Near-Optimal MIMO Solutions in WiBro/WiFi/B3G Communication Standards

Sungjin Kim · Hojin Kim · Kiho Kim · Kwang Bok Lee

Recently, the industrial organizations have proposed various MIMO schemes in wireless communication standards. Major standard bodies include WiMAX/WiBro (IEEE 802.16d/e), WiFi (IEEE 802.11n), and HSDPA (3GPP). In this paper, we overview a number of selected MIMO techniques proposed by major industrial groups and investigate their performance optimality. We also present our novel multi-user MIMO scheme, of which the sum-rate performance approaches extremely close to the sum capacity of MIMO downlink channels when the number of users is larger than the number of transmit antennas. Furthermore, multi-channel diversity (MCD) in the proposed solution greatly reduces the amount of channel state information signaling, which is fed back from receivers to the transmitter in order to find optimal precoding structure at the transmitter.

Keywords: MIMO, 3GPP, HSDPA, WiMax, WiFi, WiBro, Multi-user MIMO, Sum-rate.

I. INTRODUCTION

Recently, the high-rate data transmission has been one of key issues in wireless nomadic and mobile communications. Various classes of multimedia traffic need to be supported under the wireless LAN (Local Area Network) as well as cellular environments [1],[2]. A number of approaches have been considered to improve the performance of capacity and spectral efficiency in wireless communication systems [3]–[16]. MIMO (Multiple-Input Multiple-Output) is an emerging technology offering high spectral efficiency with the increased link reliability and interference suppression.

In mobile communication standards, MIMO techniques have been proposed by different industrial groups. Major leading standard bodies include WiBro/WiMAX (IEEE 802.16d/e) [3], WiFi (IEEE 802.11n) [4]–[6], and HSDPA (3GPP) [7]. Their common target is focused on high spectral efficiency, and hence the candidate schemes are designed based on the closed-loop systems with feedback signaling.

In this paper, we overview several candidate schemes of MIMO in various standard groups, and propose a novel MIMO solution, which is applicable to cellular systems as well as wireless LAN. The paper is organized as follows. In Section II, an overview of MIMO proposals is described. Section III investigates a novel proposed scheme which exploits QR decomposition and multi-channel diversity (MCD). Performance analysis and simulation results are presented in Section IV and V, respectively. Section VI draws the conclusions.

II. MIMO PROPOSALS IN STANDARDS

1. WiBro/WiMAX (IEEE 802.16d/e)

WiMax is a wireless technology that provides broadband data at rates over 3 bits/second/Hz [3]. In order
to increase the range and reliability, the IEEE 802.16e standard supports optional multiple-antenna techniques such as space-time block coding, adaptive antenna systems and MIMO. The closed-loop MIMO schemes in IEEE 802.16e have a common feature which is transmit precoding. Multiple access scheme is based on orthogonal frequency division multiple access (OFDMA). Each transmit scheme uses different feedback signaling. Among them, Intel proposed SVD based MIMO with multiplexing transmission. There are two key features which are compact feedback signaling and per-stream adaptive bit loading. A compact feedback signaling is proposed to reduce the overhead by a factor from 3.3 to 10 at the cost of additional computations. The overhead reduction is achieved by three means. First, the receiver feeds back transmit beamforming vectors instead of the channel matrix. This reduces the overhead by a factor of more than 1.6 on average. Second, the elements of each beamforming vector are jointly quantized by vector quantization using three small codebooks of sizes 16, 32 and 64 respectively. The vector quantization reduces the overhead by a factor of two compared to the scalar quantization in current draft. Finally, the scheme feeds back the beamforming vectors only for the active spatial channels. This provides a significant overhead reduction in the case of spatial channel puncture, where the spatial channel corresponding to the weakest eigenmode is usually punctured.

The codebook is employed in the feedback from mobile user to base station. The mobile user learns the channel state information from downlink and selects a transmit beamforming matrix for the codebook. The index of the matrix in the codebook is then fed back to the base station. Each codebook corresponds to a combination of $N_t$, $N_s$, and $N_i$, where $N_t$, $N_s$, and $N_i$ are the numbers of BS transmit antennas, available data streams, and bits for the feedback index respectively. Once $N_t$, $N_s$, and $N_i$ are determined in the mobile user, the mobile user will feed back the codebook indexes each of $N_t$ bits. After receiving a $N_i$ bit index, the base station will look up the corresponding codebook and select the matrix (or vector) according to the index. There are several different types of codebooks proposed by companies, which are antenna grouping, Grasmannian, Givens, Household, etc.

Feedback methods include channel matrix index, transmit antenna index, quantized MIMO (sub) channels, quantized SVD decomposed MIMO channel.

The difference between the greatest and the smallest eigenvalues increases with the number of spatial streams, and it is greater than 17 dB for 4x4. This large difference is hard to be compensated by FEC coding and adaptive bit/power loading is required. The exact adaptive bit (or power) loading has the flexibility to put a different number of bits (or amount of power) on each OFDM subcarrier and each spatial channel. In order to reduce the overhead, we propose per-stream adaptive bit loading as shown in Figure 1. It assigns the same number of bits on each spatial channel, where the $i$-th spatial channel is formed by the $i$-th eigenmodes of each subcarrier. To further reduce the feedback overhead, we define a set of modulation coding schemes (MCSs), where each MCS specifies the modulations on each stream and the FEC code rate (and suggested power ratio across streams). The eigenvalue distributions of 4x1, 4x2, 4x3, and 4x4 are shown in Figure 2.

2. WiFi (IEEE 802.11n)

In IEEE 802.11n, there are two divided groups toward the harmonized standardization which are TGn Sync [4]–[5] and WWiSE [6]. Currently 802.11 Task Group n (TGrn) is in the process of standardizing the next-generation WLAN technology to provide over 100 Mb/s.
over 600Mbps. This complements the evolution of modern technologies such as USB 2.0, IEEE 1394b, and PCI Express to provide a dramatic performance upgrade for users of current wireless designs. Adaptive Radio Technology to intelligently use spectrum and adapt to its expansion by worldwide regulatory bodies for unlicensed and licensed applications. This allows products to remain interoperable while adapting to different numbers of spatial streams (2 to 4) as well as different amounts of spectrum (10, 20, 40MHz). Adaptive radio is essential to the mobile handsets, PC laptops, and other products that only have two antennas, because it dramatically increases their performance while functioning as an interoperable good neighbor. Both Extended Modulation Coding Scheme (MCS) and Basic Beamforming to increase the speed and reliability of data links under conditions that disrupt many MIMO networks. This enables the advanced 802.11n capabilities to be sustained over range and also maintain full interoperability with existing 802.11a/b/g devices. Timed Receive Mode Switching (TRMS) and Multiple Receiver Address (MRA) Power Management enables products to operate in extremely low power modes and engage advanced capabilities on demand. This is important for voice handsets, notebook computers and any power-sensitive applications, because it lets them take full

The design of the next-generation WLAN is based on MIMO and orthogonal frequency-division multiplexing (OFDM). As in IEEE 802.16e, SVD based MIMO was proposed by Qualcomm [4]. The MIMO WLAN uses OFDM modulation in the 20 MHz band of operation as in 802.11a/g. The 802.11a/g OFDM symbol is composed of 64 subbands where a total of 48 subbands are used for data and four as pilot.

The WWiSE technical proposal includes several innovative techniques that enhance data rate, network efficiency, operational range, and reliability [6]. One unique aspect of the activities of TGn is that both MAC and PHY changes are considered. Changes in the MAC protocol in the WWiSE proposal are implemented primarily to increase network efficiency and manage network access when 40MHz optional channels are in use. PHY enhancements are aimed primarily at increasing peak data rates.

The TGn Sync proposal expands the appeal of 802.11n beyond traditional Wi-Fi devices and high end products. Important innovations include methods to reduce power consumption for small mobile phones and increase the user capacity of public networks. MIMO Spatial Division Multiplexing to support data rates of up to 243Mbps in standard two antenna designs, with extensions to support

Figure 2. Eigenvalue distributions of spatial modes
advantage of high data rates to reduce the amount of time their radios must operate. Fast radios extend battery life.

The MCS definitions and indexing for the Basic MIMO set are found in Table 1. The same definitions are used for both 20 and 40MHz channels. There is one exception. MCS 32 (not listed in the table) is a BPSK rate 1/2 duplicate format transmission mode that provides a 6Mbps rate for 40MHz channels.

Qualcomm proposed transmit beamforming MIMO schemes, which are Full CSI schemes imply the transmitter has full knowledge of the MIMO channel (i.e., amplitude and phase response of each OFDM subband) [4].

2.2. Spatial Spreading (SS)

When full CSI is not available, it is desirable to achieve maximum diversity while transmitting on some or all spatial channels. Spatial Spreading (SS) is a generalized space-frequency code over the OFDM subbands. With SS, the transmitter forms the transmitted vector \( \mathbf{x}(k) = W(k) \delta s(k) \), where \( W(k) \) is the unitary SS matrix used in OFDM subband \( k \). The spatial spreading matrices \( W(k) \), can be selected to provide many independent "looks" at the channel over the set of OFDM subbands. One effective set of spatial spreading matrices that is simple to implement employs a fixed unitary spreading matrix \( S \) followed by a linear phase shift per transmitted stream. The transmitter "spreads" the \( N_S \) data streams across the \( N = \min(N_R, N_T) \) spatial channels of the MIMO channel using the columns of a unitary spreading matrix \( S \). For example, \( S \) may be a Hadamard matrix or a Fourier matrix. The number of data streams is determined based on SNR (or rate) feedback from the receiver. As an example, consider the case \( N_S = 2 \) and \( N_R = N_T = 4 \). Then the SS is provided by the first two columns of the 4 \( \times \) 4 Hadamard matrix, which ensures that both data streams "see" all four spatial channels. This is followed by a "uniform" phase shift steering matrix. Note that this uniform phase shift can be trivially implemented by introducing a fixed cyclic time shift in the OFDM symbol per transmit antenna. The linear phase shift across the OFDM subbands provides additional diversity in channels with low dispersion.

3. WCDMA/HSDPA (3GPP)

3.1. Per Antenna Rate Control (PARC)

Lucent initially proposed their multiple antenna solution, which is called the per-antenna rate control...
was originally proposed by Texas Instruments in 3GPP, which was compared with PARC for system performance. DSTTD has no feedback signaling, resulting in capacity degradation. Thus, Mitsubishi proposes the improved version of DSTTD which is equipped with adaptive modulations and feedback signaling for capacity enhancement.

3.5. Multipath Diversity with Rate Control (MPD-RC)

MPD also uses spatial multiplexing with rate control on each stream [13]. The difference is that each stream is transmitted from two antennas with the spreading codes differentiated by a delay of one chip interval. MPD also uses space-time block coding as in DSTTD.

3.6. TxAA based Schemes

Nokia proposed TxAA based MIMO schemes, which is an extension of the closed loop transmit diversity used in Rel99 using receiver diversity [14].

3.7. TPRC for CD-SIC MIMO

Transmit power ratio control (TPRC) was proposed by SNU & Samsung [15]. To cancel out the effect of time-domain interference signal, the code-domain interference canceller, e.g. the code-domain successive interference canceller (CD-SIC), may be preferable to the time-domain interference signal because of its good performance and simplicity.

3.8. Multi-user MIMO Schemes

We propose a multi-user MIMO scheme [16], which is the enhanced version of [17] where multi-user diversity and scheduling techniques are exploited [18]–[25]. More details are examined in the next section.

III. BLOCK MMSE-DP WITH GREEDY MCSD

1. System Model

Consider a $K$ user wireless downlink communications system with multiple transmit antennas at the base station, as shown in Figure 3, and multiple receive antennas for each user. We assume that the base station has $t$ transmit antennas, the user $k$ has $r_k$ receive antennas, and the
The number of all receive antennas in the system is \( r = \sum_{k=1}^{K} r_k \). Also, we model the channel as a frequency-flat block fading channel. Interference from neighboring cells is modeled as additive Gaussian noise, as we concentrate on the single cell model. The received signal of user \( k \) is expressed as

\[
y_k = H_k x + n_k
\]

where the \( t \times 1 \) input signal vector \( x \) is transmitted by the base station and is constrained to have power no greater than a sum-power constraint \( P \), i.e., \( \text{tr}(E[x^H x]) \leq P \), and the \( r_k \times 1 \) vector \( z_k \) represents the random additive noise for user \( k \) where \( z_k \sim \mathcal{CN}(0, I) \). The channel \( H_k \) is a \( r_k \times t \) matrix, whose entries are assumed to be independent and identically distributed (i.i.d.) circularly symmetric complex Gaussian random variables with zero-mean and unit variance. Also, \( H_k \) is independent of \( H_j \) for all \( j \neq k \).

In general, it is difficult for the base station to have the perfect knowledge of downlink channel state information (CSI) because the feedback link has delayed lossy feedback characteristics. Hence, the problem at hand is to find the transmit and receive structure that minimizes the feedback rate subject to the performance constraint such that the data throughput is kept as close as possible to the sum capacity.

### 2. Block QR Decomposition

We propose a multi-user MIMO scheme that is based on unitary beamforming and user selection diversity. It is assumed that \( t \) is the number of transmit antennas, \( r \) is the number of receive antennas, and \( K \) is the number of users. Beamforming using unitary transformation matrix \( W \) that is a function of the channel unitary matrices fed back from users is employed at the transmitter. The channel unitary matrix for feedback denotes the right-most matrix \( V_k \) obtained by SVD of the \( k \)th user channel \( H_k = U_k D_k V_k^H \). Each data stream for transmission is allocated to each beam vector of the unitary transform matrix, and the transmitter adjusts antenna rates independently. In the proposed system the channel is rotated using the right unitary matrix obtained by SVD of each user channel, so as to reduce feedback overhead at the transmitter. MIMO channel is decomposed into multiple parallel MISO channels \( F_k \) which is referred to as the effective channel

\[
F_k = U_k^H H_k = D_k V_k^H
\]

The row of the effective channel matrix \( F_k \) is also noted as the effective channel vector. In the transmitter, controlled beamforming is implemented by applying QR decomposition to the combination of the effective channels \( F = [F_1^T, ..., F_K^T]^T \). The effective BC \( F \) can then be treated as the multi-user MISO channel matrix. As in the algorithm of [6] for MISO, the QR decomposition is obtained using the Gram-Schmidt orthogonalization procedure to the rows of \( F \). That is, geometrical projection is performed based on SVD decomposition, and then the finite dimensional subspace is determined by QR process. Using QR decomposition, the effective BC is
represented as $F = RW$, where $R$ is an $r \times t$ lower triangular matrix and $W$ is a $t \times t$ matrix with orthonormal rows. The unitary matrix $W^H$ is used for beamforming, and hence is applied to the transmitted signal

$$y = Fx + z$$

$$= RWW^HZ + z$$

$$= Rs + z$$

where $y = [y_1, \ldots, y_K]^T$ and $z = [z_1^T, \ldots, z_K^T]^T$. The sum-rate performance based on block QR decomposition is maximized by adopting MCSD which is described in the next subsection.

3. Multi-Channel Selection Diversity

Multi-user diversity is the promising solution to improve capacity gain while Costa precoding is the capacity-achieving strategy in MIMO BCs. In our proposed scheme, multi-channel based selective diversity (i.e., MCSD) is exploited in combination with Costa precoding for known interference cancellation, which means that the channel vectors of active users are selected and ordered to achieve diversity gain with the increase of the number of users and antennas therein, and interference cancellation using Costa precoding is processed at the transmitter to approach maximum sum-rate.

Let $\mathcal{S} \subseteq \{1, \ldots, r\}$ be a subset of the effective channel vector indices that the BS selects for transmission using MCSD, and $F(S) = [f_1^T(S), \ldots, f_{|\mathcal{S}|}^T(S)]^T$ be the corresponding submatrix of $F$. The $t \times t$ unitary beamforming matrix $W^H(S)$ is obtained by QR decomposition of the submatrix such that $F(S) = R(S)W(S)$, where $W(S) = [w_1^T(S), \ldots, w_{|\mathcal{S}|}^T(S)]^T$ and $w_i(S)$ is a $1 \times t$ vector. Then, the achievable sum-rate of this system by Costa precoding is given by

$$R = \max_{S} \sum_{i \in S} \log\left(1 + \frac{P}{|\mathcal{S}|} |f_i(S)w_i^H(S)|^2\right),$$

$$\leq \max_{\sum_i n(Q_i) \leq P, Q_i \geq 0} \log\left|1 + \sum_{k=1}^{K} H_k^H Q_k H_k \right|$$

where each of the matrices $Q_k$ is an $r \times r$ positive semi-definite covariance matrix. The selection process is partly performed in mobile users such that they select and feed back $l$ active channels corresponding to the $l$ largest eigenmodes, which reduces the feedback amount by a factor of $l$. The upper bound is the sum capacity of the MIMO BC as described above and the bound is achievable when the power $P$ goes to infinity and the number of receive antennas is one for all receivers.

4. Candidate Schemes for Comparison

The sum-rate maximization can be solved efficiently by using SP-IWF, which achieves the sum capacity of a MIMO BC. On the other hand, time-division multiple-access (TDMA), where the BS transmits to only a single user at a time by using all transmit antennas, is a suboptimal solution when the BS has multiple transmit antennas, called TDMA-MIMO, while it achieves the sum capacity with only one transmit antenna. It is then shown that the maximum sum-rate of TDMA-MIMO is the largest single-user capacity of the $K$ users, which is given by

$$C_{\text{TDMA-MIMO}}^\text{max} = \max_{i=1, \ldots, K} C(H_i, P)$$

where $C(H_i, P)$ denotes the single-user capacity of the $i$-th user subject to power constraint $P$.

IV. PERFORMANCE ANALYSIS

In this section, the performance analysis is presented. We remind that the entries of $\{H_k\}$ are assumed to be i.i.d. zero-mean complex-Gaussian random variables. The proofs of the following lemmas and theorems are presented in [10].

**Theorem 1** (Optimizing transmit covariance matrix) The objective of the transmit covariance matrix design is to find a covariance matrix set that maximizes the system throughput, subject to the sum power constraint and the unknown-interference free constraint. The transmit covariance matrix satisfying this objective is obtained by QR decomposition of $F$.

**Lemma 1** We assume that user $k$ is not allowed to know CSI of all other users. That is, any information related to this CSI is not delivered from the transmitter as well as not exchanged between users. In this case, the
optimal processing for user $k$ is SVD-based (single-user) water-filling, in which the receive beamforming is performed with the left unitary matrix of the user $k$'s channel.

**Lemma 2** We consider a user that performs receive beamforming by the left unitary matrix of the corresponding channel. The average throughput of a MIMO BC with the user is no worse than the performance obtained based on non-cooperative reception across antennas, e.g., MMSE-DP.

**Theorem 2** Receive beamforming with the left singular matrix offers the average throughput that is no worse than any fixed unitary matrix beam scheme.

**V. NUMERICAL RESULTS**

In this section, numerical results are presented. In
In this paper, we have proposed a multiuser MIMO transmission scheme that is efficient in terms of computational complexity and feedback overhead while obtaining near the maximum sum-rate of BC. Our novel scheme has employed the block QR decomposition at the transmitter, which reduces the computational complexity to design transmit covariance matrices. Using MCSD in combination with known interference cancellation (Costa precoding), the proposed scheme with partial channel information at the transmitter has shown to still achieve the near-optimal sum capacity, which was not observed in TDMA-MIMO. Numerical results have shown that the gain of sum-rate is 2bps/Hz over the conventional MMSE-DP scheme with full channel feedback and the gap from SP-IWF is 0.4bps/Hz.

The authors would like to thank Hyeon Woo Lee, Juho Lee, and Jin-Kyu Han for their comments, as well as Lab director, Seung-yong Park. This paper has been supported in part by the Samsung Advanced Institute of Technology (SAIT) and in part by National Research Laboratory (NRL) program.

[REFERENCES]
[5] IEEE 802.11-04/891r5, TGnSync Proposal PHY Results
[6] IEEE 802.11-05/0149r1, High throughput extension to the 802.11 standard (WWiSE)


Kiho Kim obtained his bachelor’s degree in Electronics and Communications Engineering from the College of Engineering, Hanyang University, Korea in 1980, his master’s degree from KAIST in 1982 and his PhD from University of Texas at Austin in 1991. He worked at KBS technology center from 1982 to 1987. Since 1991, he has been with Samsung advanced institute of technology as vice president. His interests include signal processing and wireless communications.
E-mail: kihokim@samsung.com
Fax.: 82-31-280-9569
Tel:+82-31-280-9220
Kwang Bok Lee

Kwang Bok Lee received the B.A.Sc. and M.Eng. degrees from the University of Toronto, Toronto, Ont., Canada, in 1982 and 1986, respectively, and the Ph.D. degree from McMaster University, Canada in 1990. He was with Motorola Canada from 1982 to 1985, and Motorola USA from 1990 to 1996 as a Senior Staff Engineer. At Motorola, he was involved in the research and development of wireless communication systems. He was with Bell-Northern Research, Canada, from 1989 to 1990. In March 1996, he joined the School of Electrical Engineering, Seoul National University, Seoul, Korea. Currently he is an Associate Professor in the School of Electrical Engineering. He was a Vice Chair of the School of Electrical Engineering from 2000 to 2002. He has been serving as a Consultant to a number of wireless industries. Since 2003, he has been a senior member of the IEEE. His research interests include mobile communications, communication technique covering physical layer and upper layer. He holds ten U.S. patents and four Korean patents, and has a number of patents pending.

Dr. Lee was an Editor of the IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, Wireless Series in 2001, and has been an Editor of the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS since 2002. And he is a co-chair of the ICC2005 Wireless Communication Symposium. He received the Best Paper Award from CDMA International Conference 2000 (CIC 2000), and the Best Teacher Award in 2003 from College of engineering, Seoul National University.

E-mail: klee@snu.ac.kr
Tel.:+82-31-880-8415
Fax.:+82-31-880-8215