A Thesis for the Degree of Ph.D. in Engineering

A Study of Antenna and User Selection Schemes for Multiuser Massive MIMO Systems

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Contents

List of Figures

List of Tables

Summary

In the 4^{th} generation mobile communication system, high-speed data transmission is achieved by spatially parallel data transmission between the base station and multiuser using multiple-input multiple-output (MIMO) antennas. However, to meet the rapidly increasing traffic demand, further increase in speed and capacity is required. In mobile communication systems of the 5^{th} generation and later, many antennas are placed in the base station, and multiuser massive MIMO (MU-Massive MIMO) Time Division Duplex (TDD) mobile communication system is promising. But, to maximize the effective use of the transmission power of the base station and maximize the throughput, it is necessary to select antenna sets with excellent propagation path conditions among many antennas of base station and users while reducing the amount of calculation. In this thesis, we propose methods to efficiently select the combination of base station (BS) antennas and multiusers with a small amount of calculation, then clarify the effectiveness of the proposed methods by computer simulation for MU-Massive MIMO systems with TDD mode. Evaluation results show that high throughput can be achieved based on channel gain (CG) and signal to interference and noise ratio (SINR). Chapter 1 describes the features of high-speed, large-capacity transmission technologies such as MU-Massive MIMO and beamforming, which are promising for

mobile communications from the 5^{th} generation onward. The issues regarding the selection of the BS antennas and receive users are described, and the purpose and position of this research are summarized. Chapter 2 describes the conventional research related to our research, then clarifies their problems. Chapter 3 describes the MU-Massive MIMO system model for our research works and presents a BS antennas and users selection scheme with a small amount of calculation. The proposed method is based on the Frobenius Norm of the channel information. The selection scheme is simplified by using complexity control factor for the preselection step. And then, the brute force search (BFS) fine tuning selection will be done based on assumption of deterministic MIMO channel to avoid the high computation of singular value decomposition (SVD) requirement for beamforming transmission in downlink communication. As a result of computer simulation, it is shown that the proposed method can reduce the amount of calculation required for selection while maintaining almost the same throughput as the conventional method. Chapter 4 proposes a BS antenna and multiuser selection method based on CG as well as SINR. In the proposed method, users with higher channel gains but lower interferences from surrounding users will be selected by discarding all users who give higher interferences to the selected users in the cell. This kind of selection can be done based on the fine-tuning BFS search on the CG-based and SINR-based users sets. Computation complexity of BFS search can be reduced based on the common users of CG-based and SINR-based users sets. As a results of computer simulation, it is shown that the proposed method achieves higher throughput and reduces the amount of calculation required for user selection compared to the conventional method.

Chapter 5 is a conclusion that summarizes the content of the thesis and future issues.

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Chapter 1

Introduction

1.1 Wireless Communication History

High speed data throughput with ultra-low latency and very fast mobility in broadband mobile wireless communication system is urgently needed throughout the world because of the huge demand from users and devices of Internet of Things (IoT). The Internet has been growing exponentially, in both the number of connections with ultra-low latency and the amount of information content points of view during these years. We can see various kinds of wireless services in nearly all the countries in the world. In wireless communication era, the very first use of radio transmitted coded information was a result of the works of Maxwell and Hertz with their pioneering experiments using electromagnetic waves and papers detailing radio communication systems were described by Tesla in the late 1800's [1].

Parallel to Tesla's works, Marconi invented the telegraph machine and demonstrated the use of mobile communications by connecting wirelessly over the English Channel. For over a hundred years, research on wireless technologies continued slowly until people began to aware the usefulness of radio waves in telecommunications. During the second world war, researches on radio were targeted around radar and remote sensing due to the urgent requirements of military system. This condition gave the next major advancement on wireless communication technologies. Subsequent applicants emerged from these technologies, including TV broadcasting in the 1940‘s. In the 1970‘s, Bell Laboratory developed cellular systems and continued to give the commercial usage of mobile wireless communication with acceptable price. This can be achieved based on standardization and continuous development on mobile wireless communication technologies. Since then, huge growth in the consumer sectors has been occurred and demand on mobile wireless communication are exponentially rising in every year. From then, until now, much has moved forward within the telecommunications industry as consumer‘s demand faster, more reliable connectivity. The development from first generation mobile communication (1G) to fourth generation mobile communication (4G) and now into Long Term Evolution (LTE) and beyond to fifth generation mobile communication (5G) has accelerated the rate of advance in most technologies. [2].

1.2 Some Key Enabling Technologies for 5G and Beyound 5G Mobile and Wireless Communication

By the end of 2022, more than 90 percent of the traffic will come from cell phones. This gigantic amount of mobile data traffic is challenging to manage with the capabilities of previous generations of wireless systems [3]. The 5G mobile networks are currently starting to be implemented and aim to be 100 times faster than current 4G networks. 5G networks will offer data rates up to 10 Gbps, low latency (in milliseconds), and greater reliability. High Definition (HD) movie can be downloaded in just a few seconds. This technology can support many IoT enabled devices and smart vehicles. Efficient wireless access technology that can increase throughput without increasing the bandwidth or densifying the cell is essential to achieve the ongoing demands faced by 5G. To make

5G and beyond networks a reality, many advanced ideas have been proposed and analyzed in recent years. Some of the major key enabling technologies that have been considered for 5G and beyond 5G systems include OFDM, OFDMA, beamforming, MIMO and Massive MIMO.

1.2.1 Orthogonal Frequency Division Multiplexing (OFDM) and Orthogonal Frequency Division Multiple Access (OFDMA)

There are many difficulties, however, in providing the high-speed wireless communication in some environments which cause multipath fading and the inter-symbol interferences in the system. To handle those difficulties, OFDM technology is used. OFDM is a transmission scheme that partitions the available bandwidth into N narrowband parallel subcarriers, which are overlapping but orthogonal, as shown in Fig. 1.1. This results in a high spectral efficiency. Due to the orthogonal nature of the carriers used for different channels, it is possible to overlap the bands on each other and still recover them in the receiver without losing any quality. Because of this, OFDM is very effective in saving bandwidth. In low bandwidth systems where the demand for spectrum is very high, OFDM comes naturally as the first choice. The bandwidth saving has been shown in Fig. 1.1. Besides the above advantages, we can also use OFDM in a form of FDMA which we called OFDMA, where a user may be assigned one or more subcarriers (equivalent to FDMA frequency channels) in order to satisfy its traffic requirements. The key advantage of OFDMA is that it allows for multiuser diversity: a subcarrier that is of low quality to one user can be of high quality to another user and can be allocated accordingly. In this way, a subcarrier is left unused only if it is low quality to all users. Moreover, this approach can be combined with adaptive modulation, where modulation levels are chosen on a per-subcarrier basis according to the observed channel conditions in order to further increase spectral efficiency. Therefore OFDM/OFDMA is currently one of the key elements of most of the modern communication systems.

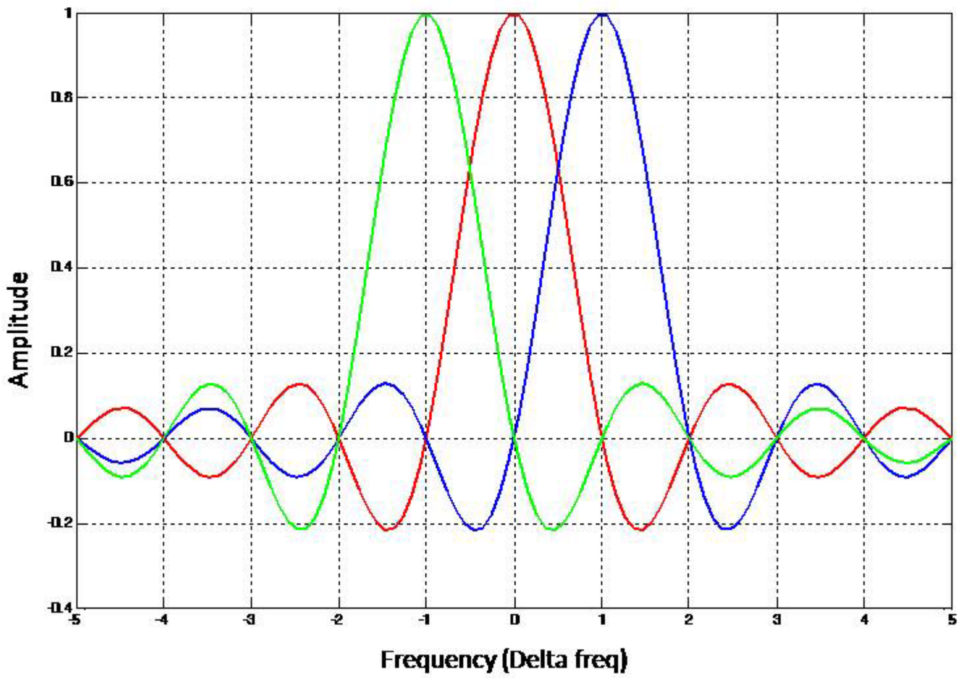


Figure 1.1: OFDM.

1.2.2 Beamforming

Two technologies, Massive MIMO and beamforming, work together to deliver 5G‘s demanding throughput and connection densities. Massive MIMO (multiple input multiple output) uses multi-antenna arrays and spatial multiplexing to transmit independent and separately encoded data signals, known as "streams". These enable simultaneous communications with multiple user equipment (UE) over the same frequency and time domain. Beamforming is the ability of the BS to adapt the radiation pattern of the antenna [4]. Beamforming helps the base station to find a suitable route to deliver data to the user,

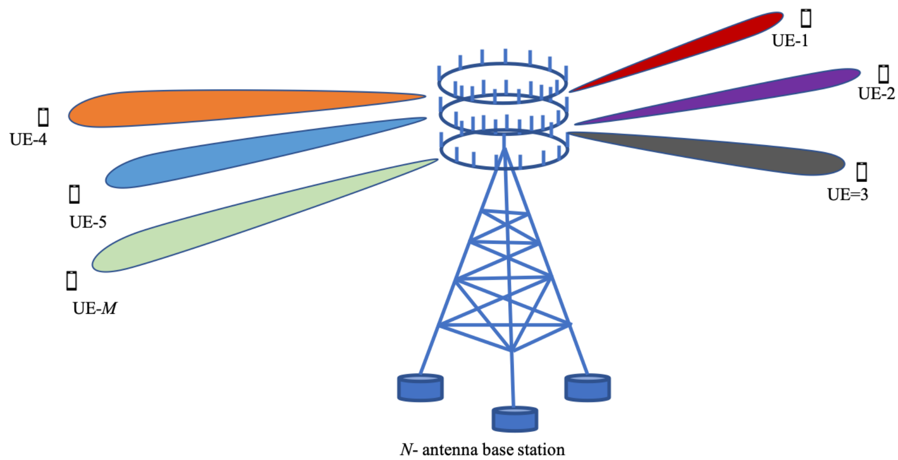


Figure 1.2: Massive MIMO and digital beamforming.

and it also reduces interference with nearby users [5], as shown in Fig. 1.2 and Fig. 1.3. Beamforming has several advantages for 5G networks and beyond. Depending upon the situation, beamforming technology can be implemented in several different ways in future networks. For massive MIMO systems, beamforming helps with increasing spectrum efficiency, and for millimeter waves, it helps in boosting data rate.

Beamforming uses multiple antennas to control the direction of a wave-front by appropriately weighting the magnitude and phase of individual antenna signals in an array of multiple antennas. That is, the same signal is sent from multiple antennas that have enough space between them (at least half-wavelength). In any given location, the receiver will thus receive multiple copies of the same signal. Depending on the location of the receiver, the signals may be in opposite phases, destructively averaging each other out, or constructively sum up if the different copies are in the same phase, or anything in between. This results in an improved signal at the user equipment (UE), and also less interference between the signals of individual UE.

Fast steering of the beam is achievable since the phase and amplitude of each signal are controlled electronically, allowing adjustments to be made in nanoseconds. There are three methods of implementing antenna beamforming:

Analogue beamforming is the simplest method as shown in Fig. 1.4. With the signal phase being changed in the analogue domain, the output from a single RF transceiver is split into a number of paths, corresponding to the number of antenna elements in the array. As shown in Fig. 1.4, RF splitter is used to split the RF signal. It has one input and two or more outputs. Generally, RF power splitters are used to split or divide RF power in two or more ports. Each signal path then passes through a phase shifter and is amplified before reaching the antenna element so that the radiation patterns from each individual element combine constructively, with those from neighboring elements forming an effective radiation pattern for the main lobe which transmits energy in the desired direction. At the same time, the antenna array is designed so that signals sent in undesired directions destructively interfere with each other, forming nulls and side lobes. The overall antenna array system is designed to maximize the energy radiated in the main lobe, whilst limiting the energy in the side lobes to an acceptable level. The direction of the main lobe, or beam, is controlled by manipulating the radio signals applied to each of the individual antenna elements in the array. Each antenna is fed with the same transmitted signal but the phase and amplitude of the signal fed to each element is adjusted, steering the beam in the desired direction as shown in Fig. 1.3.

This is the most cost-effective way of implementing beamforming, since it uses a minimal amount of hardware, however an analogue beamforming system can only handle one data stream and generate one signal beam, limiting its effectiveness in 5G, where multiple beams are required.

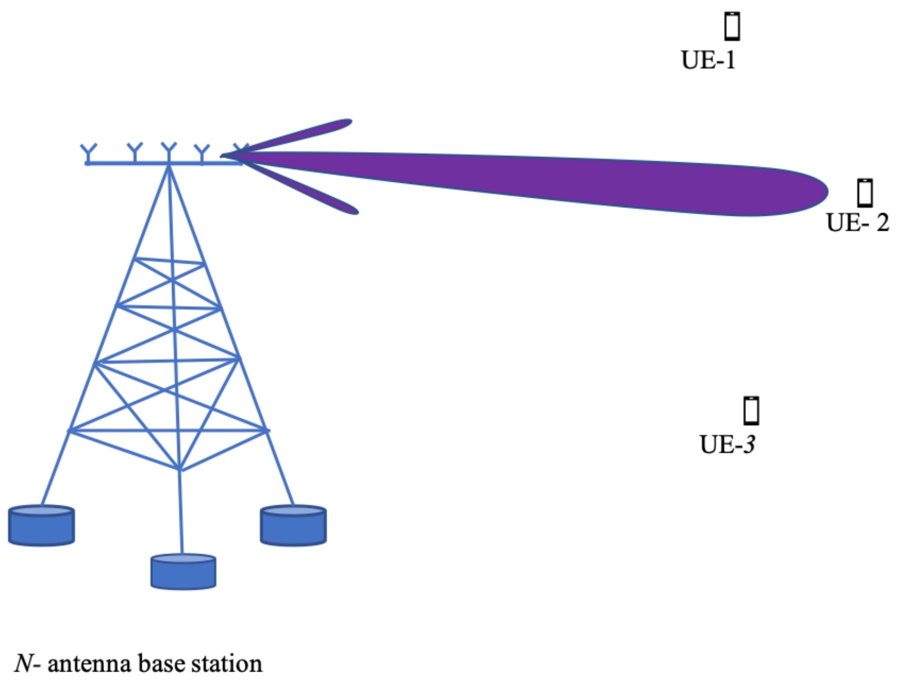


Figure 1.3: Massive MIMO and analogue beamforming.

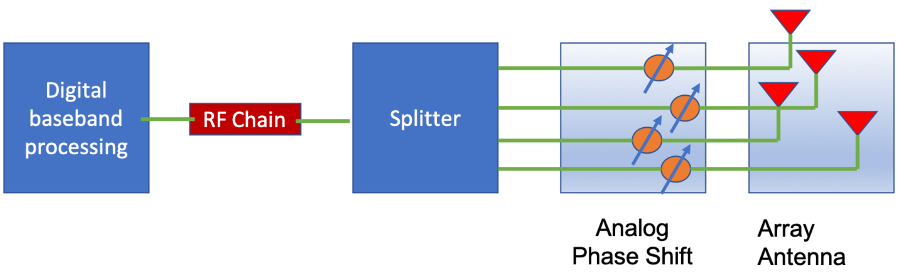


Figure 1.4: Analogue beamforming.

Fig. 1.5 shows the block diagram of digital beamforming, each antenna element is fed by its own transceiver and data converters, and each signal is pre-coded (with amplitude and phase modifications) in baseband processing before RF transmission. Digital beamforming enables several sets of signals to be generated and superimposed onto the antenna array elements, enabling a single antenna array to serve multiple beams, and hence multiple users. Although this flexibility is ideal for 5G networks, digital beamforming requires more hardware and signal processing, leading to increased power consumption, particularly at mmWave frequencies, where several hundred antenna elements are possible.

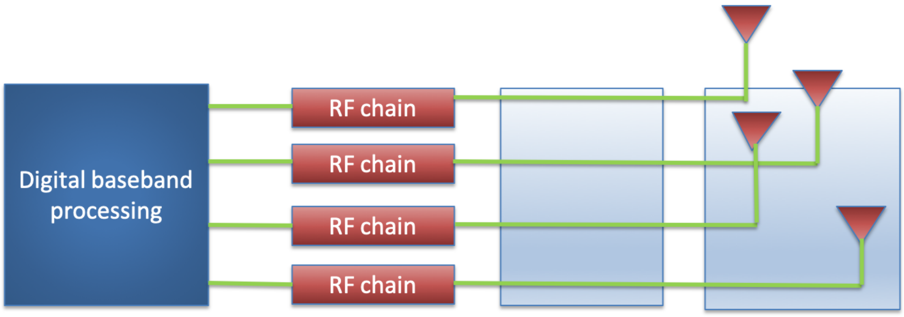


Figure 1.5: Digital beamforming.

Fig. 1.6 shows the block diagram of Hybrid beamforming. Where, analogue beamforming is carried out in the RF stage, and digital beamforming in the baseband. The hybrid effect offers a compromise between the flexibility of digital beamforming and the lower cost and power consumption of analogue. Hybrid beamforming is recognized as a cost-effective solution for large-scale, mmWave antenna arrays and various architectures are being developed for 5G and beyond 5G network implementations. These architectures divide broadly into fully connected, where each RF chain is connected to all antennas; and sub-connected or partially connected, in which each RF chain is connected to a set of antenna elements. Each architecture aims to reduce the hardware and signal processing complexity, while providing near optimal performance: the closest to that of pure digital beamforming.

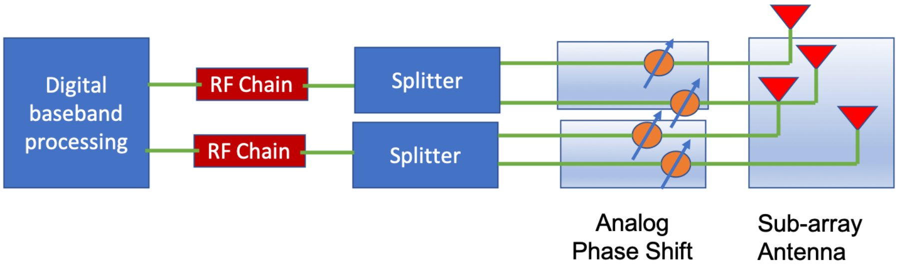


Figure 1.6: Hybrid beamforming.

Beamforming effectively uses electromagnetic nature to avoid the interference and enhance the precision of 5G connections and throughput. Moreover, beamforming increases the connection density of 5G network cells. The resultant highly directional transmissions are particularly beneficial with mmWave transmissions, which suffer heavily from path loss and do not propagate well through obstacles such as walls. The improved Signal-to-Noise Ratios (SNR), enabled by beamforming, increase signal range for both outdoors and - importantly - indoor coverage. Beamforming‘s ability to cancel out or "null" interference is also a significant benefit in crowded, urban environments with high densities of UEs, where multiple signal beams can potentially interfere with each other. Overall, by reducing internal and external interference and improving SNR, beamforming supports higher-order signal modulation schemes, such as 64QAM and 16QAM - all of which contribute to a substantial improvement in network cell capacity.

1.2.3 Multiple-Input Multiple-Output (MIMO)

MIMO systems are an integral part of current wireless systems, and in recent years they have been used extensively to achieve high spectral efficiency and energy efficiency.

Before the introduction of MIMO, single-input-single-output systems were mostly used, which had very low throughput and could not support a large number of users with high reliability. The wireless users have increased exponentially in the last few years, and these users generate trillions of data that must be handled efficiently with more reliability. To accommodate this massive user demand, various new MIMO technology were developed [6, 7, 8, 9, 10, 11]. In ideal conditions (uncorrelated high rank channel) the MIMO capacity scales roughly linearly as the number of Tx/Rx antennas although the effect of channel correlation is to decrease the capacity. However, the radio spectrum available for wireless services is extremely scarce. Consequently, a prime issue in current wireless systems is the conflict between the increasing demand for wireless services and the scarce electromagnetic spectrum. Spectral efficiency is therefore of primary concern in the design of future wireless data communication systems with the very limited bandwidth constraint. The use of multiple antennas at the receiver can significantly increase the channel capacity by exploiting the spatial diversity, for example, to combat fading and to perform interference cancellation. If simultaneous spatial diversity is employed both at the transmitter and the receiver as shown in Fig. 1.7, then a MIMO channel naturally arises with the additional property that several sub streams can be opened for communication within the MIMO channel (this is the so-called multiplexing gain). This scenario has gained a significant popularity due to studies indicating a linear increase in capacity with the number of antennas [12] and [13]. MIMO technology can be generally classified into three categories: Single User MIMO (SU-MIMO), Multiuser MIMO (MU-MIMO), and MU-Massive MIMO.

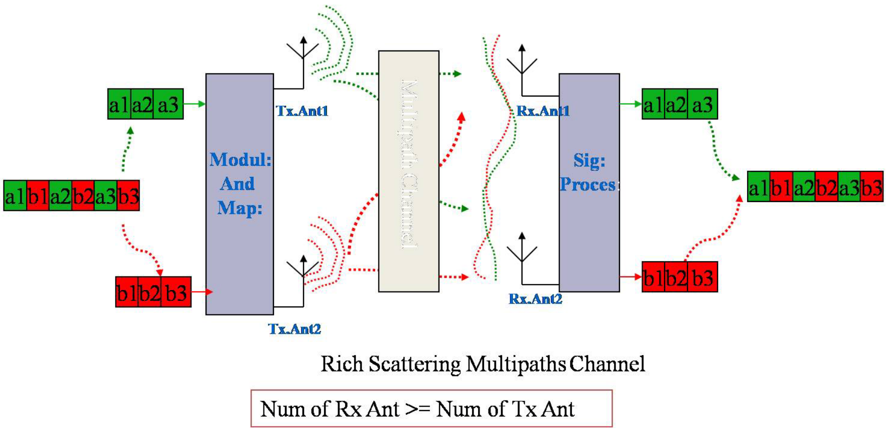


Figure 1.7: MIMO system.

1.2.3.1 Single User MIMO

SU-MIMO emerged in the late 1990s [13, 7] and represents the simplest form of MIMO: a base station (BS) equipped with an antenna array serves a user's equipment (UE) implemented with an antenna array as shown in Fig. 1.8. In SU-MIMO, a vector is transmitted and a vector is received. In the presence of additive white Gaussian noise at the receiver, Shannon theory, yields the following capacity formulas for the link spectral efficiency in bps/Hz:

$$C^{ul} = \log_2 \left| \mathbf{I}_N + \frac{p_{ul}}{M} \mathbf{H}\mathbf{H}^H \right|. \tag{1.1}$$

$$C^{dl} = \log_2 \left| \mathbf{I}_M + \frac{p_{dl}}{N} \mathbf{H}\mathbf{H}^H \right|. \tag{1.2}$$

In (1.1) and (1.2), $\mathbf{H}$ is an $N \times M$ matrix that represents the frequency response of the channel between BS and UE; p_{ul} and p_{dl} are the uplink and downlink signal-to-noise ratios (SNRs), which are proportional to the corresponding total radiated power; N is the number of BS antennas; and M is the number of terminal antennas. The normalization

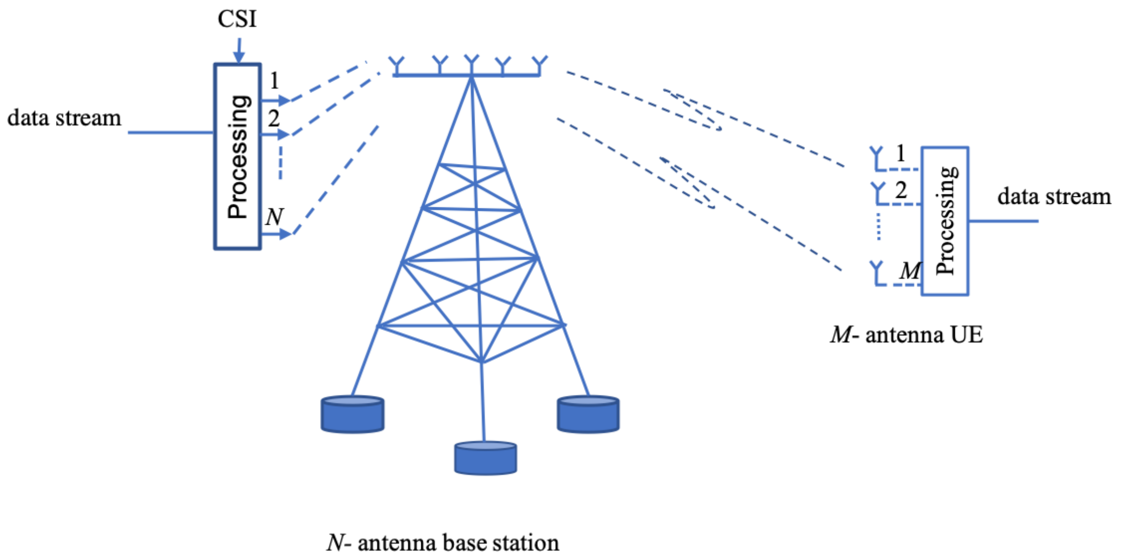


Figure 1.8: SU-MIMO system.

by M and N reflects the fact that for constant values of p_{ul} and p_{dl} total radiated power is independent of the number of antennas. (1.1) and (1.2) assume that $\mathbf{H}$ is only known by receiver. If channel state information (CSI) is known to transmitter, performance can be improved more. In practice, Point-to-Point MIMO has two limitation factors. First, UE must be equipped with independent RF chains per antenna and need to do the advanced digital processing to separate the data streams. Second, it is not likely to have the favorable propagation environment for SU-MIMO. For example, when facing with line of sight (LOS) condition, SU-MIMO cannot achieve the support of $min(M,N)$ independent streams.

1.2.3.2 Multiuser MIMO

When a single BS serves many terminals using same time-frequency domain, this kind of system can be called as MU-MIMO. MU-MIMO scenario can be obtained by breaking up the K-antennas SU-MIMO into multiple autonomous terminals. The basic concept of

MU-MIMO is quite old [14, 15]. However, research and nalysis of MU-MIMO based on information theory emerged much later [16, 13]. Detail explanations of transition from SU-MIMO to MU-MIMO can be found in [17]. Common scenario of MU-MIMO can be found with N antennas in the BS and M terminals equipped with single antenna in each terminal as shown in Fig. 1.9. Let $\mathbf{H}$ be an $N \times M$ matrix corresponding to the frequency response between the BS array and the M termianls. The uplink and downlink sum rate efficiencies are given by [18].

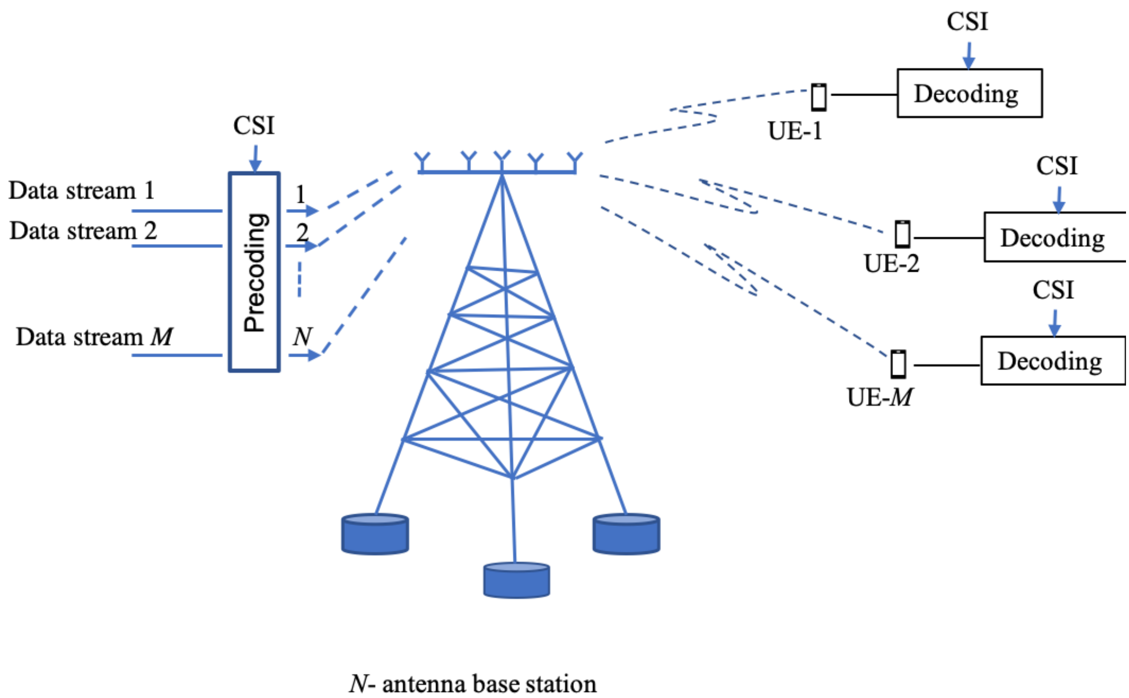


Figure 1.9: MU-MIMO system.

$$C^{ul} = \log_2 \left| \mathbf{I}_N + p_{ul} \mathbf{H}\mathbf{H}^H \right|. \tag{1.3}$$

$$C^{dl} = \log_2 \left| \mathbf{I}_M + p_{dl} \mathbf{H} \mathbf{D}_v \mathbf{H}^H \right|. \quad (1.4)$$

Where $v = [v1, v2,, vk]^T$, p_{ul} is the uplink SNR per termainal, and p_{dl} is the downlink SNR. It should be noted that, the total uplink power is M times greater than for the point-to-point MIMO model for a given p_{ul}. On uplink equation (1.3) , the BS alone must know the channels, and each terminal has to be inform its permissible uplink transmission rate separately. On the downlink equation (1.4), both BS and UE must have CSI. MU-MIMO has two fundamental advantages over SU-MIMO. First, propagation environment such as line of sight (LOS) does not give high impact on MU-MIMO since user terminals are normally scattering in the environment. Second, user terminal must not require to equip with multiple antenna in the UE. However, MU-MIMO is not scalable either with respect to N or to M since (1.3) and (1.4) require complicated signal processing by both the BS and UEs. Additional to this, both the BS and UE must know H, which requires substantial resources to be set aside for transmission of pilots in both directions.

1.2.3.3 Massive MIMO

Massive MIMO is a useful and scalable version of MU-MIMO [19, 20]. Massive MIMO represents a clean break from conventional MU-MIMO. Massive MIMO has three fundamental advantages over MU-MIMO. First, only the BS learns $\mathbf{H}$. Second, N is typically much larger than M, although this does not have to be the case. Third, simple linear signal processing is used both on the uplink and on the downlink. These features render Massive MIMO scalable with respect to the number of BS antennas, N [18]. Example of Massive MIMO can be seen in Fig. 1.10.

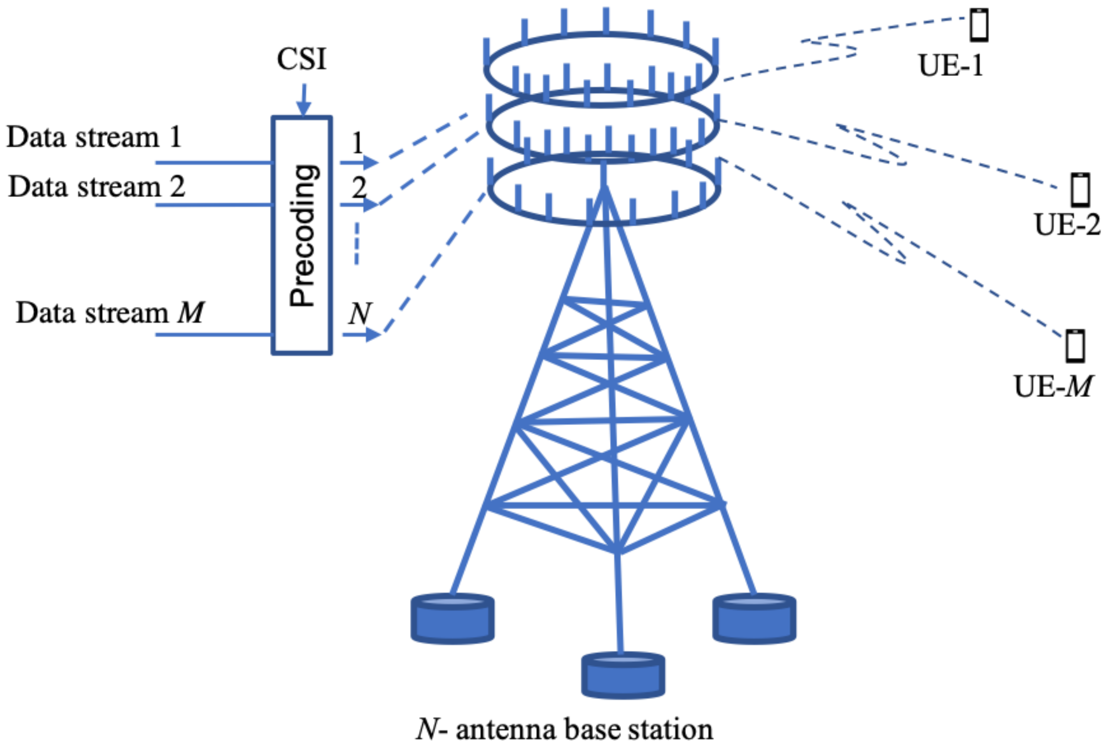


Figure 1.10: Massive MIMO system.

Each BS is equipped with a large number off antennas, N, and serves a cell with many terminals, M. The terminals typically have a single antenna each. Different BSs serve different cells, and with the possible control and pilot assignment, Massive MIMO does not cooperate among BSs. Either in uplink or in downlink transmissions, all terminals occupy the full time-frequency resources concurrently. On the uplink, the BS has to recover the individual signals transmitted by the terminals. On the downlink, the BS has to ensure that each terminal receives only the signal intended for it. The BS‘s multiplexing and de-multiplexing signal processing is made possible by utilizing many antennas and by its possession of CSI. In time division duplex (TDD) operation, the BS acquires CSI by measuring pilots transmitted by the terminals, and exploiting reciprocity between the uplink and downlink channel.

1.3 Importance of Massive MIMO Technologies

The primary issue with the ongoing development of the wireless network is that it is dependent upon either increasing bandwidth (spectrum) or densifying cells to achieve the required area throughput. These resources are rare and are reaching their saturation point within a few years. Also, increasing bandwidth or densifying the cells increases the cost of the hardware and increases latency. One concept which can improve area throughput, that is, spectral efficiency, has remained mostly untouched and unchanged during this rapid development and growth of the wireless network. Additionally, there are billions of IoT devices, having various applications to smart healthcare, smart homes, and smart energy, that contribute to the data traffic. It is predicted that there will be around 29.3 billion connected devices by 2023 [3]. The current MIMO technologies associated with 4G/LTE network is unable to handle this huge data traffic with more speed and reliability. An efficient wireless access technology that can increase the wireless area throughput without increasing the bandwidth or densifying the cell is essential to achieve the ongoing demands faced by the wireless carriers.

The 5G network is considering Massive MIMO technology as a potential technology to overcome the problem created by massive data traffic and users [21, 22]. Several studies on Massive MIMO have been conducted on Massive MIMO systems and their benefits [23, 24]. Massive MIMO is the most captivating technology for 5G and beyond 5G wireless access era. Massive MIMO is an extension of MIMO technology, which involves using hundreds and even thousands of antennas attached to a BS to improve spectral efficiency and throughput. The extra antennas that Massive MIMO users will help focus energy into a smaller region of space to provide better spectral efficiency and throughput. This technology is about bringing together antennas, radios, and spectrum together to enable higher capacity and speed for the incoming 5G [25, 26, 27, 28]. The capacity of Massive MIMO to increase throughput and spectral efficiency has made it a crucial technology for emerging wireless standards [21, 23]. Massive MIMO with huge multiplexing gain and beamforming capabilities can sense data from concurrent sensor transmission with much lower latency and provide sensors with higher data rates and reliable connectivity. Massive MIMO systems will perform a crucial role to allow information gathered through smart sensors to be transmitted in real-time to central monitoring locations for smart sensor applications such as an autonomous vehicle, remote healthcare, smart grids, smart antennas, smart highways, smart building, and smart environmental monitoring.

Since the Massive MIMO concept was introduced a few years ago, it has gained new heights every year. It has become one of the hottest research topics in the wireless communication community due to its immense benefits in 5G standardization. The current MIMO systems have been unable to cope with the massive influx in wireless data traffic. With the introduction of concepts like IoT, machine to machine communication, virtual reality, and augmented reality, the current system is unable to deliver the required spectral efficiency. The recent experiments in the Massive MIMO system have proven its worth by showing record spectral efficiency. A research conducted by Lund University together with Bristol University in 2015 achieved 145.6 bits/s/Hz spectral efficiency for 22 users, each modulated with 256-Quadrature Amplitude Modulation (256-QAM), on a shared 20 MHz radio channel at 3.51GHz with 128 antennas at the BS [29, 30]. The improvement in spectral efficiency was huge when compared with 3 bit/s/Hz, which is International Mobile Telecommunications (IMT) advanced requirement for 4G.

Theoretically, Massive MIMO systems can have an infinite number of antennas at the BS. In practical, 64 to 128 have been used usually used in Massive MIMO base station. Recently, Sprint Network working along with companies like leaders Ericsson, Nokia, and Samsung Electronics have deployed 128 antennas Massive MIMO systems (64 antennas to receive signal and 64 antennas to transmit signal). One of the prominent advantages of Massive MIMO is that we only need sophisticated hardware at the BS, while the UE can have a single antenna and a simple antenna design. Thus, for Massive MIMO higher number of the antenna is only needed at the BS but not at UE. The current smartphones have 2 to 4 antennas. The current smartphones have 2 to 4 antennas, but for Massive MIMO, having only one antenna at the UE will suffice [31].

1.4 Some Challenges in Massive MIMO

The Massive MIMO technology is more than just an extension of MIMO technology, and to make it a reality, there are still many issues and challenges that need to be addressed.

1.4.1 Pilot Contamination

In Massive MIMO systems, the BS needs the channel response of the user terminal to get the estimate of the channel. The uplink channel is estimated by the BS when the user terminal sends orthogonal pilot signals to the BS. Furthermore, with the help of channel reciprocity property of Massive MIMO, the BS estimates the downlink channel towards the user terminal [20]. If the pilot signals in the home cell and neighboring cells are orthogonal, the BS obtains the accurate estimation of the channel. However, the number of orthogonal pilot signals in given bandwidth and period is limited, which forces the reuse of the orthogonal pilots in neighboring cells[32]. The same set of orthogonal pilot used in neighboring cells will interfere with each other, and the BS will receive a linear combination of channel response from the home cell and the neighboring cells. This phenomenon is known as pilot contamination, and it limits achievable throughput [33]. During downlink, the BS will beamform towards the user in its home cell along with undesired users in the neighboring cells. The effect of pilot contamination on system performance has been studied in [34, 35]. There are several techniques designed to mitigate the effect of pilot contamination in Massive MIMO systems.

1.4.2 Channel Estimation

Massive MIMO relies on CSI for signal detection and decoding. CSI is the information of the state of the communication link from the transmitter to the receiver and represents the combined effect of fading, scattering, and so forth. If the CSI is perfect, the performance of Massive MIMO grows linearly with the number of transmitting or receive antennas, whichever is less [36]. For a system using Frequency Division Duplexing (FDD), CSI needs to be estimated during both downlink and uplink. During uplink, channel estimation is done by the BS with the help of orthogonal pilot signals sent by the user termin. During the downlink, the BS sends pilot signals towards the user, and the user acknowledges with the estimated channel information for the downlink transmission. For a Massive MIMO system with many antennas, the downlink channel estimation strategy in FDD becomes very complex and difficult to implement in real-world applications.

TDD provides the solution for the problem during downlink transmission in FDD systems. In TDD, by exploiting the channel reciprocity property, the BS can estimate the downlink channel with the help of channel information during uplink. During uplink, the user will send the orthogonal pilot signals towards the BS. Based on these pilot signals, the BS will estimate the CSI to the user terminal [32]. Using the estimated CSI, the BS will beamform downlink data towards the user terminal. Since there is a limited number of orthogonal pilots that can be reused from one cell to another, the pilot contamination problem arises and is a significant challenge during Massive MIMO channel estimation. Other challenges are increased hardware and computational complexity due to more number of antennas. Thus, low complexity and low overhead channel estimation algorithm are very desirable for Massive MIMO systems [37].

1.4.3 Precoding

Precoding is a concept of beamforming which supports the multi-stream transmission in multi-antenna systems. Precoding plays an imperative role in Massive MIMO systems as it can mitigate the effect created by path loss and interference, and maximizes the throughput. In Massive MIMO systems, the BS estimates the CSI with the help of uplink pilot signals or feedback sent by the user terminal. The received CSI at the BS is not uncontrollable and not perfect due to several environmental factors on the wireless channel [38]. Although the BS does not receive perfect CSI, still the downlink performance of the BS largely depends upon the estimated CSI. Thus, the BS uses the estimated CSI and the precoding technique to reduce the interference and achieve gains in spectral efficiency. The performance of downlink Massive MIMO depends upon the accurate estimation of CSI and the precoding technique employed. Although the precoding technique provides immense benefits to Massive MIMO systems, it also increases the computational complexity of the overall system by adding extra computations. The computational complexity increases along with the number of antennas. Thus, low complex and efficient pre-coders are more practical to use for Massive MIMO systems.

1.4.4 Energy Efficiency

Energy efficiency is the ratio of spectral efficiency and the transmit power, and Massive MIMO can provide substantial energy efficiency gains by achieving higher spectral efficiency with low power consumption. However, the increasing number of the antenna does always increase the spectral efficiency, because the power consumption also increases along with the number of antennas and more number of users. Based on this analogy, many studies have been carried out to build energy-efficient Massive MIMO systems. Many low complex and low-cost methods for precoding, detection, channel estimation anduser scheduling have been proposed recently to reduce the power consumption at the Massive MIMO base station. Some researchers have focused on antenna and power amplifier design to reduce the power consumption of the system.

1.4.5 Antenna Selection for Massive MIMO Systems

A Massive MIMO refers to a system where the BS is equipped with a large number of antennas (e.g. tens or hundreds) and communicates with several single-antenna users in the same time-frequency domain [20]. The increasing capacity results from aggressive spatial multiplexing used in the Massive MIMO. The basic premise behind the Massive

MIMO is to reap all of the benefits of the conventional MIMO, but on much greater scale [21]. It has been shown that the large antenna array at BS could provide high degrees of freedom and thus increase significantly the system capacity, the link reliability, and the radiated-energy efficiency [26, 39, 20, 21]. Also, based on the random matrix theory, it was demonstrated that the Massive MIMO system could achieve the capacity gain with simple and linear signal processing methods [40]. In practical, number of RF chains at the BS cannot be large very much due to the constraints in hardware cost and the complexity. Adding more antennas at the BS is usually inexpensive. However, the RF elements, such as radio-frequency (RF) amplifier, mixer and analog-to-digital/digital-to-analog (AD/DA) converters can be relatively expensive. Therefore, most Massive MIMO systems should consider to implement the BS with larger number of antenna elements but fewer number of RF chains to reduce the hardware cost in the BS side [41]. Since all antennas are not equally good in real propagation channels, it is possible to reduce RF chains to be used with selected active antennas, which contribute the most in the system performance and discarding the rest of antennas. Such antenna selection could simplify the design of a Massive MIMO base station and lead to energy and cost savings [42]. In this case, selecting and using the best antennas among the available large number of antenna elements in BS is an important issue in Massive MIMO technology.

1.4.6 User Selection for MU-Massive MIMO Systems

Massive MIMO equipped with a large number of antennas at the BS can communicate with multiple users simultaneously. Simultaneous communication with multiple users creates multiuser interference and degrades the throughput performance. Precoding methods are applied during the downlink to reduce the effect of multiuser interference. Since the number of antennas is limited in Massive MIMO base station, if the number of users becomes more than the number of antennas, proper user selection scheme is applied before precoding to achieve higher throughput and sum rate performance. Therefore, the user selection is also a critical important factor for optimizing the overall performance of Massive MIMO systems. Recently, many researchers have published their research works about antenna and user selection schemes for Massive MIMO systems [43, 44, 45].

1.4.7 Antenna and User Selection for MU-Massive MIMO Systems

Antenna selection and user selection in the MU-Massive MIMO systems have been widely studied as presented in above, but all of them consider only for antenna selection in the BS side or the user selection in the user side. To the best of our knowledge, there are only few studies on joint antenna selection for MU- Massive MIMO systems [42, 46, 47]. In [42], a FDD-based Massive MIMO downlink channel is considered to develop a low complexity algorithm that runs joint antenna selection and grouping of receiver nodes. In [46], the authors propose to solve the joint antenna selection and user scheduling problem, for the distributed Massive MIMO systems under backhaul capacity constraint. In these schemes, the joint antenna selection and user scheduling are proposed and the research results are presented in terms of sum-rate or BER performances. However, the effect of complexity reduction of their proposed schemes was not analyzed and thus the practical feasibility of these schemes was not verified. Therefore, we do the research work to find the suboptimal scheme for the joint antenna and user selection in the MU Massive MIMO system to reduce the complexity as well as to improve the sum-rate in this system.

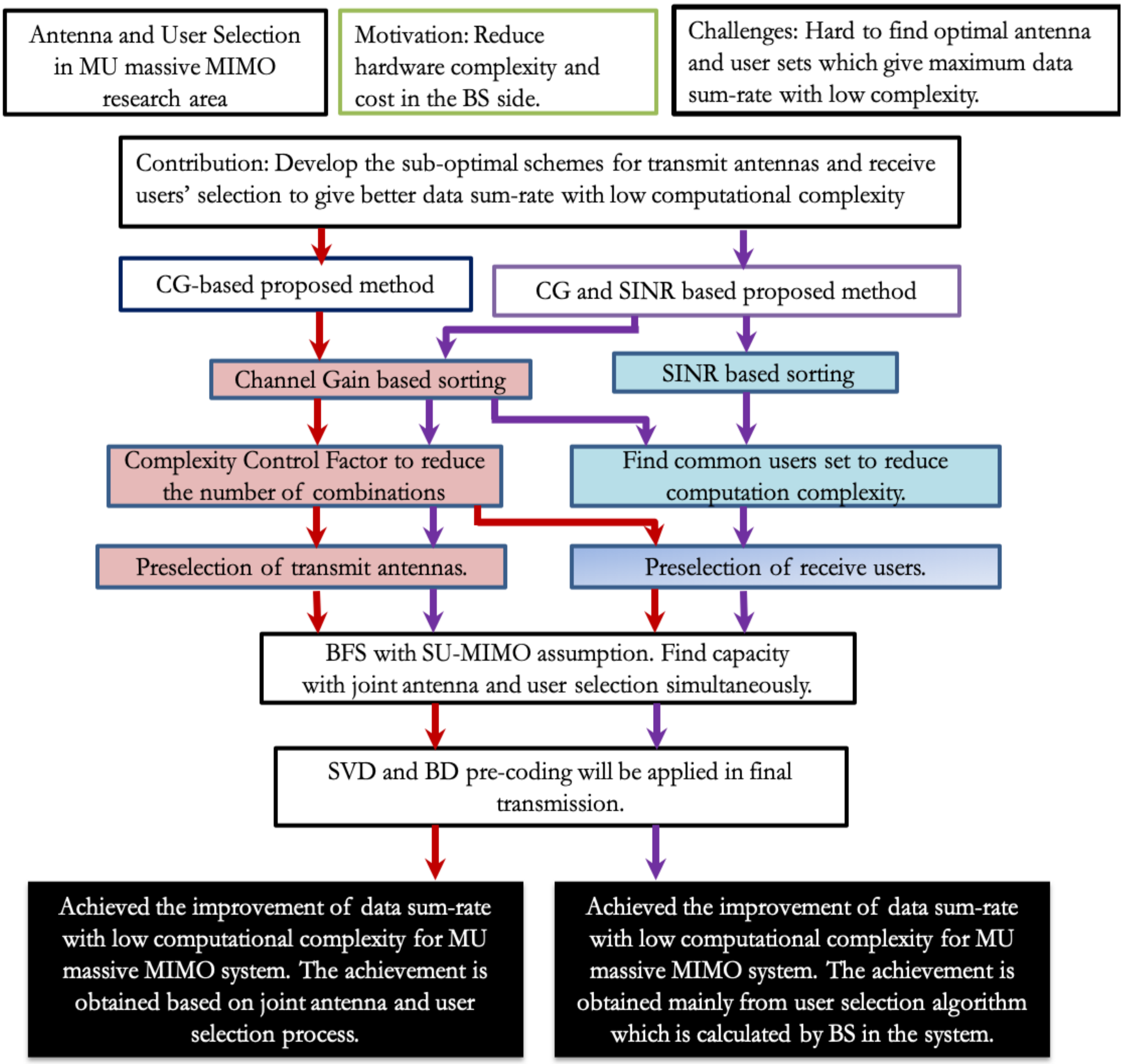


Figure 1.11: Position and relationship of research works and contribution.

1.5 Position of the Research and Contributions in this Dissertation

This section briefly describes the position of the research in the mobile broadband wireless communication area and the contributions in this dissertation. Massive MIMO has been recognized as one of the key technologies in the current 5G and beyond 5G networks. MU-Massive MIMO system can serve multiple single-antenna users in the same time-frequency block by equipping base stations with a large-scale antenna array. Many studies have shown that it can greatly improve the performance in spectral and energy efficiency by exploiting the special diversity brought by massive number of transmit antennas. However, the amount of corresponding radio-frequency (RF) hardware (e.g., low noise amplifiers, frequency up/down converters, and analog-to-digital (ADC) and digital-to-analog (DAC) converters that increase linearly with the number of antennas can become a challenging issue for both implementation complexity and financial cost. Therefore, signal processing techniques using reduced number of RF chains have gained great attentions in the massive MIMO literature. Antenna/user selection is a signal processing technique that activates a selected subset of available antennas in multi-antenna systems to give the best service for selected users in the system. Based on the antenna/user selection schemes, a performance-hardware trade-off can be achieved by reducing the number of costly RF chains. The biggest challenge of antenna/user selection scheme is the combinatorial complexity problem which arises from the very large number of possible outcomes of antenna and user combination in the preselection stage. Combinatorial complexity problem makes it more challenging for massive MIMO systems equipped with large-scale antenna arrays with many users in the system. In our research work, we tried to develop the low computational complexity antenna/user selection schemes to use for

MU-Massive MIMO systems. Our research works try to maximize the data sum-rate of M single-antenna users by using low computation processing in BS side. The research in this dissertation mainly focuses on two research directions: finding antenna selection and user selection algorithms which can give not only the improvement of data sum-rate performances but also the reduction of computational complexity of selection algorithms in MU-Massive MIMO systems. Fig. 1.11 and Table. 1.1 provide the overview of the motivation of the research, how they are related in the mobile wireless communication era. As shown in Fig. 1.11, antenna and user selection scheme can give the reduction of hardware complexity and cost in the BS. But finding the optimal antenna and user sets is brute force search and it is high complexity combinatorial search. Its complexity is based on the number of available antennas N and users M in the system. The BFS search will be infeasible since the MU Massive MIMO system is generally implemented by the very large number of antennas in the BS side and users in the user side. Therefore, we tried to find the sub-optimal antenna and user selection algorithms which can give not only the data sum-rate improvement but also the low computational complexity in the finding process. This low computational complexity can also give low processing time and energy consumption of processing units in the BS. Research in Chapter 3 is developed based on the complexity control factor and channel gain based (CG-based) preselection in BS side and user side. After that, temporary assumption of SU-MIMO concept will be applied on the selection algorithm to reduce the BFS search in joint antenna and user selection for final BD transmission. Chapter 4 presents the extended research work based on research work in Chapter 3. In Chapter 4, a novel low complexity user selection scheme is presented based on the joint consideration of CG-based selection and signal to interference plus noise ratio based (SINR-based) selection in the system. Applying set theory to this joint consideration, we can reduce the number of outcomes in the combination of user for the BFS search. And higher data sum-rate is also achieved after joint consideration of CG-based and SINR-based selection.

Table 1.1: Summary of chapter contents.

Chapter	**Contents**
Chapter 1	It introduces the over view of wireless communcation systems and basic concepts of promising technologies for 5G and beyond 5G. Motivation, contribution and position of research works and their relationship are also discussed in this chapter.
Chapter 2	Relate works and literature reviews are discussed in here.
Chapter 3	This chapter presents a low-complexity joint antenna and user selection scheme with block diagonalization (BD) precoding for MU-Massive MIMO downlink channel in the TDD system.
Chapter 4	A novel user selection scheme based on jointly combining CG and SINR is discussed in this chapter. The proposed scheme is developed to improve the data sum-rate as well as to reduce the computation complexity of MU-Massive MIMO downlink transmission through a BD precoding technique.
Chapter 5	We conclude this dissertation and discusses the further study of research works.

Chapter 2

Literature Review and Related Works

Over the recent years, the mobile broadband data traffic has been increasing exponentially every year. The 5^{th} generation (5G) broadband wireless access network, which targets data rate over 10Gbps, is expected to be ready for launch by 2020 [48]. Therefore, it is necessary to find a most promising technology to fulfill the requirements of 5G data rate in near future. On the other hand, Massive MIMO systems have a great potential to improve the capacity without increasing the system bandwidth or the transmission power for the wireless communications [49]. Moreover, Massive MIMO can increase the capacity throughput 10 times or more and improve the radiated energy-efficiency simultaneously in the order of 100 times compared with the current wireless communication system [21]. Therefore, the Massive MIMO technology is considered as a promising technology for 5G wireless communication systems [50, 51].

2.1 Literature Reviews

A Massive MIMO refers to a system where the BS is equipped with a large number of antennas (e.g. tens or hundreds) and communicates with several single-antenna users in the same time-frequency domain [26]. The increasing capacity results from aggressive spatial multiplexing used in the Massive MIMO. The basic premise behind the Massive MIMO is to reap all of the benefits of the conventional MIMO, but on much greater scale [21]. It has been shown that the large antenna array at BS could provide high degrees of freedom and thus increase significantly the system capacity, the link reliability, and the radiated-energy efficiency [39, 26, 21]. Also, based on the random matrix theory, it was demonstrated that the Massive MIMO system could achieve the capacity gain with simple and linear signal processing methods [40].

In practical, number of RF chains at the BS cannot be large very much due to the constraints in hardware cost and the complexity. Adding more antennas at the BS is usually inexpensive. However, the RF elements, such as RF amplifier, mixer can be relatively expensive. Therefore, most Massive MIMO systems should consider to implement the BS with larger number of antenna elements but fewer number of RF chains to reduce the hardware cost in the BS side [41]. Since all antennas are not equally good in real propagation channels, it is possible to reduce RF chains to be used with selected active antennas, which contribute the most in the system performance and discarding the rest of antennas. Such antenna selection could simplify the design of a Massive MIMO base station and lead to energy and cost savings [42].

In this case, selecting and using the best antennas among the available large number of antenna elements in BS is an important issue in Massive MIMO technology. Antenna selection in the Massive MIMO system has been studied in [52, 53, 54, 55, 56]. In [52], antenna selection in the Massive MIMO was addressed for mm-wave wireless communications system. In [53], Ban and Jung showed that significantly higher performance could be achieved with antenna selection in the MU-Massive MIMO system. In [54], the antenna selection for maximizing signal-to-noise ratio (SNR) was studied. The authors in [55] evaluated the characteristics of interference rejection with antenna sector selection in the Massive MIMO, based on measured channels in the 2 GHz band with 96 antenna elements. Larsson et al. also studied for an antenna selection method to apply in real propagation environments for Massive MIMO systems in [56].

On the other hand, Massive MIMO can simultaneously serve multiple user equipments (UEs) within a cell using the same time-frequency domain and thus, the spectral efficiency is dramatically improved. But, the user selection is also a critical important factor for optimizing the overall performance of Massive MIMO systems. Recently, many researchers have published their research works about antenna and user selection schemes for Massive MIMO systems [43, 44, 45]. By exploiting the instantaneous CSI of candidate UEs, Lee and Sung proposed the semiorthogonal user selection method in [44], and Xu et al. developed a greedy user selection scheme in [45] to be applied in FDD-based Massive MIMO downlink scenarios. By contrast, Liu et al. considered a pair of low-complexity user selection methods for TDD-based Massive MIMO downlink scenarios [43].

To fully exploit such large number of BS's antennas, it is necessary to use an equal number of RF chains. However, employing such large number of antennas will cause prohibitive hardware cost because it is very expensive to deploy RF chains for all antennas at the BS [57]. Thus, although Massive MIMO systems are implemented employing a larger number of antennas, they should use a much smaller number of RF chains to reduce the hardware cost [41].

It is thus clear that the maximum number of users that can be simultaneously served by the BS is limited by the number of available RF chains. If the number of users is larger than that of the selected/activated BS antennas, the scheduling of the users is done according to the the wireless channel operating conditions. High system performance can be achieved by selecting users with the good channel quality. Consequently, not only the

BS antenna selection but also the user selection need to be performed in MU-Massive MIMO systems [58].

For example, studies [59], [60] assume that multiple users are simultaneously served in the MU-Massive MIMO downlink systems by using linear precoding beamforming techniques. Among the various linear precoding techniques, BD is one of the promising techniques for MU-Massive MIMO downlink system due to their simplicity and good performance [60]. However, the number of users that can be simultaneously supported with BD is limited by the number of transmit and receive antennas, and the rank condition in the channels [60]. Therefore, the selection of users maximizing the total aggregate error-free throughput is used in connection with multi-usersystems employing a very large number of users. But how to find the best user set with low computation complexity is the most challenging task in the MU-Massive MIMO system [60]. It is well known that, a given antenna and the user sets, optimal strategy for achieving the best sum-rate in a MIMO broadcast channel is the full combination brute-force search (BFS), which can guarantee the maximization of sum-rate in the system. However, the complexity is prohibitive to apply for a large number of the BS antennas and total users in the MU-Massive MIMO system [60]. Thus, sub-optimal low complexity antennas and users selection schemes are necessary to be used in connection with MU-Massive MIMO systems which do not significantly decrease the data sum-rate of the system.

2.2 Related Works on Channel Gain-based Selection Methods

Antenna selection and user selection in the MU-Massive MIMO systems have been widely studied as presented in above, but all of them consider only for antenna selection in the BS side or the user selection in the user side. Antenna/user selection in conventional MIMO systems has been previously considered in [61, 62, 63, 64, 65, 66, 67]. For Massive MIMO systems, [68] proposed a pair of heuristic antenna selection algorithms with the goal of improving energy efficiency. In our research works, we would like to emphasize to develop a low computation complexity joint antenna and user selection scheme that maximizes the sum-rate of MU massive MIMO systems. We note that there are already several existing studies considering either antenna selection or user selection in the massive MIMO communication systems. For instance, antenna selection in full duplex cooperative non-orthogonal multiple access systems is considered in [69]. The authors in [70] propose a successive user selection algorithm to maximize the sum-rate of the system. The user selection algorithm proposed in [71] considers the tradeoff between increasing the sum-rate and decreasing the user-to-user interference. However, to the best of our knowledge, antenna and user selection schemes are still needed to develop in the MU-massive MIMO system. Therefore, we focus on joint antenna and user selection in MU massive MIMO communication systems, which can further improve the sum-rate of the system under low computational complexity in the system. To the best of our knowledge, there are only few studies on joint antenna selection for MU-Massive MIMO systems [42, 46, 47]. In [42], a FDD-based Massive MIMO downlink channel is considered to develop a low complexity algorithm that runs joint antenna selection and grouping of receiver nodes.

In [46], the authors propose to solve the joint antenna selection and user scheduling problem, for the distributed Massive MIMO systems under backhaul capacity constraint. In these schemes, the joint antenna selection and user scheduling are proposed and the research results are presented in terms of sum-rate or BER performances. But, the effect of complexity reduction of their proposed schemes was not analyzed and thus the practical feasibility of these schemes was not verified. In [47], the user and antenna joint selection algorithm with suboptimal was proposed and they also presented the performance results of sum-rate as well as the effect of complexity reduction to fulfill the requirement of feasibility in the real word scenario.

In [47], sorted CG with norm based selection criteria has been used in the first step of antenna selection algorithm in the MU-Massive MIMO system. The idea of antenna selection with the sorted CG in descending order is not a very new idea [72, 73, 74, 75, 76, 77, 78, 79, 80] and it has been already presented in well-known textbook [80] in August 2010. In their algorithm, the antennas are sorted in descending order based on CG (norm value) in the first step. The antenna selection algorithm chooses the best antennas based on highest CGs. However, the algorithm is considered only for orthogonal space-time block code (OSTBC) system and it is not possible to apply in the MU-Massive MIMO case. However, this sorted antenna with norm based selection was re-considered for the MU-Massive MIMO case in [47] and they also used this classical concept "sorted antenna with norm based" in the first-step of their algorithm.

Although sorted antennas in descending order based on CG is a useful idea, this concept alone cannot give the best antenna/user set to improve the system performance. In the wireless communication system, the channel quality can be easily decided based on minimum singular value [81, 82]. This minimum singular value is also related to two factors, the first one is CG and the second one is correlation in the channel [81, 82]. This relationship has been presented by our work in [81, 82] at 2007 and 2010, respectively. According to [81, 82], we can say that higher norm value will indicate the better channel condition and lower channel correlation will also give better channel condition. But, higher CG with highly correlated channel might have worse channel condition than lower CG with low correlated channel system. Therefore, deciding the channel condition based only on CG might not give the guarantee to get the best channel condition for wireless communication system. It is highly possible that the higher CGs antennas/users might have highest correlations and this will cause decreasing in sum-rate. Therefore, fine-tuning selection process is still required to eliminate the highly correlated antenna/user set in the initial sorted antenna/user with norm based selection list. In this fine-tuning selection, the scheme in [47] uses sliding windows antenna combination and calculates the capacity for this combination based on the SVD to eliminate the correlated antenna/user pair in their selection. And, their scheme considers all antennas starting from highest one to the lowest CG in the sorted list. However, they just slide the window sequentially and there has some missing combinations from the fine-tuning consideration even these combinations are situated in upper part of the sorted list. They also did not present how to eliminate the huge complexity SVD calculation in the capacity equation (5) for each sliding window combination. These are their weaknesses in the selection process.

In [47], the performance is compared with optimal selection algorithm and it shows that the complexity of [47] is much lower than optimal scheme. But, sum-rate of [47] is still lower than optimal scheme. So, the benefit of trade-off is not clear in [47]. Therefore, finding of other suboptimal schemes are still open research areas in the MU-Massive MIMO systems. Therefore, we try to develop the scheme, which can reduce the complexity as well as increase the sum-rate simultaneously in the system.

2.3 Related Works on SINR-based and Channel Gain-based Selection Methods

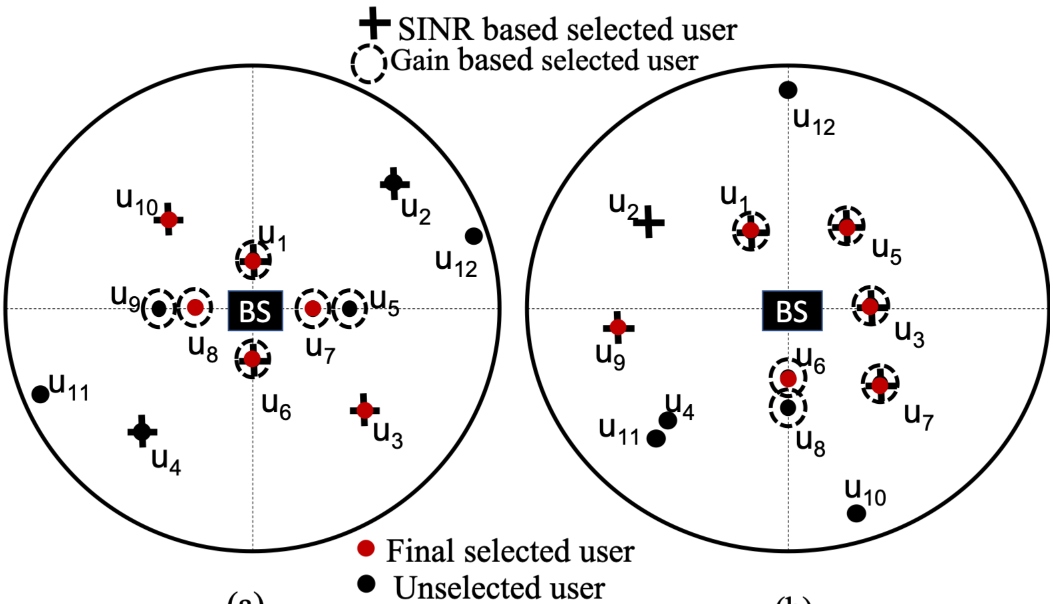
To the best of our knowledge, only a few studies have dealt with the antenna/user selection problems in the context of MU-Massive MIMO systems with the pre-coded transmission, namely [47], [83]. Research of antenna/user selection algorithm with the pre-coded transmission is still active in theoretical interest and great practice in the MU-Massive MIMO system.

In particular, the sliding window (SW method) selection algorithm was presented in [47] based on the sliding window antennas group on the BS side and the singular value decomposition (SVD) base SINR calculated selection on the user side. In the SW Method, antenna set $\mathcal{A}$ and user set $\mathcal{U}$ can be obtained from the CSI and known channel matrix. All antennas included in $\mathcal{A}$ are sorted based on channel gain in descending order and this sorted antenna can be noted as $\mathcal{A}^*$. Then a window is created to slide over the sorted antenna set $\mathcal{A}^*$. This window size is equal to number of available RF chain (S). At first slide in BS side, the window permit to select first antenna position to S^{th} antenna position in the sorted $\mathcal{A}^*$. This condition can be known as first window antenna set in their method. Based on the first window antenna set, all users are sorted according to their channel gain in descending order and noted as $\mathcal{U}1^*$. While holding first window antenna set, first position user in the sorted user set $\mathcal{U}1^*$ will be selected and this can be known as first window in user side. And SW Method calculates the capacity for that antenna window and user window pair. In the next step, first and second positioned users in the sorted user set $\mathcal{U}1^*$ will be selected and it can be known as second window in user side. And capacity is calculated and noted. Size of user window will be varied from 1 to $K = min(S, M)$ in the system. And pairs of first window antenna set and all user windows are calculated based on BD precoding transmission to know the capacity and noted for final selection stage. After calculated for pairs of first window antenna set and all user windows, a window on the BS side will be slided down one position over the sorted antenna set $\mathcal{A}^*$ and this can be known as second window antenna set in BS side. Based on the second window antenna set, all users are sorted again according to their channel gain in descending order and noted as $\mathcal{U}2^*$. And then, capacity will be calculated for all possible pairs of second window antenna set and all user windows. This kind of calculation is repeatedly done until a window on the BS side has been sliding down to reach the lowest channel gain antenna position in the sorted antenna set $\mathcal{A}^*$. At the final selection stage, capacities of all pairs of antenna windows and user windows are compared and we select one pair which gives the highest capacity results for each channel realization in the system. This kind of repeated calculation and choosing the best one can be known as BFS search for fine tuning stage of antenna/user selection methods. However, the SW Method did not present how to eliminate the high computation complexity for the SVD calculation in each sliding window. In [83], user and antenna selection (CG-based method) algorithms with sub-optimal scenario were proposed based on the sorted CGs not only on the user side but also on the BS side. However, its operation was purely CG-based and also did not consider the interference effect of each user in the system. Therefore, high interference among selected users will cause a lower sum-rate for the scheme in [83].

From the above it is clear that, finding a user selection scheme that can produce not only a higher sum-rate but also lower computation complexity is still an open research area in the MU-Massive MIMO system. This problem can be addressed when we jointly consider both the effects of CG and SINR values for each user operating in the system. The following subsection will explain and highlight the weakness of CG-based and SINR-based selection schemes. In addition, the advantages of joint consideration of CG-based and SINR-based selection schemes will be presented to give a clear understanding of the proposed scheme in our paper.

2.3.1 User Selection Schemes Based on Frobenius Norm of the CG and SINR

When a scheme focuses only on CG for the selection, it usually selects all the high CG users group even though they are closely packed within the cell. Therefore, CG-based selection will operate under poor SINR condition because of the high interference effect among these closely packed selected users. This will cause the degradation of sum-rate improvement in the MU-Massive MIMO system. On the other hand, SINR-based selection will not choose any users among a closely packed user group in a cell to avoid the poor SINR conditions among them, though they might have good CG conditions. In this sense, SINR-based selection will miss the chance to improve the sum-rate of MU-Massive MIMO system. However, a users selection method that employs CG (Frobenius Norm) might be modified by combining with SINR-based selection and the final selected user set can give higher sum-rate improvement for MU-Massive MIMO with BD precoding transmission. In order to clearly explain this, we would like to give a brief explanation with some various scenarios of users' placements in a single cell MU-Massive MIMO system.



(a) 2 common users in final selection.

(b) 4 common users in final selection.

Figure 2.1: Various scenarios of user placements with small groups of interference.

Figures 2.1 and 2.2 present different scenarios of user placements in a single cell BS with the 6 RF chains and 12 users case, respectively. By using 6 RF chains, the BS's user selection algorithm can select 6 users among 12 available users in the cell.

Figure 2.1 represents the user placements with lower interference effect on each other except some small user groups who are affected by the high interference from other users in a group. For the scenario in Fig. 2.1(a), if the selection algorithm is only CG-based, the selected set of users is $\mathcal{U}^{Gpre} = \{u_1, u_5, u_6, u_7, u_8, u_9\}$. For the SINR-based selection, the selected user set $\mathcal{U}^{\Gamma pre} = \{u_1, u_2, u_3, u_4, u_6, u_{10}\}$ will be obtained. It is clear that neither selections chooses the set of the best users $\mathcal{U}^* = \{u_1, u_3, u_6, u_7, u_8, u_{10}\}$. After combining the two sets of CG-based and SINR-based selection, u_5 and u_9 will be discarded because of high interference to u_7 and u_8. u_2 and u_4 are also discarded since they possess low CGs comparing with CGs of selected users in the set $\mathcal{U}^*$. It is noted that common users u_1 and u_6 who are included not only in the CG-based user set but also in the SINR user set, are successfully included in the final selection set $\mathcal{U}^*$. For the scenario in Fig. 2.1(b), if the selection algorithm considers only CG-based selection, the selected set of users is given by $\mathcal{U}^{Gpre} = \{u_1, u_3, u_5, u_6, u_7, u_8\}$. For the SINR-based selection, the selected user set $\mathcal{U}^{\Gamma pre} = \{u_1, u_2, u_3, u_5, u_7, u_9\}$ will be obtained. After combining CG-based selection and SINR-based selection, u_8 will be discarded because of its high interference to u_6. Then the combined selection algorithm will mark u_9 as a selected user since it is closer than u_2 to the BS and thus it will give higher sum-rate improvement in the BD beamforming transmission. Finally, as illustrated in Fig. 2.1(b) the best user set $\mathcal{U}^* = \{u_1, u_3, u_5, u_6, u_7, u_9\}$ is selected. From the above example, it is clear that the common user set $\mathcal{U}^I = \mathcal{U}^{Gpre} \cap \mathcal{U}^{\Gamma pre}$ should always be included in the final selection of the best set of users $\mathcal{U}^*$.

Figure 2.2 represents the user placement with larger user groups, in which they are operating in the presence of high system interference. Although in practice such user placement does not always occur in a real-time scenario, we should also observe the results of the CG-based and the SINR-based selections.

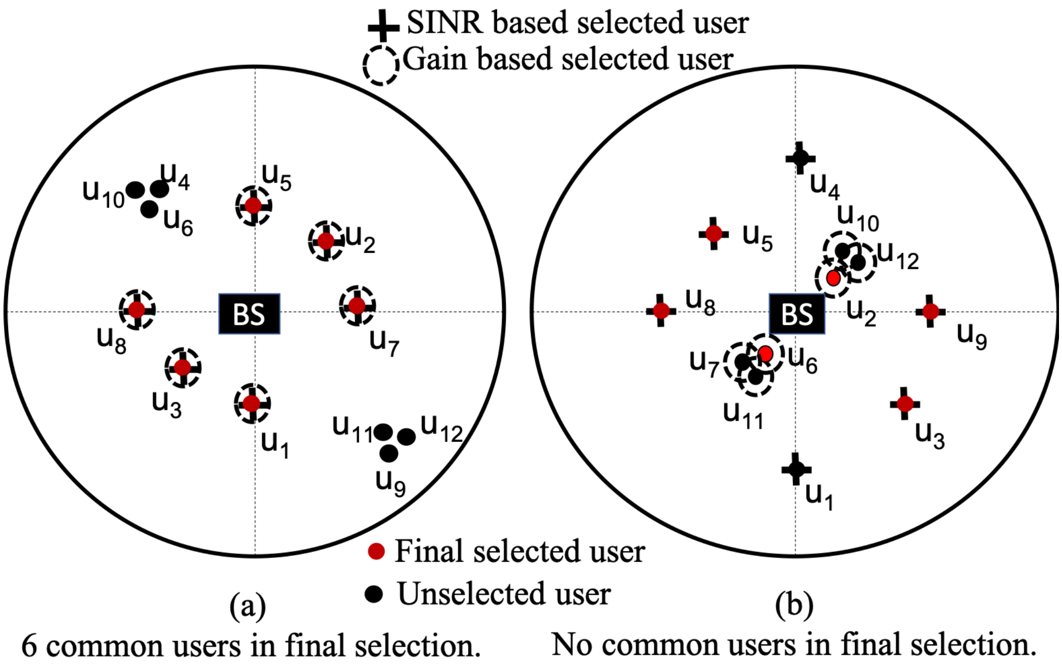


Figure 2.2: Various scenarios user placements with large groups of interference.

For the scenario in Fig. 2.2(a), CG-based and SINR-based selection methods select the same user set for their final selection of best user set $\mathcal{U}^* = \{u_1, u_2, u_3, u_5, u_7, u_8\}$. Therefore no further user selection is needed, resulting in minimum computation complexity for the user selection part. On the other hand, CG-based and SINR-based selection methods give a total different user set for Fig. 2.2(b), when higher interference user groups are closer in range with the BS of the cell. For the final selection of best user set $\mathcal{U}^* = \{u_2, u_3, u_5, u_6, u_8, u_9\}$, two users u_2 and u_6 will be selected from $\mathcal{U}^{Gpre} = \{u_2, u_6, u_7, u_{10}, u_{11}, u_{12}\}$ and four users u_3, u_5, u_8, u_9 from $\mathcal{U}^{\Gamma pre} = \{u_1, u_3, u_4, u_5, u_8, u_9\}$ will be selected in the final selected-best user set. However, since both user sets $\mathcal{U}^{Gpre}$ and $\mathcal{U}^{\Gamma pre}$ have no common user set, this will cause higher computation complexity compared to other scenarios in the user selection part. However, this kind of scenario does not always occur in practical situations and we can get computation complexity reduction in average count according to the law of large numbers [84].

Chapter 3

Low-Complexity Joint Antenna and User Selection Scheme for the Downlink Multiuser Massive MIMO System with Complexity Reduction Factors

MU-Massive MIMO is considered as a promising technology for the fifth generation (5G) of the wireless communication system. In this paper, we propose a low-complexity joint antenna and user selection scheme with BD precoding for MU-Massive MIMO downlink channel in the TDD system. The BS is equipped with a large-scale transmit antenna array while each user is using the single receive antenna in the system. To reduce the hardware cost, BS will be implemented by limited number of RF and BS must activate some selected transmit antennas in the BS side for data transmitting and some users' receive antennas in user side for data receiving. To achieve the reduction in the computation complexity in the antenna and user selection while maintaining the same or higher sum-rate in the system, the proposed scheme relies on three complexity reduction key factors. The first key factor is that finding the average CGs for the transmit antenna in the BS side and the receive antenna in the user side to select the best CG antennas and users. The second key factor called the complexity control factor ζ(Zeta) for the antenna set and the user set limitation is used to control the complexity of the BFS search. The third one is that using the assumption of the SU-MIMO channel model to avoid the SVD computation in the BFS search. We show that the proposed scheme offers enormous reduction in the computation complexity while ensuring the acceptable performance in terms of total system sum-rate compared with optimal and other conventional schemes.

3.1 Introduction

In our scheme, we propose totally different algorithm in fine-tuning process. In our algorithm, we just consider only upper part of the sorted list and lower part is eliminated by using average CG and ζ value. After this elimination, we need to consider very few antenna/user elements for the selection process and these few elements will give few combinations. Therefore, we can consider all of the possible combinations in the upper part of sorted list and we do not miss any combinations, which might have high CG as well as very low correlation in the system. This is how different our scheme in fine-tuning of antenna/user selection process. And another main difference is elimination of SVD calculation base on assumption of SU-Massive MIMO system by neglecting the interference from other users in the MU-Massive MIMO system. The idea of our scheme is very simple but no one has been proposed as far as our knowledge.

Therefore, we do the research work to find the suboptimal scheme for the joint antenna and user selection in the MU-Massive MIMO system to reduce the complexity as well as to improve the sum-rate in this system. The proposed scheme aims to approach the maximum achievable sum-rate by exploiting both multi-userdiversity gain and the spatial selectivity gain offered by the antenna and user selection in BS, respectively. To achieve the reduced complexity in the antenna and user selection while maintaining the same or higher sum-rate in the system, the proposed scheme relies on three complexity reduction key factors. The first key factor is that finding the average CGs for the transmit antenna in the BS side and the receive antenna in the user side to select the best CG antennas and users. The second key factor called the complexity control factor (ζ) for the antenna set and the user set limitation is used to control the complexity of BFS search. The third one is that using the assumption of the SU-MIMO channel model to avoid the SVD computation in BFS search. In the proposed system model, we will apply one of the digital beamforming methods called block diagonalization (BD) precoding technique to give fair comparison with other conventional methods in the evaluation of performance results. When BD precoding technique is used for beamforming transmission, it is important to choose the channel matrix with higher ranking order. Due to the rank condition imposed by the fact that each users precoding matrix must lie in the null space of all other users channels, the number of users that can be simultaneously supported with BD is limited by the number of transmit antennas, the number of receive antennas, and the richness of the channels [59]. Therefore, we must choose antennas and users carefully to give the higher rank for the selected channel matrix in the MU-massive MIMO system. The conventional method did not consider to avoid the very high computation complexity of SVD at the preselection stages of transmit and receive antennas. The preselection stage is necessary to do for many times because it is a kind of BFS search. In each time, SVD calculation is necessary and this causes high computation complexity burden for conventional method. In our proposed method, we tried to avoid high computation complexity of SVD in the preselection stage. BD precoding will apply only one time in the final transmission to give the fair comparison of performance evaluation with other methods.

The simulation results show that proposed scheme can give the same or better sum-rate with less complexity in calculation when compared with scheme in [47].

3.2 System Model

We consider a single cell MU-Massive MIMO downlink channel in the TDD system consisting of BS, which has antennas set $\mathcal{N} = \{1, 2, \cdots, N\}$ and user set $\mathcal{M} = \{1, 2, \cdots, M\}$ with single receive antenna for each user in the network as illustrated in Fig. 3.1. Moreover,

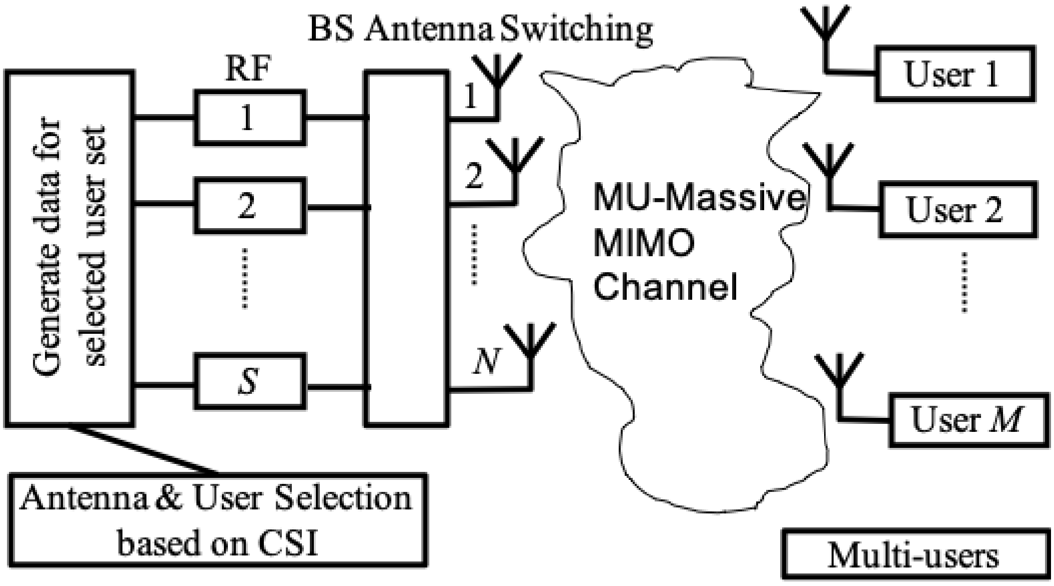


Figure 3.1: System model.

BS can know the perfect CSI because of the channel reciprocity in the TDD system. The main channel between all of the transmitting antennas and receiving users can be represented by a channel matrix $\mathbf{H}_{(\mathcal{M},\mathcal{N})} = \left[h_{i,j}\right]_{i\in\mathcal{M}, j\in\mathcal{N}}$ and $h_{i,j} \in \mathbb{C}^{M\times N}$ represents a channel coefficient between a receive user i and transmit antenna j. Here, the upper-case bold letter represents for matrices and the upper-case calligraphic bold letter represents for the set, respectively. The channel is assumed to be a quasi-static block fading as well as independent and identically distributed (i.i.d) with zero mean circularly symmetric Complex Gaussian (ZMCSCG) Rayleigh fading channel. It is well known that the optimal strategy for achieving the best sum-rate in a MIMO broadcast channel is full combination search in the given antenna set and user set. However, its implementation is impractical because of high complexity when number of antennas and users are increased in the Massive MIMO system. Therefore, we assume the Massive MIMO system with $S(S \leq N)$ RF chains in BS to reduce the hardware cost and complexity and BS will select and activate the S transmit antennas to use for the data transmission to the selected users in the network. BS performs jointly the antenna selection by choosing S antennas among the Nantennas, and scheduling $U(U \leq S)$ users among the M users within the cell to be served simultaneously. To maximize the sum-rate in the data transmission, BS creates two sets $\mathcal{A}$ and $\mathcal{U}$, defined as sets of selected transmit antennas to be activated and selected users, respectively. For the given $\mathcal{A}$ and $\mathcal{U}$, the channel between the selected activated transmit antennas j and selected scheduled users i can be represented by a channel matrix $\mathbf{H}_{(\mathcal{U},\mathcal{A})} = \left[h_{i,j}\right]_{i\in\mathcal{U},j\in\mathcal{A}}$.

For the antenna and user selection in our system, we try to improve not only for reduction of the complexity but also for increasing of higher sum-rate with the lower user interference in the system. To achieve the higher sum-rate with the good signal-to-interference-plus-noise-ratio (SINR) value, we consider to use the BD precoding technique. Because of full known CSI at the BS for downlink transmission, we assumed that perfect beamforming can be done in the BS side and we have not considered any improvement or modification on beamforming/precoding methods. In BD transmission, the transmitted signal vector ($\mathbf{d}^i_{\mathcal{U}}$) for the i^{th} user in set $\mathcal{U}$ is formed by the product of desired scalar signal ($\mathrm{x}^i_{\mathcal{U}}$). The associated precoding vector ($\mathbf{w}^i_{\mathcal{U}}$) for user i in the set $\mathcal{U}$ and can be expressed as follows:

$$\mathbf{d}^i_{\mathcal{U}} = \mathrm{x}^i_{\mathcal{U}}\mathbf{w}^i_{\mathcal{U}}, \tag{3.1}$$

where the lower-case bold letter is used for vector, $(\mathbf{w}^i_{\mathcal{U}}) \in \mathbb{C}^{S\times 1}$ is the precoding vector for the i^{th} user in set $\mathcal{U}$ and it satisfies $||\mathbf{w}^i_{\mathcal{U}}||^2_F = 1$. Moreover, $\mathrm{x}^i_{\mathcal{U}}$ must be satisfied $||\mathrm{x}^i_{\mathcal{U}}||^2_F = p^i_{\mathcal{U}}$, where $||.||^2_F$ denotes the squared Frobenius norm of a matrix and $\sum_{i\in\mathcal{U}} p^i_{\mathcal{U}} \leq P$. $p^i_{\mathcal{U}}$ and P represent the transmit power assigned to the i^{th} user in set $\mathcal{U}$ and total transmit power for set $\mathcal{U}$, respectively. By using BD precoding vector $\mathbf{w}^i_{\mathcal{U}}$, i^{th}user in set $\mathcal{U}$ can avoid the interference from other users at set $\mathcal{U}$ in the same frequency and time domain as shown below:

$$\mathbf{h}^i_{\mathcal{U}}\mathbf{w}^k_{\mathcal{U}} = 0 \text{ for all } i \neq k \text{ and } i \in \mathcal{U}, k \in \mathcal{U}, \tag{3.2}$$

where $\mathbf{h}^i_{\mathcal{U}}$ denote the i^{th} row of $\mathbf{H}_{(\mathcal{U},\mathcal{A})}$. Therefore, the received signal $\mathbf{y}^i_{\mathcal{U}}$ at the i^{th} user in set $\mathcal{U}$ can be written as:

$$\mathbf{y}^i_{\mathcal{U}} = \mathbf{h}^i_{\mathcal{U}}\mathbf{w}^i_{\mathcal{U}}\mathrm{x}^i_{\mathcal{U}} + \mathbf{h}^i_{\mathcal{U}} \sum_{k\in\mathcal{U},k\neq i} \mathbf{w}^k_{\mathcal{U}}\mathrm{x}^k_{\mathcal{U}} + n_i \tag{3.3}$$

n_i is the additive white Gaussian (AWGN) noise with zero mean and variance N_0 at the receiver of the i^{th} user in set $\mathcal{U}$. The signal to interference plus noise ratio $\gamma^i_{\mathcal{U}}$ at the i^{th} user in set $\mathcal{U}$ can be described as:

$$\gamma^i_{\mathcal{U}} = \frac{p^i_{\mathcal{U}}\left|\mathbf{h}^i_{\mathcal{U}}\mathbf{w}^i_{\mathcal{U}}\right|^2}{N_0 + \sum_{k\in\mathcal{U},k\neq i} p^k_{\mathcal{U}}\left|\mathbf{h}^i_{\mathcal{U}}\mathbf{w}^k_{\mathcal{U}}\right|^2} = \frac{\mathrm{SNR}^i_{\mathcal{U}}\left|\mathbf{h}^i_{\mathcal{U}}\mathbf{w}^i_{\mathcal{U}}\right|^2}{1 + \sum_{k\in\mathcal{U},k\neq i} \mathrm{SNR}^k_{\mathcal{U}}\left|\mathbf{h}^i_{\mathcal{U}}\mathbf{w}^k_{\mathcal{U}}\right|^2}, \tag{3.4}$$

where, $|.|$ denotes the cardinality of a set or the absolute value of a scalar and $\mathrm{SNR}^i_{\mathcal{U}}$ defined by $\frac{p^i_{\mathcal{U}}}{N_0}$ denotes the signal to noise ratio for the i^{th} user in the set $\mathcal{U}$. Finally, the downlink sum-rate for the given set $\mathcal{A}$ and $\mathcal{U}$ can be calculated as:

$$R_{sum}(\mathcal{U},\mathcal{A}) = \sum_{i\in\mathcal{U}} \log_2(1 + \gamma^i_{\mathcal{U}}). \tag{3.5}$$

3.2.1 Problem Formulation

The joint antenna and user selection can be formulated as an optimization problem and can be expressed as follows:

$$\underset{(\mathcal{U},\mathcal{A})}{max}.R_{sum}(\mathcal{U},\mathcal{A}) = \underset{(\mathcal{U},\mathcal{A})}{max}.\sum_{i\in\mathcal{U}}\log_2(1+\gamma^i_{\mathcal{U}}), \tag{3.6}$$

subject to:

$$|\mathcal{U}| \leq |\mathcal{A}| \leq S \leq |\mathcal{N}|, \tag{3.7}$$

$$\sum_{i\in\mathcal{U}} p^i_{\mathcal{U}} \leq P. \tag{3.8}$$

Constraint in (3.7) ensures that the number of selected users $|\mathcal{U}|$ does not exceed the number of selected and activated antenna $|\mathcal{A}|$ at the BS. Moreover, number of selected and activated antenna $|\mathcal{A}|$ also does not exceed the number of available RF chains S in BS and all equipped antennas $|\mathcal{N}|$ in BS as being restricted by (3.7). Constraint in (3.8) ensures that the summation of the transmit power of all users' data signal must be within the allowed total transmit power P in BS. Moreover, we consider equal power allocation for all users in the system to reduce the calculation complexity in our scheme. Therefore, equation (3.8) can be simplified and each user's transmit power $p^i_{\mathcal{U}}$ can be express as follow:

$$p^i_{\mathcal{U}} = \frac{P}{|\mathcal{U}|}\cdot \tag{3.9}$$

The formulated problem is a combinatorial problem, which involves finding the optimal received user set and transmit antenna set represented by binary integer variables. The only known technique that can find the optimal solutions to this problem is the exhaustive search [85, 86]. The corresponding computation complexity grows exponentially with the values of $|\mathcal{N}|$ or $|\mathcal{M}|$. Moreover, BD precoding technique requires for calculating the beamforming vector of a user $i, (1 \leq i \leq M)$, BS firstly calculates the null space of the remaining $(M-1)$ users, except user i. The null space of a matrix can be obtained by using the SVD method [47]. And this SVD will add extra heavy calculation on the antenna and user selection scheme.

Because of very high complexity in the optimal scheme, it is not practical to be applied in the real implementation although it is useful for the performance benchmark. Therefore, the suboptimal scheme is presented in section 3.3 to be used in the real implementation for the joint antenna and user selection for the MU-Massive MIMO system.

3.3 Proposed Joint Selection Scheme for Antennas in BS and Users

In this section, we explain about a reduced complexity joint antenna and user selection scheme that can be implemented in the practical MU-Massive MIMO downlink systems. The proposed scheme aims to approach the maximum achievable sum-rate by exploiting both the multi-userdiversity gain and the spatial selectivity gain offered by the antenna and user selection in BS, respectively. One of the key ideas of complexity reduction in the proposed scheme is that using the assumption of SU-MIMO channel model to avoid the SVD computation in BFS search. When we are considering the Massive MIMO system, this kind of system is generally implemented with very large number of transmit and receive antennas in the system. When the numbers of transmit and receive antennas are very large, the capacity of the spatially white MIMO channel becomes deterministic and its capacity can be expressed as follows [87]:

$$C = \log_2 \det \left(\mathbf{I} + \frac{P}{SN_0} \mathbf{H}\mathbf{H}^H \right), \tag{3.10}$$

where $(.)^H$ represents the Hermitian matrix. Based on (3.10), we can avoid the finding of beamforming vector for SINR information in (3.4) and (3.5) which requires the high complexity calculation for the SVD method. By using (3.10), equation (3.6) in the problem formulation can be rewritten as follows:

$$\underset{(\mathcal{U},\mathcal{A})}{max}.R_{sum}(\mathcal{U},\mathcal{A}) = \underset{(\mathcal{U},\mathcal{A})}{max}.\log_2 \det\left(\mathbf{I}_{\mathcal{U}} + \frac{P}{SN_0}\mathbf{H}_{(\mathcal{U},\mathcal{A})}\mathbf{H}^H_{(\mathcal{U},\mathcal{A})}\right). \tag{3.11}$$

Even though, we avoid the SVD calculation to find the highest sum-rate channel matrix with the selected BS antenna and user set in the system, we still need to make the BFS search to find the best matrix in (3.11). This is the high complexity combinatorial search and its complexity is based on the number of available antennas N and users M in the system and the required amount of iteration τ for the calculation can be expressed as follow:

$$\tau = \binom{N}{S}\binom{M}{U} = \frac{N!}{S!(N-S)!} \times \frac{M!}{U!(M-U)!}, \tag{3.12}$$

where U is the number of selected users from total users M. τ will be very huge hence the Massive MIMO system is generally implemented by the very large number of transmit and receive antennas. Therefore, we will try to limit the considered BS antenna N and user M in (3.12) by using complexity control factor ζ. ζ will be determined at the initialization steps of our proposed algorithm. This ζ value can be decided based on the processing power of the BS in the system, since BS must be done for all calculation of the proposed methods. The maximum number of the considered transmit antenna and user must not be larger than the summation of predefined ζ and the available RF chains S. And (3.12) can be rewritten as follow by using this updated number for the antenna set and user set in the system.

$$\tau^{limited} = \binom{S+\zeta}{S}\binom{K+\zeta}{K} = \frac{(S+\zeta)!}{S!(\zeta)!} \times \frac{(K+\zeta)!}{K!(\zeta)!}, \tag{3.13}$$

where $K = min(M,S)$. To apply (3.13) in the proposed scheme, we first need to find the channel Frobenius norm values. The motivation is that the capacity is closely related to the eigenvalues of the effective channel after precoding. Although the channel Frobenius norm cannot characterize the capacity completely, it is related to the capacity because the Frobenius norm indicates the overall energy of the channel, i.e., the sum of the eigenvalues of $\mathbf{HH}^H$ equals to $||\mathbf{H}||_F^2$ [88]. Pseudo code of the proposed selection algorithm is described in Table 3.1. The details operation of the algorithm is explained as follows:

Firstly, the proposed scheme initializes ζ to the predetermined value, which depends on the processing ability of BS. And then, initialized the sets $\mathcal{A}^{init} = \{1, 2, \cdots, N\}$, and $\mathcal{U}^{init} = \{1, 2, \cdots, M\}$ and obtains the corresponding $\mathbf{H}^{init}_{(\mathcal{U}^{init}, \mathcal{A}^{init})}$.

All available antennas N in the BS side and users M in the receiver side are necessary to be sorted in descending order based on the channel Frobenius norm value. And we need to find the mean CG at the transmit antenna side and the receive user side. The mean channel gain can be calculated for each channel realization by using known channel matrix of MU-Massive MIMO system. For the downlink communication, column vector of main channel matrix will give channel gain for each transmit antenna and row vector of main channel matrix will give channel gain for each user, respectively. Frobenius norm of each vector is related to channel gain for transmit antenna and received user. After getting those values, BS can calculate for mean CG-values for transmit antenna and received users in the system for each channel realization. For the processing of the BS side, all the antennas included in the set $\mathcal{A}^{init}$ are sorted according to $||\mathbf{h}^i_{\mathcal{A}^{init}}||_F^2$ $\left(1 \le i \le \left|\mathcal{A}^{init}\right|\right)$ in descending order, where $\mathbf{h}^i_{\mathcal{A}^{init}}$ is the i^{th} column of $\mathbf{H}^{init}_{(\mathcal{U}^{init}, \mathcal{A}^{init})}$ and denotes the channel coefficients

Table 3.1: Pseudo code for the proposed scheme's algorithm.

Steps	**Description**
1	Input: CSI information for all users and antennas in the BS side, Number of RF chains S and ζ
2	Initialization: $\mathcal{A}^{init} = \{1, 2, \cdots, N\}$ and $\mathcal{U}^{init} = \{1, 2, \cdots, M\}$, $\mathbf{H}^{init}_{(\mathcal{U}^{init}, \mathcal{A}^{init})} = \left\|h_{ij}\right\|_{i \in \mathcal{U}^{init}, j \in \mathcal{A}^{init}}$
3	Create the set $\mathcal{A}^{sort}$ with sorted antennas according to $\|\|\mathbf{h}^i_{\mathcal{A}^{init}}\|\|_F^2$ $(1 \le i \le \left\|\mathcal{A}^{init}\right\|)$ in descending order.
4	Find the mean CG $\mu_{\mathcal{A}}$ for the transmit antennas in the BS side. $\mu_{\mathcal{A}} = \frac{1}{\|\mathcal{A}^{sort}\|} \sum_{i \in \mathcal{A}^{sort}} \|\|\mathbf{h}^i_{\mathcal{A}^{sort}}\|\|_F^2$
5	Count the number of antennas $(q_{\mathcal{A}})$ which channel gains are larger than mean the CG $(\mu_{\mathcal{A}})$
6	If $q_{\mathcal{A}} \le S$, then $\mathcal{A}^{est} = \{1, 2, \cdots, S\}$. Else if $S < q_{\mathcal{A}} < S + \zeta$, then $\mathcal{A}^{est} = \{1, 2, \cdots, S, \cdots, q_{\mathcal{A}}\}$. Else $\mathcal{A}^{est} = \{1, 2, \cdots, S, \cdots, q_{\mathcal{A}}, \cdots, S + \zeta\}$. End, (where $\mathcal{A}^{est} \subseteq \mathcal{A}^{sort}$).
7	If $\left\|\mathcal{U}^{init}\right\| \le S$, then $\mathcal{U}^{est} = \mathcal{U}^{init}$ and go to the 11^{th} step. Else, create the set $\mathcal{U}^{sort}$ with sorted antennas according to $\|\|\mathbf{h}^k_{\mathcal{U}^{init}}\|\|_F^2$ $(1 \le k \le \left\|\mathcal{U}^{init}\right\|)$ in descending order.
8	Find the mean CG $\mu_{\mathcal{U}}$ for the receive antenna in the user side. $\mu_{\mathcal{U}} = \frac{1}{\|\mathcal{U}^{sort}\|} \sum_{k \in \mathcal{U}^{sort}} \|\|\mathbf{h}^k_{\mathcal{U}^{sort}}\|\|_F^2$
9	Count the number of antennas $(q_{\mathcal{U}})$ which channel gains are larger than the mean CG $(\mu_{\mathcal{U}})$
10	If $q_{\mathcal{U}} \le S$, then $\mathcal{U}^{est} = \{1, 2, \cdots, S\}$. Else if $S < q_{\mathcal{U}} < S + \zeta$, then $\mathcal{U}^{est} = \{1, 2, \cdots, S, \cdots, q_{\mathcal{U}}\}$. Else $\mathcal{U}^{est} = \{1, 2, \cdots, S, \cdots, q_{\mathcal{U}}, \cdots, S + \zeta\}$. End, (where $\mathcal{U}^{est} \subseteq \mathcal{U}^{sort}$).
11	In (3.11), the well known BFS search will be applied on the given sets $\mathcal{A}^{est}$ and $\mathcal{U}^{est}$ to find the BS antenna set $\mathcal{A}^{sel}$ and the user set $\mathcal{U}^{sel}$ which can give the maximum sum-rate channel matrix $\mathbf{H}^{sel}_{(\mathcal{U}^{sel}, \mathcal{A}^{sel})}$ for the system. Number of iteration will be limited by (3.13) to reduce the complexity of the proposed scheme.
12	The BD precoding technique will be applied on the selected channel matrix $\mathbf{H}^{sel}_{(\mathcal{U}^{sel}, \mathcal{A}^{sel})}$ in step-11 to get the required beamforming vector and the SINR value for each user in the MU-Massive MIMO downlink scenario.

between i^{th} antenna in the set $\mathcal{A}^{init}$ and all users in the set $\mathcal{U}^{init}$. The set of sorted antennas is newly denoted by $\mathcal{A}^{sort}$ and thus it satisfies

$$||\mathbf{h}^1_{\mathcal{A}^{sort}}||_F^2 \geq ||\mathbf{h}^2_{\mathcal{A}^{sort}}||_F^2 \geq, \cdots, \geq ||\mathbf{h}^{|\mathcal{A}^{sort}|}_{\mathcal{A}^{sort}}||_F^2. \tag{3.14}$$

Then, we find the mean CG $\mu_{\mathcal{A}}$ in the BS side by using (3.15).

$$\mu_{\mathcal{A}} = \frac{1}{|\mathcal{A}^{sort}|} \sum_{i \in \mathcal{A}^{sort}} ||\mathbf{h}^i_{\mathcal{A}^{sort}}||_F^2. \tag{3.15}$$

After that, we count and note the number of BS antennas, which has larger CG than $\mu_{\mathcal{A}}$ in (3.15) and denoted as $q_{\mathcal{A}}$. If this counted number $q_{\mathcal{A}}$ is not higher than the number of available RF chains S in BS, then the estimated antenna set $\mathcal{A}^{est}$ will be created by selecting the antennas from 1 to S in $\mathcal{A}^{sort}$. If the $q_{\mathcal{A}}$ is situated between S and $(S+\zeta)$, then the estimated antenna set $\mathcal{A}^{est}$ will be created by selecting the antennas from 1 to $q_{\mathcal{A}}$ in $\mathcal{A}^{sort}$. And if the $q_{\mathcal{A}}$ is larger than $(S+\zeta)$, then the estimated antenna set $\mathcal{A}^{est}$ will be created by selecting the antennas from 1 to $(S+\zeta)$ in the $\mathcal{A}^{sort}$. After that, we will get the estimated antenna set for the BS side and it is denoted by $\mathcal{A}^{est}$.

For the processing of the user side, the total number of user in the set $\left(|\mathcal{U}^{init}|\right)$ and the available RF chains S in BS are compared firstly. If the total number of user in the set $\left(|\mathcal{U}^{init}|\right)$ is not greater than the available RF chains S, then the estimated user set $\mathcal{U}^{est}$ will be created by selecting all users from the set $\mathcal{U}^{init}$. If the total number of user $\left(|\mathcal{U}^{init}|\right)$ is larger than the available RF chains S in BS, then all users included in the set $\mathcal{U}^{init}$ are sorted according to $\left\|\mathbf{h}^k_{\mathcal{U}^{init}}\right\|_F^2$ in descending order, where $\mathbf{h}^k_{\mathcal{U}^{init}}$ is the k^{th} row of $\mathbf{H}^{estA}_{(\mathcal{U}^{init},\mathcal{A}^{est})}$ and denotes the channel coefficients between user k in set $\mathcal{U}^{init}$ and all antennas in the set $\mathcal{A}^{est}$. The set of sorted users is newly denoted by $\mathcal{U}^{sort}$ and thus it satisfies (3.16).

$$||\mathbf{h}^1_{\mathcal{U}^{sort}}||_F^2 \geq ||\mathbf{h}^2_{\mathcal{U}^{sort}}||_F^2 \geq, \cdots, \geq ||\mathbf{h}^{|\mathcal{U}^{sort}|}_{\mathcal{U}^{sort}}||_F^2. \tag{3.16}$$

After that, we will continue to find the mean value of user CG $\mu_{\mathcal{U}}$ by using (3.17).

$$\mu_{\mathcal{U}} = \frac{1}{|\mathcal{U}^{sort}|} \sum_{k \in \mathcal{U}^{sort}} ||\mathbf{h}^{k}_{\mathcal{U}^{sort}}||^2_F. \tag{3.17}$$

We count and note the number of users, which has larger channel value than $\mu_{\mathcal{U}}$ value in (3.17) and denoted as $q_{\mathcal{U}}$. If this counted number $q_{\mathcal{U}}$ is not higher than the number of available RF chains S in BS then the estimated user set $\mathcal{U}^{est}$ will be created by selecting the user from 1 to S. If the $q_{\mathcal{U}}$ is situated between S and $(S+\zeta)$ then the estimated user set $\mathcal{U}^{est}$ will be created by selecting the user from 1 to $q_{\mathcal{U}}$. And if the $q_{\mathcal{U}}$ is larger than $(S+\zeta)$, then the estimated user set $\mathcal{U}^{est}$ will be created by selecting the user from 1 to $(S+\zeta)$. After that, we will get the estimated user set and it is denoted by $\mathcal{U}^{est}$.

The optimal BS antenna set $\mathcal{A}$ and the user set $\mathcal{U}$ can be found by using (3.11) with the optimal BFS search to achieve the maximum sum-rate in the system. The number of iteration for this search will be limited by (3.13). At the end of this step, we will get the selected channel matrix and it is denoted by $\mathbf{H}^{sel}_{(\mathcal{U}^{sel},\mathcal{A}^{sel})}$. In the last step, BD precoding techniques will be applied in the selected channel matrix in the previous step to avoid the user interference in the MU-Massive MIMO downlink system.

3.4 Computation Complexity Analysis

In this section,computation complexities of the proposed and conventional schemes are expressed based on FLOP count. All matrix manipulations will require some FLOPs count for the arithmetic operation. Counting the FLOP for each matrix manipulation was already defined in [88, 89, 90]. We also present the complexity analysis by counting the FLOP requirements based on matrix manipulation process in each algorithm.

When the maximum sum-rate is required, the calculation of the channel capacity can be done based on the CSI and the selected antenna and user sets. The possibility of the combination of antenna and user sets depends on the implemented antenna number N, RF chains S in BS, and the total number of user M in the system. This possibility of optimal BFS search can be expressed by using binomial coefficient for the BS side and the user side as follow in (3.18).

$$\mathcal{O}_{opt} = \binom{N}{S}\binom{M}{min(M,S)}. \tag{3.18}$$

In the proposed scheme, major steps which require the large complexity calculation can be found in step-3, 7 (Else condition), 11 and 12 of the algorithm in Table 3.1. Step-3 and 7 (Else condition) are doing the sorting of channel matrix based on the Frobenius norm for the transmit antenna N and the receive antenna in user M. For the $N \times M$ complex-valued matrix $\mathbf{H} \in \mathbb{C}^{N\times M}$, the floating point operation (FLOP) count for Frobenius norm is $4NM$ [88]. Therefore, step-3 will need $4NM$ FLOPs count and step-7(Else condition) also need $4NM$ FLOPs count to make the descending order of antennas and users in these steps. In step-11, one operation of matrix multiplication and one operation of determinant of matrix are required to solve equation (3.11) for each selected matrix. The FLOPs count required is $2K^2S$ for the multiplication of the matrix with size $(K \times S)$ and $(S \times K)$ [89]. The FLOPs count required for the determinant operation of matrix size $(K \times K)$ is $K^{log_2(7)}$ [90]. Therefore, each calculation of (3.11) requires $2K^2SK^{log_2(7)}$ FLOPs count. This is necessary to be multiplied by total iteration number of combinatorial result τ to complete the brute force optimal search in (3.11). To reduce further the combinatorial search τ, the complexity control factor (ζ) is introduced in (3.13). After getting the best channel matrix in the 11^{th} step, we will apply the SVD method to find the beamforming vector and the

SINR information for the BD precoding technique. The required FLOPs count for SVD can be calculated as follows [47]:

$$24S^2 + 48S + 54 \cdots \text{ if } K = 1. \tag{3.19}$$

$$K\left[24(K-1)S^2 + 48(K-1)^2 S + 54(K-1)^3\right] \cdots \text{ if } K \geq 2. \tag{3.20}$$

In the proposed scheme, the second dimension (column) of the selected channel matrix will be equal to RF chains S and the first dimension (row) will be equal to $min(S, M)$ users in the system since the maximum number of selected users must not be larger than the available RF chains in (3.7). The FLOPs count required in the 12^{th} step can be found by using (3.20) with $K = min(S, M)$ in the proposed scheme. Therefore, total FLOPs count for the proposed scheme can be represented as follow:

$$\begin{aligned} F^{[prop]} = & \binom{S+\zeta}{S}\binom{K+\zeta}{K} 2K^2 S K^{log_2(7)} + 8NM \\ & + K\Big[24(K-1)S^2 + 48(K-1)^2 S + 54(K-1)^3\Big]. \end{aligned} \tag{3.21}$$

It should be noted that complexity in (3.21) is the upper bound for the given (ζ) value and the actual complexity will not reach to that upper bound, since the BFS search might not be required to use every time in step-11. Some times, total count of the transmit antenna/user, whose SNR values are higher than the average SNR in the initial antenna and user sets, is less than the available RF chains S. When this condition occurs, the BFS search with (3.11) is not required anymore and (3.21) can be updated as (3.22). We should note that this is the lower bound for the proposed scheme:

$$F^{[prop]} = 8NM + K\Big[24(K-1)S^2 + 48(K-1)^2 S + 54(K-1)^3\Big]. \tag{3.22}$$

Therefore, the actual complexity will fall between these lower bound and upper bounds for the proposed scheme based on the real time channel matrix condition. On the other hand, the FLOPs count required for the optimal scheme ($F^{[prop]}$) and the SW Method ($F^{[SW]}$) can be expressed as follows [47]:

$$F^{[opt]} = \binom{N}{S}\Bigg[\binom{M}{1}(24S^2+48S+54) + \sum_{K=2}^{min(M,S)}\binom{M}{K}K\Big(24(K-1)S^2+48(K-1)^2S+54(K-1)^3\Big)\Bigg]. \tag{3.23}$$

$$F^{[SW]} = (N-S+1)\Bigg[24S^2+48S+54 + \sum_{K=2}^{min(M,S)}K\Big(24(K-1)S^2+48(K-1)^2S+54(K-1)^3\Big)\Bigg]. \tag{3.24}$$

3.5 Simulation Results

Table 3.2: Simulation parameters.

Parameter	**Description**
Channel	Rayleigh Fading (with Block)
SNR	10dB
Cell	Single
Number of Packets	10,000
Frames/Packet	10
Number of antennas in BS	N
Number of RF chains in BS	S
Number of users	M
Transmit beamforming	Block Diagonalization

The simulation parameters are shown in Table 3.2. We compare the performances of the proposed scheme in terms of the computational complexity and the average sum-rate for the MIMO system. To show the various scenarios for the MU-Massive MIMO system, we consider the cases with the various user number M, the various transmit antenna number N and the available RF chains S in the given system. We consider the cases, when number of RF chains is equal to 25%, 33% and 50% of the BS antenna in the system. Complexity results are normalized by using the smallest lower bound value in each complexity performance figures to clarify the ratio of complexity for each scheme. Fig. 3.2 shows the complexity performances for the theoretical calculation and the real CPU usage time in the MATLAB simulation platform for the proposed scheme and other two conventional schemes. In this case, the fixed BS antenna number $N = 12$ and RF chains $S = 3$ (25% of N) are used for the increasing number of users M from 2 to 20 shown in the following figures.

To reduce the complexity in the proposed scheme, $\zeta = 1$ and $\zeta = 2$ are used and the lower bound result is also presented for the complexity analysis. In Fig. 3.2a for FLOPs comparison, we can see that the complexity of the proposed scheme with $\zeta = 2$ is situated above the complexity plot of SW Method. On the other hand, the CPU usage time for all of the proposed schemes are lower than the SW Method and the optimal scheme. When lower number of ζ values are used in the proposed scheme, we can make the reduction in complexity as shown in Fig. 3.2b. Moreover, we do not use the high complexity SVD method in finding of the best antenna and user sets in the system when we are using (3.11) for the BFS search. Further reduction of complexity can be achieved by avoiding the calculation requirement of the BFS search at some conditions i.e., when number of available RF chains S is larger than numbers of antennas and users whose CGs are higher than mean SNR value at step-5 and step-9 in the proposed algorithm.

In Fig. 3.2a, we can notice that the upper bound complexity of the proposed scheme with $\zeta = 2$ is higher than the SW Method while CPU time of the proposed scheme with $\zeta = 2$ is lower than the SW Method in Fig. 3.2b. For this explanation, we have to note that

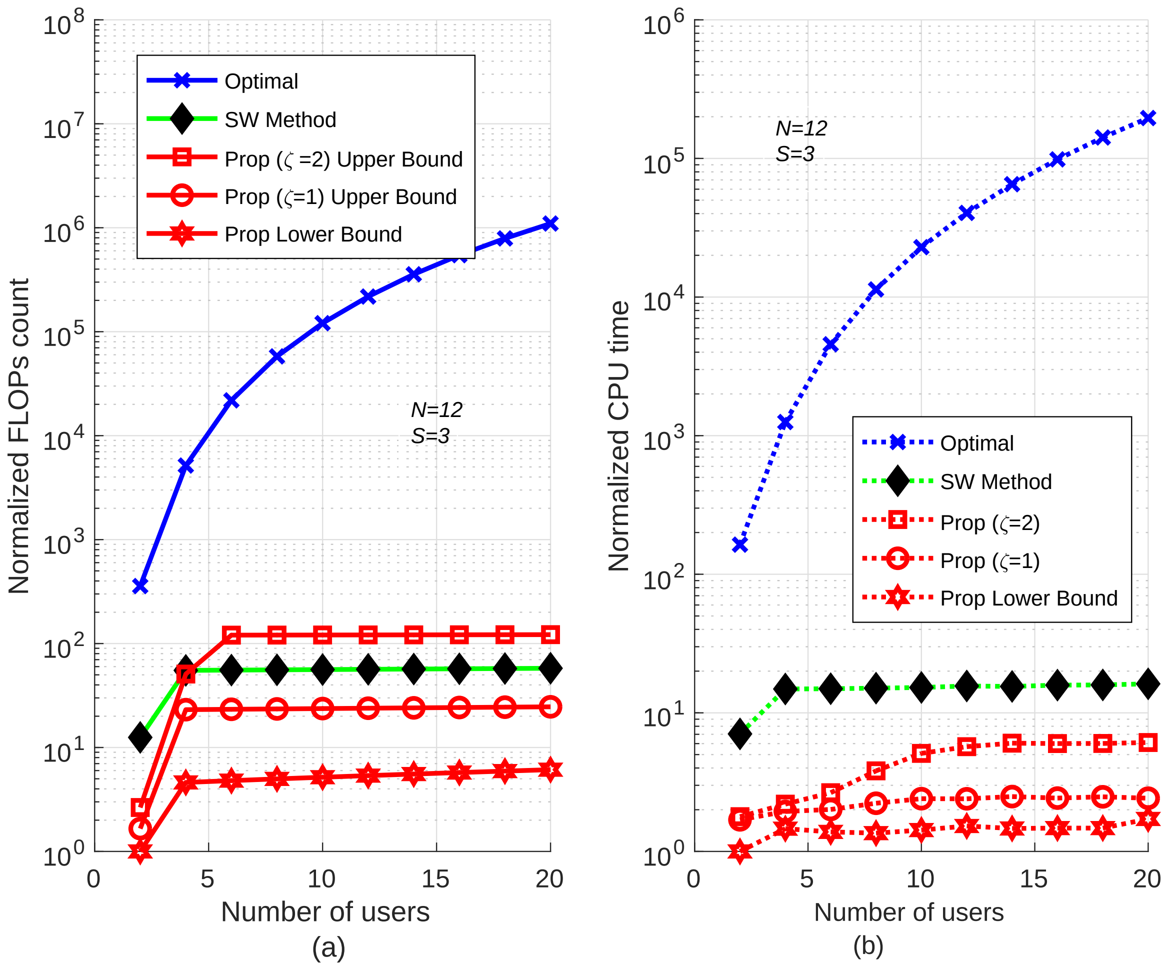


Figure 3.2: Comparison of complexity for various M with $S = \frac{N}{4}$ (a) Normalized FLOPs count (b) Normalized CPU time.

(3.13) will limit the maximum number of iterations τ in step-11 of Table 3.1. And this maximum τ can be reached only when $q_{\mathcal{A}} \geq (S + \zeta)$ and $q_{\mathcal{U}} \geq (S + \zeta)$ at step-6 and step-10 of Table 3.1, respectively. On the other hand, $\mathcal{A}^{est} = \{1, 2, \cdots, S\}$ and $\mathcal{U}^{est} = \{1, 2, \cdots, S\}$ will be obtained when $q_{\mathcal{A}} \leq S$ and $q_{\mathcal{U}} \leq S$ at step-6 and step-10 of Table 3.1, respectively. When $\left|\mathcal{A}^{est}\right| = S$ and $\left|\mathcal{U}^{est}\right| = S$, optimal (brute force) search is not necessary to be done in step-11, since $\mathcal{A}^{est}$ will become $\mathcal{A}^{sel}$ directly and $\mathcal{U}^{est}$ will also become $\mathcal{U}^{sel}$ directly. And this condition can be known as lower bounded condition and ($\tau = 1$) can be obtained. However, we cannot always hope to obtain maximum τ but also minimum τ in real time scenario. If we have the condition with $\left|\mathcal{A}^{est}\right| = q_{\mathcal{A}}$ and $\left|\mathcal{U}^{est}\right| = q_{\mathcal{U}}$ then the number of iteration τ will be situated between maximum τ and minimum τ. Moreover, the simulation results for the real CPU usage time represent the actual condition of real scenario for given system. Therefore, we will get maximum τ for some channel realizations, some other channel realizations will give minimum τ and remaining channel realizations will give the τ between maximum and minimum values. And the final simulation result in Fig. 3.2b is the mean value of many thousands of this channel realization time. On the other hand, the FLOPs count curves for the proposed schemes in Fig. 3.2a are calculated based on only maximum τ case for upper bound and this condition is not represent for real scenario of given system. Therefore, simulation results of CPU time for the proposed schemes are lower than the conventional scheme in Fig. 3.2b while upper bound FLOPs counts of the proposed schemes are higher than the conventional scheme in Fig. 3.2a. Same reason can also be applied in Fig. 3.3, 3.5 and 3.6. And we will see that simulation results of CPU time for the proposed schemes are lower than the conventional schemes in Figs. 3b, 5b and 6b, while upper bound FLOPs counts of the proposed schemes are higher than the conventional schemes in Figs. 3a, 5a and 6a.

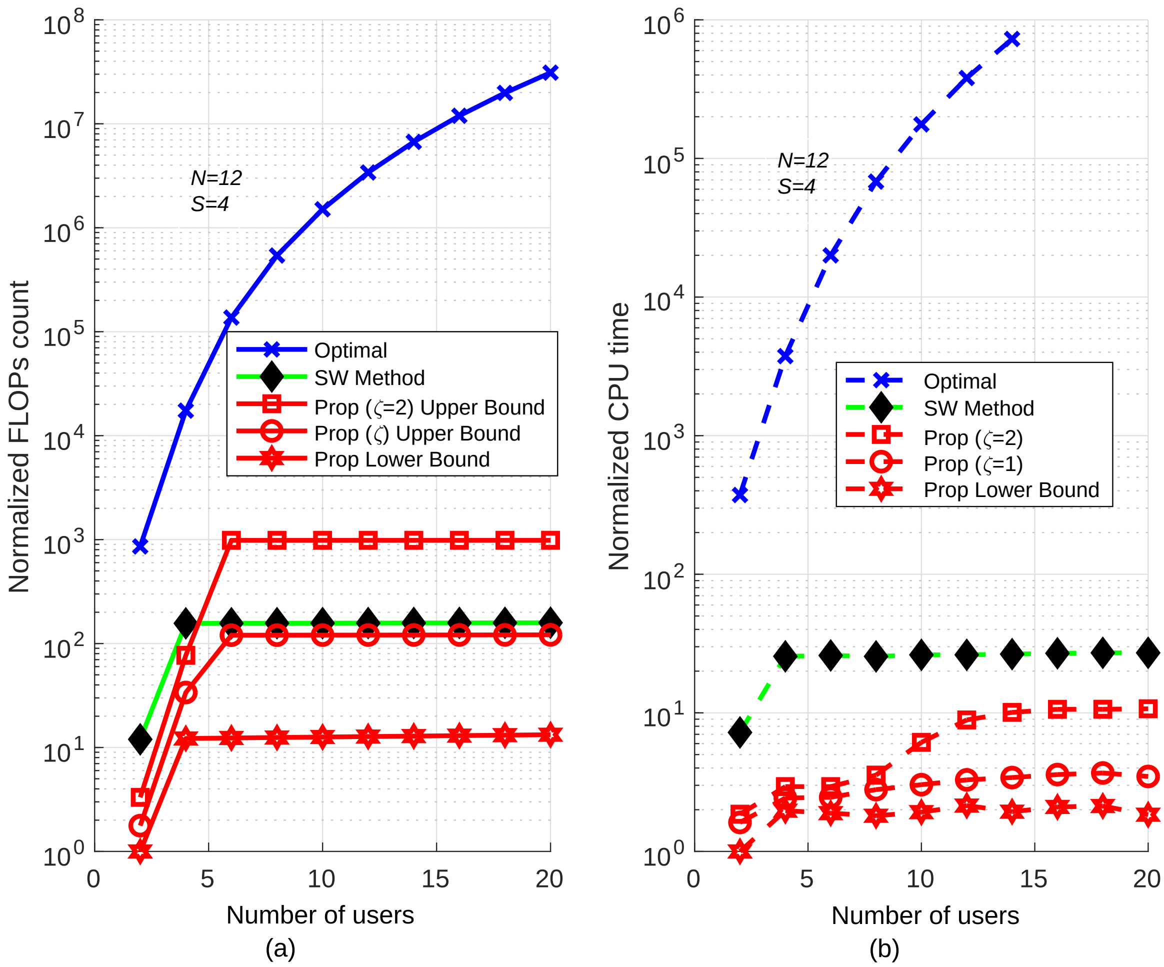


Figure 3.3: Comparison of complexity for various M with $S = \frac{N}{3}$ (a) Normalized FLOPs count (b) Normalized CPU time.

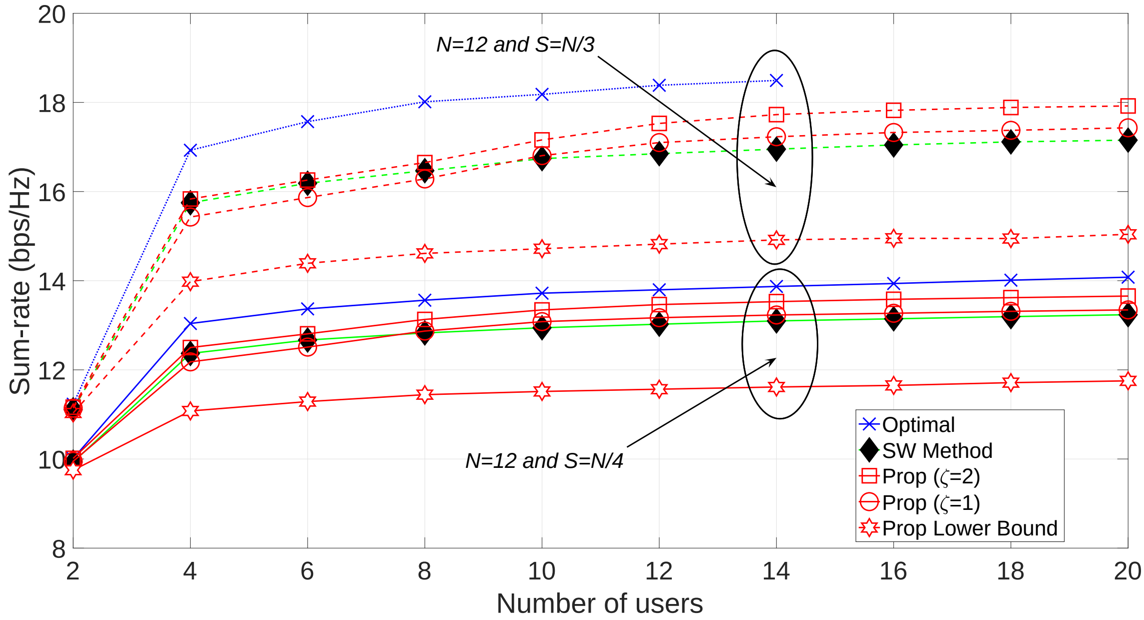


Figure 3.4: Comparison of sum-rate for various M with $S = \frac{N}{3}$ and $S = \frac{N}{4}$.

As shown in Fig. 3.3, the similar results are obtained when the number of RF chains is equal to 33% ($S = N/3$) of the BS antenna. The only difference can be found in the sum-rate in Fig. 3.4 for the usage of RF chains is 25% ($S = N/4$) and 33% ($S = N/3$) of antenna in BS. For both cases, sum-rate performances of the proposed schemes ($\zeta = 1$ and 2) are generally higher than the SW Method except for smaller number of users region in the horizontal axis. When the number of users is small, the proposed scheme has not many options to determine the good user set to avoid the user interference among them. Because the proposed scheme is selecting the users which is equal to number of available RF chains in the system. All of these selected users will be assigned with the equal power distribution manner to reduce the complexity in the transmit power distribution as expressed in (3.9).

On the other hand, the SW Method, will not select the fixed number of users in the system. It might select the number of users starting from 1 to the available RF chains S. Therefore, it has more options to create the good user set in the system. Moreover, the proposed scheme has more restricted condition to create the good user set, if there are not many users compared with the available RF chains in the system. Comparing with the SW Method for using larger number of user M, the proposed scheme with $S = N/3$ can give better sum-rate than the proposed scheme with $S = N/4$. However, the proposed scheme with $\zeta = 2$ can give better capacity results with the lower complexity for all number of users M as shown in Fig. 3.4. More improvement can be obtained especially for larger number of user M for both types of RF chains usage in the system.

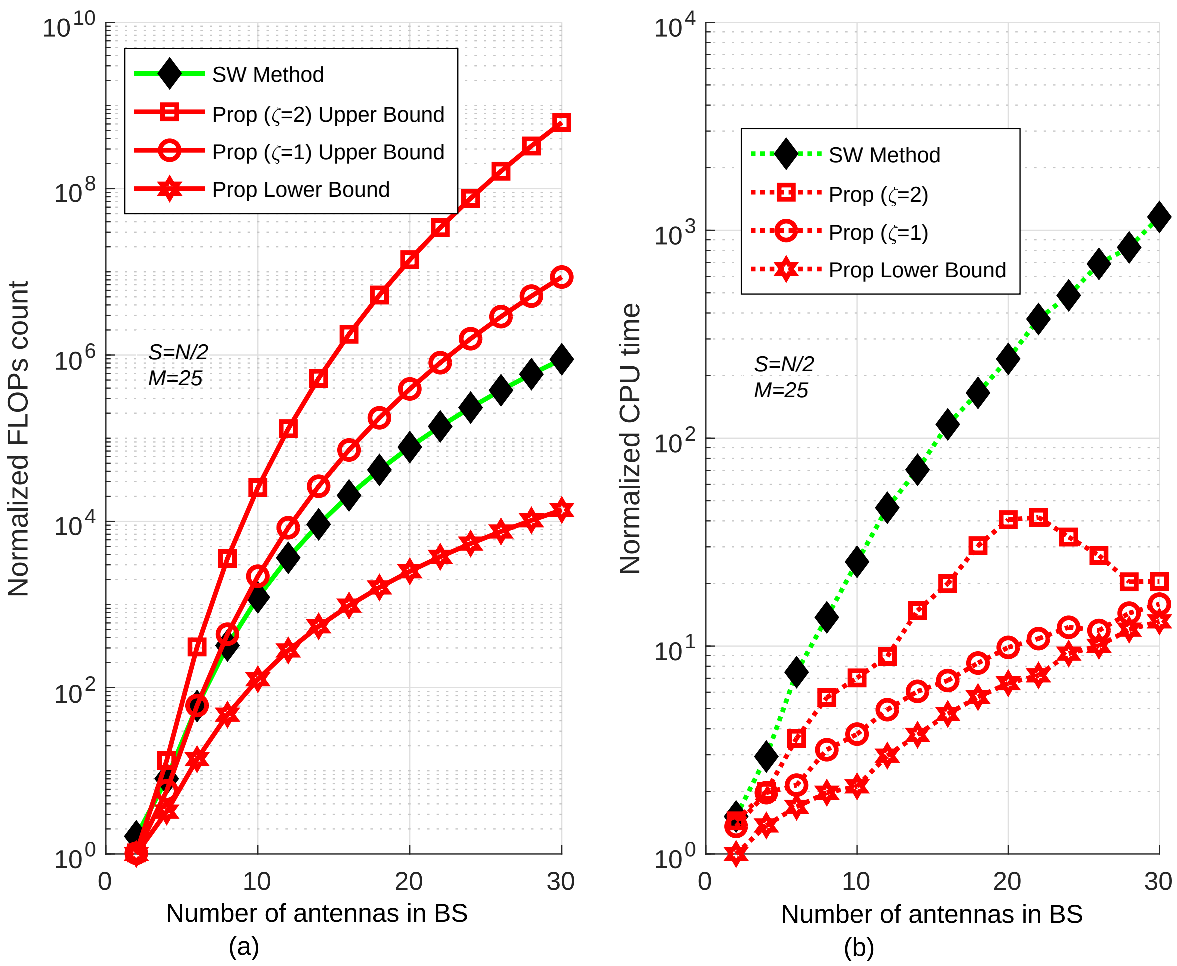


Figure 3.5: Comparison of complexity for various N with $S = \frac{N}{2}$ and M=25(a) Normalized FLOPs count (b) Normalized CPU time.

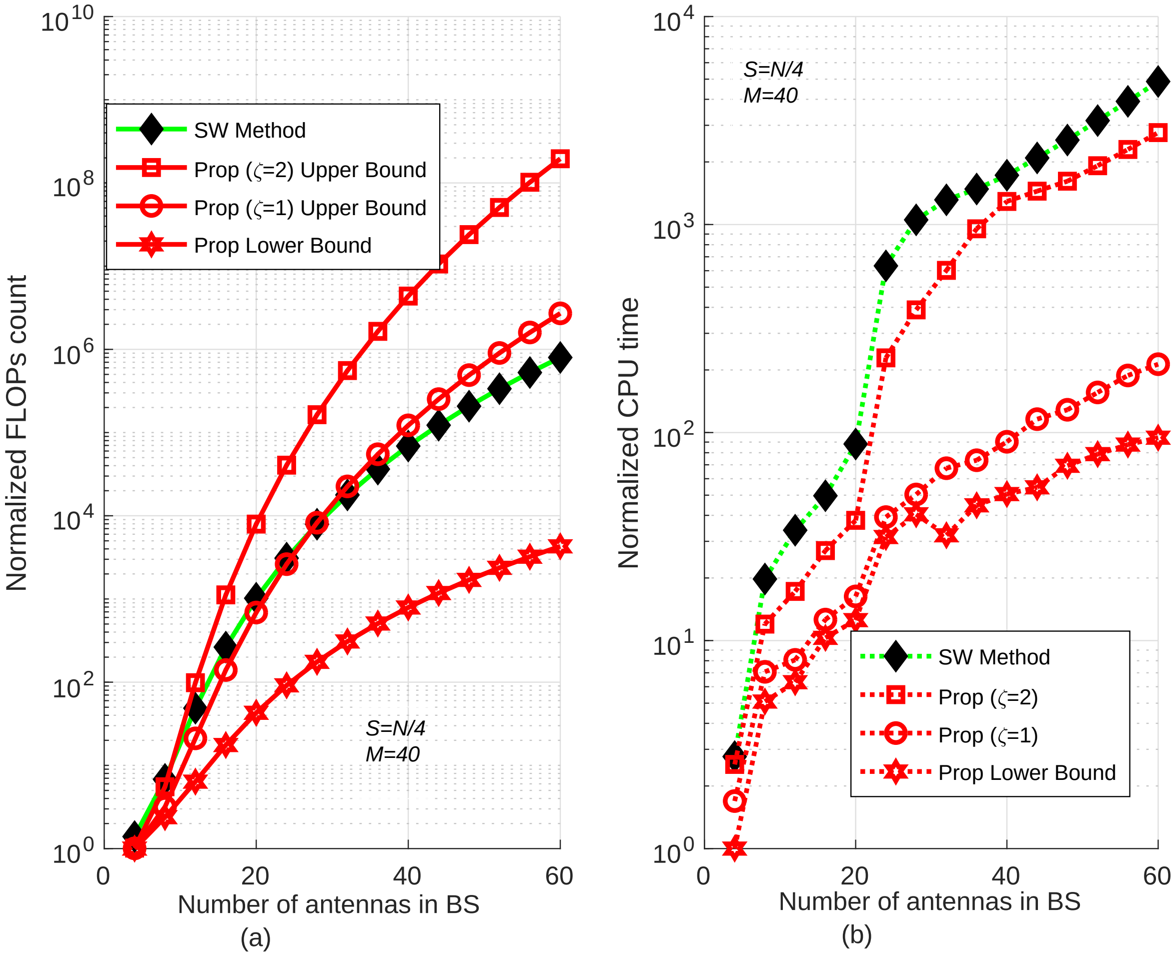


Figure 3.6: Comparison of complexity for various N with $S = \frac{N}{4}$ and M=40 (a) Normalized FLOPs count (b) Normalized CPU time.

In the remaining figures, we are considering the scenario with various BS antenna numbers to show the comparison results for the complexity and the sum-rate. In these figures, the number of BS antennas will be lower than the fixed user number initially and this BS antenna number will be eventually increased until the BS antenna number is larger than the available user number in the system. Therefore, we can see the various situations such as $(M > N)$ and $(M < N)$.

For the FLOPs count plots in Fig. 3.5a and Fig. 3.6a, the complexity of the proposed scheme with the lower bound case is always lower than the SW Method while other two proposed schemes ($\zeta = 1$ and 2) are not always lower as shown in figures. CPU usages of all of the proposed schemes are always lower than the SW Method. The results are shown in Fig. 3.5b and Fig. 3.6b.

In Fig. 3.5b, the complexity of the proposed scheme with $\zeta = 2$ is suddenly decreasing when $S + \zeta$ is approached to the half of the number of users $M/2$ in the system. For the smaller number of antenna usage N in Fig. 3.5b, user side selection is the main effect which causes the increment in complexity curve for $\zeta = 2$. Since smaller value of N will cause $(S = N/2 \ll M)$ and this will make higher chance to match with $q_{\mathcal{U}} \geq (S + \zeta)$ condition in step-10 of Table 3.1 and $\mathcal{U}^{est}$ will be created as $\{1, 2, \cdots, S + \zeta\}$. And the BFS search is necessary in step-11 of Table 3.1. And this will add extra complexity for $\zeta = 2$ case. On the other hand, the antenna number N is gradually increasing while constant number of user M is using in this figure. Increasing antenna number N will also increase the $S = N/2$ RF chains in Fig. 3.5b. When number of S is increasing for constant M user in the system, there has more chance to match the $q_{\mathcal{U}} \leq S$ condition in step-10 of Table 3.1. This will cause the creation of $\mathcal{U}^{est} = \{1, 2, \cdots, S\} = \mathcal{U}^{sel}$ and no more optimal (brute force) search is required in step-11 to create the user set $\mathcal{U}^{sel}$. Therefore, the complexity affected by user side M will diminish for higher region of N in horizontal axis.

We can see more clearly about this condition in Fig. 3.6b when the usage of RF chains is 25% of antennas in BS. In this case, $S + \zeta$ would never become large enough to reach the half of the number of users in the system. Therefore, BFS search is frequently needed to use and the complexity will not be dropped suddenly for the plots in Fig. 3.6b. Nevertheless, we can achieve the lower complexity results for all of the proposed schemes compared with SW Method.

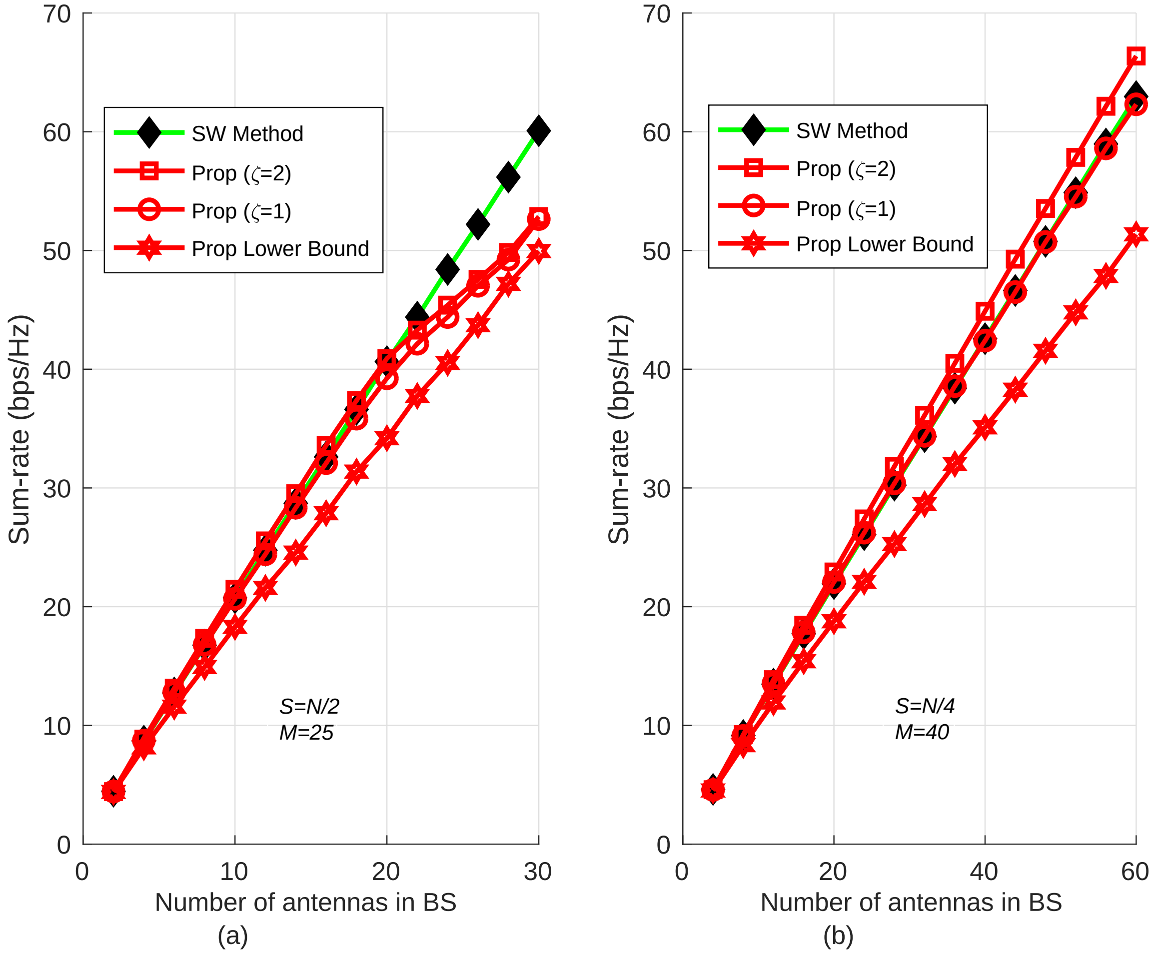


Figure 3.7: Comparison of sum-rate for various N with (a) $S = \frac{N}{2}$, M=25 and (b) $S = \frac{N}{4}$, M=40.

Fig. 3.7 shows the sum-rate plots for the proposed schemes and the SW Method. The performance of the proposed scheme in Fig. 3.7b is better than those of Fig. 3.7a. In Fig. 3.7a, the number of users M in Fig. 3.7a is not too much larger than the available RF chains S in the system. In Fig. 3.7a, the results of the proposed scheme is gradually worse than the SW Method for increasing number of antenna N. When N is increasing, $S = N/2$ will also increase and this will cause creating the set $\mathcal{U}^{est} = \{1, 2, \cdots, S\}$ in larger N values condition. Because, user number $M = 25$ will be kept at constant value and there has more chance to match the $q_{\mathcal{U}} \leq S$ condition in step-10 of Table 3.1. By creating the set $\mathcal{U}^{est} = \{1, 2, \cdots, S\}$, there has no option to select the best user for this set and so we can not expect much more sum-rate improvement from the $\mathcal{U}^{est}$.

As for Fig. 3.7b, the number of users M in Fig. 3.7b is much larger than the available RF chains S in the system. In Fig. 3.7b, the result of proposed scheme is still better than SW Method until $N = 60$. Even N is increasing in this figure, $S = N/4$ RF chains is using and it is much smaller than constant number of user $M = 40$. So, there has more chance to match with $q_{\mathcal{U}} \geq (S + \zeta)$ condition in step-10 of Table 3.1. And $\mathcal{U}^{est}$ will be created with $\{1, 2, \cdots, S + \zeta\}$. Therefore, it has still chance to choose the best user among the elements of $\mathcal{U}^{est}$ by using optimal (brute force) search and more sum-rate improvement can be expected from this condition. Therefore, Fig. 3.7b can give better sum-rate improvement than Fig. 3.7a. We can conclude that, the proposed scheme can give higher sum-rate than the SW Method for using larger number of users M as shown in Fig. 3.4 and Fig. 3.7.

3.6 Summary of Contribution in MU-Massive MIMO System

In this paper, we have proposed the low complexity joint antenna and user selection scheme for the downlink MU-Massive MIMO TDD system. To achieve the reduced complexity in the antenna and user selection while maintaining the same or higher sum-rate in the system, the proposed scheme relies on three complexity reduction key factors. The first key factor is that finding the average CGs for the transmit antenna in the BS side and the receive antenna in the user side to select the best CG antennas and users. The second key factor called the complexity control for the antenna set and the user set limitation is used to control the complexity of BFS search. The third one is that using the assumption of SU-MIMO channel model to avoid the SVD computation in BFS search. The numerical complexity analysis is also used to compare the lower and upper bound of the proposed scheme with the optimal and the SW Method. It can be seen that lower bound of the proposed scheme is always lower than other two schemes and we can use the various ζ value to control the complexity in the proposed schemes. Moreover, simulation results show that the proposed scheme outperforms the two conventional methods in the CPU usage time while maintaining the same or higher sum-rate in most of the scenarios of the MU-Massive MIMO communication. When number of RF chains is large enough to compare with the half of the number of users or the BS antenna in the system, the proposed scheme faces the restricted condition to choose the better SINR user to create the good transmit antenna set and receive user set in the system. This will cause lower sum-rate in some particular cases.

Chapter 4

A Novel Low Complexity Scheme for MU-Massive MIMO Systems

In the previous chapter 3, I proposed the joint antenna and user selection scheme for MU-Massive MIMO wireless communication system under the TDD downlink communication system. In the mobile wireless communication, BS has to compute channel estimation, channel coding, subcarrier, bit and power allocation etc for each user in the system and this will cause the high computational complexity in the BS. Because of the simultaneous resource allocation in BS antennas for multi-users, the processing time of the BS might be too slow to response the rapidly changing mobile channel environment. Therefore, it is necessary to reduce the complexities in each step of the wireless communication system as much as possible to reduce the over all processing time for the mobile wireless system. So, I emphasized on the research work which is related to the reduction of complexity in the MU-Massive MIMO wireless communication system and I also proposed the reduced complexity scheme for the user selection in the MU-Massive MIMO wireless communication system in this chapter.

In this chapter, we propose a novel user selection scheme based on jointly combining CG and signal to interference plus noise ratio (SINR) to improve the sum-rate as well as to reduce the computation complexity of MU-Massive MIMO downlink transmission through a BD precoding technique. By jointly considering CG and SINR based user sets, sum-rate performance improvement can be achieved by selecting higher gain users with better SINR conditions as well as by eliminating the users who cause low sum-rate in the system. Through this approach, the number of possible outcomes for the user selection scheme can be reduced by counting the common users for every pair of user combinations in the selection process since the common users of CG-based and SINR-based sets possess both higher CGs and better SINR conditions. The common users set offers not only sum-rate performance improvements but also computation complexity reduction in the proposed scheme. It is shown by means of computer simulation experiments that the proposed scheme can increase the sum-rate with lower computation complexity for various numbers of users as compared to conventional schemes requiring the same or less computational complexity..

4.1 Introduction

Motivated by the discussions in the related works section, we propose a novel user selection scheme based on jointly combining CG and SINR in MU-Massive MIMO system to improve the sum-rate as well as to reduce the computation complexity. In the proposed scheme, computation complexity is reduced by counting the common users for every pairs of user combinations in the receive user selection part. The number of possible outcomes of the BFS combination can be reduced after setting common users as fixed members in all possible BFS combinations. Such a selection is necessary to achieve the fine tuning of antenna and user selections. Since the common user set has the advantages of highest gain and low interference effects in the system, the participant of this common user set will lead the sum-rate increase in the system. Moreover, the complexity control factor (ζ)

is also applied in the transmit antenna selection on the BS side, to give the fair comparison with the conventional schemes.

Throughout the paper, the upper-case bold letter represents the matrix and lower-case bold letters are used for vectors; $\|.\|_F^2$ denotes the squared Frobenius norm of a matrix; $|\,.\,|$ denotes the cardinality of a set or the absolute value of a scalar; curly alphabet denotes the notation of a set; and $(.)^H$ represents the Hermitian matrix.

4.2 System Model and BD Precoding

4.2.1 System Model

Following to [47], [83], a single cell MU-Massive MIMO downlink channel in the TDD system is also considered in this paper. The BS has N antennas forming the set $\mathcal{A}^{\mathcal{T}}$, whereas the user set $\mathcal{U}^{\mathcal{T}}$ consists of M users each having a single-antenna. By using single-antenna in the user side, the words "user selection" and "receive antenna selection" will be used interchangeably throughout this paper. The channel between the N transmit antennas and all the M users can be represented by a channel matrix $\mathbf{H}_{(\mathcal{U}^{\mathcal{T}},\mathcal{A}^{\mathcal{T}})} = \left[h_{i,j}\right]_{i\in\mathcal{U}^{\mathcal{T}},j\in\mathcal{A}^{\mathcal{T}}}$, where $h_{i,j} \in \mathbb{C}^{M\times N}$ represents a channel coefficient between a user i and transmit antenna j. Moreover, $\mathbf{H}$ is assumed to be a frequency-flat block-fading channel model which remains constant during the coherence block interval but changes independently during every block interval. The elements of $\mathbf{H}$ are independent and identically distributed (i.i.d.) with zero mean circularly symmetric Gaussian (ZMCSG) Rayleigh fading channel. When the wireless channel is Rayleigh faded, and the array antennas do not introduce additional correlation to the transmitted/received signal, then the channel matrix becomes spatially white [83, 91, 87].

It is further assumed that, in order to reduce the complexity and implementation costs, only S ($S \leq N$) RF chains will be available at the BS. Because of channel reciprocity in the TDD system, the perfect CSI can be known by the BS. The BS performs joint antenna selection by choosing only S antennas among the N antennas available at the BS, and schedules $K = min(S, M)$ users within the cell to be served simultaneously. To maximize the sum-rate in data transmission, BS uses two sets $\mathcal{A}$, $\mathcal{U}$, defined as sets of selected transmit antennas to be activated and selected users to be served, respectively. Therefore, the number of elements in the antenna set $\mathcal{A}$ will be equal to the available RF chains S, and the number of elements in the user set $\mathcal{U}$ will be equal to schedule K users. For the given $\mathcal{A}$ and $\mathcal{U}$, the channel between the selected activated transmit antennas j and selected scheduled users, i, can be represented by a channel matrix $\mathbf{H}_{(\mathcal{U},\mathcal{A})} = \left[h_{i,j}\right]_{i\in\mathcal{U}, j\in\mathcal{A}}$.

4.2.2 BD Precoding

In order to achieve high sum-rate performance with a good SINR value, the BD precoding is applied for final transmission stage. Based on the presented formulas for the BD precoding technique in [47], [83], the downlink sum-rate for the given set $\mathcal{A}$ and $\mathcal{U}$ can be derived as follows:

$$R_{sum}(\mathcal{U},\mathcal{A}) = \sum_{i\in\mathcal{U}} \log_2\left(1 + \text{SINR}_{\mathcal{U}}^i\right) = \sum_{i\in\mathcal{U}} \log_2\left(1 + \frac{\text{SNR}_{\mathcal{U}}^i \left|\mathbf{h}_{\mathcal{U}}^i \mathbf{w}_{\mathcal{U}}^i\right|^2}{1 + \sum_{k\in\mathcal{U}, k\neq i} \text{SNR}_{\mathcal{U}}^k \left|\mathbf{h}_{\mathcal{U}}^i \mathbf{w}_{\mathcal{U}}^k\right|^2}\right), \quad (4.1)$$

where $(\mathbf{w}_{\mathcal{U}}^i) \in \mathbb{C}^{S\times 1}$ is the precoding vector for the i^{th} user in set $\mathcal{U}$, and it satisfies $||\mathbf{w}_{\mathcal{U}}^i||_F^2 = 1$. $\mathbf{h}_{\mathcal{U}}^i$ denotes the i^{th} row of $\mathbf{H}_{(\mathcal{U},\mathcal{A})}$. And, $\text{SNR}_{\mathcal{U}}^i$ denotes the signal to noise ratio for the i^{th} user in the set $\mathcal{U}$. By using the BD precoding vector $\mathbf{w}_{\mathcal{U}}^i$, the i^{th}user in the set $\mathcal{U}$ can avoid the interference from other users at set $\mathcal{U}$ in the same frequency and time domain.

4.3 Proposed Scheme

4.3.1 Problem Formulation

To simplify the resource allocation in our proposed scheme, activated numbers of transmit and receive antennas will be maximized based on the available RF chains S in the system. Moreover, we consider equal power allocation for all users in the system to reduce the calculation complexity for transmit power loading in our scheme. Therefore, under the constraint of maximizing the usage of RF chains and the equal power allocation, the joint antenna and user selection can be formulated as the following optimization problem:

$$\{\mathcal{U}^*, \mathcal{A}^*\} = \underset{(\mathcal{U},\mathcal{A})}{max}.R_{sum}(\mathcal{U}, \mathcal{A}). \tag{4.2}$$

Unfortunately, as this is a combinatorial problem, its exact solution to this problem can be obtained only by exhaustive BFS. Since the computational complexity of the solution grows exponentially as the values of N or M increase [85, 86]. A suboptimal and less complex solution, based upon a joint antenna and user selection strategy, will be presented in the next section.

4.3.2 Computation Complexity Reduction

This section explains how the computation complexity of joint antenna and user selection scheme can be reduced while maintaining the achievable sum-rate of MU-Massive MIMO downlink systems.

In order to identify the best transmit antenna set $\{\mathcal{A}^*\}$ and user set $\{\mathcal{U}^*\}$ among total transmit antenna N and M, it is necessary to compute (4.1) by Ω times, where Ω is the total outcomes of possible combination in the proposed system and can be expressed as

$$\Omega = \Omega^{\hat{BS}} \times \Omega^{\hat{U}} = \binom{N}{S}\binom{M}{K} = \frac{N!}{S!\,(N-S)!} \times \frac{M!}{K!\,(M-K)!}, \tag{4.3}$$

where $\Omega^{\hat{BS}}$ and $\Omega^{\hat{U}}$ are the possible combinations in transmit antennas selection on the BS side and receive users selection on the user side, respectively. And K is the number of selected users from the total users set $\mathcal{U}^{\mathcal{T}}$.

The computation of (4.1) for Ω times is essentially an exhaustive BFS and, as such, it will require high computation complexity burden on the selection scheme since SVD calculation is required to solve (4.1). Moreover, Ω may be very large hence MU-Massive MIMO system is generally implemented by the very large number of transmit antennas and receive users. Therefore, it is necessary to avoid the SVD calculation as much as possible and limit the considered BS antennas N and users M in (4.3) to reduce the complexity the the proposed scheme.

SVD calculation in the proposed scheme can be avoided based on following assumption: One of the key ideas of complexity reduction in the proposed scheme is to use the assumption of SU-MIMO channel model in order to avoid the high computation problem of SVD calculation in the BFS search. In this case, the capacity of the SU-MIMO channel can be expressed as follows: [87]

$$\{\mathcal{U}^*, \mathcal{A}^*\} = \underset{(\mathcal{U},\mathcal{A})}{max}.\log_2 \det\left(\mathbf{I}_{\mathcal{U}} + \frac{P}{SN_0}\mathbf{H}_{(\mathcal{U},\mathcal{A})}\mathbf{H}^H_{(\mathcal{U},\mathcal{A})}\right), \tag{4.4}$$

where P denotes the total transmit power and N_0 is average noise power in the system. Clearly, since the solution of (4.4) does not require SVD in order to find the beamforming vector, it is much simpler and far less complex then solving directly (4.1). High computation for (4.1) is no longer necessary to solve (4.3).

One more innovative idea is still required to reduce the large number of outcomes of Ω value in (4.3), although the repeated usage of SVD calculation is avoided by using (4.4). To reduce the outcome of (4.3), it is clear that we need to reduce the values of N and M on the BS side and the user side, respectively. In other words, only a limited number of transmit antennas and receive users will be selected in advance based on certain criterias such as Frobenis Norm of the CG and SINR values. In order to identify the best transmit antenna and receive user pair, the BFS based fine-tuning selection will be applied on this limited number of transmit antennas and receive users. To achieve the limited number of pre-selected transmit antenna set and user set, we will be including in the selection algorithm a complexity control factor (see subsection 3.2.1) and a novel selection procedure (see subsection 3.2.2).

4.3.2.1 Complexity Control Factor (ζ) on the BS Side

The BS side transmit antenna selection algorithm presented in [83] will be included in the proposed scheme to make a fair comparison with conventional schemes in [47], [83], although we emphasized mainly the user selection on the receiver side. The computational complexity of transmit antenna selection on the BS side will be limited by the complexity factor, $\zeta \in Z$ which will be used to decide the pre-selected transmit antenna set $\mathcal{A}^{Gpre}$. $\mathcal{A}^{Gpre}$ can be obtained by selecting the transmit antennas which possess higher values of Frobenius Norms of the CGs than unselected transmit antennas in $\mathcal{A}^{\mathcal{T}}$. Note that the elements of $\mathcal{A}^{Gpre}$ must not be greater than $(S + \zeta)$. After that, the maximum outcomes of possible combination Ω^{BS} of transmit antenna sets on the BS side will be limited by ζ value and it can be expressed as follows:

$$\Omega^{BS} = \binom{(S+\zeta)}{S} = \frac{(S+\zeta)!}{S!\ \zeta!}. \tag{4.5}$$

4.3.2.2 CG-based and SINR-based User Sets

In order to select the best users to improve the sum-rate with low computation complexity, it is necessary to create two kinds of user sets based on Frobenius Norm of the CG and SINR value of each user. The CG-based user set $\mathcal{U}^{Gpre}$ will be created by selecting users who possess higher CGs than unselected users in $\mathcal{U}^{\mathcal{T}}$. Afterwards, SINR-based user set $\mathcal{U}^{\Gamma pre}$ will be created by selecting users who possess higher SINR values than unselected users in $\mathcal{U}^{\mathcal{T}}$.

If users are selected based only on the CG, the interference effect of other users will not be considered in the system. When users are closely packed and placed near the BS of the cell, although they will have higher gains at the same time they will cause to each other high interference effect levels. For such case, the CG-based selection will likely lead to a deterioration of the sum-rate performance for BD transmission technique. On the other hand, the SINR-based set might avoid the selection of the closely packed users because of their high mutual interference. Therefore, we should consider the combined effect of CG-based and SINR-based selection to take the advantages of both user sets.

In other words, obtaining the SINR by using (4.1) will cause higher computation complexity. Note that the SINR of each user is needed only to compare the interference effect in the system. It is necessary to avoid the calculation of (4.1) as much as possible during the selection stages. The BD precoding transmission is going to be applied after getting the final selected transmit antennas set $\mathcal{A}^*$ and receive users set $\mathcal{U}^*$ in the system. The BD precoding technique needs to solve the SVD calculation, and it causes higher computation complexity in finding the SINR information of each user. On the other hand, the maximum ratio combining based (MRC-based) SINR calculation has no SVD calculation and computational complexity is not as high as (4.1). Therefore, the MRC-based SINR calculation will be used to find the ${}^{mr}\text{SINR}^i_{\mathcal{U}}$ for each user i in the total users set $\mathcal{U}^{\mathcal{T}}$ by using (4.6),

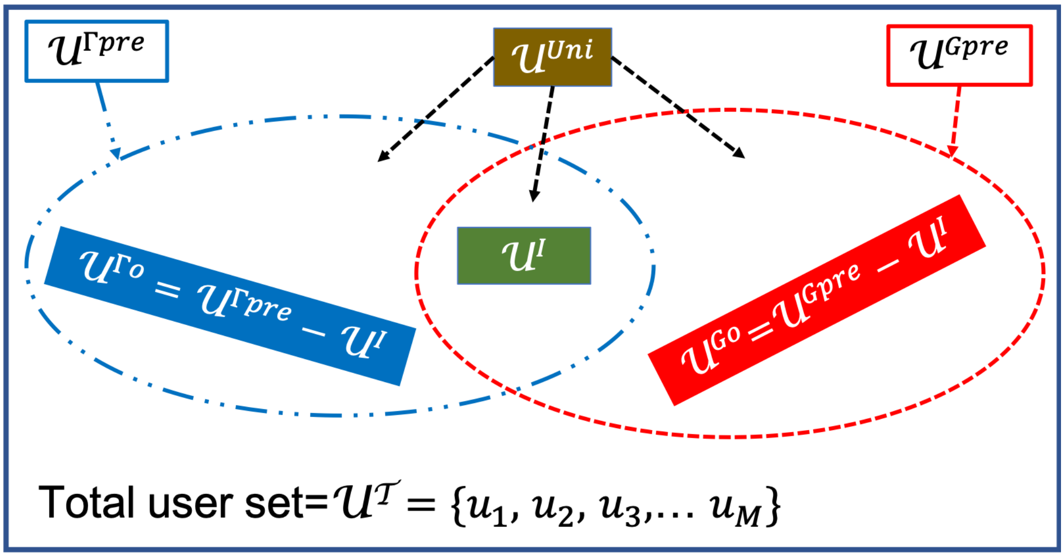


Figure 4.1: Venn diagram of user sets.

$$ {}^{mr}\text{SINR}^i_{\mathcal{U}} = \frac{\text{SNR}^i_{\mathcal{U}} \left|\mathbf{h}^i_{\mathcal{U}}\right|^4}{\left|\mathbf{h}^i_{\mathcal{U}}\right|^2 + \sum_{k\in\mathcal{U}, k\neq i} \text{SNR}^k_{\mathcal{U}} \left|\mathbf{h}^{k\,H}_{\mathcal{U}} \mathbf{h}^i_{\mathcal{U}}\right|^2}. \tag{4.6} $$

A virtual illustration of how the previously presented algorithm reduces the number of user selection can be found in Fig. 4.1, which is a general Venn diagrams of total user set $\mathcal{U}^{\mathcal{T}}$, and it's subsets $\mathcal{U}^{Gpre}$ and $\mathcal{U}^{\Gamma pre}$. In this figure, the rectangular area representing set $\mathcal{U}^{\mathcal{T}}$, and the overlapping area of $\mathcal{U}^{Gpre}$ and $\mathcal{U}^{\Gamma pre}$ will be the intersection of these two sets and will be represented by $\mathcal{U}^{I}$. The union of these two sets will be expressed with $\mathcal{U}^{Uni}$. Uncommon users which are included in $\mathcal{U}^{Gpre}$ and $\mathcal{U}^{\Gamma pre}$ but outside of $\mathcal{U}^{I}$ can be expressed by $\mathcal{U}^{Go} = (\mathcal{U}^{Gpre} - \mathcal{U}^{I})$, $\mathcal{U}^{\Gamma o} = (\mathcal{U}^{\Gamma pre} - \mathcal{U}^{I})$, respectively.

Table 4.1: Pseudocode for the proposed scheme's algorithm.

Step	Description
1	Input: CSI information for all users M and antennas N on the BS side, number of RF chains S and predetermined ζ.
2*	Create the BS transmit antenna set $\mathcal{A}^{Gsort} = \{a_1, a_2, \cdots, a_N\}$ which is sorted by descending order of CG according to $\|\mathbf{h}_j\|_F^2$ $(1 \leq j \leq N)$.
3*	Count the number of antennas $(q_{\mathcal{A}})$ which CGs are larger than the mean CG. $\mu_{\mathcal{A}} = \frac{1}{N}\sum_{i=1}^{N}\|\mathbf{h}^i_{\mathcal{A}^{Gsort}}\|_F^2$.
4*	If $q_{\mathcal{A}} \leq S$, then $\mathcal{A}^{Gpre} = \{1, 2, \cdots, S\}$. Else if $S < q_{\mathcal{A}} < S + \zeta$, then $\mathcal{A}^{Gpre} = \{1, 2, \cdots, S, \cdots, q_{\mathcal{A}}\}$. Else $\mathcal{A}^{Gpre} = \{1, 2, \cdots, S, \cdots, S + \zeta\}$. End, (where $\mathcal{A}^{Gpre} \subseteq \mathcal{A}^{Gsort}$). $\mathbf{H}_{(\mathcal{U}^{\mathcal{T}}, \mathcal{A}^{\mathcal{T}})} = \mathbf{H}_{(\mathcal{U}^{\mathcal{T}}, \mathcal{A}^{Gpre})}$.
5	If $M \leq S$, then $\mathcal{U}^* = \mathcal{U}^T$ and go to the 10^{th} step. Else, Create the user set $\mathcal{U}^{Gsort} = \{u_1^G, u_2^G, \cdots, u_M^G\}$ which is sorted by descending order of CG according to $\|\mathbf{h}_i\|_F^2$ $(1 \leq i \leq M)$. End.
6	Extract the preselected user set $\mathcal{U}^{Gpre} = \{u_1^G, u_2^G, \cdots, u_K^G\}$. (where $K = min(S, M)$ and $\mathcal{U}^{Gpre} \subseteq \mathcal{U}^{Gsort}$).
7	Create the user set $\mathcal{U}^{\Gamma sort} = \{u_1^\Gamma, u_2^\Gamma, \cdots, u_M^\Gamma\}$ which is sorted by descending order of SINR value of each user.
8	Extract the preselected user set $\mathcal{U}^{\Gamma pre} = \{u_1^\Gamma, u_2^\Gamma, \cdots, u_K^\Gamma\}$. (where $K = min(S, M)$ and $\mathcal{U}^{\Gamma pre} \subseteq \mathcal{U}^{\Gamma sort}$).
9	Find $\mathcal{U}^I$ and $\mathcal{U}^o$ by using the preselected sets $\mathcal{U}^{Gpre}$ and $\mathcal{U}^{\Gamma pre}$.
10	Well known BFS will be done by using $\mathcal{A}^{Gpre}$, $\mathcal{U}^I$ and $\mathcal{U}^o$ to find the best antenna set $\mathcal{A}^*$ in the BS side and the best user set $\mathcal{U}^*$ in the user side which can give the maximum sum-rate channel matrix for the system. By using (4.4), we can avoid the high complexity SVD computation scheme for this BFS. Where $\|\mathcal{A}^*\| = S$ and $\|\mathcal{U}^*\| = K$.
*	Remark: For the transmit antenna selection on the BS side, Steps 2* to 4* are similar to method in [83].

In Fig. 4.1, we can see that elements of $\mathcal{U}^I$ set are selected by the CG-based condition as well as SINR-based condition. Therefore, we can conclude that the set $\mathcal{U}^I$ has the advantages of both CG-based and SINR-based selection methods and we will always put the elements of $\mathcal{U}^I$ set in the user selection process. Therefore, alternate draw out will only apply to the elements of set $\mathcal{U}^o = \left(\mathcal{U}^{Go} \cup \mathcal{U}^{\Gamma o}\right)$. This will reduce the consideration of elements from M to $|\mathcal{U}^o|$. Moreover, if $\left|\mathcal{U}^I\right| > 0$, then the possible outcomes of combination of users for this situation will be reduced more, and it can be expressed as follows:

$$\Omega^U = \binom{|\mathcal{U}^o|}{K - \left|\mathcal{U}^I\right|} = \frac{|\mathcal{U}^o|!}{\left(|\mathcal{U}^o| - \left(K - \left|\mathcal{U}^I\right|\right)\right)!\ \left(K - \left|\mathcal{U}^I\right|\right)!}. \tag{4.7}$$

After solving (4.4) for $\Omega^{BS} \times \Omega^U$ times, the best transmit antenna and user sets for the given channel condition can be identified. Using the sets, $\mathcal{U}^I$ and $\mathcal{U}^o$, we can benefit from $\mathcal{U}^{Gpre}$ and $\mathcal{U}^{\Gamma pre}$ sets. At the same time, a reduction of computation complexity can be obtained based on the permanent selection of $\mathcal{U}^I$ for all of the possible combinations on the user side in (4.7).

The pseudocode of the proposed selection scheme's algorithm is described in Table 4.1.

4.4 Computation Complexity Analysis

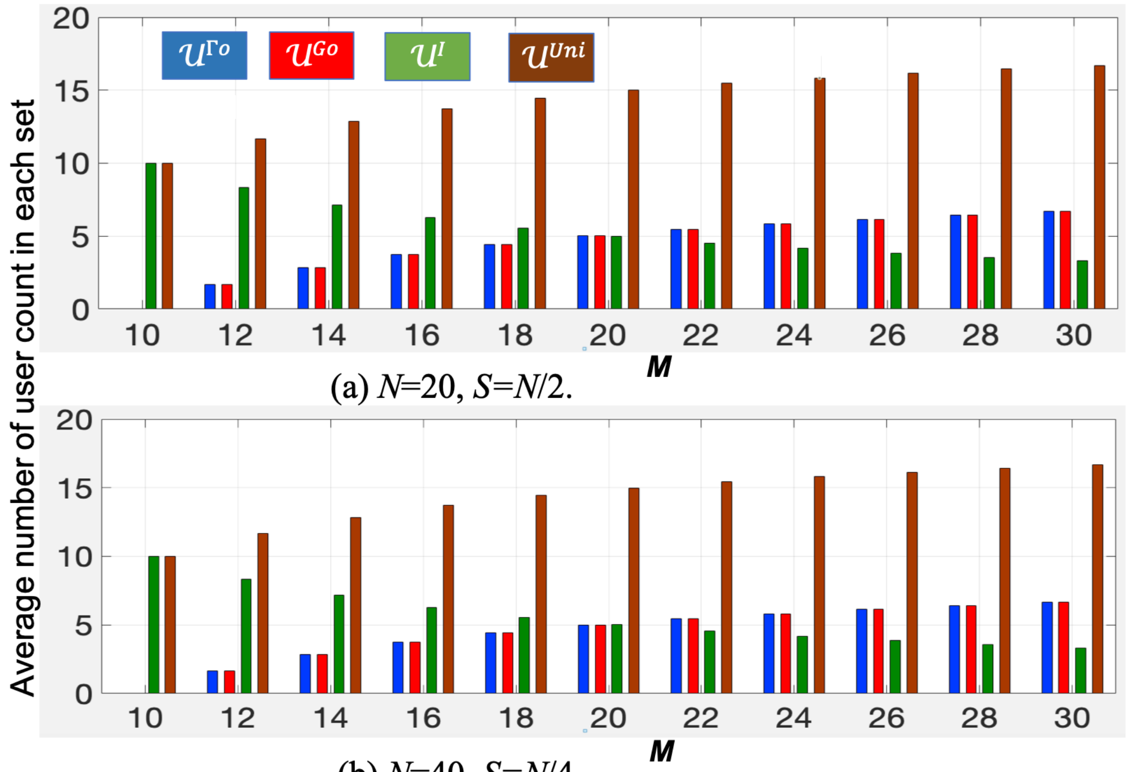
Computation complexities of the proposed and conventional schemes will be analyzed in terms of the number of possible outcomes of combination for transmit antenna set and receive user set selection in the subsection 4.1. After that, FOLPs count analysis will be presented in subsection 4.2.

4.4.1 Number of Outcomes for the Possible Combinations in Selection Scheme

Using (4.5) and (4.7), we tried to reduce the number of possible combinations for the transmit antenna selection on the BS side and receive user selection on the user side. As already explained in Sections 3.2.1 and 3.2.2, a maximum number of possible combinations will be limited by ζ for the transmit antenna selection. User sets $\mathcal{U}^I$ and $\mathcal{U}^o$ determine the number of possible combinations in (4.7). Results of (4.5) can be easily calculated for the given values of S and ζ. However, it is not possible to derive a formula which can give the exact number of user sets $\mathcal{U}^I$ and $\mathcal{U}^o$ for every channel realization of the MU-Massive MIMO system. Instead, we have simulated the MU-Massive MIMO system model in Matlab simulation environment using the simulation parameters listed in Table 4.2. Through many simulation experiments an exact number of common user $\mathcal{U}^I$ count will be noted for every channel realization, and (4.7) will be calculated by using these data. For 50,000 times of channel realizations, the average value will be used to give the analysis in this subsection.

Figure 4.2 shows the number of user count in $\mathcal{U}^{\Gamma o}$, $\mathcal{U}^{Go}$, $\mathcal{U}^I$ and $\mathcal{U}^{Uni}$ sets. When the total number of user is equal to the available RF chains, i.e., M=S=10, there is no need to do the selection on the user side. When the total number of users gradually increases in the system, the user diversity increases and it will give more degree of freedom to choose not only for $\mathcal{U}^{Gpre}$ set but also for $\mathcal{U}^{\Gamma pre}$ set. Therefore, fewer and fewer common users can be obtained in the $\mathcal{U}^I$ set. This will give more and more possible outcomes in (4.7) for decreasing the number of user count in the $\mathcal{U}^I$ set. However, there still exist some common users in the $\mathcal{U}^I$ set, and it will give a reduction of possible outcomes in (4.7).

Figure 4.3 shows the total number of combinations that is necessary to use in the BFS step for each method. As illustrated in Fig. 4.2, the number of possible outcome will be



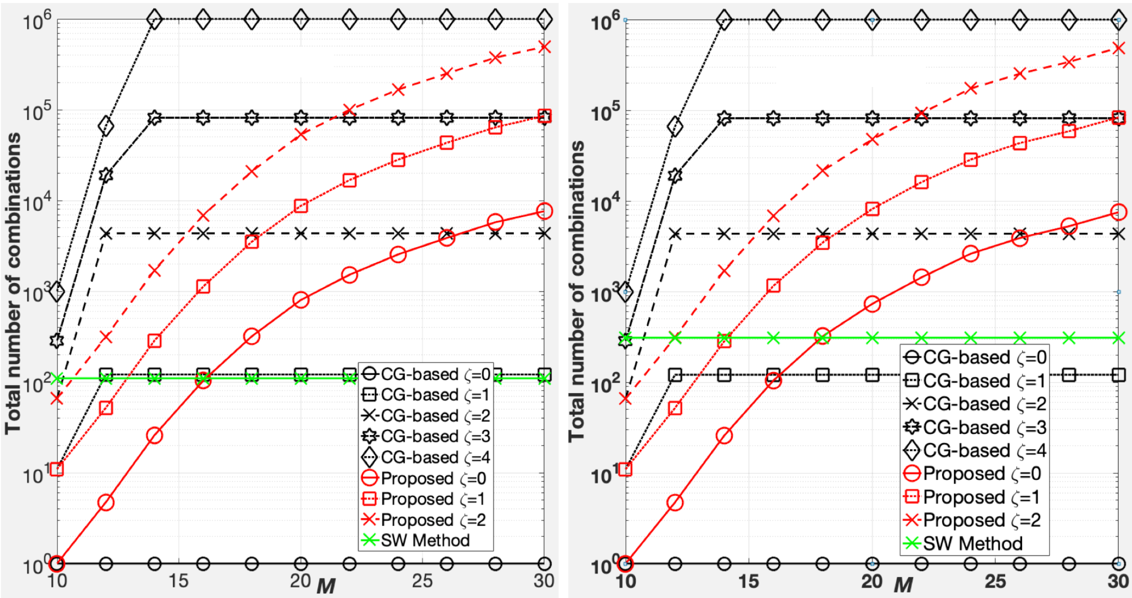
(a) N=20, S=N/2.

(b) N=40, S=N/4.

Figure 4.2: Comparison of average number of user count in each set for various number of total users M (a) N=20 and S=$N/2$ (b) N=40 and S=$N/4$.

Table 4.2: Simulation parameters.

Parameter	**Description**
Cell	Single, TDD Mode
Channel	Rayleigh
Communication	Downlink
Average SNR	10 dB
Complexity control factor	ζ= 0, 1, 2, 3 and 4
Number of total antennas in BS	N
Number of RF chains in BS	S=$N/2$ and S=$N/4$
Number of total users	M
Transmit beamforming	Block Diagonalization
Frames/Packet	5
Number of packets in simulation	50,000



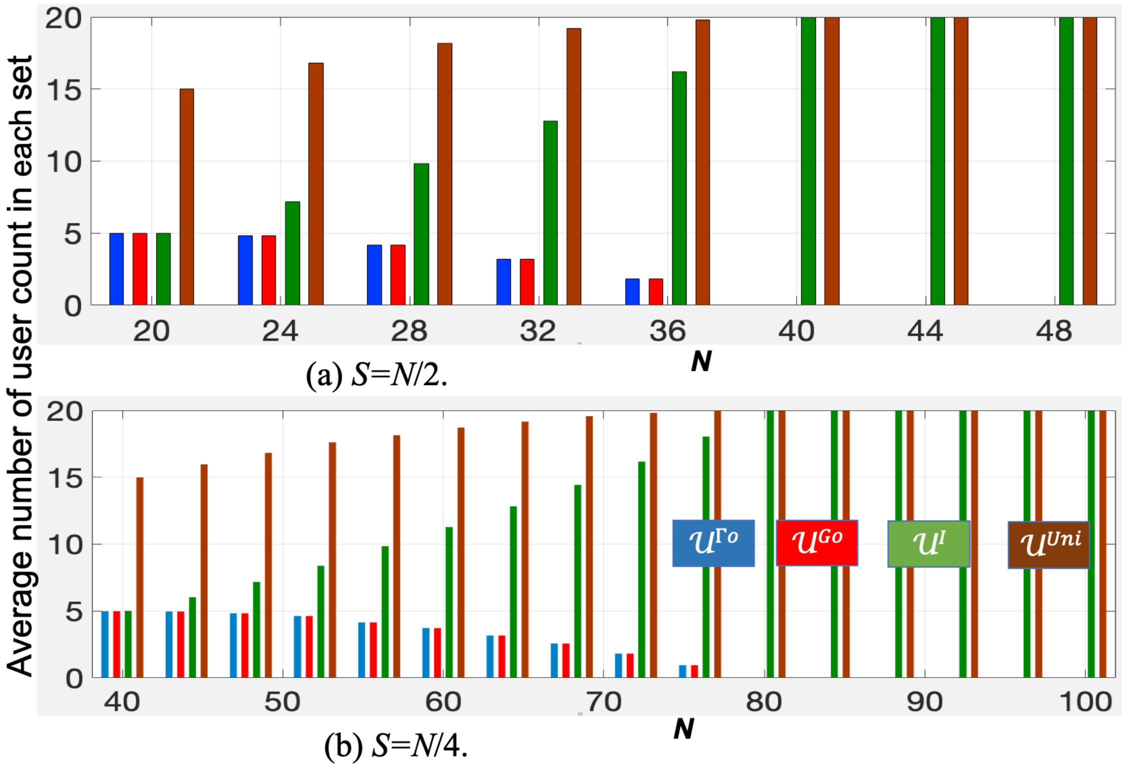
(a) N=20, S=N/2.

(b) N=40, S=N/4.

Figure 4.3: Comparison of possible combinations for the BFS search for various number of total users M.

the same with the CG-based method at the point of M=S=10 since it is no need to apply the user selection part in both CG-based and proposed methods. When M is greater than S, it is necessary to do the user selection parts, and this adds extra complexity for selection algorithms. However, the upper bound complexity of the CG-based method is limited by the ζ value, and the possible outcome will be constant when $M \geq (S+\zeta)$. On the other hand, the possible outcomes of the proposed method will be gradually increased as M is increasing, since a fewer number of elements in the common user set $\mathfrak{U}^{I}$ will give higher result in (4.7).

Figure 4.4 shows the number of user count in $\mathfrak{U}^{\Gamma o}$, $\mathfrak{U}^{Go}$, $\mathfrak{U}^{I}$ and $\mathfrak{U}^{Uni}$ sets. In Fig. 4.4 (a), total number of user M=20 is used as a constant value, while BS antenna N and RF chains ($S = N/2$) are gradually increased from N=20 to N=48. The step-by-step increment in S will need the collection of more users to serve from the constant number of M, and

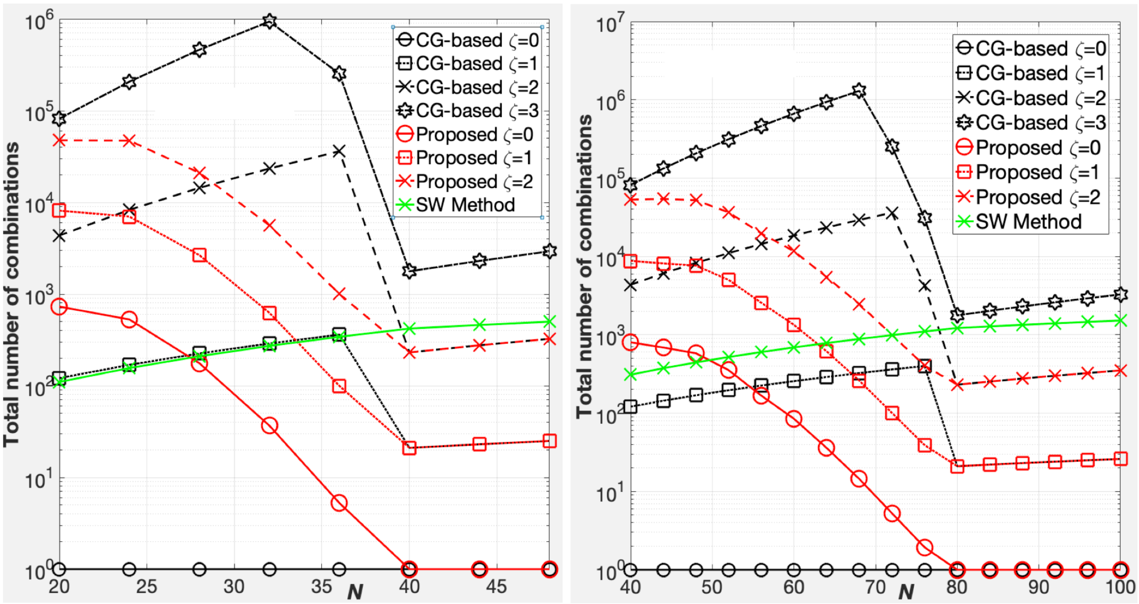


(a) S=N/2.

(b) S=N/4.

Figure 4.4: Comparison of average number of user count in each set for fixed number of M=*20* and various number of the BS antenna N.

it will cause more common users in the set $\mathcal{U}^I$. When N=40, RF will become 20, and S will be equal to all the available users in the cell. Therefore, all users can be chosen to serve, and common user set will be maximum after S=M. Although, a larger number of N with S=$N/4$ are used in Fig. 4.4(b), we can see a similar situation as it was explained in Fig. 4.4(a).



(a) S=N/2. (b) S=N/4.

Figure 4.5: Comparison of possible combinations for the BFS search for fixed number of M=*20* and various number of the BS antenna N.

Figure 4.5(a) shows the number of possible combinations to use for the BFS for each method. The total combinations of the proposed method will be gradually decreased from N=20 to N=48 since results of (4.7) will influence for the total number of combinations. When S is larger than the number of available users M, there is no need to do the user selection part, and only the results of (4.5) will decide for a total number of combinations, and it gives a little bit increase in total number of combinations for the BFS. A similar behavior can be noted by observing the results illustrated in Fig. 4.5(b), since both figures are simulated based on the constant number M.

4.4.2 FLOPs Count Analysis for the Proposed Scheme

Table 4.3: FLOPs count description.

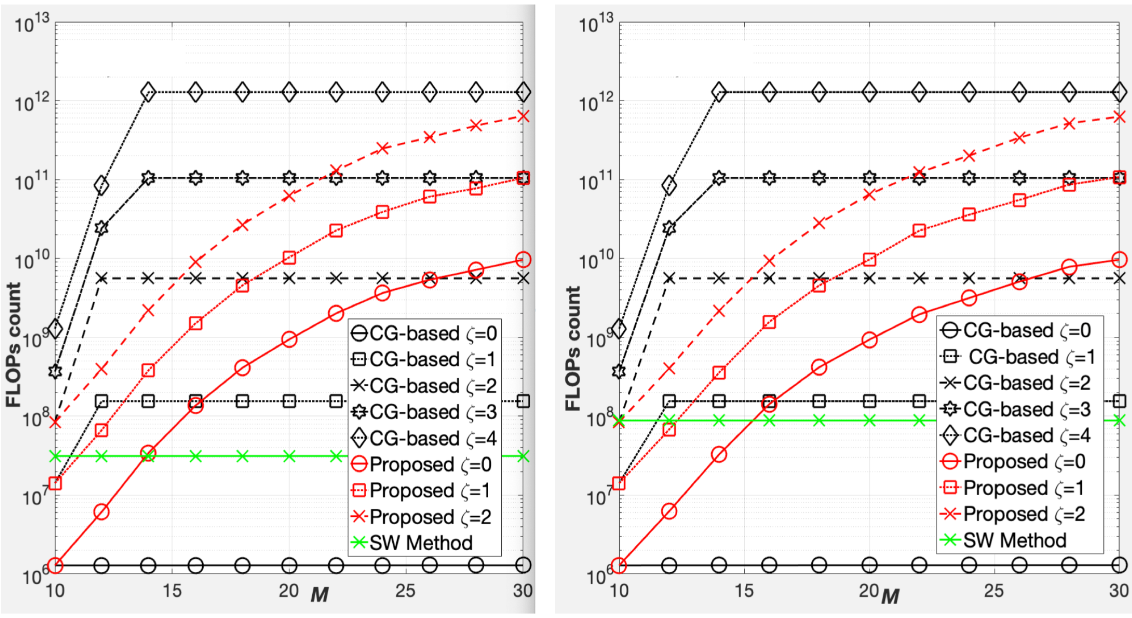
Sr.	**Description**	**Step**	**FLOPs**
1.	Sorting with channel gains for the BS side	2	$4NM$
2.	Sorting with updated channel gains for the user side	5	$4M(S+\zeta)$
3.	Sorting with SINR values for the user side by using (4.6)	7	$M[(M-1)\{4(S+\zeta)^2+2(S+\zeta)^2\}]$
4.	Matrix multiplication to solve (4.4)	10	$2K^2S$ (where K=min(S,M))
5.	Matrix determinant to solve (4.4)	10	$K^{log_2(7)}$ (where K=min(S,M)

This subsection will present the complexity analysis by using the FLOPs count requirements based on the matrix manipulation process, which was already defined in [60, 89, 90]. Table 4.3 shows the main steps of the proposed algorithm, which required a high number of FLOPs count for the calculation. In the proposed scheme, matrix manipulation is needed only once for the calculation in each of the steps 2, 5 and 7 (see Table 4.1). However, in order to solve (4.4) it is required to do step-10 for the BFS search and thus (4.4) is necessary to multiply by the number of combinations Ω^{BS}, and Ω^{U}. Based on the expression in Table 4.3 and (4.5) and (4.7), the total FLOPs count for the proposed scheme can be mathematically expressed as:

$$\text{FLOPs}^{upper} = \Omega^{BS}\Omega^{U}(2K^2S)(K^{log_2(7)}) + 4NM \cdots if M \leq S. \quad (4.8a)$$

$$\text{FLOPs}^{upper} = \Omega^{BS}\Omega^{U}(2K^2S)(K^{log_2(7)}) + 4NM + 4M(S+\zeta)$$

$$+ M[(M-1)\{4(S+\zeta)^2 + 2(S+\zeta)^2\}] \cdots if M > S. \quad (4.8b)$$

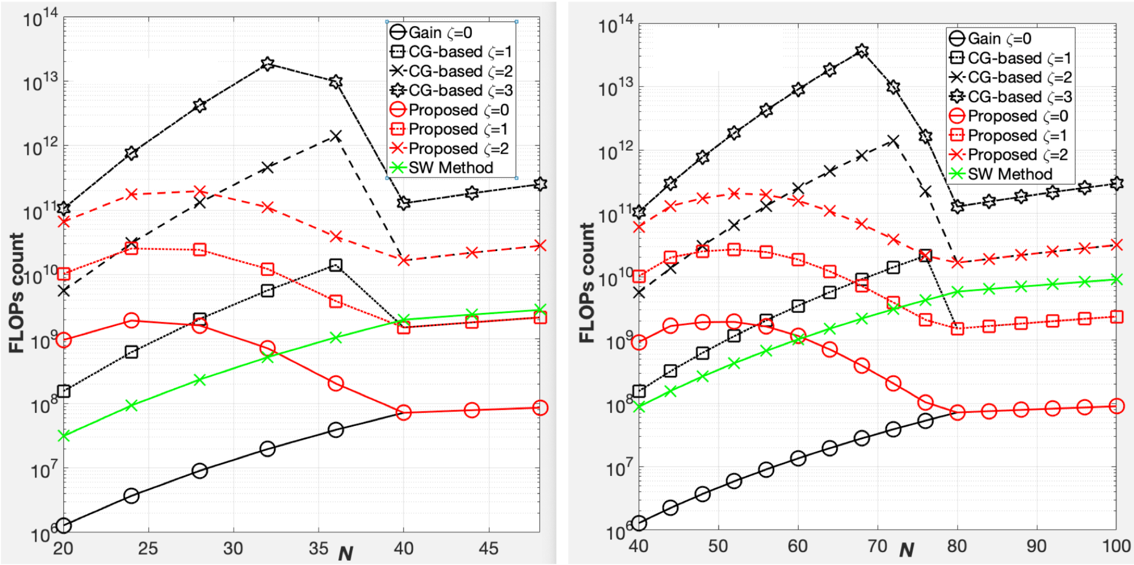


(a) N=20, S=N/2.

(b) N=40, S=N/4.

Figure 4.6: Comparison of FLOPs count for various number of total users M.

Figures 4.6 and 4.7 show the comparison of FLOPs count for proposed and conventional methods. The slopes of the curves of the FLOPs count are similar to the total number of combinations in Fig. 4.3 and Fig. 4.5 since the number of combinations is the main influence factor for the complexity calculation in the selection scheme. FLOPs counts expressed in (4.8) are upper bounds for the computation complexity, and the actual computation complexity might not reach that upper bounds, since the BFS search may not be required for some channel realizations.



(a) S=N/2. (b) S=N/4.

Figure 4.7: Comparison of FLOPs count for fixed number of M=20 and various number of the BS antenna N.

4.5 Performance Evaluation, Results and Discussion

By using simulation parameters in Table 4.2, performances of schemes are compared in terms of the CPU usage time and the sum-rate for the MU-Massive MIMO system under consideration for the following four cases. The first one is increasing numbers of users M with constant N and S. The second one is a stable numbered users M, and numbers of antennas N and RF chains S increasing on the BS side for the given system. In addition, two more set of performance results are obtained for the cases where S=N/2 and S=N/4. CPU usage time for the calculation complexity results is normalized by using the smallest value in each complexity performance figure to clarify the ratio of complexity for each scheme.

Figure 4.8 shows the total sum-rate of the proposed system model. As ζ increases, the proposed method can give more noticeable sum-rate improvement than methods in [47]

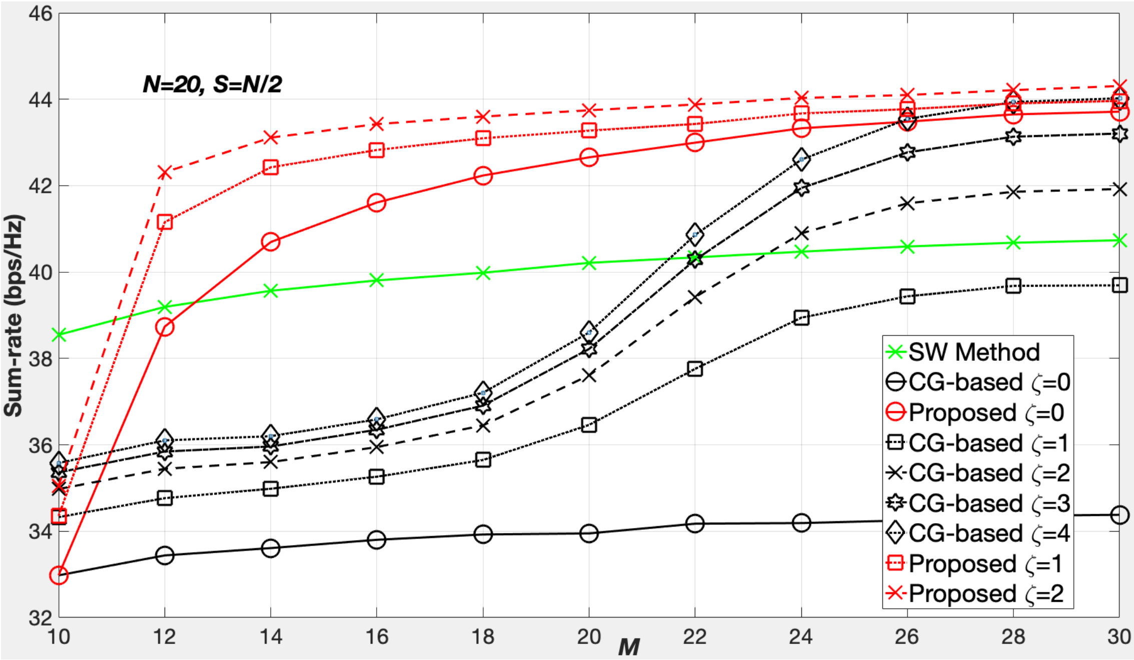


Figure 4.8: Comparison of sum-rate for various number of user M, BS antenna N=20 and RF chains S=$N/2$.

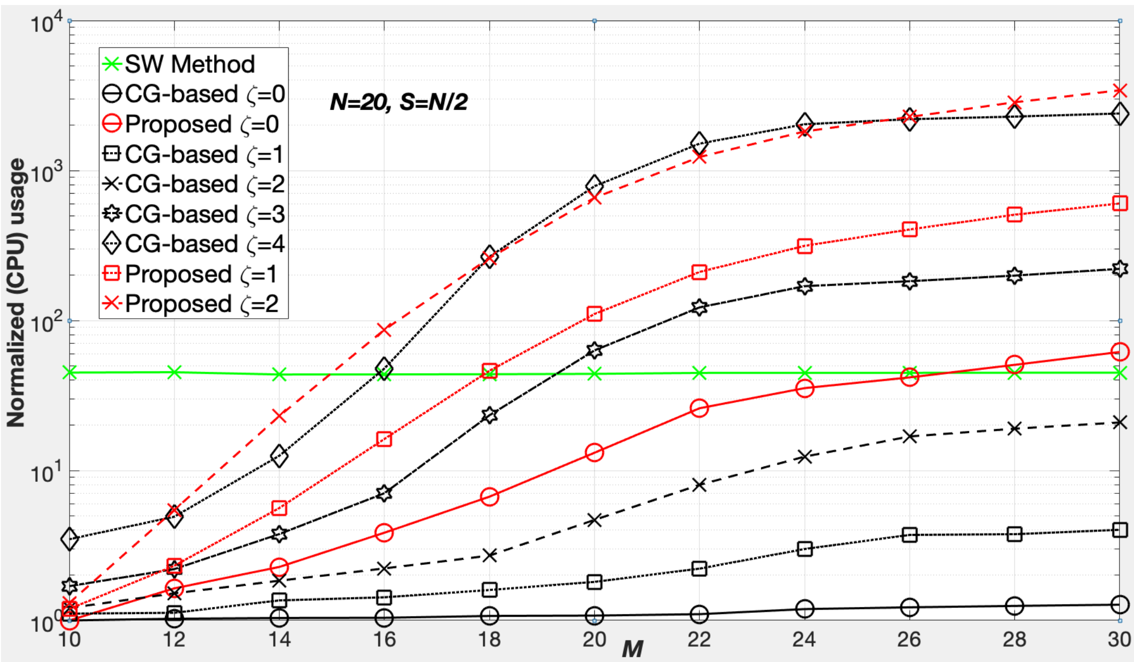


Figure 4.9: Comparison of CPU usage time for various number of users M, BS antenna N=20 and RF chains S=$N/2$.

and [83], especially for a moderate amount of user numbers in the cell. For M=S=10, there is no user selection, and sum-rate improvement can be achieved only from transmit antenna selection from the BS side. Therefore, no sum-rate improvement is possible for the proposed method in the M=10 condition. However, when the number of users is more considerable larger than available RF chains S in the system, significant sum-rate improvement is achieved, as shown in Fig. 4.8. When M is much larger than S, the method in [83] also achieves the distinguishable sum-rate improvement with more user diversity in the system. On the other hand, the SW Method will give nearly flat conditions on the sum-rate graph since their sum-rate improvement depends greatly on the transmit antenna selection on the BS side with the sliding window method. Constant number N and RF chain S will not support giving much more sum-rate improvement for SW method as shown in Fig. 4.8.

Figure 4.9 shows the normalized CPU usage for each method. The proposed method uses ζ = 0, 1 and 2 for the transmit antenna selection on the BS side. In contrast, the method in [83] uses ζ = 0, 1, 2, 3, and 4 to control the computation complexity for the transmit antenna selection on the BS side and receive user selection on the user side. When a lower ζ value is applied to the method of [83], the CPU usage curves of ζ = 0, 1, and 2 are lower than CPU usage curves of the proposed method. Little amount of the BFS is necessary to do for the small number of possible combinations in transmit antenna set and receive user set.

At that time, the proposed method has an overhead usage of CPU time for two sortings on the user side. The proposed scheme is necessary to do not only for the CG computation but also for the SINR computation to find the CG-based sorted user set $\mathcal{U}^{Gsort}$ and the SINR-based sorted user set $\mathcal{U}^{\Gamma sort}$ for receive user selection. Although, this SINR computation is not necessary to use SVD, this overhead SINR calculation gives a higher impact than a small amount of the BFS. However, the value of ζ becomes larger, this will increase the computation complexity in the BFS for the possible combination of transmit antennas and receive user sets. Therefore, the method in [83] gives more CPU usage for the higher value of ζ. On the other hand, the SW Method provides the nearly constant value of CPU usage all over the numbers of M since numbers of the BS antenna N and RF chains S are always constant in this simulation. The SW Method uses sliding windows and the number of windows depends on the available BS transmit antenna N, and RF chains S. Therefore, it gives nearly constant value of CPU usage in Fig. 4.9.

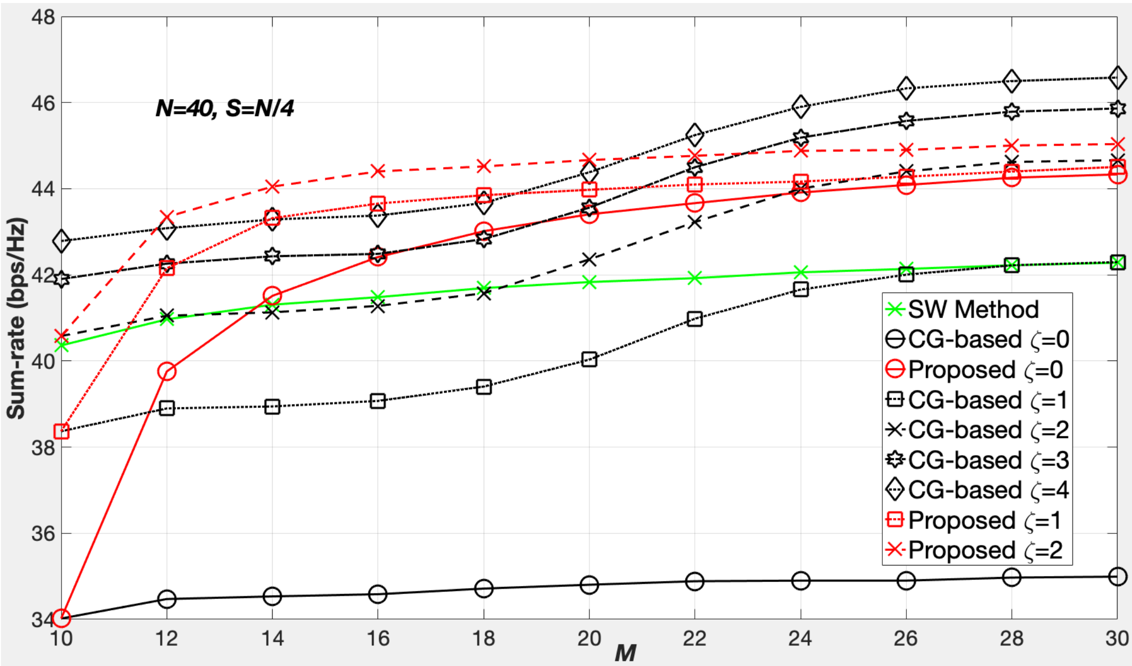


Figure 4.10: Comparison of sum-rate for various number of users M, BS antenna N=*40* and RF chains S=*N/4*.

Figures 4.8 and 4.10 show the sum-rate improvement of $S = N/2$ (S = 50% of N) and $S = N/4$ (S = 25% of N) conditions for each method. Both the proposed and CG-based methods have same preselection steps for the transmit antenna selection case on the BS side. In step-4, $\mathcal{A}^{Gpre}$ is created based on $q_{\mathcal{A}}$ which can be obtained in step-3. When S

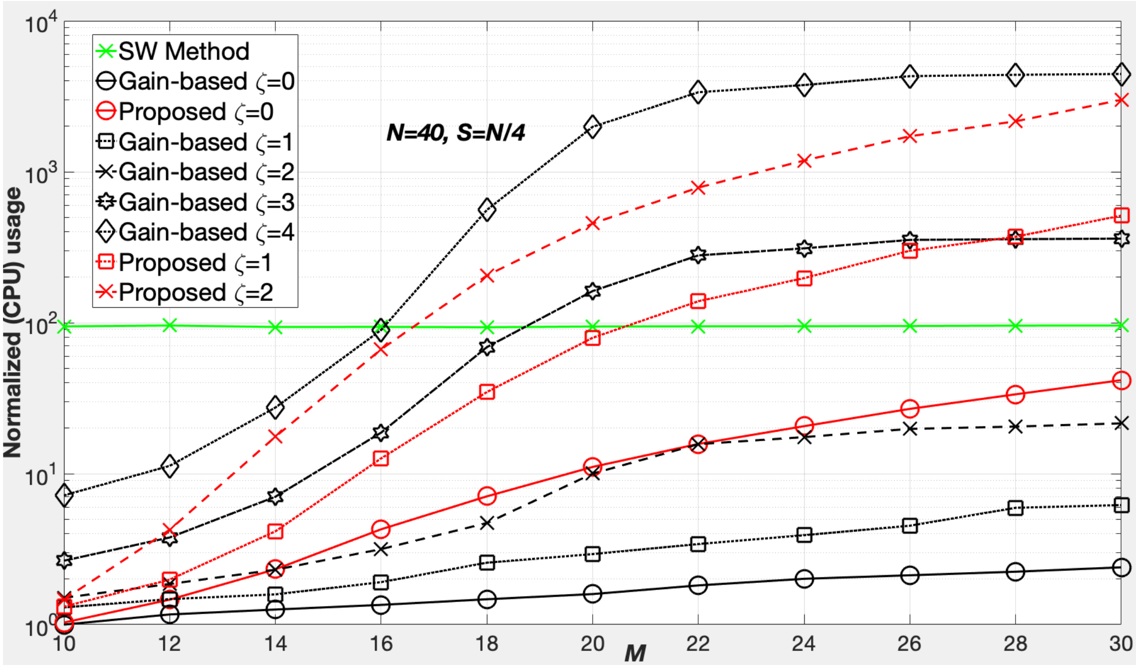


Figure 4.11: Comparison of CPU usage time for various number of users M, BS antenna *N=40* and RF chains *S=N/4*.

is constant (S = 10 in both figures), a smaller number of N will give a lower $q_{\mathcal{A}}$ value, and the larger number of N will give a higher $q_{\mathcal{A}}$. Lower $q_{\mathcal{A}}$ will give the lower number of preselected transmit antenna elements in $\mathcal{A}^{Gpre}$ set, and higher $q_{\mathcal{A}}$ will give the larger $\mathcal{A}^{Gpre}$ according to the conditional statements in step-4. If $\mathcal{A}^{Gpre}$ is large, we have more chance to choose the best transmit antennas set by using the BFS search in step-10, and this will give more sum-rate improvement for larger number of N. Since $\mathcal{A}^{Gpre}$ in Fig. 4.10 is larger than $\mathcal{A}^{Gpre}$ in Fig. 4.8, and this will lead higher sum-rate improvement.

For the user selection part in the proposed method, the number of preselected users in the $\mathcal{U}^{Gpre}$ and $\mathcal{U}^{\Gamma pre}$ sets are not affected by the number of transmit antennas on the BS side as shown in Fig. 4.2. For the same user number in Fig. 4.8 and Fig. 4.10 (e.g., M=12), extra sum-rate improvement of the proposed method is achieved mainly from the transmit antenna selection on the BS side. And the sum-rate plots of the proposed scheme have the similar slopes for each M in both figures.

On the other hand, the CG-based method used the same preselection concept for the BS and user side [83]. When number of user M is not considerably larger than the number of RF chains S, the CG-based method will produce a small preselected user set $\mathcal{U}^{Gpre}$ under the limitation of $q_{\mathcal{U}}$. $q_{\mathcal{U}}$ is the number of users which CGs are larger than the mean CG [83]. It will cause the lower number of combinations in the BFS search, and give a slight sum-rate improvement from the user side. When M is lower than 20, not as much sum-rate improvement can be achieved from the $\mathcal{U}^{Gpre}$ set in both figures. Therefore, $\mathcal{A}^{Gpre}$ will influence mainly for the lower number of M, and this gives the sum-rate improvement at the condition of lower M ($M < 20$) for the CG-based method in Fig. 4.8 and Fig. 4.10.

When the number of users is gradually increased, more user elements are assigned in $\mathcal{U}^{Gpre}$ and higher chance to select the best users from the larger $\mathcal{U}^{Gpre}$. Therefore, the noticeable increasing sum-rate can be seen between M=20 to 26 for the CG-based method. When the number of users M is much larger than RF chain S, the maximum size of $\mathcal{U}^{Gpre}$ is limited by $(S + \zeta)$ and $\mathcal{U}^{Gpre}$ will be gradually situated. The situated $\mathcal{U}^{Gpre}$ cannot give a more significant sum-rate improvement for larger user numbers M in Fig. 4.8 and Fig. 4.10.

Figures 4.10 and 4.11 compare the performances of S=N/4 case with N=40 for various numbers of M. When N is much larger than S, extra sum-rate improvement comes from more diversity and freedom of transmit antenna selection on the BS side. This benefit can be seen not only in the proposed method but also in other methods. The CG-based method shows distinguish sum-rate improvement with extra computation complexity as shown in Fig. 4.10 and Fig. 4.11. The proposed method has the same condition of user selection parts since numbers of user distribution in the sets $\mathcal{U}^{\Gamma o}$, $\mathcal{U}^{Go}$, $\mathcal{U}^{I}$ and $\mathcal{U}^{Uni}$ are not much different with the S=N/2 case. For the selection scheme in the SW Method, all of the available antenna elements on the BS side are considered by using the sliding window method. Therefore, this method also gives nearly constant value of sum-rate and CPU usage for constant value of N in the figure.

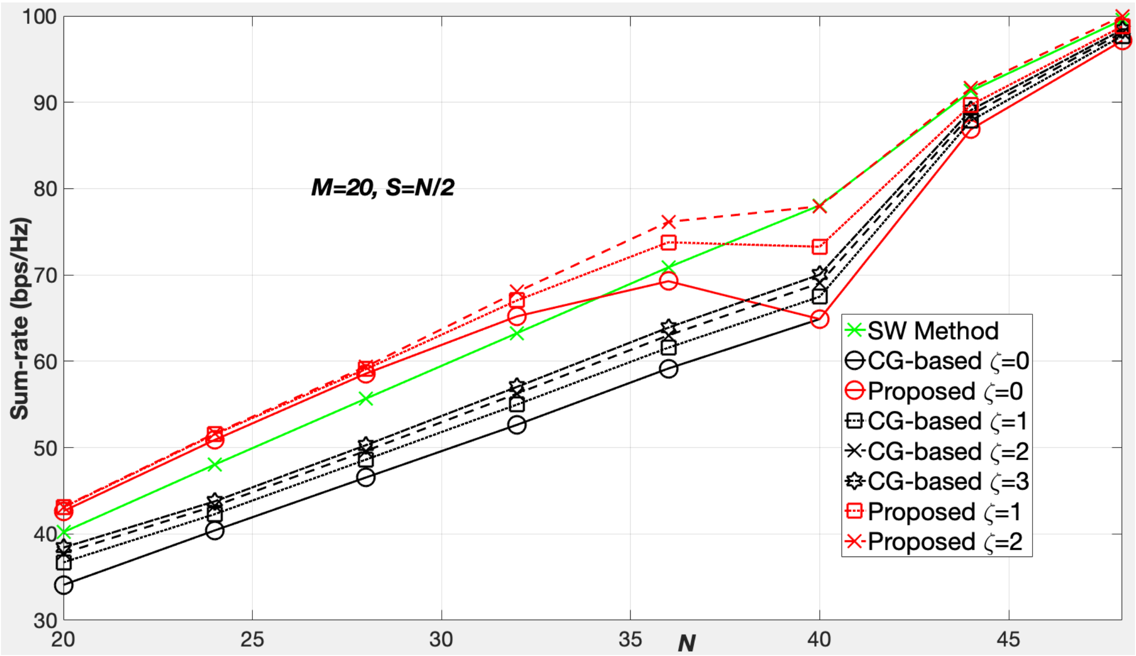


Figure 4.12: Comparison of sum-rate for various number of the BS antenna N and RF chains S=N/2, with total users M=20.

Figures 4.12 to 4.15 compare the performances of each method. As presented and explained in Fig. 4.4, the number of user count in the sets $\mathcal{U}^{\Gamma o}$, $\mathcal{U}^{Go}$ is gradually decreased until S is approximately equal to M. The computation complexity also depends on the size of sets $\mathcal{U}^{\Gamma o}$, $\mathcal{U}^{Go}$ as stated in (4.7). Therefore, decreasing the size of sets $\mathcal{U}^{\Gamma o}$, $\mathcal{U}^{Go}$ will give fewer possible combinations and this will cause a reduction in computation complexity in the selection scheme. Moreover, the number of elements in the sets $\mathcal{U}^{I}$ is gradually increased for increasing number of N. This condition gives less number of outcome for the possible combinations in (4.7). Therefore, we can obtain the reduction of

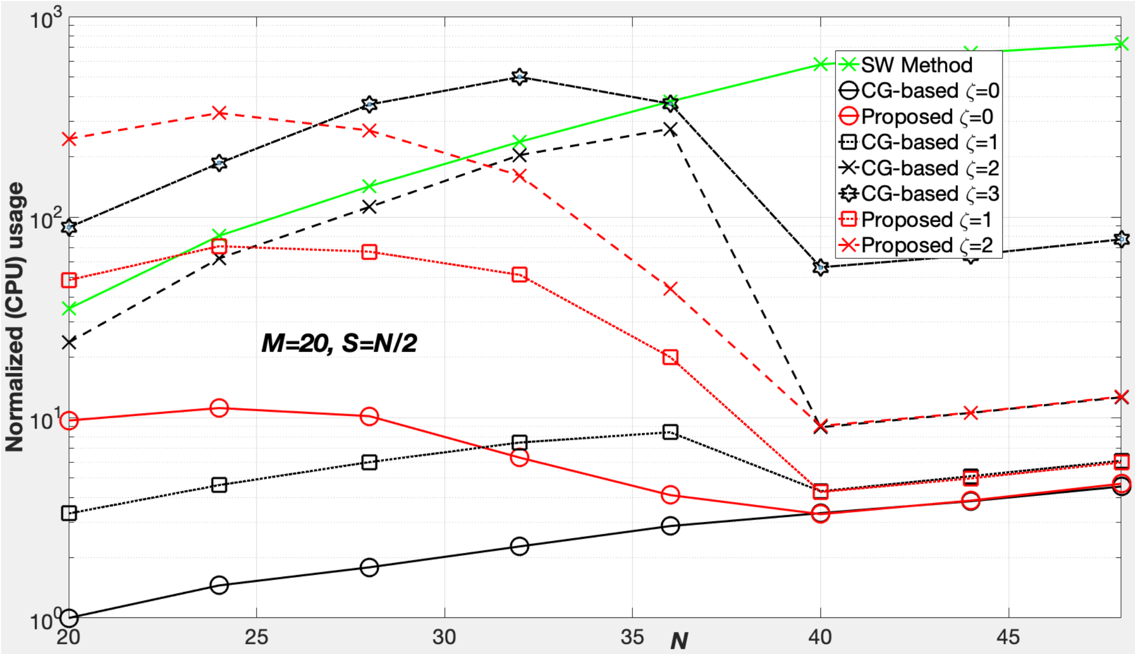


Figure 4.13: Comparison of CPU usage time for various number of the BS antenna *N* and RF chains *S=N/2*, with total users *M=20*.

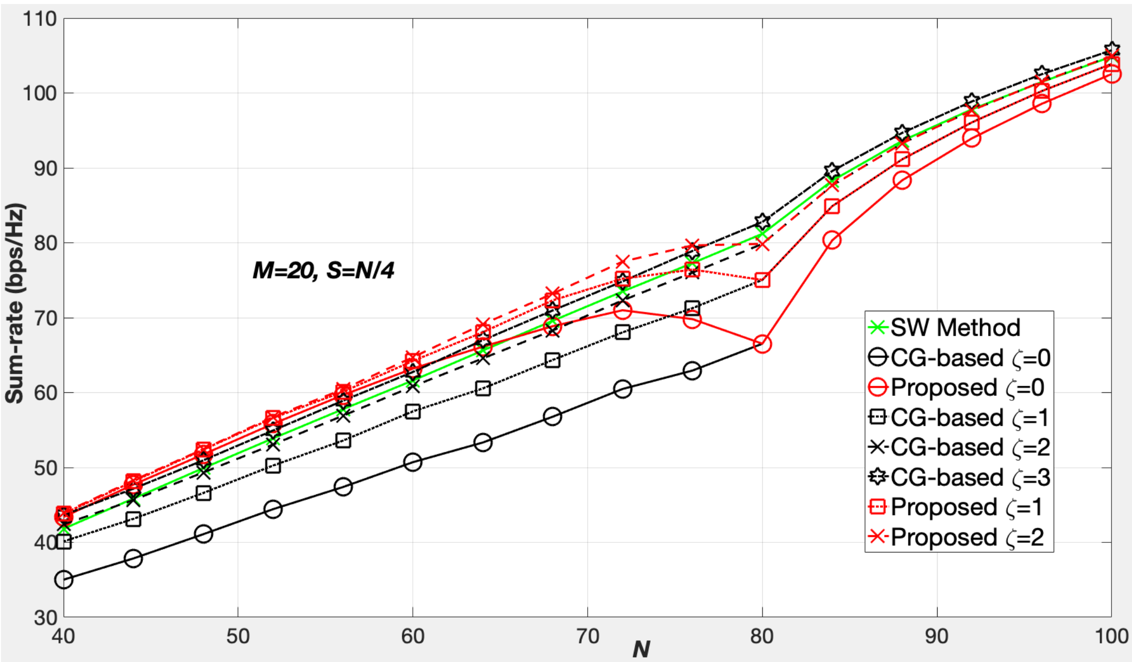


Figure 4.14: Comparison of sum-rate for various number of the BS antenna *N* and RF chains *S=N/4*, with total users *M=20*.

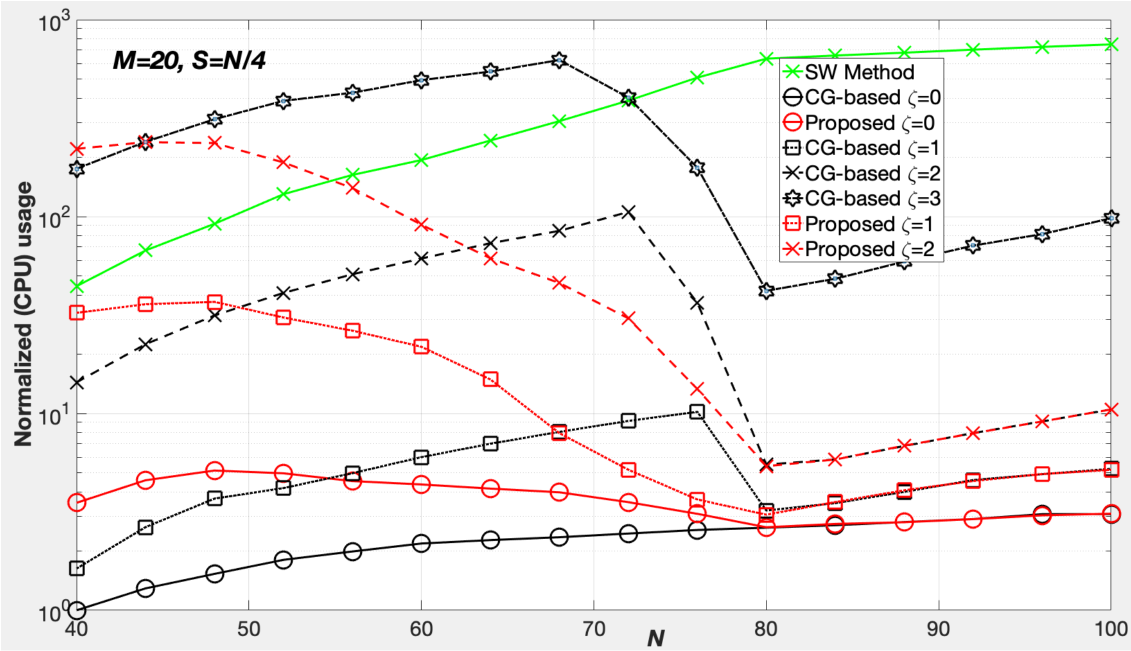


Figure 4.15: Comparison of CPU usage time for various number of the BS antenna N and RF chains S=$N/4$, with total users M=20.

computation complexity of the proposed method as shown in Fig. 4.13. The conventional SW Method gradually increases the computation complexity since it is necessary to use SVD calculation for more number of sliding windows on the BS side to find the best transmit antenna set. The method in [83] gives decreasing pattern of computation complexity when number of S is approached to M. In that condition, the user selection is not necessary to do the full combination search, because the available RF chain is approached to the total user number in a cell. The computation complexity from the user side is eventually diminished for increasing number of S. However, when S is larger than total user M then the total sum-rate and computation complexity of the proposed method and CG-based method will be overlapped since there has no more user selection is included in both methods. The constant increment of sum-rate improvements in Fig. 4.12 and Fig.4.14 come from the constant increment of transmit antenna N and RF chains S.

However, the proposed method can give higher sum-rate than conventional methods from a smaller number of transmit antenna to a larger number of transmit antenna case. This improvement can be achieved mainly from the user side selection part. When number of RF chains S is approached to M, no more user diversity is achieved and the sum-rate of the proposed method will be overlapped with the method in [83].

4.6 Summary of Contribution in MU-Massive MIMO System

We have presented the combined method of CG-based and SINR-based receive user selection schemes for the downlink MU-Massive MIMO TDD system with BD transmission. The proposed scheme can reduce the computation complexity of antenna/user selection while improving sum-rate performance in the system, especially for the system parameters when the number of user M is not much larger than available RF chains S. When M is much larger than S, the user diversity is more than enough and the sum-rate improvement of the proposed scheme is not much obvious when compared with the conventional schemes.

Chapter 5

Conclusion

In this dissertation, we presented our research works on promises technologies for next generation broadband wireless mobile communication systems. In Chapter 1, history and evolution of mobile wireless generation are presented in first and after that, the back ground information and theories of OFDM/OFDMA, MIMO, antenna and user selection methods are introduced. MIMO technologiy can be categorized as SU-MIMO, MU-MIMO and Massive MIMO. MIMO technologies can give the high speed internet access under the limited resources of radio frequency without additional transmit power in the wireless system. MIMO technology in spectral multiplexing system will work more efficiently if there has rich scattering multipath channel environment to give the low correlated channel matrix in the system. Therefore, our research works focused on this MIMO technologies in spatial multiplexing system for higher data transfer rate in next generation mobile wireless system.

When a BS is equipped with a large number of antennas (e.g. tens or hundreds) and communicates with several single-antenna users in the same time-frequency domain, then this system can be known as Massive MIMO [18]. The increasing capacity results from aggressive spatial multiplexing used in the Massive MIMO. The basic premise behind the Massive MIMO is to reap all of the benefits of the conventional MIMO, but on much greater scale. It has been shown that the large antenna array at BS could provide high degrees of freedom and thus increase significantly the system capacity, the link reliability, and the radiated-energy efficiency. Also, based on the random matrix theory, it was demonstrated that the Massive MIMO system could achieve the capacity gain with simple and linear signal processing methods. However, number of RF chains at the BS cannot be large very much due to the constraints in hardware cost and the complexity for practical system. Adding more antennas at the BS is usually inexpensive. However, the RF elements, such as RF chains can be relatively expensive. Therefore, most Massive MIMO systems should consider to implement the BS with larger number of antenna elements but fewer number of RF chains to reduce the hardware cost in the BS side. Since all antennas are not equally good in real propagation channels, it is possible to reduce RF chains to be used with selected active antennas, which contribute the most in the system performance and discarding the rest of antennas. Such antenna selection could simplify the design of a Massive MIMO base station and lead to energy and cost savings. In this case, selecting and using the best antennas among the available large number of antenna elements in BS is an important issue in Massive MIMO technology. Massive MIMO equipped with a large number of antennas at the BS can communicate with multiple users simultaneously. Simultaneous communication with multiple users creates multiuser interference and degrades the throughput performance. Precoding methods are applied during the downlink to reduce the effect of multiuser interference. Since the number of antennas is limited in Massive MIMO base station, if the number of users becomes more than the number of antennas, proper user selection scheme is applied before precoding to achieve higher throughput and sum rate performance. Therefore, the user selection is also a critical important factor for optimizing the overall performance of Massive MIMO systems. Antenna selection and user selection in the multi user Massive MIMO systems have been widely studied as presented in above, but all of them consider only for antenna selection in the BS side or the user selection in the user side. To the best of our knowledge, there are only few studies on joint antenna selection for MU-Massive MIMO systems. Therefore, we emphasized to do the research works on finding of antenna and user selection in Massive MIMO system.

In this dissertation, I presented the low complexity joint antenna and user selection scheme for the downlink MU massiveMIMOTDD system in Chapter 3. To achieve the reduced complexity in the antenna and user selection while maintaining the same or higher sum-rate in the system, the proposed scheme relies on three complexity reduction key factors. The first key factor is that finding the average CGs for the transmit antenna in the BS side and the receive antenna in the user side to select the best CG antennas and users. The second key factor called the complexity control for the antenna set and the user set limitation is used to control the complexity of brute force search. The third one is that using the assumption of point-to-point deterministic MIMO channel model to avoid the SVD computation in brute force search. The numerical complexity analysis is also used to compare the lower and upper bound of the proposed scheme with the optimal and sliding window based scheme. It can be seen that lower bound of the proposed scheme is always lower than other two schemes and we can use the various value to control the complexity in the proposed schemes. Moreover, simulation results show that the proposed scheme outperforms the two conventional methods in the CPU usage time while maintaining the same or higher sum-rate in most of the scenarios of the MU-Massive MIMO communication. When number of RF chains is large enough to compare with the half of the number of users or the BS antenna in the system, the proposed scheme faces the restricted condition to choose the better SINR user to create the good transmit antenna set and receive user set in the system. This will cause lower sum-rate in some particular cases.

A novel user selection scheme which is based on the previous research work are presented in Chapter 4. The proposedd novel selection scheme is a combined method of CG-based and SINR-based receive user selection schemes for the downlink MU-Massive MIMO TDD system with BD transmission. The proposed scheme can reduce the computation complexity of antenna/user selection while improving sum-rate performance in the system, especially for the system parameters when the number of user M is not much larger than available RF chains S. When M is much larger than S, the user diversity is more than enough and the sum-rate improvement of the proposed scheme is not much obvious when compared with the conventional schemes.

As an overall conclusion, this dissertation contributes the antenna and user selection schemes with exact fulfilment of low computational complexity requirement for downlink MU-Massive MIMO system. Noticeable data sum-rate improvements are also achieved in the system.

In future extension of our research, we will consider to develop the selection schemes for various wireless environments such as multi-cell, Rician fading etc. For Rician fading environment CG-based selection method might select users which cannot give higher data sum-rate when compared with Rayleigh fading environment. As already discussed in Chapter 2, CG-based selection method will choose users with highest channel gains with no consideration of interference effects of nearby users. This kind of selectin give low sum-rate results in the system. If user distribution in the cell is more scatter in the Rician fading environment, the proposed method might have more common users in the preselection stage and it will give more computation complexity reduction. Therefore, we should do research for different levels of user distributions in the cell to compare data sum-rate and complexity results for CG-based and the proposed methods. It is also possible to develop the antenna and user selection schemes for multi-cell environment with both uplink and downlink communication. When multi-cell environment is considered, one should carefully examine about imperfect CSI because of neighburing cells if there has no co-operation from those neighbouring cells in the system. Because of imperfect CSI and interference from the neighbouring cells, joint consideration of CG-based and SINR-based selection might have superior performance than CG only based selection scheme in the system. When uplink communication is considered in the system, we can expect similar sum-rate performance improvements like downlink communication for TDD system since uplink communication is the reciprocal of downlink communication in the MU-Massive MIMO system.

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Appendix A

Publication List

A.1 Journals

1. Aye Mon Htun, Maung Sann Maw, Iwao Sasase, “Low-Complexity Joint Antenna and User Selection Scheme for the Downlink Multiuser Massive MIMO System with Complexity Reduction Factors, ” IEICE Trans Communications., Vol. E102-B No.3, pp.592-602, Mar. 2019.
2. Aye Mon Htun, Maung Sann Maw, Iwao Sasase, “A Novel Low Complexity Scheme for Multiuser Massive MIMO Systems, ” IEICE Trans Communications., Vol. E105-B,No.1, pp.-, Jan. 2022.

A.2 Articles on international conference proceedings (peer-reviewed full-length papers)

1. Aye Mon Htun, Maung Sann Maw, Iwao Sasase,“Reduced Complexity on Mobile Sensor Deployment and Coverage Hole Healing by Using Adaptive Threshold Distance in Hybrid Sensor Networks, ” on 25th IEEE Personal Indoor and Mobile Radio Communications (IEEE PIMRC 2014) Washington. DC, USA, September 2014.
2. Aye Mon Htun, Maung Sann Maw, Iwao Sasase, “Relocation of Mobile Sensor Nodes

with Battery Aware Threshold Distance Algorithm in Wireless Sensor Networks, " on Regional Conference on Computer and Information Engineering JICA AUN/SEED-Net), Yangon, Myanmar, October 2016. (Best Paper Award).

3. Aye Mon Hun, Maung Sann Maw and Iwao Sasase, "Resource Allocation for Hyper-MIMO System with Block Diagonalization Precoding Technique, " 2018 Information and Communication Technology Forum (ICTF-2018), Graz, Austria, July 2018.

A.3 Other international conference papers (full-length papers)

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2. Maung Sann Maw, Aye Mon Htun and Iwao Sasase, "Adaptive Usage of Polarization and Physical Carrier Sensing in Wireless Ad Hoc Networks, " The 20th Asia-Pacific Conference on Communications (APCC2014), Pattaya, Thailand, October 2014.

A.4 Presentations at domestic meetings

1. Aye Mon Htun, Maung Sann Maw, Iwao Sasase, "Relocation Method of Mobile Noes for Recovering from Node Failures in Wireless Sensor Networks, " Broadband Access Systems, Home Networks, Network Services, Applications for Communications, etc. IEICE Technical Report CS2013-43, pp.15-20, Hokkaido, Japan, November 2013.

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