Ph.D. Dissertation

SVD-Based Unitary Processing for Downlink Multiuser MIMO Systems

(다중사용자 다중안테나 시스템을 위한
SVD 기반의 유니터리 프로세싱)

BY

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이 논문을 공학박사 학위논문으로 제출함

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ABSTRACT

Over the last decade, multiple-user multiple-input multiple-output (MU-MIMO) processing has gained considerable attention in the wireless communication standards such as 3GPP-LTE Advanced, IEEE 802.16m, and IEEE 802.11ac. MU-MIMO processing is capable of simultaneously supporting multiple users and therefore attains large cell capacity increase. In this dissertation, MU-MIMO processing with low-computational complexity and applicability to diverse wireless communication systems is proposed for practical interests. For evaluating average sum-rate of the proposed MU-MIMO processing, two different wireless communication systems, cellular systems and wireless local area network (WLAN) systems, are considered in Parts I and II.

In Part I of this dissertation, we focus on cellular systems where low feedback bits are allocated to report user channel information. For practical downlink MU-MIMO processing, we propose a linear beamforming MU-MIMO processing with low-computational complexity that includes preferred-beam index feedback, user selection algorithms, and beamforming matrix construction method. The preferred-beam index feedback efficiently conveys information on both the channel states of users and the effect of interuser interference especially in low-rate feedback environments. The proposed user selection algorithms exploits multiuser diversity to

improve average sum-rate for the case when the number of users exceeds the number of transmit antennas. The proposed beamforming matrix construction method easily computes unitary beamforming matrix based on the feedback information using singular value decomposition (SVD) operation, which results in significant computational complexity reduction compared to the conventional methods. Simulation results show that the proposed SVD-based unitary MU-MIMO processing achieves higher average sum-rate particularly at low-rate feedback, while the computational complexity is kept reasonable.

In Part II of this dissertation, IEEE 802.11ac-based WLAN systems are considered where Access Point (AP) can transmit multiple data streams to different users in parallel by MU-MIMO processing. Unlike cellular systems, the considered WLAN systems assign high-rate bits to feedback user channel information and utilize an efficient feedback mechanism using Givens rotation that reduces the overhead of feedback information. As a result, a channel quantization error caused by low-rate feedback could be negligible. In WLAN systems, however, there may be long feedback delay, more than 200 ms in reality, that leads to severe performance degradation. In addition, WLAN systems are difficult to directly apply conventional user selection algorithms including the proposed one in Part I since group identification (ID) and user scheduling that WLAN standard newly defines for MU-MIMO processing should be considered. Based on these features, we propose an efficient and a practical user selection algorithm with low-computational complexity. Simulation results also present that the proposed MU-MIMO processing combined with the proposed user selection algorithm considerabley outperforms conventional MU-MIMO processing such as zero-forcing beamforming (ZFBF) especially in low signal to noise ratio (SNR) region and/or long feedback delay.

Keywords: MU-MIMO processing, cellular systems, channel feedback, user selection, beamforming, WLAN systems, IEEE 802.11ac, channel sounding, user grouping, user scheduling

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Chapter 1

Introduction

Over the last decade, multiple-user multiple-input multiple-output (MU-MIMO) processing has gained considerable attention in the wireless communication standards such as 3GPP-LTE Advanced, IEEE 802.16m, and IEEE 802.11ac. The MU-MIMO processing is capable of simultaneously supporting multiple users and therefore attains large cell capacity. In this dissertation, MU-MIMO processing with low-computational complexity and applicability to diverse wireless communication systems is proposed for practical interests. For evaluating average sum-rate of the proposed MU-MIMO processing, two different wireless communication systems, cellular systems and wireless local area network (WLAN) systems, are considered in Parts I and II.

1.1 SVD-Based Unitary MU-MIMO Processing in Cellular Systems

In the last decade, linear beamforming processing for multi-user multiple input multiple output (MU-MIMO) cellular systems has been extensively studied such as zero-forcing beamforming (ZFBF) [1], block diagonalization (BD) [3], and generalized multiuser orthogonal space-division multiplexing [4] based on a theoretical approach. Recently, the studies have been extended to more important and practical scenario of partial channel state information at the transmitter (CSIT) such as limited feedback-based ZFBF [5], BD [6], coordinated beamforming (CB) [7]. In the studies, it has been verified that the majority of MU-MIMO processing, particularly ZFBF and BD, is very sensitive to CSI accuracy [8], [9]. Thus, they suffer from severe performance degradation especially at low feedback rate [10]. To alleviate this problem, quantization-based combining (QBC) [11] and maximum expected signal-to-interference and noise ratio combiner (MESC) [12] which improve receiver combining technique to reduce the required feedback rate were proposed. However, in cellular systems, low channel feedback rate is still a major limiting factor.

On the contrary, random orthogonal beamforming (ROB) processing in [2] is designed to be appropriate for MU-MIMO cellular systems with low feedback rate. It is shown that the ROB also achieve the sum-rate capacity only if the number of users goes to infinity. Hence, a per-user unitary and rate control (PU^{2}RC) scheme [14,15] which is a practical implementation of the ROB has become one of the major candidates for MU-MIMO cellular systems in next generation wireless communication standards [16,17]. However, the major drawback of the PU^{2}RC is that the choice of beamforming matrix at the base station (BS) is limited within the predefined codebook. Thus, the system becomes inefficient when there are finite number of users whose channels are not well-matched to the beamforming matrix in the predefined codebook.

The solutions for the problem have been researched in two ways. One approach is to improve the codebook to exploit the channel statistic efficiently [13]. The other approach is to compute the beamforming matrix adaptively. Unfortunately, both approaches have not provided noticeable improvements, practically. As an example of the later, an enhanced unitary beamforming processing which constructs the beamforming matrix without constraint of the predefined codebook has been proposed [18]. However, the enhanced unitary beamforming processing in [18] includes an iterative algorithm for the construction of the appropriate beamforming matrix, which results in high computational complexity in return for the increased average sum-rate.

In this part, we propose a new MU-MIMO processing which includes the improvements in both channel feedback of users and beamforming matrix construction at the BS. As the simulations results will show, the proposed MU-MIMO processing provides the improved average sum-rate especially at low feedback rate reducing the required computational complexity for the determination of the beamforming matrix.

1.2 SVD-Based Unitary MU-MIMO Processing in WLAN Systems

With increasing demand of various multimedia service via wireless communication networks, the next generation WLAN standards such as IEEE 802.11ac have been under development. In IEEE 802.11ac standard, WLAN systems provide at least 1 Gbps throughput for multiple stations. For this purpose, the standard has adopted a downlink MU-MIMO processing that enables an access point (AP) to simultaneously transmit multiple data streams for multiple stations. Using downlink MU-MIMO processing, WLAN systems take advantage of multiplexing and user diversity gains, which results in significant throughput improvement compared with previous standards including IEEE 802.11n.

Based on ongoing development of IEEE 802.11ac standard, downlink MU-MIMO processing for WLAN systems has been extensively studied in literature [26–32]. In [26–28], it is demonstrated through analysis and simulation evaluation that MU-MIMO processing in WLAN systems achieves the enhanced throughput performance by exploiting user diversity. In [29–32], realizing MU-MIMO processing is confirmed in real-world WLAN systems and throughput performance is evaluated using extensive measurements as a function of various factors such as channel conditions, signal power, and interference power.

The aformentioned studies, however, have limitations to directly apply in practical WLAN systems besed on IEEE 802.11ac standard since they do not consider new concepts and features defined in the standard such as channel sounding that estimates the behavior of wireless channels between AP and users, group identification (ID) and user scheduling operation that are used for selecting the number of transmitted users and data streams per user. Moreover, they use assumptions that are invalid in real-world WLAN systems such as same average SNR and the same number of antennas and only investigate the specific MU-MIMO processing, ZFBF, among diverse pragmatic MU-MIMO processing, which results in insufficient understanding of system performance when MU-MIMO proceeing is applied in WLAN systems.

In this part, we apply the proposed SVD-based unitary MU-MIMO processing to IEEE 802.11ac-based WLAN systems. To reflect real-world condition of WLAN systems, we consider that stations are randomly located within a cell and therefore experience different SNR [33]. In addition, wireless channels vary continuously depending on the WLAN system environemnt. Based on these considerations, through numerical results, we evaluate average sum-rate of the proposed MU-MIMO processing and confirm performance improvement compared with ZFBF. And then, we propose an adaptive user scheduling algorithm to effectively adjust the number of transmitted users and data streams per user. The proposed user scheduling algorithm is based on accurate closed-form expression derived for achievable average sum-rate for the different number of users and data streams per user, and has low-computational complexity since only average SNR, channel variation, and the number of AP and station antennas need to be computed and compared.

1.3 Outline of Dissertation

The remainder of the dissertation is organized as follows. Chapter 2 (Part I) describes the proposed SVD-based unitary processing for downlink MU-MIMO cellular systems. The proposed MU-MIMO processing includes a channel feedback method to convey channel state information combined with the effect of interference, a low computational complexity algorithm to constructs a unitary beamforming matrix by using SVD operation, a user selection algorithm to exploit mutiuser diversity. Numerical results show that the proposed MU-MIMO processing achieves higher average sun-rate performance than conventional MU-MIMO processing, especially at low-feedback rate and with small user pool. In Chapter 3 (Part II), the proposed MU-MIMO processing is applied to WLAN systems and confirmed for average sum-rate improvement. In addition, an adaptive user scheduling algorithm based on closed-form expression of achievable average sum-rate is proposed to effectively adjust the number of transmitted stations and streams per station. Finally, conclusions are drawn in Chapter 4.

Chapter 2

SVD-Based Unitary MU-MIMO Processing in Cellular Systems

2.1 System Model

As depicted in Fig. 2.1, downlink MU-MIMO cellular systems are considered, where the BS has N_T antennas and each of K users has N_R antennas. In the considered cellular systems, we assume an independent and identically distributed (i.i.d.) Rayleigh flat fading channel and therefore the elements of the user channel matrix are independent complex Gaussian random variables with zero mean and unit variance. For simulation and limited feedback codebook design purposes, the block fading channel is also assumed to be static during a time slot and changing independently over time slots, which can be attained practically using multiple input multiple output orthogoanl frequency division multiplexing (MIMO-OFDM).

Based on the assumptions and considerations, the received signal at the k-th user after receiver combining is given by

$$y_k = \mathbf{r}_k(\sqrt{\rho_k} \cdot \mathbf{H}_k \mathbf{F} \mathbf{x} + \mathbf{n}_k), \quad k = 1, 2, \cdots, K, \tag{2.1}$$

where $\mathbf{H}_k \in \mathbb{C}^{N_R \times N_T}$ is the channel matrix of the k-th user, $\mathbf{F} \in \mathbb{C}^{N_T \times N_T}$ is the beamforming matrix, $\mathbf{x} \in \mathbb{C}^{N_T \times 1}$ is the transmitted symbol vector, $\mathbf{r}_k \in \mathbb{C}^{1 \times N_R}$ is the unit norm receiver combining vector for the k-th user, and $\mathbf{n}_k \in \mathbb{C}^{N_R \times 1}$ is the additive white Gaussian noise vector at the receiver. ρ_k is the signal to noise ratio (SNR) at the k-th user reflecting random geometry as $\rho_k = \frac{P}{N_0 d_k^\alpha}$, where P, d_k, α, and N_0 denote the total transmit power, distance of the k-th user from AP, path loss exponent, noise power, respectively. Here, N_T users are supported simultaneously after user selection and each selected user is allocated with single data stream. Equal power allocation for each data stream is assumed to be $\mathrm{E}[\mathbf{x}\mathbf{x}^{\mathbf{H}}] = \frac{1}{N_T}\mathbf{I}_{N_T}$. And, perfect CSI at the user terminal, an error-free and zero-delay feedback link are also assumed.

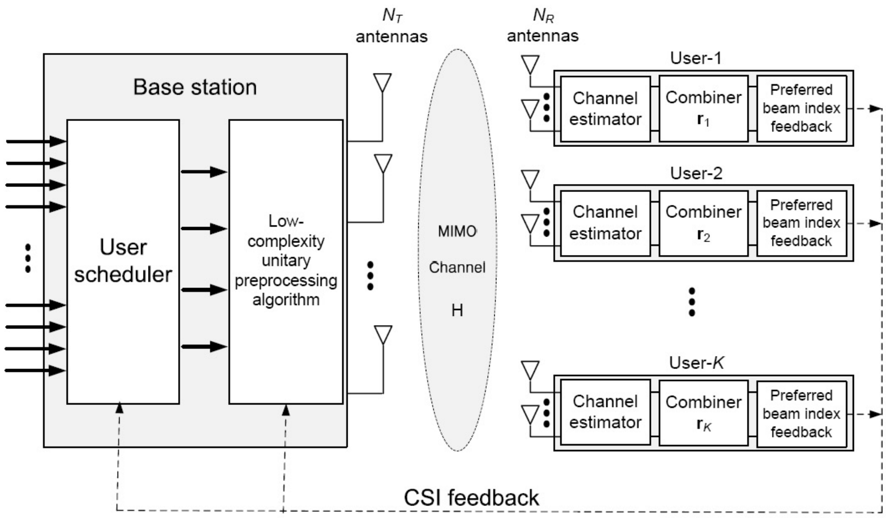


Figure 2.1: MU-MIMO system model.

For better understanding of the proposed MU-MIMO processing, a timing diagram is illustrated in Fig. 2.2. At first, each user estimates its own channel from pilot broadcasting. Then, each user quantizes its channel information into channel quality information (CQI) and channel direction information (CDI) using the codebook, $\mathbf{C} = \{\mathbf{c}_1, \mathbf{c}_2, \ldots, \mathbf{c}_{2^B}\}$, generated by Grassmannian line packing (GLP) method [19], where B denotes the number of feedback bits per user. The quantized user channel information reports to the BS. Based on feedback information of all users, the BS selects N_T users to transmit simultaneously, and constructs the unitary beamforming matrix for downlink transmission. Finally, the BS broadcasts information of the set of the selected users and beamforming vector of each selected user through feedforward channels before it transmits user data through data channels.

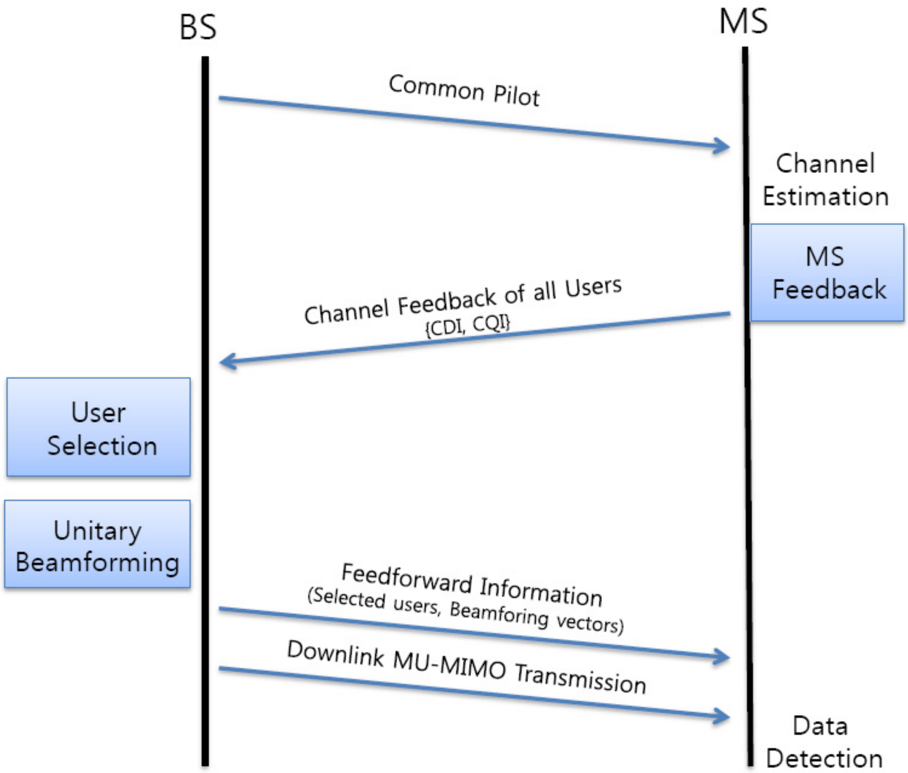


Figure 2.2: Timing Diagram of Operation in Proposed MU-MIMO Processing.

2.2 Proposed SVD-Based Unitary MU-MIMO Processing

In this section, a new user feedback method is proposed which efficiently conveys information on both channel state and the effect of inter-user interference at low feedback rate. Then, two user selection methods for the case when the number of users exceeds the number of transmitting antennas are presented and compared. And, it is also explained how a unitary beamforming matrix can be easily constructed at the BS with simple manipulations using singular value decomposition (SVD). Finally, receive antenna combining and data decoding at the selected users are described.

2.2.1 User Feedback

For an effective user channel feedback, signal power to interference and noise power ratio (SINR) is considered to capture the effects of inter-user interference when determining MS feedback.

Theorem 1 *If the beamforming matrix,* $\mathbf{F} = \begin{bmatrix} \mathbf{f}_1 & \mathbf{f}_2 & \cdots & \mathbf{f}_{N_T} \end{bmatrix}$*, is a unitary matrix, the SINR of the k-th user after linear minimum mean square error (LMMSE) combining,* η_k*, depends only on both the corresponding beamforming vector,* $\mathbf{f}_k$*, and the instantaneous channel matrix,* $\mathbf{H}_k$*.*

$(proof)$

$$\begin{aligned}\eta_k &\overset{(a)}{=} \frac{1}{\left[\left(\frac{\rho_k}{N_T}\mathbf{F}^{\mathrm{H}}\mathbf{H}_k^{\mathrm{H}}\mathbf{H}_k\mathbf{F} + \mathbf{I}_{N_T}\right)^{-1}\right]_{k,k}} - 1 \\ &\overset{(b)}{=} \frac{1}{\left[\mathbf{F}^{\mathrm{H}}\left(\frac{\rho_k}{N_T}\mathbf{H}_k^{\mathrm{H}}\mathbf{H}_k + \mathbf{I}_{N_T}\right)^{-1}\mathbf{F}\right]_{k,k}} - 1 \\ &= \frac{1}{\mathbf{f}_k^{\mathrm{H}}\left(\frac{\rho_k}{N_T}\mathbf{H}_k^{\mathrm{H}}\mathbf{H}_k + \mathbf{I}_{N_T}\right)^{-1}\mathbf{f}_k} - 1, \end{aligned} \tag{2.2}$$

where (a) is from [20], and (b) follows from $\mathbf{F}^{\mathrm{H}}\mathbf{F} = \mathbf{F}\mathbf{F}^{\mathrm{H}} = \mathbf{I}_{N_T}$. [1]

According to the theorem, user-k can find the best $\mathbf{f}_k$ that maximizes η_k regardless of the beamforming vectors of other users. Since users should feedback their channel information using the predefined codebook, $\mathbf{C}$, the feecback information can be determined as

$$\pi(k) = \arg \max_{i=1,\ldots,2^B} \frac{1}{\mathbf{c}_i^{\mathrm{H}}(\frac{\rho_k}{N_T}\mathbf{H}_k^{\mathrm{H}}\mathbf{H}_k + \mathbf{I}_{N_T})^{-1}\mathbf{c}_i} - 1. \tag{2.3}$$

[1] Derivations in (2.2) also used in [18] for a different application.

Here, $\mathbf{c}_{\pi(k)}$ implies the preferred beamforming vector of the k-th user. Now, the k-th user reports the index, $\pi(k)$, and the corresponding SINR value, η_k, as feedback information.

Conventional user feedback methods in [5, 11, 18] only consider the CSI of individual users without inter-user interference; i.e., user feedback is determined by computing inner products between own channel direction and codeword in the codebook. Thus, all processes for interference mitigation are performed at the BS, which becomes inefficient, especially in a low-rate feedback channel. In contrary, a key advantage of the proposed feedback method is that it considers inter-user interference at the feedback stage. Thus, each user is able to effectively convey its CSI combined with the effect of inter-user interference, to the BS, even in a low-rate feedback channel. [2]

Note that the user feedback method of the $\mathrm{PU^2RC}$ in [14,15] also consider both CSI and inter-user interference. However, the major weakness of the $\mathrm{PU^2RC}$ codebook is that it should be implemented with the specific codebook structure; sets of N_T-by-N_T orthonormal matrices. One practical example of designing $\mathrm{PU^2RC}$ codebook is using discrete Fourier transformation (DFT) [16]. When the number of users is extremely large, there always exists a user whose channel is well-matched to one of the codebook. As shown in the previous literature, DFT-based codebook provides good performance in this case. However, when the number of users is mod-

[2] It is worth mentioning that the key idea of the proposed feedback method can be applied to different applications. In recent parallel works, similar channel feedback idea is adopted in zero-forcing beamforming (ZFBF) based MU-MIMO systems [12,13]. Normally, the beamforming matrix of the ZFBF system is not unitary. Assuming infinite number of users, an ideal scheduler makes the beamforming matrix unitary in this case. Thus, the underlying system model becomes identical to our unitary beamforming based MU-MIMO system.

erate or low, the codebook becomes inefficient, which results in severe performance degradation. On the contrary, the proposed user feedback method described above can be implemented with any codebooks including Grassmannian which is proven to be optimal [19] and DFT-based codebooks, which is the great advantage over the conventional user feedback methods. Later in the simulation results, Grassmannian codebook was adopted for simulations.

2.2.2 User Selection

When the number of users exceeds the number of transmit antennas, i.e., $K \geq N_T$, the BS selects up to N_T users for simultaneous transmission based on the user feedback, $\pi(k)$ and η_k. In this subsection, two user selection algorithms are presented and compared.

Max-SINR User Selection

A simple and an effective algorithm to exploit multi-user diversity for the BS is to select the user with the largest η_k in the user pool, and repeat the selection process until all N_T users have been selected. The algorithm only considers the SINR values, η_k, reported from the users and therefore it can be implemented through simple ordering of scalar values. Hence, the required computational complexity is extremely low.

Semi-Orthogonal User Selection

The reported preferred beamforming feedback vectors, $\mathbf{c}_{\pi(k)}$, as well as reported SINR values, η_k, are also important factors for improving user selection performance. Since the final unitary beamforming matrix is constructed from preferred beamforming feedback vectors of the selected users as will be discussed in the next section, user selection without considering the direction information of the users may result in large discrepancies between the preferred beamforming feedback vectors, $\mathbf{c}_{\pi(k)}$, and the final beamforming vectors, $\mathbf{f}_k$. To minimize such discrepancies, it is effective to select users whose preferred vectors are as orthogonal as possible. The semi-orthogonal user selection in [1] which is based on greedy user selection [25] may be used to consider both SINR values and preferred beamforming feedback vectors.

Note that greedy user selection applied here is different from the original form in that we use the SINR value, η_k, instead of the channel gain, and the preferred beamforming vector, $\mathbf{c}_{\pi(k)}$, instead of the channel direction vector. Compared with the maximum-SINR user selection, this semi-orthogonal user selection exploits better multi-user diversity gain in return for the increased computational complexity.

2.2.3 Construction of Unitary Beamforming Matrix

The optimal unitary beamforming matrix can be found when the sum-rate which will be expressed in (2.10) is maximized. Unfortunately, this is a non-convex problem, and there has been no general solution in the literature to the best of our knowledge. In our earlier work [18], we proposed an iterative algorithm to search a sub-optimal unitary beamforming matrix. In spite of the improved sum-rate performance, the proposed algorithm is not appropriate for practical implementations due to high computational complexity. Instead, we introduce an alternative method to construct the unitary beamforming matrix in this work. By modifying the sum-rate maximization problem as follows, we can determine the beamforming matrix with extremely low computational complexity.

When each user reports its preferred beamforming vector at the feedback stage, the users believes that the reported preferred beamforming vectors would be served with them. However, it is impossible to use them directly after aggregation as a beamforming matrix since they are not orthogonal to each other. Hence, the BS needs to construct a new unitary beamforming matrix, $\mathbf{F}$, such that each beamforming vector in $\mathbf{F}$, $\mathbf{f}_k$, is as close to the reported preferred beamforming vector, $\mathbf{c}_{\pi(k)}$ as possible. Computation of the appropriate unitary beamforming matrix, $\mathbf{F}$, can be formulated as the following problem.

$$\begin{aligned} &\text{maximize} \;\; \sum_{k=1}^{N_T} \left|\left\langle \mathbf{c}_{\pi(k)}, \mathbf{f}_k \right\rangle\right| \\ &\text{subject to} \;\; \mathbf{F}^{\mathrm{H}}\mathbf{F} = \mathbf{F}\mathbf{F}^{\mathrm{H}} = \mathbf{I}_{N_T}, \end{aligned} \tag{2.4}$$

where $\langle \cdot, \cdot \rangle$ denotes inner product operation of two vectors. The unitary beamforming matrix, $\mathbf{F}^*$, maximizes the sum of the inner products between the preferred beamforming vector, $\mathbf{c}_{\pi(k)}$, and the corresponding beamforming vector, $\mathbf{f}_k^*$. In other word, the optimal beamforming vector, $\mathbf{f}_k^*$, is closely tuned to the preferred beamforming vector, $\mathbf{c}_{\pi(k)}$, in terms of chordal distance. [3]

To solve the optimization problem in (2.4), a well-known result of matrix computation [24] can be used. The steps to construct the optimal beamforming matrix are described as follows. First, the preferred beamforming vectors of the selected N_T users are aggregated as

$$\mathbf{P} = \left[\mathbf{c}_{\pi(1)}, \mathbf{c}_{\pi(2)}, \ldots, \mathbf{c}_{\pi(N_T)}\right]. \tag{2.5}$$

Then, the aggregated preferred beamforming matrix is decomposed by singular value decomposition (SVD) as

$$\mathbf{P} = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^{\mathrm{H}}, \tag{2.6}$$

where $\mathbf{U}, \mathbf{V}$ are unitary matrices, and $\mathbf{\Sigma}$ is a diagonal matrix. Finally, the optimal beamforming matrix is simply computed as

$$\mathbf{F}^* = \mathbf{U}\mathbf{V}^{\mathrm{H}}, \tag{2.7}$$

where the optimal beamforming vectors, $\mathbf{f}_k^*$, are the column vectors of $\mathbf{F}^*$. The details of proof can be found in [24].

Note that the derived solution, $\mathbf{F}^*$, is optimal for the alternative problem in (2.4), which implies that it does not guarantee its optimality in terms of sum-rate.

[3] In limited-feedback closed-loop multi-antenna systems which require efficient algorithms for the quantized information of beamforming vector and feedback vector, it is well-known that chordal distance is an appropriate design criterion to improve system performance in terms of SNR maximization as well as outage minimization [22], [19]. Therefore, based on these results, in the literature [11], [5], [23] and future wireless communication standards [16], such as LTE-Advanced and IEEE 802.16m, the design criterion using chordal distance has been adopted for the design of beamforming vector and feedback vector.

Nonetheless, the solution, $\mathbf{F}^*$, is closely related to the optimal beamforming matrix which maximizes the sum-rate since the beamforming vectors tends to align with user feedback if they are optimal. Perhaps surprisingly, the beamforming matrix, $\mathbf{F}^*$, indeed provides better sum-rate performance than the iterative algorithm [18] as will be shown in simulation results. Furthermore, the beauty of this solution is that it can be obtained with only simple matrix computations. One SVD and one matrix multiplication are all required computations, which can be implemented within the computation complexity of $O({N_T}^3)$. Thus, the solution enables extremely low-complexity construction of the beamforming matrix at the BS.

2.2.4 User Data Decoding

For coherent data decoding, the selected users require the beamforming vectors, $\mathbf{f}_k$. As presented in sytem model, the information can be conveyed in feedforward channel or broadcasted by dedicated pilot. Given the information of the beamforming vector, the LMMSE receiver of the k-th user is[4]

$$\mathbf{r}_k = \frac{\mathbf{f}_k^{\mathrm{H}}(\frac{\rho_k}{N_T}\mathbf{H}_k^{\mathrm{H}}\mathbf{H}_k + \mathbf{I}_{N_T})^{-1}\mathbf{H}_k^{\mathrm{H}}}{\left\|\mathbf{f}_k^{\mathrm{H}}(\frac{\rho_k}{N_T}\mathbf{H}_k^{\mathrm{H}}\mathbf{H}_k + \mathbf{I}_{N_T})^{-1}\mathbf{H}_k^{\mathrm{H}}\right\|}. \tag{2.8}$$

The post processing SINR of the k-th user after receive combining is expressed as

$$\mathrm{SINR}_k = \frac{1}{\mathbf{f}_k^{\mathrm{H}}(\frac{\rho_k}{N_T}\mathbf{H}_k^{\mathrm{H}}\mathbf{H}_k + \mathbf{I}_{N_T})^{-1}\mathbf{f}_k} - 1. \tag{2.9}$$

Finally, the sum-rate, R, can be computed as

$$\begin{aligned} R &= \sum_{k=1}^{N_T} \log\left(1 + \mathrm{SINR}_k\right) \\ &= -\sum_{k=1}^{N_T} \log \mathbf{f}_k^{\mathrm{H}}(\frac{\rho_k}{N_T}\mathbf{H}_k^{\mathrm{H}}\mathbf{H}_k + \mathbf{I}_{N_T})^{-1}\mathbf{f}_k. \end{aligned} \tag{2.10}$$

[4]From [20], LMMSE combining receiver of the k-th user can be derived as the kth row vector of $(\frac{\rho_k}{N_T}\mathbf{F}^{\mathrm{H}}\mathbf{H}_k^{\mathrm{H}}\mathbf{H}_k\mathbf{F} + \mathbf{I}_{N_T})^{-1}\mathbf{F}^{\mathrm{H}}\mathbf{H}_k^{\mathrm{H}}$. Since $\mathbf{F}^{\mathrm{H}}\mathbf{F} = \mathbf{F}\mathbf{F}^{\mathrm{H}} = \mathbf{I}_{N_T}$, the LMMSE combining receiver is transformed as (2.8)

2.3 Simulation Results

In this section, the average sum-rate performance of the proposed SVD-based unitary MU-MIMO processing is evaluated and compared with conventional beamforming processing through simulation. Simulation results are averaged over 1,000 independent channel realizations.

In Fig.2.3, average sum-rate performance versus SNR is plotted for 4 BS antennas (N_T), 2 user antennas (N_R), 4 users (K), 4 bits (B) for user feedback. The proposed MU-MIMO processing outperforms previous processing such as PU^{2}RC [13, 14], ZFBF [11, 12], and enhanced unitary beamforming [18] in all SNR regions. Since the user pool is not large enough to match users to predefined beamforming vectors efficiently, PU^{2}RC shows low average sum-rate performance. Although PU^{2}RC with improved codebook increases average sum-rate performance, PU^{2}RC still suffers from ineffective matching in small user pool environment.

As shown in Fig.2.3, ZFBF becomes inefficient in low-SNR region and high channel quantization error by its nature. Even though ZFBF combined with QBC [11] or MESC [12] alleviates performance degratation resulting from channel quantization error by effectively using multiple receiving antennas, ZFBF still shows low average sum-rate performance especially in a low-rate feedback.

Moreover, compared with the enhanced unitary beamforming processing [18], the proposed unitary beamforming system provides higher average sum-rate, especially in the high-SNR region. This is because the effect of inter-user interference at the user is not considered in [18]. In the proposed unitary beamforming system, information on both user channel state and the effect of inter-user interference is compressed and reported through a low-rate feedback channel. Therefore, the BS can effectively mitigate inter-user interference even with limited feedback information.

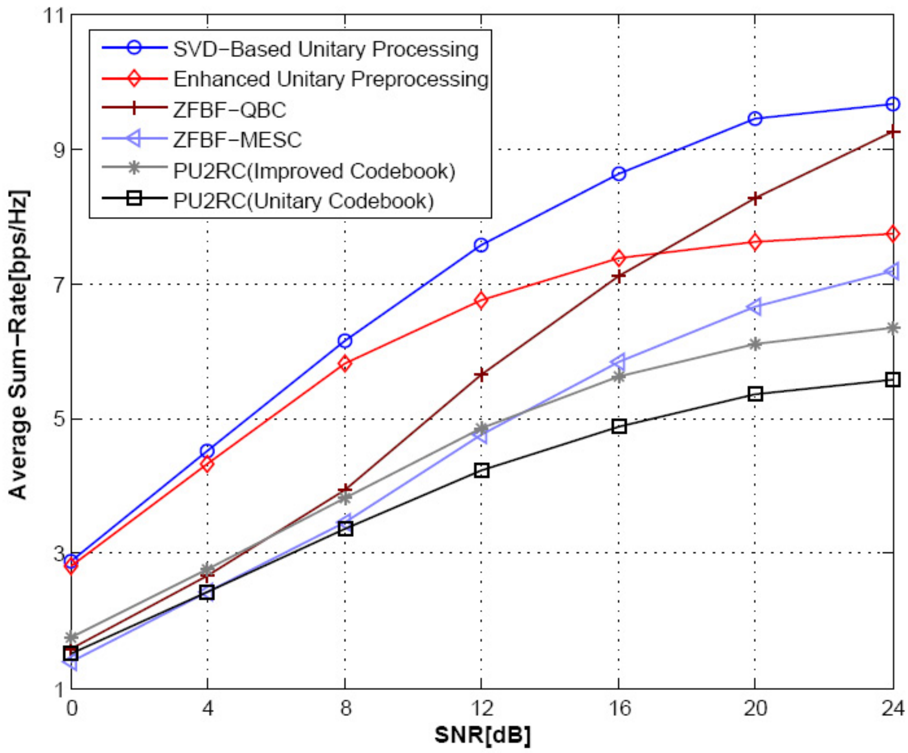


Figure 2.3: Average sum-rate versus SNR, where $N_T = 4$, $N_R = 2$, $K = 4$ and $B = 4$.

Fig. 2.4 shows average sum-rate variations along with the number of users when the number of users exceeds the number of transmit antennas. The proposed unitary MU-MIMO processing that adopts maximum-SINR user selection and semi-orthogonal user selection are compared with PU^2RC [13,14] and ZFBF [11,12]. [5] In both cases, the proposed processing outperforms PU^2RC, ZFBF-QBC and ZFBF-MESC especially in the presence of small and medium numbers of users. In detail, the proposed MU-MIMO processing adopting semi-orthogonal user selection algorithm outperforms the proposed processing using maximum-SINR user selection. This is achieved because the semi-orthogonal user selection algorithm jointly utilizes both the preferred beamforming feedback vector information, $\mathbf{c}_{\pi(k)}$, and the SINR information, η_k when selecting users. And, Fig. 2.4 indicates that PU^2RC with improved codebook [13] boosts average sum-rate rapidly as the number of users increases. It is because PU^2RC with improved codebook can efficiently compensate for performance degradation from ineffective matching between users and predefined beamforming vectors in the medium or large user pool.

[5] The user selection method for ZFBF-QBC [11] has not been explicitly discussed. Hence, we also use the conventional greedy user selection algorithm in [25] for user selection.

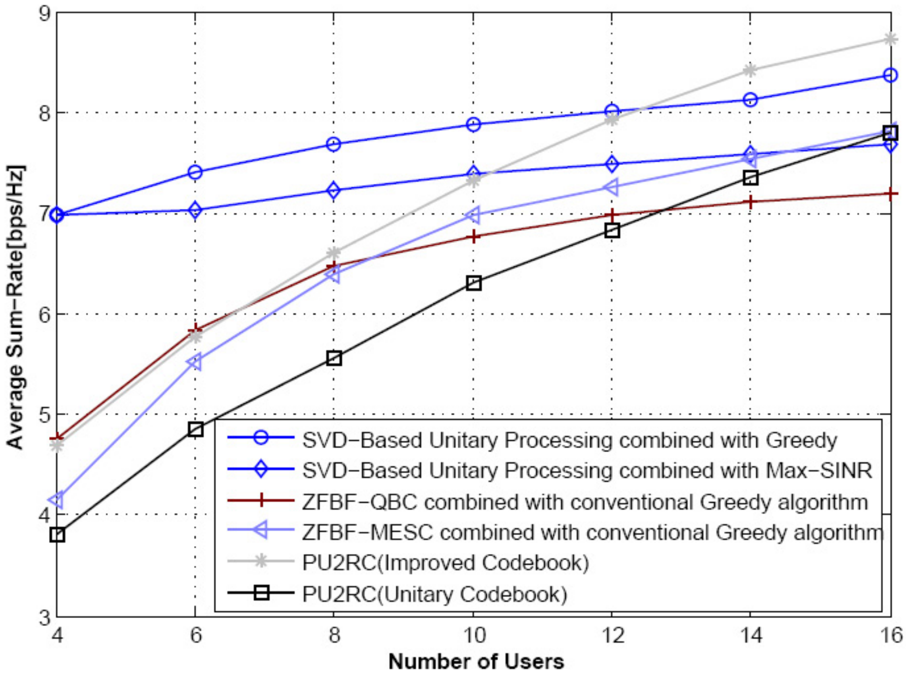


Figure 2.4: Average sum-rate versus number of users, where $N_T = 4$, $N_R = 2$, $B = 4$ and SNR $= 10$dB.

In Fig. 2.5-2.6, the average sum-rate performance is evaluated when a high-rate feedback is employed at MU-MIMO system. In Fig. 2.5, a cellular system with 4 BS antennas (N_T), 2 user antennas (N_R), 4 users (K), 8 bits (B) for user feedback is considered. Note that feedback bits of $\mathrm{PU^2RC}$ are fixed for 4 bits because in high-rate feedback, $\mathrm{PU^2RC}$ suffers from considerable performance loss due to ineffective matching in small user pool environment. The proposed SVD-based unitary MU-MIMO processing achieves higher sum rate performance than the enhanced unitary beamforming processing. In addition, the proposed processing requires extremely low computational complexity compared to the enhanced unitary beamforming. As a result, the proposed processing is highly appropriate for practical MU-MIMO systems. ZFBF combined with QBC or MESC tends to achieve higher sum-rate in high SNR regions than the proposed processing as the feedback bits increase. This behavior of the proposed SVD-based unitary beamforming processing results from the constraint which the beamforming matrix should be a unitary matrix, and is consistent with that of general unitary MU-MIMO processing in [2], [14], [18].

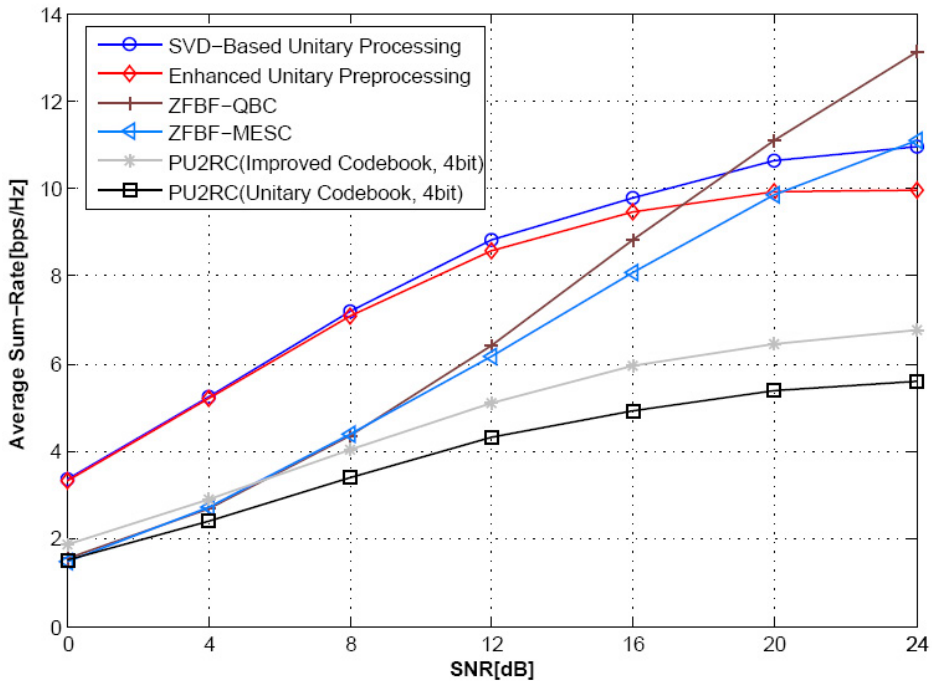


Figure 2.5: Average sum-rate versus SNR, where $N_T = 4$, $N_R = 2$, $K = 4$ and $B = 8$.

In Fig. 2.6, we plot the simulation results for a system with 4 BS antennas (N_T), 2 user antennas (N_R), 8 bits (B) for user feedback. In this case, we assume that the SNR is equal to 10 dB. The proposed SVD-based unitary MU-MIMO processing outperforms PU^{2}RC and ZFBF in the presence of small numbers of users. In high-rate feedback, ZFBF-MESC achieves higher sum-rate than the proposed processing as the number of users increases because it is reasonable to apply assumptions in [12] that the selected users are almost orthogonal to each other.

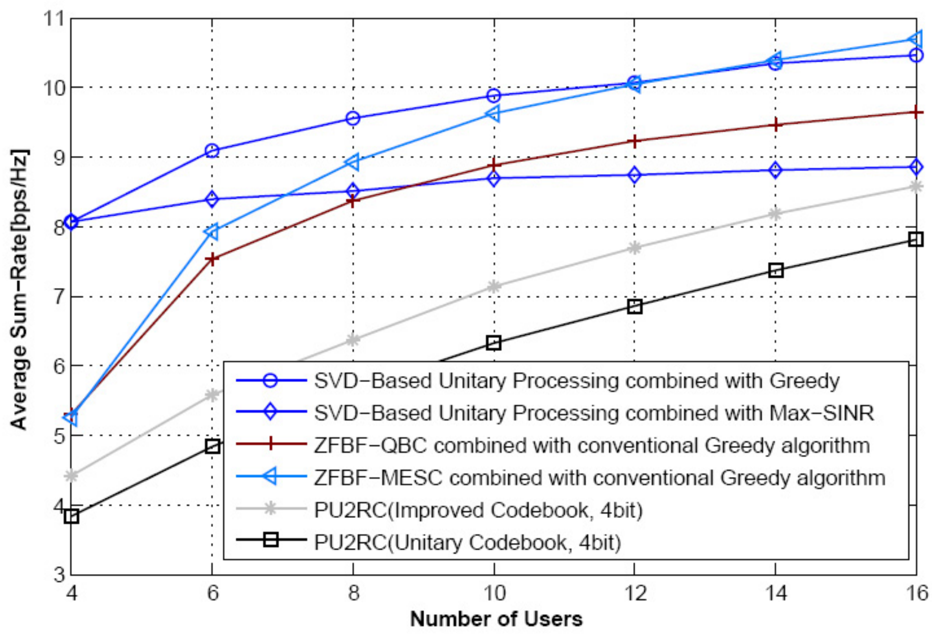


Figure 2.6: Average sum-rate versus number of users, where $N_T = 4$, $N_R = 2$, $B = 8$ and SNR = 10dB.

2.4 Summary

In this part, a new low-feedback-rate and low-complexity processing for downlink MU-MIMO cellular systems is proposed. The main features of the proposed processing are that both user channel state and inter-user interference effect information are effectively conveyed even in a low feedback rate, and the beamforming matrix is computed with extremely low computational complexity by using SVD. Our simulation results have verified that the proposed processing achieves higher average sum-rate performance than previous MU-MIMO systems such as PU^2RC, ZFBF-QBC, ZFBF-MESC and enhanced unitary preprocessing processing. Based on the aforementioned features and the simulation results, the proposed processing appears highly appropriate for practical MU-MIMO systems.

Chapter 3

SVD-Based Unitary MU-MIMO Processing in WLAN Systems

3.1 System Model

In this part, we consider an IEEE 802.11ac-based WLAN system with an infrastructure network topology where an AP and many mobile stations form a single basic service set (BSS) or cell. In BSS, the AP and its associated mobile stations are interconnected depending on existing communication infrastructures and all communication activities are facilitated via the AP. For simplicity, we focus on WLAN system where AP and stations have N_T multiple antennas and only single antenna at first. And then, we extend a practical WLAN system where various types of stations exist such as the different number of station antenna and data streams per station.

In the considered WLAN system, the received signal of the k-th user is represented as

$$y_k = \sqrt{\rho_k} \cdot \mathbf{h}_k \mathbf{F} \mathbf{x} + n_k, \quad k = 1, 2, \cdots, K, \tag{3.1}$$

where $\mathbf{h}_k \in \mathbb{C}^{1 \times N_T}$ is the channel matrix of the k-th user, $\mathbf{F} \in \mathbb{C}^{N_T \times M}$ is the beamforming matrix, $\mathbf{x} \in \mathbb{C}^{M \times 1}$ is the transmitted symbol vector, and $n_k \in \mathbb{C}^{1 \times 1}$ is the additive white Gaussian noise vector at the receiver. M is the number of the selected stations for data stream transmission. Equal power allocation for each data stream is assumed to be $\mathrm{E}[\mathbf{x}\mathbf{x}^{\mathrm{H}}] = \frac{1}{M}\mathbf{I}_M$. ρ_k is the average signal-to-noise ratio (SNR) reflecting random geometry as $\rho_k = \frac{P}{N_0 d_k^{\alpha}}$, where P, d_k, α, and N_0 denote the total transmit power, distance of the k-th user from AP, path loss exponent, noise power, respectively.

Note that unlike cellular systems, IEEE 802.11ac-based WLAN systems assign high-rate bits to feedback user channel information and utilize an efficient feedback mechanism using Givens rotation that reduces the overhead of feedback information [34]. As a reult, a channel quantization error caused by low-rate feedback could be negligible. However, there may be long feedback delay, more than 200 ms in reality, that leads to severe performance degradation. Therefore, the beamforming vectors are calculated based on the delayed channel feedback information. Using a first-order Gauss-Markov process [1], the relation between the current channel and the delayed channel feedback is given as

$$\mathbf{h}_k = \varepsilon_k \cdot \mathbf{h}_k^{(\tau)} + \sqrt{1 - \varepsilon_k^2} \cdot \mathbf{h}_w, \tag{3.2}$$

where $\mathbf{h}_w$ denotes the uncorrelated components with $\mathbf{h}_k$ and consists of i.i.d. circular symmetric complex Gaussian random variables with zero mean and unit variance.

[1]It has been proven in [35, 36] that the first-order Gauss-Markov process model is reasonably accurate for the communication systems.

The scalar values of ε_k is the temporal correlation coefficient for user channel and can be characterized by

$$\varepsilon_k = \frac{\left|\mathbf{h}_k \mathbf{h}_k^{(\tau)\mathrm{H}}\right|}{\|\mathbf{h}_k\| \left\|\mathbf{h}_k^{(\tau)}\right\|}, \tag{3.3}$$

where τ is the feedback delay time. ε_k can be also represented as $\cos\theta$ where θ is the phase variation of channel. From Fig.3.1 [31], the phase variation behavior in an indoor WLAN environment is observed as a function of feedback delay time. When feedback delay time is more than 200 ms, there is a high unpredictability for information of user channel due to significant phase variation.

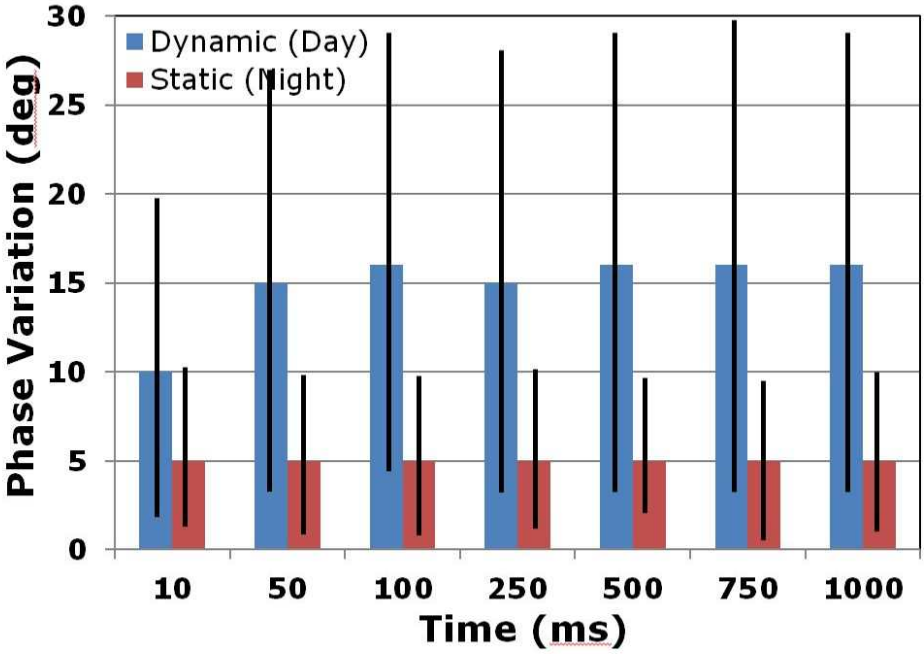


Figure 3.1: Phase variation of channel as a function of feedback delay time.

3.2 Proposed SVD-Based MU-MIMO Processing

3.2.1 Channel Sounding and User Feedback

In IEEE 802.11ac-based WLAN systems, channel sounding protocol that exercises the full dimentionality of the channel is defined for user channel information feedback. As described in Fig. 3.2, AP transmits null data packet (NDP) announcement packet and notifies stations about an upcomming NDP packet transmission at first. Then, the receiving stations are stimulated to feedback their channel state information using a compressed beamforming weights feedback. Generally, based on the feedback information, AP selects the transmitted stations and computes beamforming matrix for achieving high performance of WLAN systems such as high average sum-rate.

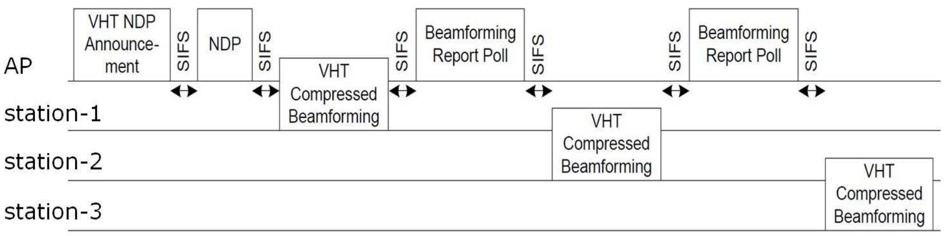


Figure 3.2: NDP channel sounding protocol.

In the compressed beamforming weights feedback, stations calculate SVD of their channels as follows.

$$\mathbf{h}_k = \mathbf{U}_k \mathbf{S}_k \mathbf{V}_k^{\mathrm{H}}, \quad k = 1, 2, \cdots, K, \tag{3.4}$$

where $\mathbf{U}_k$ and $\mathbf{V}_k$ are unitary matrices, and $\mathbf{S}_k$ is a diagonal matrix of singular values. The k-th station feedbacks maximum singular value, $\sigma_k^{(1)}$, and corresponding column of $\mathbf{V}$ matrix, $\mathbf{v}_k^{(1)}$, as its channel quality information and channel direction information, respectively [37]. In the process of channel feedback, the channel direction information, $\mathbf{v}_k^{(1)}$, is effectively compressed using Givens rotation that reduces a number of bits to represent the complex values with limited quantization loss. In addition, high-rate bits for channel information feedback are assigned in IEEE 802.11ac-based WLAN systems. As a result, channel quantization error caused by low-rate feedback could be negligible.

Note that the proposed user feedback in equation (2.3) of Part II is approximately the same as the compressed beamforming weights feedback when the number of feedback bits per user, B, is large. In large B, the equation can be transmformed into Rayleigh quotient as

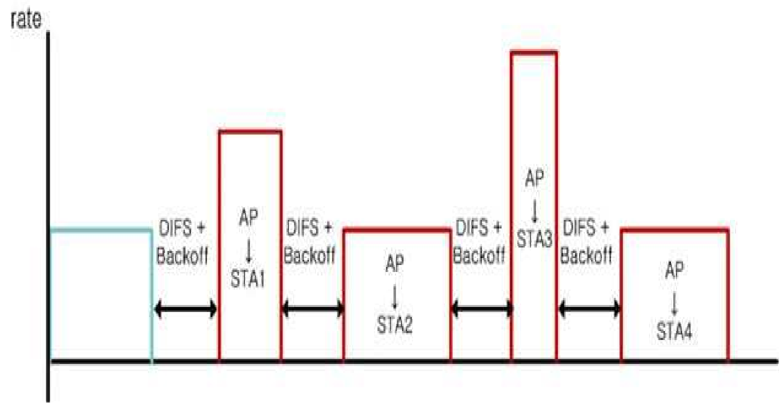
$$\mathbf{c}_k^{opt} = \arg\max_{\mathbf{c}_k} \frac{\mathbf{c}_k^{\mathrm{H}} \mathbf{c}_k}{\mathbf{c}_k^{\mathrm{H}} \left(\frac{\rho_k}{N_T} \mathbf{h}_k^{\mathrm{H}} \mathbf{h}_k + \mathbf{I}_{N_T} \right)^{-1} \mathbf{c}_k} \quad \text{s.t. } \|\mathbf{c}_k\|^2 = 1 \tag{3.5}$$

Since $\left(\frac{\rho_k}{N_T} \mathbf{H}_k^{\mathrm{H}} \mathbf{H}_k + \mathbf{I}_{N_T} \right)$ is always invertible, the above equation can be solved using the result of the generalized eigenproblem and the Rayleigh-Ritz theorem [24]. The solution is the unit-norm eigenvector associated with the largest eigenvalue of $\left(\frac{\rho_k}{N_T} \mathbf{H}_k^{\mathrm{H}} \mathbf{H}_k + \mathbf{I}_{N_T} \right)$, which is the same as $\mathbf{v}_k^{(1)}$.

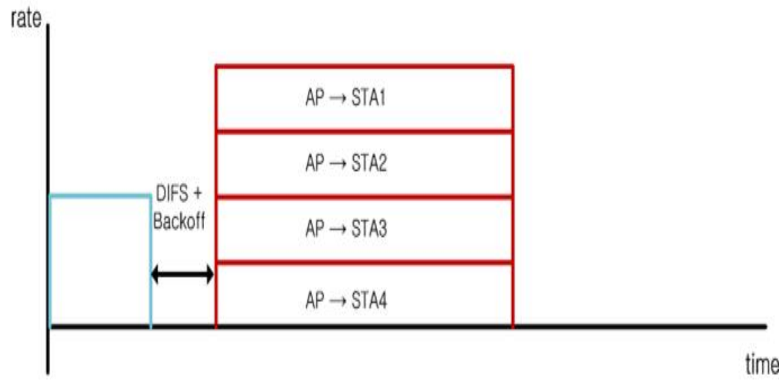
In practical WLAN systems, however, there may be substantial feedback delay due to long channel sounding period. Since frequent channel sounding operation occurs huge overhead for wireless channel user due to packet transmissions between AP and stations, long channel sounding period, more than 200 ms, is considered for implimentation. For example, the time for channel sounding operation is approximately 4 ms or 20 ms when AP has 4 antennas or 8 antennas and 10 stations with single antenna exist. Even though 4 ms seems to be short, it may be huge overhead in real-world WLAN systems where multiple APs exist and share the same operating wireless channel. Therefore, we consider downlink MU-MIMO WLAN systems with long channel sounding period, especially focus on 200 ms period in simulation.

3.2.2 User Grouping and User Scheduling

In IEEE 802.11ac-based WLAN systems, AP has an option to transmit multiple users simultaneously or singl user when it obtains access of wireless medium as shown in Fig. 3.3(a)-3.3(b). The downlink MU-MIMO transmission consists of multiple data streams that are spatially separated using beamforming vectors and targeted to different users. To facilitate operation of MU-MIMO transmission in practical WLAN systems, AP and users are needed to exchage information for indicating receiving users and their positions in MU-MIMO transmission packet. In addition, AP needs to inform the number of data streams for each receiving user.



(a) Single-user transmission



(b) Multi-user transmission

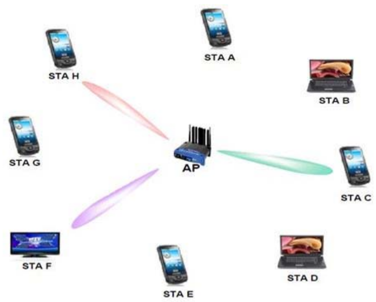
Figure 3.3: Comparison between single-user and multi-user transmissions

IEEE 802.11ac standard has defined new fields of group ID and the number of data stream for information exchange. The group ID field is used to inform the receiving users and their positions, and the field for the number of data streams indicates how many data streams are destined for each receiving user. In the standard, 6 bits are assigned for group ID and only 62 groups can be made for MU-MIMO transmission[2]. Practically, the number of station sets could exceed the available number of group IDs. For example, the number of possible 4-user set[3] is 210 when 10 stations are associated with AP. In order to cover the large number of station group sets, group IDs are allowed to overload.

Allocations of Ggoup ID and position are conducted by AP and the allocation results are conveyed to stations. In the process, a group of users may be assigned to the same group ID and different positions, which indicates that the transmitted MU-MIMO packets are only sent to the users in this group. To maintain information of allocations for group ID and position, AP makes a table as shown in Fig.3.4 for example. The table in Fig.3.4 consists of 62 rows, one for each group ID, and 4 columns, one for each position, and users belong to the entries of the table. Practically, the entries of the table may change when users associate and deassociate to AP. The changed information of the table is notified to users before MU-MIMO transmission.

[2]All group IDs are not used for MU-MIMO transmission. Group IDs of 0 and 63 are reserved for broadcast and single-user transmissions, respectively.

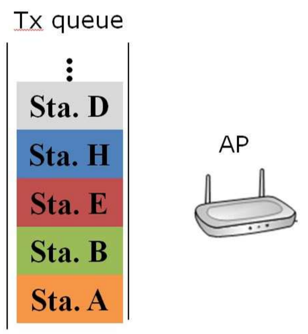
[3]In IEEE 802.11ac standard, the maximum number of data streams equals 8 and up to 4 stations can be inclued in MU-MIMO transmission.



Group ID	Position 0	Position 1	Position 2	Position 3
0	A,E	B,F	C,G	D,H
1	A	E	B	H
2	A,F	D,H	E	B,G
3	B	C	F,G	E,D
⋮	⋮	⋮	⋮	⋮

Figure 3.4: Group ID example.

When AP begins MU-MIMO transmission, it has to select users to transmit and the number of data streams per each user with specific rule. If a packet for certain user reaches the head of the queue, AP selects one group ID including the corresponding user. Moreover, in the selected group ID, AP chooses some of users and the number of data streams per each user. This whole process is called user scheduling, and Fig.3.5 shows an example of user scheduling when a packet for station A arrives at the head of the queue. Since performance such as average sum-rate and quality of service (QoS) for users is considerably influenced by the selected users and the number of data streams per user, an efficient user scheduling algorithm is needed for downlink MU-MIMO of WLAN system.



Group ID	Position 0	Position 1	Position 2	Position 3
0	A,E	B,F	C,G	D,H
1	A	E	B	H
2	A,F	D,H	E	B,G
3	B	C	F,G	E,D
⋮	⋮	⋮	⋮	⋮

Figure 3.5: User scheduling example.

Practically for implementation, the efficient user scheduling algorithm in downlink MU-MIMO WLAN systems should have low-computational complexity and consider the following issues. Firstly, unlike cellular MU-MIMO systems where users can use a part of subcarriers dynamically, stations in MU-MIMO WLAN systems use only all subcarriers. Therefore, the average system performance for whole channel bandwidth should be considered for the efficient user scheduling. Secondly, utilizing long-term channel statistics of users is effective including average SNR depending on user location and channel correlation since channel feedback information may have a high unpredictability due to long feedback delay as described in Section 3.1. Finally, various types of users such as the different number of user antennas and data streams per user could be significant for the design of user scheduling algorithm.

In this subserction, we propose an effective user scheduling algorithm to adaptively select the number of transmit users and data streams per user for acheiving high average sum-rate. Considering the aforementioned issues, we derive a closed-form expression of achievable sum-rate that needs only average SNR, channel correleation coefficient, and the number of user and AP antennas. Based on the achievable sum-rate expression, the proposed user scheduling algorithm can determine the number of transmit users and data streams per user for the highest average sum-rate. For simplicity, we describe the proposed algorithm where all stations have single antenna at first. And then, we extend the practical case where various types of stations exist.

In MU-MIMO systems, the achievable sum-rate is computed as

$$R = \sum_{k=1}^{M} \log\left(1 + \mathrm{SINR}_k\right), \tag{3.6}$$

where M is the number of selected users for transmission and SINR_k is signal-to-interference-plus-noise ratio of the kth user.

For linear MU-MIMO processing with feedback delay, the beamforming matrix is calculated based on the delayed channel feedback information. The SINR for the k-th user is expressed as

$$\mathrm{SINR}_k = \frac{\frac{\rho_k}{M} \cdot {\sigma_k^{(1)}}^2 \left| {\mathbf{v}_k^{(1)}}^{\mathrm{H}} \mathbf{w}_k \right|^2}{1 + \frac{\rho_k}{M} \cdot {\sigma_k^{(1)}}^2 \sum_{j \neq k} \left| {\mathbf{v}_k^{(1)}}^{\mathrm{H}} \mathbf{w}_k \right|^2}. \tag{3.7}$$

For given feedback information, the expected SINR at the kth user is given by

$$\begin{aligned} E\left[\mathrm{SINR}_k\right] &= E\left[\frac{\frac{\rho_k}{M} \cdot {\sigma_k^{(1)}}^2 \left| {\mathbf{v}_k^{(1)}}^{\mathrm{H}} \mathbf{w}_k \right|^2}{1 + \frac{\rho_k}{M} \cdot {\sigma_k^{(1)}}^2 \sum_{j \neq k} \left| {\mathbf{v}_k^{(1)}}^{\mathrm{H}} \mathbf{w}_k \right|^2} \right] &(3.8) \\ &\geq \frac{\frac{\rho_k}{M} \cdot E\left[{\sigma_k^{(1)}}^2 \left| {\mathbf{v}_k^{(1)}}^{\mathrm{H}} \mathbf{w}_k \right|^2 \right]}{1 + \frac{\rho_k}{M} \cdot E\left[{\sigma_k^{(1)}}^2 \sum_{j \neq k} \left| {\mathbf{v}_k^{(1)}}^{\mathrm{H}} \mathbf{w}_k \right|^2 \right]} &(3.9) \\ &= \frac{\frac{\rho_k}{M} \frac{{\sigma_k^{(1)}}^2}{N_T} (N_T - M + 1)}{1 + \frac{\rho_k}{M} \frac{{\sigma_k^{(1)}}^2}{N_T} (1 - \varepsilon_k^2)(M-1)}, &(3.10) \end{aligned}$$

where the inequlity follows form Jensen's inequality and final expression is because the expected desired signal term and interference term have chi-square random variables with (N_T-M+1) and 1 degrees of freedom, repectively. Therefore, the average achievable sum-rate is

$$\begin{aligned} E\left[R\right] &= E\left[\sum_{k=1}^{M} \log_2\left(1 + \mathrm{SINR}_k\right) \right] &(3.11) \\ &\approx \log_2 \left(1 + \frac{\frac{\rho_1}{M} \frac{{\sigma_k^{(1)}}^2}{N_T} (N_T - M + 1)}{1 + \frac{\rho_1}{M} \frac{{\sigma_k^{(1)}}^2}{N_T} (1 - \varepsilon_1^2)(M-1)} \right) \cdots \left(1 + \frac{\frac{\rho_M}{M} \frac{{\sigma_k^{(1)}}^2}{N_T} (N_T - M + 1)}{1 + \frac{\rho_M}{M} \frac{{\sigma_k^{(1)}}^2}{N_T} (1 - \varepsilon_M^2)(M-1)} \right). &(3.12) \end{aligned}$$

Table 3.1: SINR threshold for AMC

Rate (Mbps)	0	6	9	12	18	24	36	48	54
SINR (dB)	≤ -8	≤ 12.5	≤ 14	≤ 16.5	≤ 19	≤ 22.5	≤ 26	≤ 28	≤ 22.5

Note that as the number of the selected users, M, increases, the achievable multiplexing gain increases but the average SINR per user decreases.

Based on the expected average SINR for each user, transmission rate can be determined by the following table [38]. In the table, the particular SINR values are used for adaptive modulation and coding (AMC).

In real-world WLAN systems, average service time for serving N users and average sum-rate can be approximately calculated as a function of the determined transmission rates and scheduled user set as follows.

$$T_M = \frac{N}{M} \cdot t_{\min-\text{service}} + \frac{N}{M} \cdot (t_{\text{DIFS}} + t_{\text{backoff}}), \tag{3.13}$$

where $t_{\min-\text{service}}$ is minimum service time among scheduled M users including preamble time and transmission time of packet payload, t_{DIFS} is distributed interframe space (DIFS) interval, and t_{backoff} is average backoff time. Using the calculated average service time for the scheduled M users, the average sum-rate is represented by

$$R(M) = E\left[\sum_{k=1}^{M} \frac{L_k}{T_M}\right] \tag{3.14}$$

$$\approx M \cdot \frac{L}{T_M}, \tag{3.15}$$

where L_k is payload size of the k-th user and the above approximation is for the scheduled users with the same payload size, L. From equation (3.14), users that achieve the higheste average sum-rate can be selected as

$$S^{*} = \underset{S \subset \{1, \cdots K\}}{\arg\max} \; R(M). \tag{3.16}$$

Note that in user scheduling based on (3.16), a simple optimization problem is considered since it needs only average SNR, channel correleation coefficient, and the number of AP anteenas to compute and compare.

The proposed user scheduling can be extended when users have multple antennas and therefore multiple data streams per user can be allocated. In this case, users feedback their channel information for multiple data streams including multiple singlular values, $\sigma_k^{(1)}$,..., $\sigma_k^{(N_k)}$, and corresponding columns of matrix V_k, $\mathbf{v}_k^{(1)}$,..., $\mathbf{v}_k^{(N_k)}$, in decreasing order where N_k is the number of data streams for the kth station. Based on the feedback information, the average SINR for the ith stream of the kth user can be computed as

$$E\left[\mathrm{SINR}_{k,i}\right] \approx \frac{\frac{\rho_k}{M} \cdot \frac{\sigma_k^{(i)}}{N_T} \cdot (N_T - M + N_k)}{1 + \frac{\rho_k}{M} \cdot \frac{\sigma_k^{(i)}}{N_T}\left(1 - \varepsilon_k^2\right) \cdot (M - N_k)}. \tag{3.17}$$

Note that in equation (3.17), the average SINR equation converges to equation (3.7) at single data stream case ($N_k = 1$). In addition, we can see the effects of the number of data streams for the k-th user, N_k in terms of channel direction and channel quality. The channel directions of multiple data streams for the kth station, $\mathbf{v}_k^{(1)}$,..., $\mathbf{v}_k^{(N_k)}$, are orthogonal to each others, which results in the avoidance of interference among the data streams. Therefore, the denominator of equation (3.17) consists of $(M - N_k)$ term. The channel qualities, $\sigma_k^{(1)}$,..., $\sigma_k^{(N_k)}$, have probability density function (PDF) of eigenvalues in [39]. Generally, the gap among channel qualities of multiple data streams becomes larger as the number of AP's antennas increases.

Based on the expected average SINR for each user and each data stream, transmitssion rate and average sum-rate can be also calculated similarly as equations (3.13)-(3.16). Therefore, the proposed user scheduling can efficiently select the number of transmit stations and data streams per station for the highest average sum-rate.

3.3 Simulation Results

This section shows simulation results to demonstrate average sum-rate of the proposed MU-MIMO processing in WLAN systems where AP and stations have four antennas and single antenna. Simulation results are averaged over 1,000 independent channel realization.

Fig. 3.6 dipicts how average sum-rate varies with SNR according to the amount of phase variation. The simulation result indicates that average sum-rate is improved using the proposed MU-MIMO processing when users have low SNR and/or phase variation is more than 20 degrees. And, the performance gap increases with the phase variation since the proposed MU-MIMO processing efficiently reduces adverse effect of interference caused from channel change.

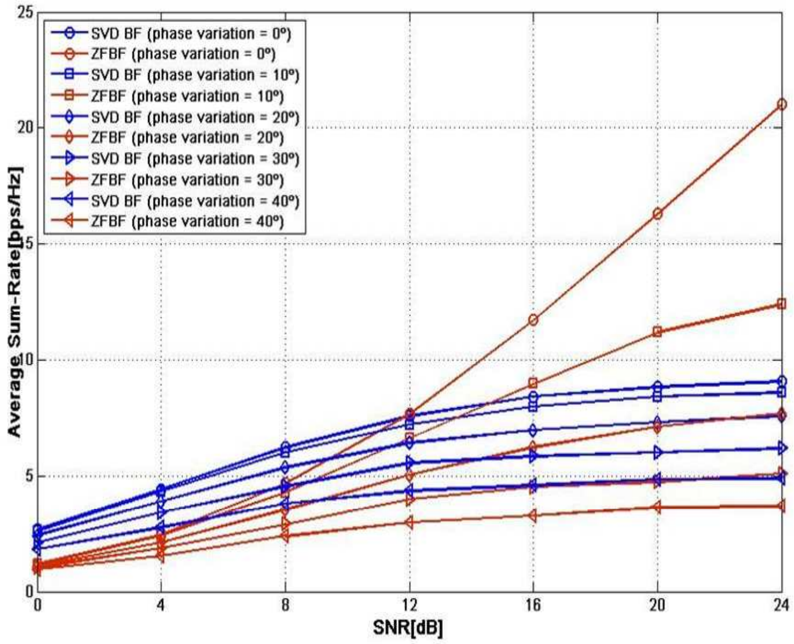


Figure 3.6: Average sum-rate versus SNR according to phase variation, where $N_T = 4$, $N_R = 1$, and $K = 4$.

Fig. 3.7 shows average sum-rate vs. SNR according to the number of selected users to transmit. In simulation, 20 degrees of phase variation, 1500 bytes of packet size, 31 of minimum contention window size are set. In addition, DIFS, SIFS, and slot time are 34, 16, and 9 microseconds, respectively. In this condition, optimal number of selected users from equation (3.16) is four. As we can see from the figure, the proposed MU-MIMO processing with four selected users outperforms ZFBF irrespective of the number of selected users.

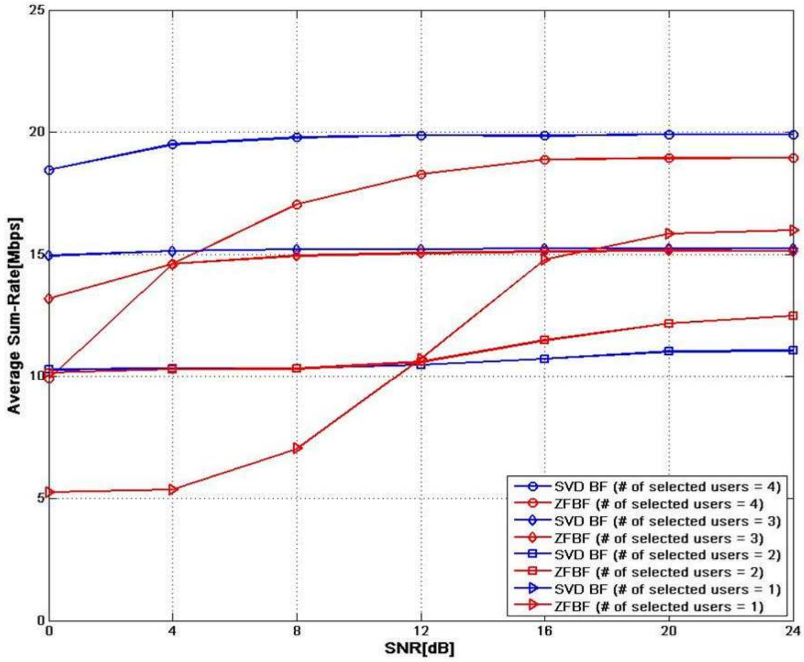


Figure 3.7: Average sum-rate versus SNR according to number of selected users, where $N_T = 4$, $N_R = 1$, and phase variation=20°.

To explain the reason about performance improvement of the proposed MU-MIMO processing, Fig. 3.8 compares average SINR, minimum and maximum user's SINR of the proposed MU-MIMO and ZFBF. In low SNR region, users with the proposed MU-MIMO processing have high average, minimum and maximum SINR. In high SNR region, even though average SINR is similar, SINR gap of users with the proposed MU-MIMO between minimum and maximum is less than that of users with ZFBF. As a result, the proposed MU-MIMO processing has an advantage over ZFBF when user payload size and transmission rate are same.

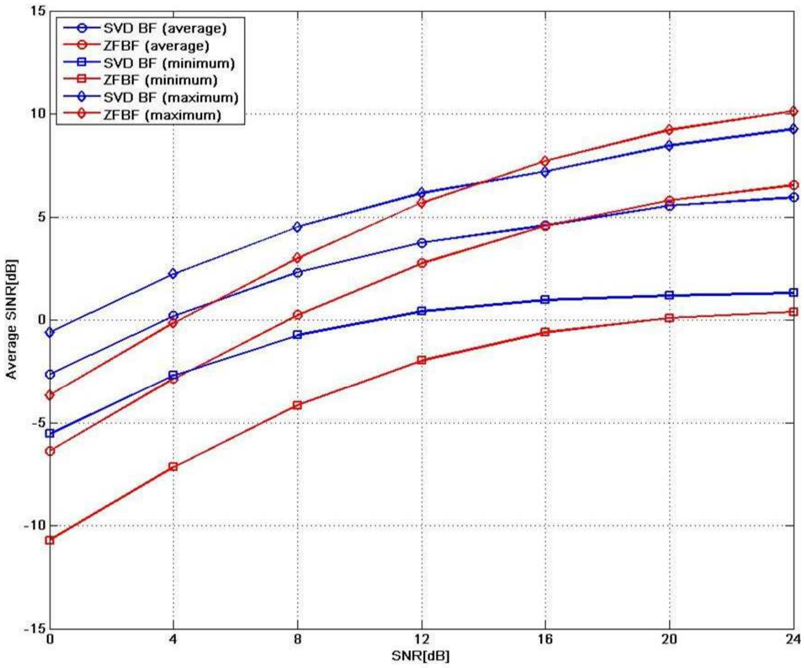


Figure 3.8: Average SINR versus SNR, where $N_T = 4$, $N_R = 1$, $K = 4$ and phase variation=20°.

3.4 Summary

In this part, we apply the proposed MU-MIMO processing to practical WLAN systems and confirm that the proposed MU-MIMO processing achieves higher average sum-rate than ZFBF especially when users have low average SNR and/or large cannel variation occurs in environmental condition. In addition, we proposed user scheduling algorithm to efficiently select the number of transmit users and streams per user for average sum-rate maximization using only average SNR, correlation coefficient, and the number of AP and stations antennas. Therefore, the proposed MU-MIMO processing with user scheduling algorithm appears highly appropriate for practical WLAN systems due to the aformentioned low computational complexity and the simulation results.

Chapter 4

Conclusion and Future Work

4.1 Conclusion

In the first part of the dissertation in Chapter 2, cellular systems where low feedback bits are allocated to report user channel information are considered. For practical downlink MU-MIMO cellular systems, we propose a low-complexity MU-MIMO processing that includes preferred-beam index feedback, user selection algorithms, and beamforming matrix construction method. The preferred-beam index feedback efficiently conveys information on both the channel states of users and the effect of interuser interference especially in low-rate feedback environments. The proposed user selection algorithms exploits multiuser diversity for the case that the number of users exceeds the number of transmit antennas. The proposed beamforming matrix construction method easily computes unitary beamforming matrix based on the feedback information using singular value decomposition (SVD) operation, which results in significant computational complexity reduction compared to the conventional methods. Numerical results show that the proposed low-complexity

MU-MIMO processing achieves a higher sum-rate particularly at low-rate feedback, while the computational complexity is kept reasonable.

In the second part of this dissertation, WLAN systems are considered where Access Point (AP) can transmit multiple spatial streams to different users in parallel by MU-MIMO processing. Unlike cellular systems, WLAN systems assign high-rate bits to feedback user channel information and utilize an efficient feedback mechanism using Givens rotation that reduces the overhead of feedback information. As a reult, channel quantization error caused by low-rate feedback could be negligible. In WLAN systems, however, there may be long feedback delay that leads to severe performance degradation, more than 200 ms in reality. In addition, WLAN systems are difficult to apply conventional user selection algorithms as well as the proposed one since group identification (ID) that WLAN standard newly defines for MU-MIMO should be considered. To select users in WLAN systems, we propose an efficient user selection algorithm with low-computational complexity. Numerical results also present that the proposed MU-MIMO processing combined with the proposed user selection algorithm considerabley outperforms previous MU-MIMO processing such as zero-forcing beamforming (ZFBF) especially in low signal to noise ratio (SNR) region and/or long feedback delay.

4.2 Future Work

Future research will include evaluation of the proposed unitary processing for practical MU-MIMO WLAN systems. To accomplish this,using extensive measurements in real-world deployments, we first investigate the impact of various factors such as the received SNR and outdated channel feedback information that considerably influence system performance. Based on the measured results, we analyze how these factors affect system performance of the proposed MU-MIMO processing. And then, we confirm the potential benefits in increasing SINR and higher average sum-rate than conventional MU-MIMO processing.

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초 록

다중 사용자 다중 안테나 프로세싱은 동시에 여러 명의 사용자에게 서비스를 제공함으로써 커다란 셀 용량 증대를 얻을 수 있는 기술로 지난 10년간 3GPP-LTE Advanced, IEEE 802.16m, IEEE 802.11ac 등의 차세대 무선 통신 표준에 상당한 관심을 받아왔다. 이 학위 논문에서는 현실적인 구현을 고려하여 적은 계산량과 다양한 무선 통신 시스템에 적용 가능성을 지닌 다중 사용자 다중 안테나 프로세싱 방법을 제안한다. 특히 다른 두 무선 통신 시스템인 셀룰라 시스템과 무선랜 시스템에 적용하여 제안하는 다중 사용자 다중 안테나 프로세싱 방법의 평균적인 총 전송률을 평가하고 이를 part I과 part II에 각각 설명한다.

학위 논문의 part I에서는 셀룰라 시스템에 초점을 맞춘다. 셀룰라 시스템은 사용자의 채널 정보를 피드백하기 위해 적은 양의 피드백 비트가 할당되어 있다. 현실적인 구현 가능성을 높이기 위해 적은 계산량을 필요로 하는 선형 빔포밍 다중 사용자 다중 안테나 프로세싱 방법을 제안한다. 제안하는 선형 빔포밍 다중 사용자 다중 안테나 프로세싱 방법은 선호빔 색인 피드백, 사용자 선택 알고리즘, 빔포밍 매트릭스 형성 방법이 포함되어 있다. 먼저, 선호빔 색인 피드백 방법은 특히 적은 양의 피드백을 사용하는 시스템에서 사용자의 채널 상태와 인접 사용자와의 간섭의 영향에 관한 정보를 효과적으로 기지국에게 전달한다. 또한, 사용자 선택 방법은 사용자의 수가 기지국의 안테나 수 보다 많은 경우 다중 사용자 다이버시티를 활용하여 평균적인 총 전송률을 향상시킨다. 마지막으로 빔포밍 매트릭스 형성 방법은 사용자로부터의 피드백 정보를 바탕으로 SVD 동작을 통해 쉽게 빔포밍 매트릭스가 계산되기 때문에 기존 다중 사용자 다중 안테나 프로세싱에 비해 계산상의 복잡도를 크게 줄일 수 있다. 시뮬레이션을 통한 수치 결과를 통해 제안하는 SVD 기반의 다중 사용자 다중 안테나 프로세싱 방법이 기존 프로세싱 방법에 비해 더 높은 평균 총 전송률 얻을 수 있다는 것을 확인하였다.

part II에서는 AP가 다중 사용자 다중 안테나 기술을 통해 여러 사용자에게 동시에 데이터를 전송할 수 있는 IEEE 802.11ac 기반의 무선랜 시스템이 고려되었다. 고려된 무선랜 시스템은 part I에서의 셀룰라 시스템과는 달리 사용자 채널 정보 피드백을 위해 많은 양의 피드백 비트가 할당되었으며, Givens rotation이라는 효과적인 피드백 방법을 사용하여 피드백 정보의 오버헤드를 줄일 수 있다. 그 결과 적은 양의 피드백 할당에 의해 야기되는 채널 양자화 오류를 무시할 수 있다. 그러나 무선랜 시스템에서는 심각한 성능 저하를 일으키는 긴 피드백 지연이 (현실적으로 200 ms이상) 발생할 수 있다. 이와 더불어 무선랜 표준에서 다중 사용자 다중 안테나 프로세싱 구현을 위해 새롭게 정의한 그룹 식별 및 사용자 스케쥴링으로 인해 기존에 셀룰라 시스템에 제안되었던 사용자 선택 방법 등을 직접 적용하기 힘들다. part II에서는 이러한 새로운 내용을 고려하여 효과적이고 현실적인 사용자 스케쥴링 방법을 제안한다. 제안한 스케쥴링 방법은 적은 계산량을 가지고 있으며 평균 총 전송률을 향상시킬 수 있다. 시뮬레이션을 통한 수치 결과를 통해 사용자 스케줄링을 통한 제안한 SVD 기반의 다중 사용자 다중 안테나 프로세싱 방법은 기존의 프로세싱에 비해 훨씬 좋은 성능을 나타냄을 보여주고, 특히 작은 SNR 영역과 긴 피드백 지연 환경에서 상당한 성능 이득이 있음을 확인하였다.

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주요어 : 다중 사용자 다중 안테나, 셀룰라 시스템, 무선랜 시스템, 빔포밍, 채널 피드백, 사용자 선택

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이제 이동 통신 연구실 박사 졸업생이라는 막중한 책임감을 가지고 사회에 나가 새로운 도전을 하려 합니다. 석사·박사 과정의 기간 동안의 소중한 배움과 교수님의 자상한 지도, 저와 함께 동고동락하였던 선후배님들의 따뜻한 관심이 새로운 시작을 준비하는 저에게 커다란 용기를 불어 넣어 줄 것임을 믿어 의심치 않습니다. 7년이라는 시간에 의해 뜨거웠던 열정과 다짐들이 퇴색되거나 무뎌지지 않도록 다시금 마음을 다잡고, 미흡하나마 석사·박사 과정의 기간 동안 제가 조그마한 성취를 이룰 수 있도록 믿고 도와주신 모든 분들께 감사의 글을 올립니다.

먼저 석사·박사 과정의 기간 동안 아낌없는 지도와 격려를 해주신 이광복 교수님께 진심으로 감사를 드립니다. 모자랐던 제가 교수님의 따뜻한 지도 덕분에 많이 발전하고 성숙할 수 있었고 따끔한 가르침은 현실에 안주하지 않을 수 있게 하였습니다. 그리고 끊임없는 연구에 대한 열정을 가지고 저의 모자란 지식을 채워주시고 조언을 아끼지 않으셨던 최성현 교수님께도 깊은 감사를 드립니다. 또한, 바쁘신 와중에도 논문 심사에 열의를 다해주신 박세웅 교수님, 김영한 교수님, 신오순 교수님께도 진심으로 감사의 말씀을 전합니다. 교수님들의 훌륭한 조언 덕분에 졸업 논문을 완성할 수 있었습니다. 다시 한번 감사의 말씀을 올립니다.

연구실 생활을 하는 동안 소중한 인연을 맺었던 수많은 선배님들께도 깊이 감사드립니다. 언제나 자신감 넘치시던 희원이형, 세심한 배려와 도움으로 저를 이끌어주셨던 일수형, 짓궂은 장난에도 항상 웃으시는 너그러운 병옥이형, 연구에 대해 많이 챙겨주고 도와주었던 원무형, 언제나 믿고 따르고 싶어지는 고마운 길남이형, 동생이지만 배려심 많은 동현이, 성실함과 열정, 배려의 아이콘인 제가 가장 좋아하는 연구실 동기 성진이형, 비록 함께한 시간은 짧지만 만나면 늘 반가운 수종이, 기일이형, 준일이형, 익현이형, 세형이형, 김도에게 진심으로 감사의 말씀을 드립니다. 모두 건승하시길 기원하면서 사회 초년생으로서 아직 부족한 저에게 아낌없는 조언 부탁드립니다.

제가 떠난 후에도 연구실을 훌륭히 지키며 발전시켜 나갈 여러 후배님들께도 감사하다는 말씀을 전합니다. 이제 곧 가장 고참이 될 믿음직한 선익이, 늘 나를 챙겨주던 배려심 많은 룸메이트 두희, 연구실의 미래 준수, 연애는 해봤지만 모태솔로와 다를 바 없는 교회오빠 진엽이, 센스가 있다고 굳게 믿고 있는 준영이, 연구실의 분위기 메이커로 나의 연구실의 마지막을 즐겁게 해준 우현이와 승민이까지 모두 감사드립니다. 비록 늦었지만 좀 더 좋은 선배가 되어주지 못한 것에 대한 미안함을 전하며 사회에 나가서도 평생 함께하는 인연이 되도록 노력하겠습니다. 이미 사회 각 분야에서 활약하고 있는 한영이, 상우, 태욱이, 재성이, 건일이, 동혁이, 원준이, 준호, 경수 뿐 아니라 연구실의 살림을 든든하게 맡아주신 여규랑씨에게도 감사의 말씀을 드리고 싶습니다.

오늘의 제가 있기까지 항상 힘이 되어 주었던 가족, 친지들에게도 감사의 말씀을 전하고 있습니다. 특히 늘 저에게 든든함 버팀목이 되어주신 아버지, 항상 보살펴 주시고 따뜻하게 감싸주시는 어머니, 마음 여리고 싹싹한 나의 착한 동생 창주, 모두 고맙고 사랑합니다. 앞으로 더욱더 자랑스러운 아들, 믿음직한 형이 되기 위해 노력하겠습니다. 또한, 중학교 때부터 내 곁을 지켜주는 늘 고마운 나의 친구들에게도 감사의 말씀을 전합니다. 저를 많이 챙겨주고 또 많은 것은 함께 나눈 용균이에게 감사하는 말과 진심으로 결혼을 축하한다는 말을 전합니다. 생각이 깊고 마음 따뜻한 상우, 한국에 돌아와 자주 봐서 반갑고 좋은 봉철이에게도 고맙다는 말을 전합니다.

마지막으로 7년이라는 시간 동안 나에게 늘 힘이 되어주는 나의 짝궁 희현이에게도 고맙다는 말과 사랑한다는 말을 전하고 싶습니다. 이제는 조금 더 자랑스러운 남자 친구가 된 것 같아 더없이 기쁩니다. 함께 한 시간 동안 있었던 즐거웠던 일, 행복했던 일, 고마웠던 일들을 잊지 않고 항상 기억하며 지금보다 더 아끼고 사랑하겠습니다. 지금 생각해보면 희현이를 만난 후 모든 일이 잘 풀리는 것 같다는 생각이 듭니다. 그로 인해 웃음도 더 많아지고, 밝아지고, 긍정적이 된 것 같아 어떻게 감사해야 할지 모를 정도로 한없이 고맙습니다. 앞으로 희현이가 내게 힘이 되었듯 저도 희현이에게 많은 힘이 되도록 노력하겠습니다. 사랑합니다.