Chapter 1

Introduction

1.1 Millimeter Wave Communication

With the rapid development of electronic devices such as smartphones, tablets, personal computers, and various emerging applications like virtual reality, augmented reality, artificial intelligence, three-dimensional media, ultra high definition video transmission, etc. has increased demand for high data traffic in wireless communication [1]. Primarily, personal devices such as smartphone, tablet, and personal computer have become essential to modern world. Naturally, these devices are source of high data traffic volume with a high spectral efficiency per area (hundreds of bit/s/Hz/area) and the very high throughput per personal device (multiple Gbps) [2]. For instances, it is anticipated that the world wide monthly wireless data traffic of smartphones will be approximately 50 petabytes by 2021 [3], which is approximately 12 times than the traffic in 2016. Furthermore, the two prominent telecommunication companies, Nokia and Samsung, have predicted a 10,000x increase in the wireless data traffic by 2020 [4].

In order to meet the demand for wireless data traffic, millimeter wave (mmWave) frequencies turned out as a solution because they provide a larger bandwidth. mmWave frequencies are designated as the extremely high frequency band of radio frequencies in the electromagnetic spectrum, also known as mmW-ave spectrum, from 30 to 300 GHz [2–9]. Thus, utilizing unused mmWave spectrum is a key solution to satisfy the extremely high demand of data traffic and it offers a great opportunity to increase channel capacity. In the early days, mmWave spectrum was mainly used for Local Multipoint Distribution Service (LMDS), military applications, satellite communication, and long-range point-to-point communication [4]. Currently, International Mobile Telecommunication (IMT) advanced technologies such as WiMax, long term evolution (LTE), LTE Advanced, Ultra Mobile Broadband (UMB) work on maximum 20 MHz signal bandwidth [2]. However, signal bandwidth is dispensed from 1 to 2 GHz by employing the mmWave frequencies [8].

Almost 100 years ago, study of mmWaves had started. For instance, the experiments at wavelengths as short as 5 and 6 mm were performed by Bose and Lebedew in the 1890s [3]. As far its application in Radio communications was originally invented in 1990s and early 2000s, including system design and channel measurements [10]. But some important technical challenges [2, 3] like severe free path loss, high penetration losses, high power consumption, blockage due to shadowing, and hardware implementation were faced while using the mmWave frequencies as a carrier frequency. Theses technical challenges are discussed below.

1.1.1 **Technical Challenges**

1. **Free space path loss:** In free-space transmission, the power of the received signal can be determined by Friis transmission formula [2].

$$P_r(d) = PG_tG_r\left(\frac{\lambda}{4\pi}\right)^2 d^{-n}, \tag{1.1}$$

   where P is the transmit power and G_t and G_r are the antenna gains of the transmitter and receiver, respectively. Moreover, λ is the carrier wavelength, d is the transmission distance, and n is the path loss exponent [3], [8]. The wavelength of mmWaves is much shorter than a conventional microwave frequencies, operating at carrier frequency below 6 GHz [2]. Hence, if all other conditions including the antenna gain remain the same, the path loss of mmWaves waves is much higher than that of conventional microwave frequencies. Although path loss of mmWaves is generally quite high, it is feasible to communicate over the distances of a few hundreds of meters. It has been observed that the communication over 10 km range is possible under clean air conditions by using directive antennas [11]. If the air is not clean, the attenuation losses due to rain and atmospheric/molecular absorption increase the path loss which limit the communication range [12, 13]. It has been also found that the impact of these factors varies with the carrier frequency in mmWave ranges. Thus, the path loss is more at the mmWave frequencies than the conventional microwave frequencies.

2. **Penetration Losses:** The path loss was discussed for line-of-sight (LoS) communication, but the penetration loss is associated with non-line-of-sight (NLoS) scenarios. Although the penetration losses for glass and walls are relatively low for mmWaves, it is comparable to the microwave frequencies. Furthermore, the penetration losses for brick and tinted glass are relatively high for mmWaves (28-40 dB at 28 GHz), which is much higher than the conventional microwave frequencies [14]. Thus, the penetration losses are typically larger at the mmWave frequencies.

3. **High Power Consumption:** If the signal-to-noise ratio (SNR) is maintained the same [15], one needs to increase the transmission power with increase in the bandwidth in order to compensate the high path loss. In other words, the noise power grows as the signal bandwidth increases, then the transmitter needs to increase the power to sustain the same SNR, in dB.

$$\text{SNR} = \frac{P}{N_0 \text{B}}, \tag{1.2}$$

where P is the transmit power and N_0 is the noise power spectral density, and B is the signal bandwidth.

4. **Hardware Implementation:** To generate carrier waves, say mmWave frequencies, operating at the desired carrier frequency, the mixers are used for up and down-conversion using local oscillators at the transmitter and receiver side. However, due to the random deviation of the output carrier frequency around the desired carrier frequency, it is practically impossible to operate both transmitter and the receiver oscillators at the same carrier frequency, such a mismatch leads to phase noise distortion [16]. Thus, the mmWave frequencies are more sensitive to phase noise than conventional microwave frequencies due to the extremely high carrier frequency. In addition, we need to provide linear amplification to a carrier signal with very wide bandwidth. In practice, it is very difficult to design the linear power amplifiers because each

power amplifier has a non-linear behaviour [17]. Moreover, extremely high-frequency bands of mmWaves may cause many technical challenges [16, 18] in the design of the very fast analog to digital converters (ADCs) or digital to analog converters (DACs), design of antenna having a large bandwidth [19, 20], and other high frequency enabled circuit designs.

1.1.2 **Implementation and Applications**

To circumvent the above-discussed challenges to some extent, the amalgamation of multiple-input-multiple-output (MIMO) and the mmWave frequencies has been introduced, in [3], [5], [8, 9]. It shows a point-to-point or/and point-to-multipoint communication systems having extremely high frequencies, also knows as mmWave communication. Shorter wavelengths of the mmWave frequencies allows packing a large number of antenna elements in the small physical dimension which overcomes severe path loss, penetration loss, and atmospheric absorption from small raindrops, etc. by achieving high directional beamforming [7–9, 15]. mmWave communication, beyond 4G, is one of the 5G emerging technologies aka IMT-2020, and it is anticipated that the data rate of IMT-2020 technologies will be more than 10 times than IMT-Advanced technologies aka 4G [3]. Hence, mmWave communication can satisfy the hunger of a high data rate of a densely populated area, smart electronic devices, and high data rate applications.

On the other hand, to achieve all the key capabilities of 5G [21, 22] several key technologies have been identified e.g. mmWave communication cellular systems [23–27], Internet of things (IoT) [23–25], [28] small cell deployment [29, 30], full duplex relaying [31–33], device-to-device (D2D) communications [33–35], interference management techniques [25], [36] and self-backhauling [25], [33], [37]. But, mmWave communication is primarily and widely considered as the most important technology to achieve 10Gbps peak data rate [38, 39]. This is because of large amount of bandwidth available in the mmWave spectrum, and expanding the bandwidth is an efficient approach to enhance the system capacity. In particular, the channel capacity of an additive white Gaussian noise channel operating over bandwidth B Hz for given signal power is [40]

$$C = \mathrm{B}\log_2\left(1 + \frac{P}{N_0\mathrm{B}}\right) \text{ b/s.} \tag{1.3}$$

If we let P to grow in proportion to B, the system capacity increases linearly with the bandwidth B,. But, in practice government regulations limit P.

mmWave communication is particularly well-suited for scenarios with good channel conditions such as short-range small cell access [29, 29, 30], line-of-sight backhauling in mobile networks [25], [33], [37], self-backhaul [33], [37]. Self-backhaul offers a flexible and cost-efficient solution for ultra dense network (UDN) as the access point and backhaul links share the same spectrum and have identical radio access technology [41, 42]. It refers to a set of solutions where small base stations (BSs) with dedicated backhaul connect to other base stations and that dedicated backhaul link is utilizing a similar radio access technology as the one used by the user to access the wireless network.

Recently a large effort have been devoted to mmWave communication research and mmWave wireless local area networks (WLAN), e.g., IEEE 802.11ad technology operating at 60 GHz is already available [43]. More challenging development of mmWave communication is ongoing. Samsung first achieved 1 Gbps data transmission at 28 GHz in May 2013 [44]. In Japan, to prepare for 2020 Tokyo Olympic, DOCOMO and Ericsson tested at 15 GHz to reach the rates of 4.5 Gbps in outdoor environments and at 70 GHz to reach the rates of 2 Gbps in indoor environments [45]. In China, the minister of science and technology has sponsored a few projects in mmWave mobile networks and they have designed radio frequency (RF) chips at frequencies 60 GHz and 42-48 GHz [3]. Further, Huawei and China mobile also testified the 5G Dual Connectivity with AR/VR in the mobile world congress 2017 and achieved throughput 2 Gbps from 5G Sub 6 GHz network and 10-20 Gbps from 5G Ka-Band network [46].

1.2 Motivation of the Thesis

High data rate has become a primary need in the recent wireless technologies while taking into account the cost and complexity. It has been found that transmission rate increases as the number of antenna elements increase [47]. Therefore, MIMO technology has been one of the key points to increase the transmission rate in wireless communication. On the other hand, a huge signal bandwidth is also accountable to boost transmission rate. It can be supplied by unutilized frequencies available at mmWave spectrum. Thus, to employ the mmWave as a carrier frequency and to encounter severe losses, a large number of antenna elements are required. Each antenna element in MIMO system needs to be connected with the RF chain to begin the transmission process. RF chains are considerably expensive as compared to the antenna elements. Connecting each antenna element to a dedicated RF chain requires a MIMO digital architecture which is very difficult to deal with a large number of antenna elements. Moreover, deploying more RF chains increase the power consumption of the system. With the advent of MIMO hybrid architecture, the number of required RF chains are reduced [48–52] as it supports the number of RF chains as equal to the number of data streams. In fact, MIMO hybrid architecture is a concatenation of MIMO digital and analog architecture. MIMO analog architecture is deployed in the RF domain and it is responsible for the transmitting/receiving signal from the desired direction, whereas MIMO digital architecture is deployed in the digital domain and it eliminates the multi-user interference (MUI) at user's end. In addition, MIMO analog architecture requires a analog beamformer or weights which consists of RF phase shifters, and the weights need to be adjusted after each time instant to track the signal direction. Accordingly, we design a digital beamformer or weights for digital architecture to eliminate the MUI. Thus, concatenation of analog and digital beamformers in MIMO hybrid architecture is known as hybrid beamforming [48–52].

Evidently, mmWave propagation with a large antenna elements, while comprising of the hybrid beamforming, is highly sparse. As a result, the line-of-sight (LoS) path predominates over non-line-of-sight (NLoS) paths [15]. Thus, to exploit this channel sparsity, the conventional or spatial channel model is transformed into the beamspace channel by deploying discrete lens array (DLA) at the transmitter [15], known as beamspace systems. While working in the beamspace domain, the number of beams are equal to the number of RF chains and the number of beams can't be greater than the number of antenna elements. Scaling up the number of beams in the system to improve the performance of wireless transmission must be accompanied by increasing the number of RF chains, which is more expensive and it increases power consumption of the system. To avert this problem, the beam selection scheme is used to reduce the cost, and complexity of MIMO hybrid architecture accompanied by DLA without any considerable loss in the system performance. Beam selection algorithm selects only desired or favourable beams for each user as the number of required beams are function of the number of RF chains. Therefore, beam selection algorithms based on technical and mathematical concepts have been proposed to achieve this goal. Particularly, this research focuses on the performance evaluation, i.e., the spectral efficiency and energy efficiency of the beam selection algorithms for mmWave beamspace multi-user MIMO (MU-MIMO) downlink system with perfect channel state information (CSI).

1.3 Contribution of the Thesis

Contributions of this thesis are as follows

- **Designing beam selection algorithms for mmWave beamspace MU-MIMO downlink systems**

  The beam selection algorithms in mmWave beamspace MU-MIMO downlink systems are investigated in this work and new beam selection algorithms are proposed. First, a beam selection algorithm to deactivate beams which contribute least to the sum rate of users' effective channels is proposed. The algorithm repeats in descending order until the required number of beams are obtained. The proposed algorithm uses the iterative precoding design to pre-cancel MUI. Furthermore, two low complexity beam selection algorithms for the sparse systems are proposed in this work, where the number of beams are considerably larger than the number of required beams. In other words, the number of beams are considerably larger than the number of users present in the cell. First one is a greedy beam selection algorithm, and the second one is maximum weight matching (MWM) based beam selection algorithm. Greedy beam selection is a search based iterative procedure, which allocates the strongest beam to the corresponding user. If a beam is the strongest beam for more than one user then that beam will be allocated to the user who is having higher channel gain. The algorithm repeats the same process for the rest of users after removing the allocated beams from the set of available beams. This process is repeated until a beam is selected for each user. Beam selection through "MWM" finds a matching over the bipartite graph that maximizes the sum of edge weights. The edge weights are nothing but SINRs achieved by each user through each beam, and well efficient Kuhn-Munkres algorithm solves the MWM problem efficiently. After comparative study, it is observed that although complexity of the proposed algorithms is less compared to the existing algorithms and also its performance is better.

- **Designing a digital precoder for mmWave beamspace MU-MIMO downlink systems**

  Precoding is employed to eliminate the MUI at user's end. The popular linear precoder, i.e., zero-forcing (ZF), diagonalizes the channel matrix by pre-multiplying inverse of the channel matrix with the channel matrix. But, ZF precoder degrades the system performance when the channel matrix is a ill-conditioned [53]. Therefore, we propose a linear precoder that eliminates MUI completely by diagonalizing the channel matrix, and the proposed precoder can be obtained through an iterative procedure. More importantly, the process for obtaining a precoder matrix abstains from taking inversion of any such matrices, i.e., ill-conditioned matrices. Unlike ZF forcing precoder, the proposed precoder makes each user experience a distinct channel fading. This property of the proposed precoder allows further to improve the system performance through an optimal power allocating scheme, i.e., water filling power allocation. Thus, the performance of the proposed precoder has been validated and compared with the ZF precoder and the performance of the proposed precoder is found better through a comparative study.

- **Designing a decentralized beam selection algorithm for mmWave beamspace MU-MIMO downlink systems**

  For the centralized beam selection algorithms, transmitter requires channel state information to perform beam selection. But, transmitter gets heavily loaded because dimension of the channel handling matrix is large. Hence, it becomes a bottleneck to process such a large matrix and selecting the required number of beams. Therefore, we propose a decentralized beam selection algorithm, which could be a better alternative. Unlike the centralized beam selection algorithms, decentralized beam selection algorithm distributes computation to multiprocessor. These multiprocessors are users themselves. As a result, the users play an active role to perform beam selection by sharing the local information with the neighbour users [54]. The performance and complexity of the proposed decentralized beam selection algorithm has been validated and compared with the existing centralized beam selection algorithms and the performance of the proposed decentralized beam selection algorithm is better with less number of computations.

- **Designing a non-orthogonal multiple access (NOMA) power allocation scheme for mmWave beamspace MU-MIMO-NOMA downlink systems**

  Various beam selection algorithms are proposed to select distinct beams for each user. In turn, users who desire the same beam but, they have been assigned a distinct beam, are known as conflict users. Such users cause interference to each other comparatively more than the other users present in the communication network. Hence, they degrade the system performance. NOMA principle [55, 56] emerged as a solution to improve the spectral efficiency for MU-MIMO systems which can also be pertinent for mmWave beamspace MU-MIMO system. As a result, the conflict users can be served by the same beam using NOMA principle in the power domain. In particular, symbols of the conflict users are superimposed and transmitted over the same beam. Further, successive interference cancellation (SIC) is applied at users' side to decode the received symbols one by one until the desired symbol is obtained. To perform SIC, the conflict users have been assigned power coefficients according to their channel conditions in order to achieve high system performance. Therefore, a NOMA power allocation scheme for the conflict users to assign power coefficients has been proposed in this work. The performance and complexity of mmWave beamspace MU-MIMO-NOMA downlink system has been analyzed and compared with mmWave beamspace MU-MIMO downlink system and it achieves excellent performance with less number of RF chains than the existing mmWave beamspace MU-MIMO downlink system.

1.4 Organization of the Thesis

Chapter 2 presents a brief introductory background of the research work presented in this thesis. It begins with an overview of single and multi-user MIMO systems. Further, the channel capacity for both the systems is discussed. Next, the MIMO beamforming techniques are elaborated. Three techniques of beamforming viz. analog beamforming, digital beamforming, and hybrid beamforming are presented. Further, the spatial channel model for mmWave propagation is discussed. In this context, the relation between conventional (or spatial) channel model and beamspace channel model is also presented. Next, the mmWave beamspace MU-MIMO downlink communication systems is explained. Finally, transmission in mmWave beamspace MU-MIMO downlink channels is presented along with a brief discussion on the ZF precoding method by which MUI can be perfectly eliminated.

Chapter 3 presents the beam selection algorithms for mmWave beamspace MU-MIMO downlink system. It begins with a brief introduction about the advantages of beam selection and the approaches used in such a system. The system model of mmWave beamspace MU-MIMO downlink is presented, followed by a beam selection, "QR-based" algorithm, accompanied with an iterative precoding design is explained. Further, the proposed iterative precoding design to pre-cancel MUI is discussed. Simulation results i.e. spectral efficiency, energy efficiency, and complexity of the "QR-based" beam selection algorithm are compared with the other existing algorithms. A brief description of a sparse and dense medium for mmWave beamspace MU-MIMO systems with respect to the number of users in the cell is done. Next, probability of selection of the same beam for two or more users is discussed. In this context, two beam selection algorithms – greedy and "MWM-based" beam selection algorithm – are proposed. Both are low complexity beam selection algorithms. Further, the proposed precoding is employed at transmitter to eliminate MUI for each user, and this precoding method creates non-interfering parallel channels. Additionally, water-filling algorithm is applied to these non-interfering parallel channels to further improve the system performance. Finally, the performance metrics (spectral efficiency, and complexity) of the “QR-based,” greedy and “MWM-based” beam selection algorithms are compared with other existing beam selection algorithms.

Chapter 4 discusses a distributed auction based decentralized beam selection algorithm for mmWave beamspace MU-MIMO downlink systems. It begins with introduction to the schemes of auction and distributed auction. Next, the advantages of the decentralized beam selection algorithm and its usage in this technology is discussed. Finally, the performance metrics (spectral efficiency, and complexity) of the proposed algorithms are compared with the other existing centralized beam selection algorithm algorithms.

Chapter 5 begins with introduction of NOMA principle in the power domain for mmWave beamspace MU-MIMO downlink systems. Next, “a beam selection algorithm accompanied by NOMA principle followed with a power allocation scheme” for mmWave beamspace MU-MIMO downlink systems is discussed. Further, a NOMA power allocation algorithm for conflict users, those users who demand for the same beam, to successfully perform successive interference cancellation (SIC) at users’ side is discussed. Finally, the performance metrics (spectral efficiency and energy efficiency, and complexity) of mmWave MU-MIMO-NOMA downlink systems are compared with mmWave MU-MIMO downlink systems.

The research work presented in the thesis is summarized in Chapter 6. The major conclusions emanating from this research and their significance are highlighted. Finally, the scope of future work is presented. Last but not the least, Appendix A contains the procedure to find the Gram Schmidt orthogonalization.