HSDPA in Gaussian MIMO Broadcast Channels

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Abstract—We compare the achievable throughput of time division multiple access multiple-input multiple output (TDMA-MIMO) scheme illustrated in 3rd generation partnership project (3GPP) MIMO technical report (TR), versus the sum-rate capacity of a space-time multiple access (STMA). These schemes have been proposed to improve 3GPP high speed downlink packet access (HSDPA) channel by employing multiple antennas at both transmitter and receiver. Our comparisons are focused on the performance in multi-user environments, which is considered using TDMA which is a simpler technique than STMA (e.g., Qualcomm’s High Dare Rate (HDR) and WCDMA/HSDPA). In addition, we introduce optimal power allocation strategy for HSDPA MIMO schemes under Gaussian MIMO broadcast channels (BC) by using the similarity of multiple antenna systems and multi-user channel problems.

I. INTRODUCTION

In third generation wireless mobile communications (e.g., wideband code division multiple access (WCDMA)), high-rate data transmissions need to be supported for wireless multimedia services. High speed downlink packet access (HSDPA) is a solution to achieve a bit rate of 10Mbps [1]. HSDPA system includes various technologies such as adaptive modulation and coding (AMC), hybrid automatic repeat request (HARQ), fast cell selection (FCS), and multiple-input multiple-output (MIMO) antenna processing [2].

There are various categorized schemes of MIMO, depending on the target performance characteristics, which increases data rate as well as spectral efficiency [3]. Transmit diversity uses multiple transmit antennas to enhance the link reliability by transmitting multiple copied signaling in various ways. Receive diversity is reciprocal to the transmit diversity, where multiple receive antennas are used to improve the error performance by combining the received signals through multiple receive antennas. Space-time coding is a popular solution for diversity gain and/or coding gain, which can be easily combined with all kinds of multiple antenna systems [4]. Space-time block coding has been already adopted in 3rd generation partnership project (3GPP) standardizations, which is characterized by its simple transmit and receive structures for implementations [5]. Space-time trellis coding is another type of space-time coding, achieving diversity gain and coding gain at the cost of computational complexity. Beamforming is a good candidate for interference suppression and high capacity performance with a long history of research work [6]. Smart antenna exploits beamforming to boost up the system capacity and reduce the interference in cellular environments. Adaptive beamforming keeps updating the complex weights of array for an optimal signal-to-interference-plus-noise ratio (SINR), while switched beamforming switches between the predetermined beams selected from a library of weights based on the received signal strength measurements.

Spatial multiplexing is the most advanced MIMO scheme. Lucent developed the Bell laboratories layered space-time (BLAST) architecture, which may be split into vertical BLAST (V-BLAST) and diagonal BLAST (D-BLAST) [7]. BLAST-based transmission schemes exploit spatial multiplexing gain through different data streams on each transmit antenna. In V-BLAST, independent channel coding is applied to each sub-layer, i.e. the data substream corresponding to each transmit antenna. D-BLAST applies independent coding across time as well as the antennas (sub-layers) with high complexity. All sub-layers for both schemes consist of the same code rate and the same modulation order, of which the properties are modified in the enhanced schemes. Most previous MIMO schemes are based on point-to-point communications at a time, i.e., single-user MIMO (SU-MIMO). For the evaluation of system performance, the multi-user environment needs to be considered. SU-MIMO systems focus on link performance without any higher layer assumptions. In multi-user MIMO (MU-MIMO) systems, all users are controlled simultaneously for communications by considering e.g., scheduling algorithms [8], [9].

Recently, the industrial organizations have proposed their MIMO techniques in 3rd generation partnership project (3GPP) standardizations. In 3GPP, various multi-antenna schemes are on active discussions, especially when combined with high speed downlink packet access (HSDPA). In this paper, we review the proposed MIMO techniques which have been agreed to be included in 3GPP MIMO working item technical report (WI-TR) [2]. In addition to those observations, we study optimal power allocation strategy in Gaussian MIMO broadcast channels (BC) [8].

The rest of the paper is organized as follows. In Section II, we examine the characteristics of SU-MIMO and MU-MIMO. Section III reviews the MIMO candidates in 3GPP and propose...
optimal power allocation strategies for each scheme if needed. We conclude in Section VI.

Notation: The matrix norm of $H$ is defined by $\|H\| = \sqrt{\lambda_{\text{max}}(HH^H)}$.

II. SYSTEM MODEL

In Fig. 1, a multi-user MIMO system in wireless mobile channels is illustrated, in which a radio base station (BS) communicates with $K$ mobile stations (MSs). Each MS has the linear/non-linear reception entity and $M_r$ receive antennas, while the BS has $M_t$ transmit antennas. Based on the channel state information (CSI) fed back from MSs if necessary, BS performs appropriate space-time processing such as multi-user scheduling, power and modulation adaptation, beamforming, and/or space-time coding.

Assume that $H_k$ is the $M_r \times M_t$ MIMO channel matrix from the BS to $k$th MS, $x$ is the $M_t \times 1$ transmitted symbol vector, $n_k$ is the $M_r \times 1$ independent and identically distributed (i.i.d.) additive white Gaussian noise (AWGN) vector $\sim CN(0, I_{M_r})$, and $y$ is the $M_r \times 1$ received symbol vector. Then, the received signal for the $k$th MS in multi-user MIMO systems is mathematically described as

$$y_k = H_k x + n_k$$

where $k = 1, \ldots, K$. The transmitter is subject to an average power constraint $\text{Tr}(\Sigma_x) \leq P$ where $\Sigma_x \triangleq E[xx^H]$ denotes the covariance matrix of the input signal. In our analysis, the mobile channel $H_k$ is modeled as a single path Rayleigh with i.i.d. entries $\sim CN(0, 1)$ and block fading.

MIMO schemes for BC represented as (1) can be brought into several scenarios, depending on the assumptions about the BS and the constraints put on transmit streams. First, we consider two methods of multiple access, which are time division multiple access multiple-input multiple-output (TDMA-MIMO) and space-time multiple access (STMA), as shown in Fig. 2. TDMA-MIMO is a point-to-point communication at a time, in which BS transmits to the one selected user so as to optimize the link performance, while STMA allows BS to transmit to multiple users simultaneously, resulting in the capacity limit of the multiple antenna BC since the multiple antenna BC has the rank-aware degraded nature. These will be described in details in the following subsections.

Secondly, the uncoordinated BC MIMO is distinguished from the coordinated BC MIMO corresponding to the constraints on the transmit streams. If every transmit stream at BS is regarded as an individual user, (1) represents the uncoordinated BC MIMO, arising in the Vertical Bell Labs layered space-time (V-BLAST) with the per-antenna rate control (PARC). Note that in the uncoordinated BC MIMO a single user and multiple users in the system result in a vector multiple access channel (MAC) and an vector interference channel environment, respectively, with the modified power constraint, i.e., the sum power constraint is put on the transmit streams instead of separate power constraints. On the other hand, if they are not individual but allowed to cooperate, (1) represents the coordinated BC MIMO, arising in the diagonal Bell Labs layered space-time (D-BLAST) with multi-dimensional coding. Hence, in developing the optimal MIMO, similarities are noted between multiple antenna systems and the multi-user channel problems [10].

A. SU-MIMO Capacity

Before establishing the sum capacity of TDMA-MIMO and STMA in multi-user environments, we first formally define the capacity of SU-MIMO. In SU-MIMO systems, the channel capacity obtained by the optimal MIMO transceiver is given by

$$C(H_k) = \sum_{m=1}^{M_t} \log(1 + p_m \lambda_m(H_k))$$

1The multiple antenna BC is shown to have continually a non-degraded nature until the number of selected users is less than or equal to the number of transmit antennas, otherwise adding more users degrades the capacity.
where $\lambda_m(A)$ is the $m$th eigenvalue of $AA^H$. The power distribution factor $p_m$ is set to $P/M_t$ for the open-loop (OL) MIMO case, whereas the water-filling is applied with the power constraint $\sum_mp_m \leq P$ for the optimum distribution in the closed-loop (CL) MIMO case. It is shown in [11] that the ergodic capacity for OL-MIMO with e.g., $M_t = M_r$ can be precisely approximated as

$$\tilde{C}_{M_t,M_r} \approx \tilde{C}_{1,1} + (M_t - 1) \cdot \lim_{n \to \infty} \frac{\tilde{C}_{n,n}}{n} \quad (3)$$

where $\tilde{C}_{1,1}$ is the average capacity of single-input single-output (SISO) Rayleigh channel, and the other part is the capacity of both the number of transmit and receive antennas approaching infinity divided by the number of antennas.

B. TDMA-MIMO Capacity

Consider the sum-rate capacity of the TDMA-MIMO, in which BS transmits only to the user with the largest capacity at a time, and hence the sum-rate capacity is given as

$$C_{TDMA}(H_1, \ldots, H_K) = \max_{k=1,\ldots,K} C(H_k) \quad (4)$$

where we have used the definition that the maximum sum-rate of TDMA-MIMO is the largest single user capacity of the $K$ users. It is shown in [12] that the TDMA-MIMO sum-rate is lower bounded by

$$C_{TDMA}(H_1, \ldots, H_K) \geq \log(1 + P\|H_k\|^2_{\text{max}}) \quad (5)$$

where $\|H_k\|_{\text{max}} = \max_{k=1,\ldots,K} \|H_k\|$.

C. STMA Capacity

It has been known that the sum capacity of STMA is achieved by using dirty paper coding (DPC) to simultaneously transmit to not only one user but also several users optimally selected. Intuitively speaking, DPC processing for BC can be seen like the successive interference cancellation (SIC) with the minimum mean-square error (MMSE) QR decomposition at the transmitter side. So, the sum capacity of STMA, which can be achieved by DPC, is represented by the upper bound

$$C_{STMA}(H_1, \ldots, H_K) = C_{DPC}(H_1, \ldots, H_K) = \max_{\{Q_k, Q_k \geq 0, \sum_{k=1}^K \text{Tr}(Q_k) \leq P\}} \log \left| I + \sum_{k=1}^K H_k^H Q_k H_k \right| \leq M_t \log \left( 1 + \frac{P}{M_t \|H_k\|_{\text{max}}^2} \right) \quad (6)$$

where we have employed the duality of the multiple antenna BC and MAC to make simple following descriptions. In Fig. 3, the STMA and TDMA-MIMO sum capacity ($C_{STMA}(H_1, \ldots, H_K)$ and $C_{TDMA}(H_1, \ldots, H_K)$, respectively) are plotted for the 10-user, $M_t = 4, M_r = 2$ BC channel, along with the upper bound of STMA and the lower bound of TDMA-MIMO. STMA is shown in Fig. 3 to achieve the gain around two times over TDMA-MIMO.

The ergodic capacity of STMA with $K$ users in a fading channel, based on the result of (2), is upper bounded by

$$\tilde{C}_{M_t,M_r,K} \leq M_t \tilde{C}_{1,1,K} = M_t \sum_{k=1}^K \binom{K}{k} (-1)^{k+1} k^{k-1} \Gamma_0[k/P] \quad (7)$$

where $\Gamma_0[z] = \int_z^\infty t^{z-1} e^{-t} dt$ is the incomplete gamma function.

D. 3GPP Channel Preliminaries

The spatial channel model (SCM) was jointly developed by the combined 3GPP-3GPP2 spatial channel ad-hoc group. The need for specifying the SCM work is based on both the link level and system level performance evaluations. The system level simulations are required for the algorithm comparisons, while link level simulations are only for calibration purposes. There are three different environments for channel modeling, which are suburban macro, urban macro, and urban micro cases. Different path-loss models are used according to environments. System simulations consider multiple cells, BSs, and MSs with performance metrics such as throughput and delay, where parameters for temporal and spatial channel coefficients need to be defined.

III. TDMA-MIMO PROPOSALS IN 3GPP

In this section, we investigate advanced MIMO solutions, mainly focusing on MIMO candidates in 3GPP standardizations. In 3GPP, major industrial organizations proposed their schemes toward the official use of MIMO in future wireless communication systems. As mentioned in the previous sections, most techniques are based on the mixture of basic MIMO algorithms for performance improvement. We observe the system architecture of each candidate and investigate their performance analysis.

A. PARC

Lucent initially proposed their multiple antenna solution, which is called the per-antenna rate control (PARC) [13]. The transmitter structure of PARC is shown in Fig. 4, in which
Input stream
DEMUX
Encoder/Modulator
Separating code
Scrambling code
Fig. 4. Schematic of PARC transmitter

separately encoded data streams are transmitted from each antenna with equal power but possibly with different data rates while spreading code is reused through all streams. The data rates for each antenna are controlled by adaptively allocating transmit resources such as modulation order, code rate, and number of spreading codes. The post-decoding SINR of each transmit antenna is estimated at the receiver and then fed back to the transmitter, which is used to determine the data rate on each antenna. The vector signaling with more feedback overhead over the scalar signaling in conventional systems is required for link adaptation.

The MMSE filtering and SIC are applied to the receiver, i.e., SIC reception. Let
\[ G_{k,m} = (H_{k,m}^H H_{k,m} + 1/P I_{M_t-m})^{-1} \]  
where \( I_{M_t-m} \) is the \( M_t-m \) dimension square identity matrix and \( H_{k,m} \) is a deflated version of \( H_k \) in which columns 1, 2, \ldots, \( m \) have been zeroed. The received SINR of the \( m \)th stream becomes
\[ \gamma_{S,k,m} = \frac{P/M_t}{|G_{k,m}|_{m,m}} - 1. \]
The capacity is then
\[ C_k = \sum_{m=1}^{M_t} c_f(\gamma_{S,k,m}) \]
where \( c_f(\gamma) = \log(1 + \gamma) \). On the other hand, by replacing \( H_{k,m} \) by \( H_k \) in (4), the received SINR, denoted as \( \gamma_{M,k,m} \), and the capacity can be derived for MMSE reception.

B. S-PARC

The selective PARC (S-PARC) has been proposed by Ericsson, which is conceptually based on PARC scheme in the previous subsection [14]. Recent results have shown that PARC achieves the full OL capacity of the flat fading MIMO channel. However, there is a significant gap between the OL capacity and the CL capacity when signal-to-noise ratio (SNR) is low and/or the number of receive antennas is less than the number of transmit antennas. An alternative way is by S-PARC, which overcomes performance gap by the gain of antenna selection. More specifically, S-PARC adaptively selects the number of antennas, i.e., mode, and the best subset of antennas for the selected mode. Interestingly, S-PARC will operate like a single stream transmit diversity with transmit antenna selection if the number of the selected antennas is limited to one.

The antenna selection is suboptimal, so we first review the optimal power allocation across antennas before describing the operation of S-PARC. To allocate optimal power for each transmit antenna in PARC-like systems, we may use the water-filling with iterative method proposed in [15]. From the similarity of PARC and MAC, the objective of such a problem in SU-MIMO channels can be represented by the simplified form of (6), which is given by
\[ C_{S-PARC_{opt}}(H) = \max_{p_m} \log \left| I + \sum_{m=1}^{M_t} p_m h_m h_m^H \right| \]
subject to \( p_m \geq 0, \sum_{m=1}^{M_t} p_m \leq P \)

where \( H = [h_1, h_2, \ldots, h_{M_t}] \). Substantial progress for optimization has recently been made [12], [15], which is not yet completely answered because of its implication of the sum-power constraint, i.e., \( \sum_{m=1}^{M_t} p_m \leq P \).

Secondly, S-PARC performs the antenna selection based on a subset property, by which selections at the prior mode are considered, so as to reduce the amount of feedback. The schematic of the transmitter is illustrated in Fig. 5, where the adaptive modulation and code (AMC) controller handles the adaptive mode of antenna, modulation, and coding. Also, in the antenna processor the appropriate power balancing from all transmit antennas is achieved before transmission.

Fig. 6 shows the maximum achievable rate for comparison when \( M_t = 4 \) and \( M_r = 2 \), in which S-PARC outperforms PARC by about 1.8dB in all range of SNR. Note that this gain comes from antenna selection diversity.

C. TxAA MIMO schemes

The Nokia proposal, the CL-MIMO with 4Tx and 2Rx, is an extension of the transmit antenna array (TxAA) adopted in Rel99, which is still a single-stream MIMO technique.

Another proposal, double TxAA (D-TxAA), has also been contributed by LGE. In D-TxAA, if, e.g., four transmit antennas (\( M_t = 4 \)) are employed in BS, transmit antennas are
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\begin{align}
C_{D-TxAA}(H_1, H_2) = & \max_{Q_m} \log \left| 1 + \sum_{m=1}^2 H_m Q_m H_m^H \right| \\
\text{subject to } & Q_m \succeq 0, \sum_{m=1}^2 \text{Tr}(Q_m) \leq P \quad (12)
\end{align}

where $H_1 = [h_1, h_2], H_2 = [h_3, h_4]$ denote the first and second sub-group channel matrix, respectively. The capacity of D-TxAA is larger than that of S-PARC but smaller than that of optimal CL-MIMO, which can be easily proved by (12), noting that the gain over S-PARC comes from the use of additional feedback information for transmit beamforming inside the sub-group antennas.

### IV. Conclusion

We investigated the iterative water-filling algorithm to observe the sum-rate capacity of STMA, along with achievable throughput of TDMA-MIMO. Based on the similarity of multiple antenna systems and multi-user channel problems, we proposed optimal power allocation strategy for TDMA-MIMO as in 3GPP HSDPA, i.e., for S-PARC and D-TxAA, under Gaussian BC. For future work, the efficient resource allocations such as transmit power and antennas need to be taken into account for STMA.

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