Adaptive Precoder Selection for Multicast/Broadcast Services in MIMO-OFDMA Systems

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***Abstract*—The multicast/broadcast service (MBS) has emerged as a key technology for delivering multimedia contents in wireless networks. The development of orthogonal frequency division multiplexing access (OFDMA) and multiple-input multiple-output (MIMO) communications have provided a high-throughput air interface for delivering the multimedia contents in MBSs. To further improve the spectral efficiency for MIMO communications, the technique of precoding can be applied to tailor the signals to the current downlink channel quality. However, due to the broadcasting nature of MBSs, link adaptation and precoder selection for individual user is infeasible. A fixed precoding scheme where the transmitter simply uses identical precoding matrices is commonly adopted for MBS transmissions in existing systems. In this paper, we propose an effective adaptive precoder selection scheme with low complexity based on precoder training and user feedback. Simulation results show that the proposed scheme effectively improves the performance of received SINR measured at the mobile stations (MSs).**

***Index Terms*—Multicast/Broadcast service (MBS), OFDMA, MIMO, precoder selection, spatial multiplexing**

I. INTRODUCTION

The multicast/broadcast service (MBS) has emerged as a key technology for delivering multimedia contents in wireless transmission standards such as 802.16m [1] and 3GPP [2]. Typical applications of the MBS include TV broadcasing and video-on-demand [3]. In MBSs, the same information is transmitted to a group (multicast) or to all users (broadcast) simultaneously over the same frequency band, which is enabled by the concept of single-frequency networks (SFNs) [4]. The techniques of orthogonal frequency division multiplexing access (OFDMA) and multiple-input multiple-output (MIMO) communications have provided a high-throughput air interface for delivering the multimedia contents in MBSs. However, due to the broadcasting nature of MBSs, performing link adaptation for individual user is infeasible. Challenges thus exist to further improve the transmission data rate for MBSs.

Precoding is a signal processing technique for MIMO communications to exploit the knowledge of the information of the downlink channel quality at the transmitter. With precoding, the transmitter can transform signals using appropriate precoding matrices and perform power allocation adaptively according to the variation of link quality [5]. It has been shown that precoding can substantially improve the spectral efficiency for MIMO communications [6]–[9].

For the operations of precoding, the information of the downlink channel quality has to be fed back from the receiver to the transmitter side. Such signaling process incurs considerable overhead which scales with the number of antennas, i.e., the MIMO mode and is undesirable in most cases. In practical systems, the approach of codebook-based precoding is adopted to reduce the feedback overhead [10]. In codebook-based precoding a number of selected precoding matrices are known to both the transmitter side and receiver side. The receiver simply feeds back the appropriate precoding matrix index (PMI) to the transmitter based on the measured link quality. If the number of precoding matrices is set to 2^n, the length of the PMI feedback can be n bits. Codebook-based precoding can substantially reduce the feedback overhead.

The potential benefits of precoding for the case of multicast/broadcast have been investigated from a theoretical perspective in [11], [12], where a general power allocation and antenna adaptation problem is formulated for a group of receivers. It is shown that the performance of achievable throughput and transmission reliability of MBSs can be improved by employing proper precoding techniques. However, the design of a practical and efficient precoding scheme for MBSs is not as straightforward as that for the case of unicast transmissions. In MBSs, the available resource for feedback channels is limited due to its one-way transmission nature. Typically, only one or a few common feedback channels for conveying NACK or ACK information are available [1]. Furthermore, the fact that data communications in MBSs is one-to-many renders the signal adaptation process more involved; a large number of user feedback is also implied. Conventional codebook-based precoding schemes with PMI feedback for unicast transmissions are thus impractical for MBSs. To the best of our knowledge, no existing MIMO cellular system considers the design of adaptive precoder selection. A fixed precoding scheme where the trasmitter simply uses identical precoding matrices is adopted for MBS transmissions. The design of adaptive precoding schemes for MBSs is still left to be explored.

The purpose of this study is to design an adaptive precoder selection scheme for applications using MBSs. We consider a typical MIMO-OFDMA cellular system in a SFN. By utilizing the common feedback channels in MBSs, we propose an effective adaptive precoder adaptation scheme with low complexity based on precoder training and user feedback. Simulation results show that the proposed scheme effectively improves the performance of the signal-to-interference plus noise ratio (SINR) measured at the mobile stations (MSs) receiving MBS transmissions.

The remainder of this paper is organized as follows. In Section II, the system model of this work is described. In Section III, the proposed adaptive precoder selection scheme for MBSs is presented. In Section IV, the simulation results are provided. Finally, the conclusions are given in Section V.

II. System Model

We consider a MIMO-OFDMA wireless cellular system with one BS deployed in each cell. The BSs operate cooperatively to form a cellular SFN. The signal each MS receives is a superposition of the signals sent from different BSs. It is assumed that all the BSs transmit the same information over the same frequency band simultaneously such that the effect of interference can be ignored. The technique of codebook-based precoding is used in the considered cellular network. We assume that feedback channels for returning the information of ACK/NACK exist, and the utilization of such feedback channels for conveying control signaling for precoding, i.e., PMI, is impractical.

The transmission mode of spatial multiplexing is configured for MIMO in the considered network. We denote the number of transmitting and receiving antennas of each BS by M and N respectively. Let $\mathbf{x} \in \mathbb{C}^M$ denote the broadcast signal vector for the MBS. For MS j, the received signal vector, denoted by $\mathbf{y}_j \in \mathbb{C}^N$, can be expressed as

$$\mathbf{y}_j = \sum_{i=1}^{K} \mathbf{H}_{ij}\mathbf{G}_i\mathbf{x} + \mathbf{w}_j = \mathbf{H_s}\mathbf{x} + \mathbf{w}_j, \tag{1}$$

where $\mathbf{w}_j \in \mathbb{C}^N$ is a zero-mean complex Gaussian noise vector with covariance matrix $\sigma^2\mathbf{I}_{N\times N}$, $\mathbf{G}_i \in \mathbb{C}^{M\times M}$ is the adopted precoding matrix of BS i, $\mathbf{H}_{ij} \in \mathbb{C}^{N\times M}$ is the channel matrix between BS i and MS j, and $\mathbf{H_s} = \sum_{i=1}^{K} \mathbf{H}_{ij}\mathbf{G}_i$ represents the combined channel matrices with precoding of K BSs in the SFN. We consider minimum mean squared error (MMSE) receivers.

III. Adaptive Precoder Selection Scheme

In this section, an adaptive precoding scheme for MBSs is proposed. We elaborate on the proposed scheme from the perspective of a single BS as each BS operates independently. The proposed scheme allows each BS to adaptively select the best precoder according to the aggregate feedback information sent from the MSs. The BS initiates precoder selection by transmitting a series of training signals. Each MS then calculates the post-processing SINR corresponding to the precoding training signals and reports ACKs/NACKs by comparing the computed SINR to a predefined threshold. The number of ACKs/NACKs collected is then used as the criterion for precoder selection at the BS.

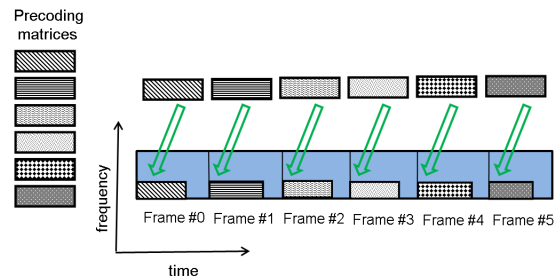

Fig. 1. The precoder training for a codebook containing 6 precoding matrices.

The proposed scheme contains four phases: the training phase, the MS feedback phase, the decision phase and the refreshing phase. Details are provided as follows.

A. Training Phase

A BS initiates the precoder training by transmitting reference signals in consecutive data frames. The reference signals carried on different data frames are processed by distinct precoders. If the codebook size is L, BS has to transmit L data frames for the purpose of precoder training. For practical implementations, the reference signals can be the midambles or the common pilots in OFDMA-based systems.

For example, we consider a case where the codebook size is 6 as depicted in Fig. 1. 6 different precoding matrices are available for signal processing, and it requires 6 continuous data frames to complete the precoder training.

B. MS Feedback Phase

After receiving the reference signals for precoder training, each MS calculates the corresponding post-processing SINR as [13]

$$\text{SINR} = \frac{1}{N}\sum_{k=1}^{N} \frac{[\mathbf{D}\mathbf{D}^*]_{kk}}{[\sigma^2\mathbf{W}^*\mathbf{W} + \mathbf{I_{self}}\mathbf{I^*_{self}}]_{kk}}, \tag{2}$$

where $(.)*$ is the Hermitian operator, and the subscript k denotes the kth stream of MIMO spatial multiplexing. $\mathbf{W}$ denotes the the MMSE linear receiver weight and is defined as [14]

$$\mathbf{W} = (P_{tx}\mathbf{H^*_s}\mathbf{H_s} + \sigma^2\mathbf{I})^{-1}\sqrt{P_{tx}}\mathbf{H_s}, \tag{3}$$

where P_{tx} denotes the transmit power. $\mathbf{D}$ is the desired signal components in diagonal matrix form and is given as

$$\mathbf{D} = \text{diag}[\sqrt{P_{tx}}\mathbf{W}^*\mathbf{H_s}]. \tag{4}$$

Finally, $\mathbf{I_{self}}$ is the self interference between MIMO streams and is of the form

$$\mathbf{I_{self}} = \sqrt{P_{tx}}\mathbf{W}^*\mathbf{H_s} - \mathbf{D}. \tag{5}$$

Based on a predefined value for SINR threshold, each MS sends an ACK through the common feedback channels to the BS if the computed SINR is larger than the given threshold (or equivalently, a NACK if the computed SINR is smaller than the given threshold).

enabling 3 sets of reference signals and common feedback channels within one data frame, the number of frames required for training a codebook of size 6 can be reduced to 2 as depicted in Fig. 2 (b).

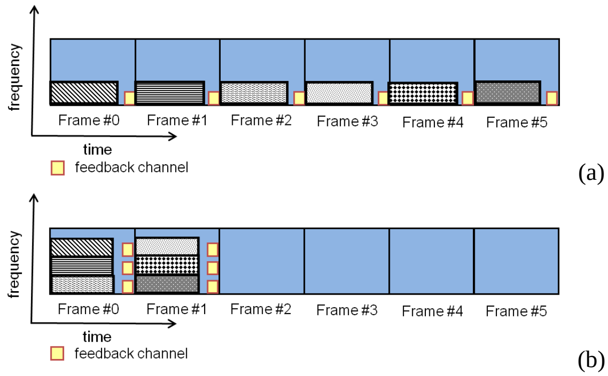

Fig. 2. The ACK/NACK feedback scheme for the case where (a) single reference signal and feedback channel are available within each frame. (b) 3 sets of reference signals and feedback channels are available within each frame.

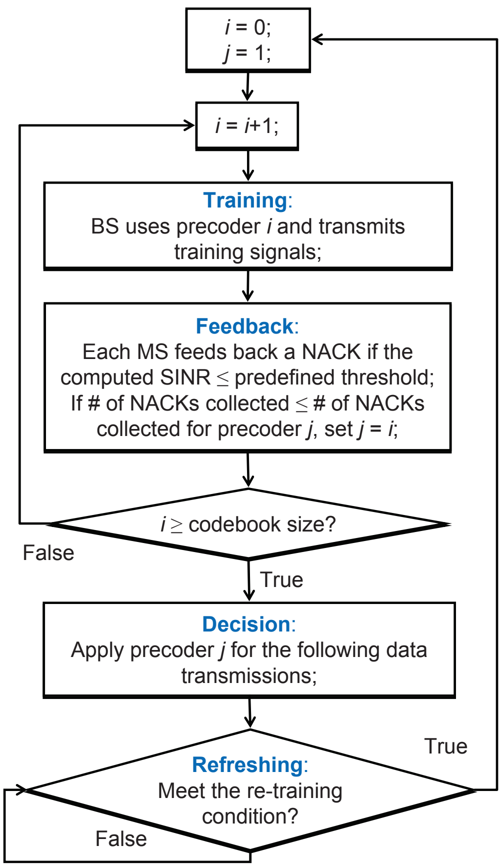

Fig. 3. The proposed adaptive precoder selection scheme for MBSs.

Consider again the case with 6 candidate precoders. As shown in Fig. 2 (a), after receiving Frame $\#i, 0 \leq i \leq 5$, each MS computes the corresponding SINR for the precoded reference signal and reports an ACK/NACK in the corresponding feedback channel. One should note that if multiple reference signals and feedback channels are allowed within a data frame, the number of data frames required to perform precoder training can be reduced correspondingly. For example, by

C. Decision Phase

In this phase, the BS counts the number of ACKs/NACKs corresponding to each candidate precoding matrix. The BS then selects the precoding matrix with the most ACKs reported (or equivalently, least NACKs reported). It is clear that such adaptive precoder selection scheme offers better SINR performance to the MSs as compared to the case of fixed precoding scheme.

To prevent BSs from frequently changing precoders, a threshold value for the number of collected ACKs/NACKs can be defined. Precoder change then only happens if a large proportion of MSs find the current precoding matrix unsatisfactory.

D. Refreshing Phase

In this phase, the BS performs regular data transmissions using the previously selected precoding matrix. The MSs continue to evaluate the post-processing SINR while receiving regular data traffic. If the computed SINR is lower than a predefined threshold, the MS reports an ACK/NACK to the BS as in the feedback phase. If the proportion of MSs reporting ACKs/NACKs is larger than a predefined threshold, the system will reenter the training phase to perform precoder adaptation.

It should be noted that the process of precoder training can also be executed on a periodic basis, which gives a lower complexity and signaling overhead. However, as suggested by numerical experiments, the achievable performance of the downlink throughput with periodic refreshing degrades significantly as compared to the approach described above due to its inability to adapt to the changing channel conditions.

We summarize the proposed adaptive precoder selection scheme in Fig. 3. The proposed scheme requires only reference signal training and ACK/NACK feedback; it is thus considered to be of low complexity.

If the codebook size is large, the duration of precoder training and hence the incurred overhead become undesirable. It is thus proposed that one partitions the codebook into several subsets. Many codebook design algorithms can be used to partition the codebook based on different criteria. The BS can first determine the most appropriate subset of codebook to match the variation of long-term channel conditions, by similar approach yet with longer period. Then the precoder can be selected from the subset of the codebook rather than the full set, following our approach to reduce the amount of feedback needed.

IV. Simulation Results

In this section, we evaluate the performance of the proposed scheme via computer simulations. The cumulative distribution function (CDF) of the received SINR at MSs is taken as

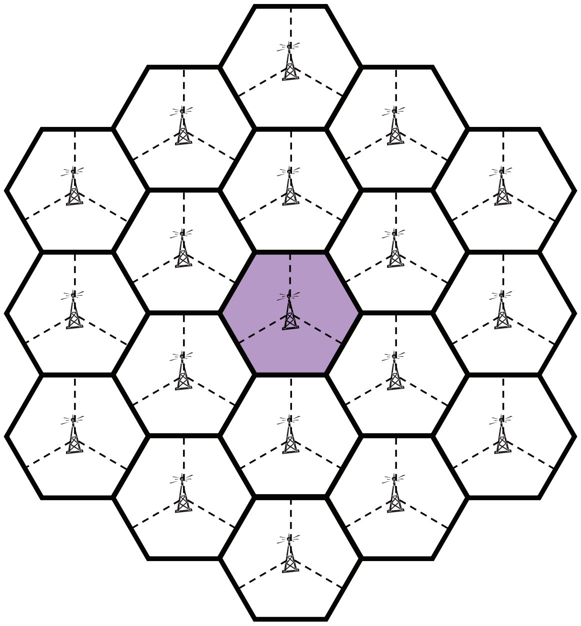

Fig. 4. A cellular network with 19 cells and 3 sectors is simulated.

TABLE I
SIMULATION PARAMETERS

Parameters	Values
Number of cells	19
Number of MSs	100 (uniformly dropped)
Number of sectors	57
Site-to-site distance	1.5 km
Center frequency	2.5 GHz
MIMO mode	2 $\times$ 2MIMO
Transmitting power	46 dBm
Path loss model	$130.19 + 37.6 \log_{10}(R)$ (R in km)
Penetration loss	10dB
Antenna gain	17dB
Block size	72 subcarriers $\times$ 6 OFDMA symbols
Channel model	10% Veh A-120km
	30% Veh A-30km
	60% Ped B-3km
Frame size	8 blocks
MS Rx combining scheme	MMSE

the performance metric. We assume an urban propagation environment. The cellular network simulated is a three tier hexagonal cellular network with 19 cells, each with 3 sectors as depicted in Fig. 4. It is assumed that a packet for MBS is constituted by 72 subchannels $\times$ 6 OFDMA symbols. We assume that 100 MSs are uniformly dropped within the shaded cell in Fig. 4. In our setup, 10% of the users are under Veh A-120km channel model, 30% under Ped B-30km channel model, and 60% under Ped B-3km modified ITU channel model. The MIMO mode is assumed to be 2 $\times$ 2 spatial multiplexing, and the definition of post-processing SINR follows (2). Table I summarizes the main parameters and settings used in the simulation.

For the simulation of the proposed scheme, BSs are triggered to perform precoder adaptation, i.e., entering the training phase, if there are more than 25% of MSs reporting NACKs for certain data transmission. We assume that multiple reference signals along with multiple common feedback channels are allowed within a frame; the number of reference signals available for precoder training is equal to the codebook size.

We present the results of the proposed scheme as well as other baseline schemes in Fig. 5. The codebook used is a 3-bit codebook following 802.16e [15], which gives a codebook size of 8. The optimal curve corresponds to the case where the signal received by each MS is preprocessed by the precoding matrix that gives the highest SINR. The optimal case requires each MS report their PMI to the BS and merely serves as a performance bound here. On the other hand, the worst curve refers to the case where the signal received by each MS is preprocessed by the precoder that gives the lowest SINR. The case of no precoder means that BS uses a fixed identity matrix as the precoder persistently. We observe that the curve corresponding to the proposed scheme is quite close to that of the optimal case. The proposed scheme provides 1.4 dB and 2.0 dB SINR gain over the case of no precoder for tail 5% and 70% MSs, respectively. As the system performance is typically dominated by the users experiencing the poorest channel quality, the SINR gain provided to the tail 5% MSs can substantially improve the overall system performance.

We then proceed to consider a 2-bit codebook following 802.16m [16]. The results of our proposed scheme and other baseline schemes are shown in Fig. 6. It is observed that the proposed scheme provides 1 dB and 1.6 dB SINR gain over the cases of no precoder for tail 5% and 70% MSs, respectively. We find that the achievable SINR gain of the proposed scheme in this case becomes smaller as compared to the case in Fig. 5. This is expected since the BS now has fewer choices of precoder selection for different channel conditions. It should be noted that, though, the signaling overhead can be reduced by using a codebook with smaller size. The tradeoff between the achievable SINR gain and the incurred signaling overhead can be left as an implementation option.

V. CONCLUSIONS

In this paper, an adaptive precoder selection scheme for MBSs has been proposed for MIMO-OFDMA based cellular systems. Traditionally, precoding requires the receiver to feed back the information of channel quality or PMI to the transmitter side, and is thus difficult to be applied to the case of MBSs. In existing systems, a fixed-precoding approach is adopted. The proposed scheme achieves precoding adaptation by utilizing reference signal training and user feedback. The scheme is effective and of low complexity. Simulation results show that an SINR gain of approximately 1.4 dB can be obtained for the tail 5% MSs by applying the proposed scheme in the case of a 3-bit codebook.

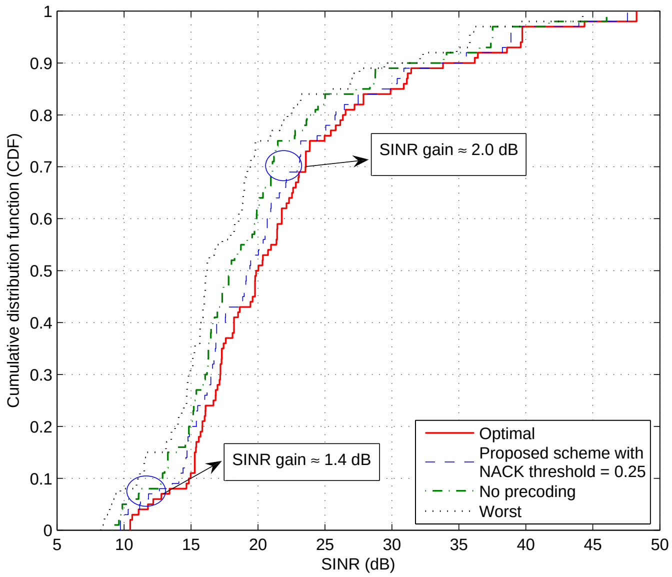

Fig. 5. The CDF of the received SINR at the MSs for the proposed schemes and other baseline schemes. A 3-bit codebook is used.

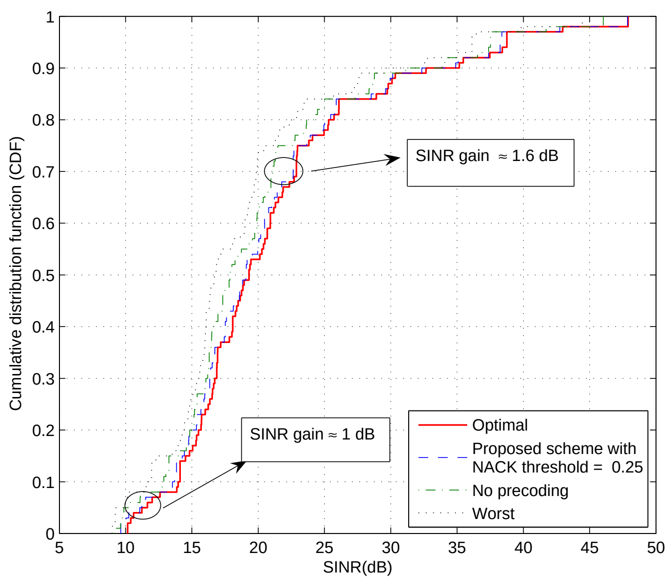

Fig. 6. The CDF of the received SINR at the MSs for the proposed schemes and other baseline schemes. A 2-bit codebook is used.

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