open loop* and *close loop* techniques [9]. The open loop methods are predetermined forms of diversity and do not rely on channel environment information. An important class of open loop methods is space-time coding (STC) [10] [11], where data is split into M streams that are simultaneously transmitted using M transmit antennas. The close loop methods require the transmitter to obtain downlink channel information from mobile stations via feedback signaling [9]. A typical close loop method is to assign a weight vector to the transmit antenna array such that receivers' signal-to-noise ratio (SNR) is optimized [12] [13].

In this paper, we will investigate both open loop and close loop TD techniques for improving the reliability of wireless multicast. An existing close loop method, presented in [12], calculates the weight vector that optimizes the SNR averaged over all receivers. This method, however, can result in uneven performance among the receivers, especially when they are at different distances from the transmitter. In many practical systems, it is often required that the quality of service of each user is above certain threshold. Therefore, we propose to design the adaptive transmit antenna array that aims to optimize the worst-case SNR. Compared with the methods in [12], a gain in decoding bit error rate (BER) is obtained even when all users have similar channel statistics.

Then, the proposed close loop method is compared with the space-time block codes [11] [14], whose design is the same for both multicast and unicast. It is interesting to observe that the STC can have better performance than the proposed close loop method when the number of multicast receivers exceeds a certain threshold. Recall that whether or not using open loop methods in *unicast* communications mainly depends on availability or accuracy of channel information at the transmitter [9] [15]. A new factor, the group size, is brought into the picture for *multicasting* in this paper. In addition, jointly utilizing STC and adaptive transmit antenna array is suggested.

The rest of the paper is organized as follows. Section II describes the basic modeling assumptions for the channel and the signal. Section III presents the adaptive transmit antenna array for multicasting and illustrates its performance through simulations. In Section IV, the proposed method is compared with space time block codes for various group size and channel conditions, followed by a preliminary discussion on jointly using the close loop and the open loop methods in Section V.

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Finally, conclusion is drawn in Section VI.

II. System Description

In this paper, we investigate a narrowband multicast system with one transmitter and N receivers. The transmitter is equipped with an M-element antenna array and each receiver is equipped with one antenna.

Let X_j denote the complex baseband signal transmitted by the j^{th} transmit antenna, and Y_i denote the received signal at the i^{th} receiver, where $j = 1, 2, \cdots, M$ and $i = 1, 2, \cdots, N$. The wireless channel is modeled as flat Rayleigh fading channel [16]. Thus, the received signal is represented as:

$$Y_i = \sum_{j=1}^{M} \alpha_{j,i} X_j + V_i, \qquad (1)$$

where $\alpha_{j,i}$ denotes the channel gain between the j^{th} transmit antenna and the i^{th} receiver, and V_i describes noise and cochannel interference at the i^{th} receiver. In Rayleigh fading, $\alpha_{j,i}$ are modeled as zero-mean circular symmetric complex Gaussian random variables [16]. In this work, we assume that the transmit antennas and the receivers are sufficiently spatially separated such that $\alpha_{j,i}$ are all mutually independent. In addition, $\{\alpha_{j,i}, j = 1, \cdots, M\}$ have the common variance, denoted by σ_i^2. Finally, V_i are modeled as circular symmetric white Gaussian noise with zero mean and variance N_0.

For the future convenience, we use matrix representation for the transmitted signal, the received signal, the noise and the channel parameters as:

$$\begin{aligned}
\mathbf{X} &= [X_1, X_2, \cdots, X_M]^T, \\
\mathbf{Y} &= [Y_1, Y_2, \cdots, Y_N]^T, \\
\alpha_{\mathbf{i}} &= [\alpha_{1,i}, \alpha_{2,i}, \cdots, \alpha_{M,i}]^T, i = 1, \cdots, N, \\
\mathbf{A} &= [\alpha_{\mathbf{1}}\ \alpha_{\mathbf{2}}\ \cdots\ \alpha_{\mathbf{N}}] \\
\mathbf{V} &= [V_1, V_2, \cdots, V_N]^T.
\end{aligned}$$

Thus, the signal model in (1) is equivalent to:

$$\mathbf{Y} = \mathbf{AX} + \mathbf{V} \qquad (2)$$

In the multicast scenario, a common signal, denoted by s, is transmitted to all receivers. When the channel information is known at the transmitter, TD can be achieved by assigning a weight vector to the transmit antenna array. In this case, let $\mathbf{w} = [w_1, w_2, \cdots, w_M]$ denote the array weight vector. Then the transmitted signal becomes $\mathbf{X} = \mathbf{w}s$. The signal-to-noise ratio of the i^{th} receiver, denoted by SNR_i, is

$$SNR_i = \left| \sum_{j=1}^{M} \alpha_{j,i} X_j \right|^2 / N_0 = \frac{|s|^2}{N_0} \mathbf{w} \alpha_{\mathbf{i}} {\alpha_{\mathbf{i}}}^H \mathbf{w}^H. \qquad (3)$$

In addition, the array weight vector is normalized as $\sum_{j=1}^{M} |w_i|^2 = 1$. The variance of the channel parameters, σ_i^2, depend on propagation loss of the wireless transmission and power gain of the antennas [17]. In this work, we assume that σ_i^2 is proportional to $1/d_i^4$, where d_i is the distance between the transmitter and the i^{th} receiver.

III. Adaptive Transmit Antenna array for multicasting

In slow fading environments, the transmitter can obtain the channel information from the receivers through feedback. In this section, we assume that the transmitter has the perfect knowledge of the channel parameter matrix A, and design the adaptive transmit antenna array for multicasting.

A. Design of adaptive transmit antenna array

For multicast communications, the close loop method in [12] designed the transmit antenna array that maximizes the SNR averaged over all receivers. The problem formulation is:

$$\max_{\mathbf{w} \in \mathbb{C}^M} \frac{\mathbf{w}\mathbf{A}\mathbf{A}^H \mathbf{w}^H}{N_0} \quad \text{subject to:} \sum_{j=1}^{M} |w_i|^2 = 1 \qquad (4)$$

It has been shown that the optimal weight vector that solves (4) is the normalized principle eigenvector of $\mathbf{AA}^H$.

Maximizing the average SNR, however, may cause uneven performance among receivers. Particularly, the solution of (4) tends to improve the SNR of the users that are close to the transmitter by sacrificing the performance of the users that are far away from the transmitter. In practice, optimizing the worst-case SNR is of most interest. Therefore, we formulate the optimization problem as:

$$\max_{\mathbf{w} \in \mathbb{C}^M} \min_{i \in \{1,2,\cdots,M\}} SNR_i \quad \text{subject to:} \sum_{j=1}^{M} |w_i|^2 = 1 \ , \qquad (5)$$

where SNR_i is calculated in (3). This minimax type optimization problem is equivalent to

$$\max_{\mathbf{w} \in \mathbb{C}^M, z \in \mathbb{R}} z \qquad (6)$$

$$\text{subject to:} \qquad z \le SNR_i \ , \quad i = 1, 2, \cdots, N \qquad (7)$$

$$\sum_{j=1}^{M} |w_i|^2 = 1 \qquad (8)$$

The $M+1$ variables in this new formulation is represented by $\mathbf{x} = (\mathbf{w} \in \mathbb{C}^M, z \in \mathbb{R})$. Let $f(\mathbf{x}) = -z$, $g_i(\mathbf{x}) = z - SNR_i$, and $h(\mathbf{x}) = \sum_{j=1}^{M} |w_i|^2 - 1$. The Karush-Kuhn-Tucker (KKT) necessary condition [18] for optimality at a feasible point $\mathbf{x}$ is:

$$\nabla f(\mathbf{x}) + \sum_{i=1}^{N} u_i \nabla g_i(\mathbf{x}) + v \nabla h(\mathbf{x}) = 0 \qquad (9)$$

$$u_i g_i(\mathbf{x}) = 0 \qquad (10)$$

$$u_i \ge 0, \text{ for } i = 1, 2, \cdots, N, \qquad (11)$$

where u_i and v are real numbers and often called as Lagrangian multipliers. We define an $N \times N$ matrix as $\mathbf{\Sigma} = diag([u_1, u_2, \cdots, u_N])$. From equation (9), we can derive:

$$\sum_{i=1}^{N} u_i = 1, \qquad (12)$$

$$\mathbf{A \Sigma A}^H \mathbf{w}^H = v \mathbf{w}^H. \qquad (13)$$

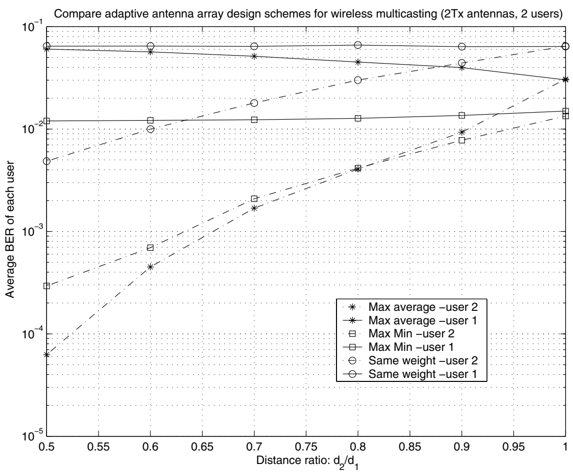

Fig. 1. Receivers' BER in different array design methods

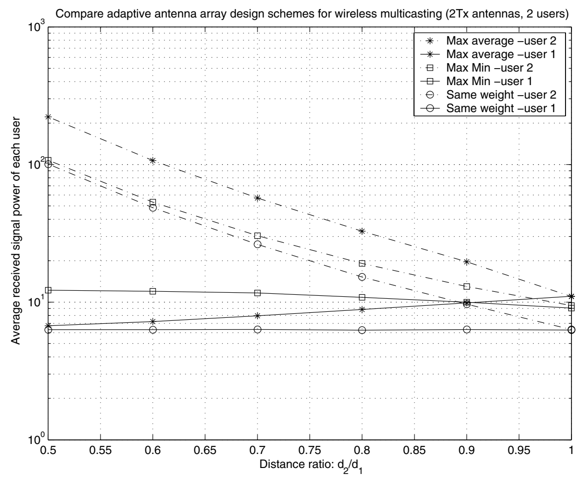

Fig. 2. Received signal power in different array design methods

In addition, the matrix representation of equation (10) is:

$$\mathbf{\Sigma A}^H\mathbf{w}^H = \sqrt{z}\mathbf{\Sigma e}, \quad (14)$$

where $\mathbf{e}$ is an N by 1 vector and every element of $\mathbf{e}$ has magnitude 1. That is, $\mathbf{e}$ can be expressed as $\mathbf{e} = [e^{j\theta_1}, e^{j\theta_2}, \cdots, e^{j\theta_N}]^T$.

From (13) and (14), we obtain:

$$\mathbf{w}^H = \frac{\sqrt{z}}{v}\mathbf{A\Sigma e} = \frac{\sqrt{z}}{v}[\alpha_\mathbf{1}\alpha_\mathbf{2}\cdots\alpha_\mathbf{L}]\begin{bmatrix} u_1e^{j\theta_1} \\ u_2e^{j\theta_2} \\ \vdots \\ u_Le^{j\theta_L}\end{bmatrix}. \quad (15)$$

Therefore, the optimal weight vector that maximizes the worst SNR should be a linear combination of users' channel parameter vectors, $\{\alpha_\mathbf{i}\}_{i=1,2,\cdots,N}$. In particular, the optimal $\mathbf{w}^H$ can be expressed as:

$$\mathbf{w}^H = \sum_{i=1}^{N} l_i\alpha_\mathbf{i}, \quad (16)$$

where $\{l_i, i = 1, \cdots, N\}$ are complex coefficients and can be written in a vector format as $\mathbf{l} = [l_1, l_2, \cdots, l_N]^T$. As a special case of multicasting, the optimal weight vector for unicast (i.e. $N = 1$) is $\frac{\alpha_1^H}{||\alpha_1||}$, which agrees with the results in previous work [12].

When the number of users is smaller than the number of transmit antennas, i.e. $N < M$, we convert the optimization problem in (5) to:

$$\max_{\mathbf{l}\in\mathbb{C}^N}\ \min_{i\in\{1,2,\cdots,M\}} SNR_i \text{ subject to: } \mathbf{l}^H\mathbf{A}^H\mathbf{A}\mathbf{l} = 1, \quad (17)$$

where SNR_i is calculated as:

$$SNR_i = \mathbf{l}^H\mathbf{A}^H\alpha_\mathbf{i}\alpha_\mathbf{i}{}^H\mathbf{A}\mathbf{l}. \quad (18)$$

To reduce the dimension of the searching space, we use the problem formulation in (5) when $N \geq M$ and the problem formulation in (17) when $N < M$. By doing so, the minimax problem is also kept regular [19], that is, the number of variables is always smaller or equal to the number of constraints in (7). Since the close form solutions of these minimax type problems are highly untraceable, we solve them using the sequential quadratic programming (SQP) method presented in [19].

B. Comparison of array design methods

We first investigate the simplest scenario where there are two transmit antennas and two receivers, i.e. $M = N = 2$. Without loss generality, we assume that user 2 is located closer to the transmitter than user 1 does, i.e. $d_1 \geq d_2$, where d_i denotes the distance between the transmitter and the i^{th} user. As suggested in Section II, we assume that $\sigma_1^2/\sigma_2^2 = d_2^4/d_1^4$, which follows the propagation model in [17].

Three design methods are compared in this special scenario through simulations. These methods are (1) maximizing the average SNR as suggested in [12]; (2) maximizing the minimum SNR as proposed in Section III; and (3) assigning the same weight for all antennas, i.e. $w_i = 1/\sqrt{M}$.

In the simulations, we always put the furthest user at distance 1 ($d_1 = 1$), and choose the variance of the channel parameters of the furthest user to be 1 ($\sigma_1^2 = 1$). The modulation constellation is 4-QAM. The channel parameters are assumed to be constant within a frame and change independently in different frames. The length of each frame is 128 symbols.

Figure 1 shows the decoding bit error rate (BER) for different values of d_2, while the transmission SNR is maintained to be 10dB. Compared with user 1, user 2 has lower or equal BER because $d_2 \leq d_1$. When user 2 moves closer to the transmitter, it is seen that the BER of user 2 is greatly reduced. At the same time, the BER of user 1, who is always located at the same distance, can also be affected by user 2's location. In particular,

- When the antenna array is designed to maximize the average SNR, the BER of user 1 increases as user 2 moves closer to the transmitter. Since tailoring the antenna array to user 2 is more effective in improving the average SNR than tailoring the array to user 1, this design method tends to make the worse user even worse and make the better user even better.
- When the antenna array is designed to maximize the minimum SNR, the BER of user 1 slightly decreases

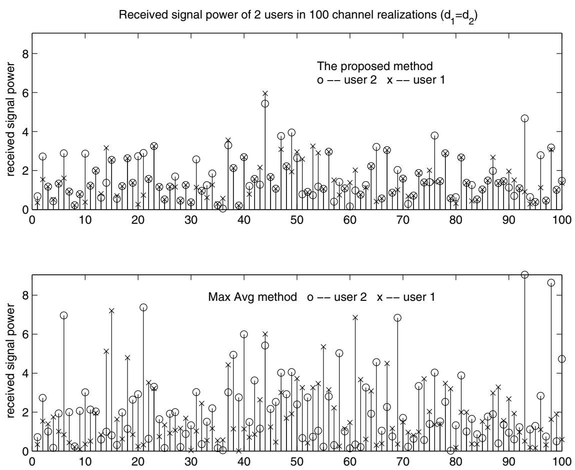

Fig. 3. SNR of user 1 and user 2 in 100 channel realizations

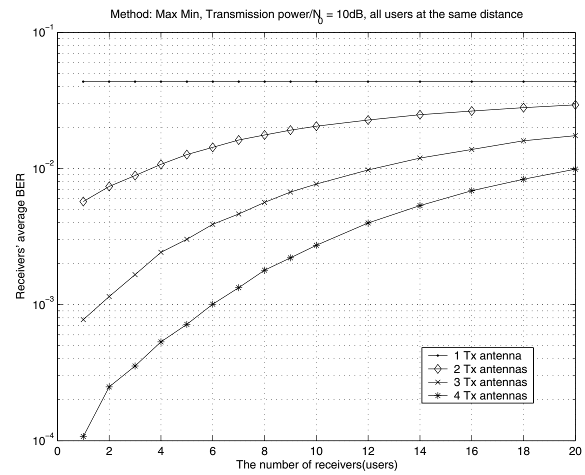

Fig. 4. Receivers' BER for different number of transmit antennas

as user 2 moves closer to the transmitter. The reason is that this design method can put more "emphasis" on the worse user when the other user already has very good performance.

- When the same weight is assigned to all antennas, the performance of user 1 is not affected by user 2.

In practical systems, it is often required that the BER of each user should be lower than a certain threshold. In these systems, the performance of the worst user determines the usage of system resources, such as transmission power. Figure 1 demonstrates that the proposed scheme achieves the best performance among all three schemes for the worse user (user 1). This is due to the fact that the proposed scheme is formulated to maximize the worst SNR.

In Figure 2, the average received signal power of each user is shown for the same simulation setup. It is noted that the method in [12] achieves higher average SNR (that is averaged over time) than the proposed scheme, when d_1 and d_2 are roughly the same. However, higher average SNR does not necessarily lead to lower BER. As demonstrated in Figure 1, the proposed scheme achieves lower BER when $d_1 = d_2$. The reason for this phenomena is illustrated in Figure 3, which shows the SNR of user 1 and user 2 for 100 independent channel realizations and $d_1 = d_2 = 1$. It is seen that the proposed scheme not only balances the SNR among different receivers, but also reduces the SNR variation over time.

C. Effects of group size

In the previous section, utilizing adaptive transmit antenna array has demonstrate its advantages in the two-antenna-two-receiver scenario. In this section, we investigate the performance of the proposed scheme when the group size (N) and the number of antennas (M) change.

Intuitively, the performance of the proposed scheme will degrade when the number of receivers increases. When $N >> M$, the limited number of antennas cannot take care of all receivers and the solution of the weight vector will be getting closer to that for simple broadcasting. In the extreme case that $N \to \infty$, the performance gain obtained from utilizing multiple transmit antennas could even vanish.

Figure 4 shows the decoding BER of the proposed scheme for different values of M and N. In the simulations, we restrict all channel coefficients to have a common variance, $\sigma_i^2 = 1$, which corresponds to all receivers being at similar distance from the transmitter. It has been shown in Section III-B that the worst user distribution for the proposed method is users being at the same distance. Thus, when some users are located closer to the transmitter than the others, the proposed scheme has better performance than that is shown in Figure 4.

As we predicted, the receivers' BER is an increasing function of N. In addition, when the number of transmit antenna increases, the BER can be greatly reduced. Even in an $N = 20$ receiver scenario, each additional antenna element provides a significant performance enhancement.

The realistic values of N highly depend on application scenarios. For multicasting in ad-hoc networks, one node usually transmits to only several other nodes. In this case, employing the proposed method is very beneficial. In 3G, since additional overhead packets are needed to initialize multicast, utilizing multicast between the base stations (BS) and the mobile users is advantageous in saving bandwidth only when more than some minimum threshold number of users are in the same cell [20]. Thus, for multicasting in 3G, the density of multicast receivers in one cell not only depends on the popularity of the program but also the threshold for implementing multicasting.

IV. Close loop vs. Open loop

Adaptive transmit antenna array for multicast is a close loop diversity technique that requires channel information. In some situations, however, collecting accurate channel information from all receivers can be expensive, especially when the group size is large. When channel information is not available at the transmitter, open loop diversity techniques should be applied.

One of popular open loop diversity techniques is space-time coding, which has received extensive studies and been proposed for the ITU endorsed 3G systems [9]. Space-time coding can be implemented in either block or trellis format.

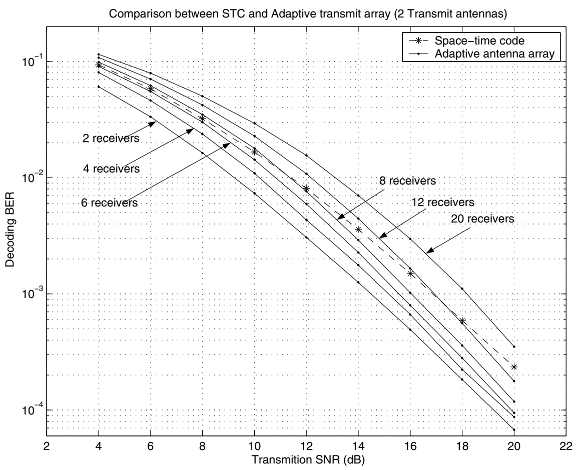

Fig. 5. Comparison between space-time block coding and adaptive antenna array (2 transmit antennas)

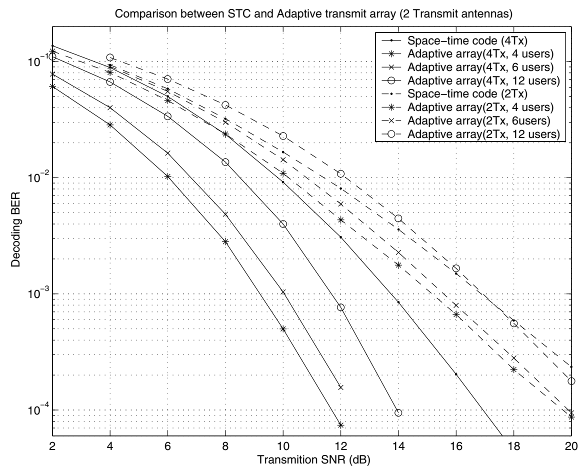

Fig. 6. Comparison between space-time block coding and adaptive antenna array for 2 and 4 transmit antennas

In this paper, we focus on space-time block codes due to their simplicity in decoding.

Space-time coding and adaptive antenna array have been compared for point-to-point communications [9]. In 3G CDMA systems with feedback, close loop solutions perform better for most channel conditions, while open loop diversity techniques have advantages only when channel changes very fast with time [9], i.e. large Doppler frequency.

In the multicast scenario, we have seen that the performance of the adaptive array degrades when the group size grows. On the other hand, the design of the space-time coding does not concern whether it is for unicast or multicast. The multicast group size does not have direct impact on the performance of space-time codes. Therefore, it is particularly interesting to compare the close loop and the open loop solutions for different number of multicast receivers. Here, we assume perfect channel information and slow fading environments.

For fair comparison, we adopt space-time block codes with coding rate 1. In particular, for two transmit antennas, we choose 2×2 orthogonal design in [10] with code matrix:

$$\begin{bmatrix} x_1 & x_2 \\ -x_2^* & x_1^* \end{bmatrix} \tag{19}$$

For four transmit antennas, we choose 4×4 qausi-orthogonal design in [14] with code matrix:

$$\begin{bmatrix} x_1 & x_2 & x_3 & x_4 \\ -x_2^* & x_1^* & -x_4^* & x_3^* \\ x_3 & x_4 & x_1 & x_2 \\ -x_4^* & x_3^* & -x_2^* & x_1^* \end{bmatrix} \tag{20}$$

In each code matrix, the symbols in one column are transmitted by the same antenna, and the symbols in one row are transmitted in the same time slot.

We first compare the performance of the STC and the proposed method when utilizing two transmit antennas. Similar as in Section III-C, all channel coefficients are restricted to have variance 1 and 4-QAM modulation is used.

Figure 5 plots decoding BER versus transmission SNR, where the dashed line represents the STC and the solid lines represent the adaptive transmit arrays for different group sizes. There is only one dashed line because the performance of the STC is not affected by the group size when all users are located at the similar distances. Comparing the STC and the proposed adaptive transmit antenna array, we can see that two factors play the major roles. The first one is the group size. For a fixed transmission power, the STC has lower BER than the adaptive array when the group size exceeds a certain threshold, and vice versa. The second factor is the transmission power. We observed that the group size threshold increases with the transmission SNR. For this particular simulation setup, several examples of the group size threshold are listed as follows.

- Transmission SNR = 4dB : adaptive array has lower BER than the STC when $N \leq 6$;
- Transmission SNR = 12dB : adaptive array has lower BER than the STC when $N \leq 8$;
- Transmission SNR = 18dB : adaptive array has lower BER than the STC when $N \leq 12$;

Besides the transmission SNR and the group size, another important factor is the number of transmit antennas (M). Figure 6 illustrates the simulation results for $M = 2$ and $M = 4$. The close loop method with 4 transmit antennas demonstrates larger advantage over the SPC than that with 2 transmit antennas. It is clear that the group size threshold increases with M.

It is important to note that the STC does not need channel information while the design of the adaptive antenna array requires feedback of the channel parameters. Therefore, when the number of multicast receivers is large, the STC has "double" advantages: (1) not requiring feedback and (2) achieving lower decoding BER.

V. Jointly using STC and adaptive transmit antenna array

For unicast communications, previous works [9] [15] have shown that the adaptive transmit array performs better when perfect channel parameters are known at the transmitter, while the STC is more desirable when the feedback is not available or not accurate enough.

For multicast communications, however, we observed that the STC can be better than the adaptive array that is designed based on accurate channel parameters, as long as the number of receivers is large. This observation indicates that the STC and the adaptive array should be jointly applied for wireless multicast. Intuitively,

- When the number of multicast receivers exceeds a certain threshold, the transmitter does not request feedback of channel information and utilizes STC.
- When the number of multicast receivers does not exceed the threshold, the transmitter requests feedback of channel information and employs the adaptive transmit antenna array as proposed in Section III.

This group size threshold depends on the transmission SNR and the number of transmit antennas, as well as the accuracy of the feedback. Calculating the group size threshold, however, is difficult because the solution of the minimax type optimization problem in (5) is hard to analyze. In practice, a set of group size thresholds for realistic channel conditions may be determined off-line through simulations.

For very popular multicast services, where each transmitter administers a large number of users, we suggest using the STC for normal transmissions and the adaptive transmit array for retransmissions. Since the number of users who will loss packets is usually small, this scheme can take advantage of jointly considering STC and adaptive transmit array without calculating the group size threshold. In addition, since the channel parameters of the users who need retransmission can be sent to the transmitter together with negative acknowledge (NACK), this method can greatly reduce feedback overhead.

The discussion in this section provides a starting point for jointly considering open loop and close loop techniques in wireless multicast communications. A better solution should be jointly designing the STC and the adaptive transmit array [15] for multicasting, which will not be discussed in this paper.

VI. CONCLUSION

In this work, transmit diversity techniques were utilized for improving the performance of multicast communication over wireless networks. An adaptive transmit antenna array was designed in the multicast scenario where the same data are conveyed to multiple receivers. Instead of using the average SNR as the performance criteria that was presented in the previous work, we designed the array weight vector to maximize the worst SNR among all receivers. The proposed design criteria, although not producing a close form solution, led to a large reduction in the decoding BER when compared with the multicast beamforming method in [12]. It was also observed that the decoding BER of the multicast close loop TD scheme increased with the multicast group size. The proposed adaptive array was compared with the space-time block codes. When the number of multicast receivers was smaller than a certain threshold, the proposed method had better performance than the STC. When the number of multicast receivers exceeded the threshold, the STC outperformed the proposed scheme. Several examples of this group size threshold were obtained through simulations. We also provided a preliminary discussion on utilizing open loop and close loop TD techniques alternatively for regular transmission and retransmission in wireless multicasting. The investigation in this paper provided a basis for jointly designing the space-time coding and adaptive transmit antenna array in the future.

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