AN ABSTRACT OF THE DISSERTATION OF

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Title: Efficient Beamforming Techniques for Millimeter Wave MIMO Systems

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Due to the continued evolution of 5G standards, the need for higher rates of data, lower latency network access, and implementations that are more energy efficient have become clear. To enable wireless communications at rates over tens of Gbps, the wide bandwidth of mmWave spectrum can be exploited. Beamforming (or precoding) is used to compensate for the high path loss in the mmWave frequencies. Although the small wavelength of mmWave signals tolerates a large number of antennas being crowded into a small area, the high-power consumption and cost of mixed signal components make it difficult to earmark a separate radio frequency (RF) chain for each antenna. The addition of analog processing to the digital precoding, known as hybrid beamforming (HB), is an efficient solution for massive MIMO systems, which results in a number of active RF chains lower than antennas.

Extensive work has determined that HB can approach the performance of the optimal precoder, assuming optimal antennas implementation, ideal environment, and full rank effective channel. However, depending on the implementation techniques adopted for the RF precoder and other system parameters, such as the number of

active RF chains, the limited distance between antennas, and the geometric placement of both ends of wireless systems, the effective channel matrix could be rank deficient, which degrades the performance of the system. The first part of this dissertation provides a new set of solutions for HB that approaches the performance of a fully digital beamformer in terms of MIMO multiplexing gains, by taking careful consideration of the matrix of the effective channel, appropriately selecting independent columns of the analog precoder, calculating the least squares solution for the digital precoder, and selecting its digital gain based on the selected columns of the RF precoder and the effective channel. Multiple hybrid precoding schemes are developed and proposed, taking careful consideration of the complexity and power consumption of the system, appropriately reducing them while keeping the same level of quality of service.

The second part considers a hybrid precoding scheme with low-resolution phase shifters (PSs) in a mmWave MIMO system. Finite resolution PSs are a good alternative because they need simpler hardware implementation than those with infinite resolution. The proposed system considers separating the antennas from each other by sufficient distance to ensure a less correlated channel, and thus, a minimal loss in the capacity, which is our objective. The capacity gap between the optimal precoder and our proposed hybrid precoding with low-resolution PSs can be reduced without increasing the number of RF chains. In particular, we focus on properly selecting the weights of the RF beamformer, which create independent beams that send data streams to the receiver. As a result, the structure of the multipath propagation channel will be exploited by the transmitted beams, which maximizes the system capacity.

Finally, this dissertation investigates technologies and methods that can be adopted to lower the cost and power of HB and are able to maintain more users while keeping higher data rates. The idea of connecting the RF chains to a subset of the antennas and spacing those sub-arrays to provide additional diversity gains is a promising approach. However, this spacing technique cannot be implemented at the receiver side due to its limited size. To reduce power at the receiver, low-resolution analog-to-digital converters (ADCs) can be implemented. This idea is powerful because with a simple circuit and digital combining based on coarse quantization, it allows a gain of performance, maintaining a low hardware complexity, and saving energy at the same time. It will be of great interest to implement and develop techniques that can merge the idea of distanced sub-arrays for the uplink between base stations with the low-resolution ADCs on the downlink.

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Efficient Beamforming Techniques for Millimeter Wave MIMO Systems

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I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Mohammed Alarfaj, Author

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DECLARATION

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other University. This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration, except where specifically indicated in the text.

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INTRODUCTION & BACKGROUND REVIEW

1.1 Scope & Objectives

Scholars specializing in wireless networks examine new energy-saving technologies and methods, which are more reliable and able to maintain more users while keeping higher rates of data.

The wide bandwidth of millimeter wave (mmWave) can provide the desired gigabit per second data rates in cellular systems [7, 64, 65, 89]. However, the issue of high path loss and signal attenuation in mmWave systems must be overcome. The small wavelength of mmWave frequencies is an advantage that can offer high beamforming gain to combat path loss in a large number of antenna elements. Beamforming techniques such as precoding can improve the performance of mmWave cellular systems [64, 65]. The type of beamforming that is used in traditional MIMO systems is the digital beamforming at the baseband. This beamforming technology is not practical for a large-scale MIMO systems because the number of expensive and power consuming radio frequency (RF) chains will be large and RF chain is needed for each antenna element [89].

Analog beamforming has recently been offered for the use in large-scale MIMO systems to save cost and energy. The benefit of this beamforming technique is that low cost phase shifters are used to manage the phase of the conveyed signals of each antenna [17, 18]. It is generally made to have a reasonable low power solution. However, analog beamforming in a MIMO system carries only a single data stream. It is hard to use this technique alone for the spatial multiplexing when numerous streams of data are being transmitted. Despite being less expensive than digital beamforming, the analog one is not able to provide equally efficient performance.

More antennas employed will lead to a large number of RF circuits which result in high-energy consumption. According to several statistics, as the number of antennas and RF chains increase, the energy consumption of cellular transmission will be dominated by the energy of RF chains [97]. Hybrid beamforming (HB) is a good approach to reduce the number of RF chains for massive MIMO systems. This analog/digital precoding model enables spatial multiplexing and multi-user MIMO. The digital layer that exists in the HB can make up for the analog limitations, due to which the HB can work closer to baseband digital performance [7, 64, 65, 89]. The HB approach is powerful because with reasonable number of RF chains, it can achieve a high performance that can be compared to the digital one. Instead of having an RF chain for each antenna as in digital beamforming, the HB structure can perform nearly as well as the digital one with smaller number of RF chains.

In this thesis, hybrid beamforming solutions for massive MIMO systems were investigated. Below is a list of the main objectives of this research:

1. Providing a new set of solutions for HB that approaches the performance of a fully digital beamformer in terms of MIMO multiplexing gains.

2. Investigating effective solutions for reducing complexity and power consumption of hybrid beamforming systems when the partially or sub connected HB architecture is used.

3. Proposing a feasible application of HB when finite resolution phase shifters (PSs) at the RF are used.

4. Considering separating antennas and sub-array from each other by sufficient distance to lower the correlation between the channels and to ensure a minimal loss in the capacity and the antenna gains.

5. Studying new techniques that can support multi-user HB systems with low cost and power and keeping the performance at a high level at the same time.

1.2 Overview of Contributions

Although mmWave signals with their small wavelength allows a large number of antennas being crowded into a small area, the high power consumption and cost of mixed signal components make it difficult to earmark a separate radio frequency chain for each antenna. Hybrid beamforming using both analog precoding at RF and digital precoding is an effective solution to reduce the complexity and power consumption of massive MIMO systems. Extensive work has determined that HB can achieve the performance of the optimal precoder, assuming optimal antennas implementation, ideal environment, and full rank effective channel. However, depending on the implementation techniques adopted for the RF precoder and other system parameters, such as the number of active RF chains, the limited distance between antennas, and the geometric placement of both ends of wireless systems, the effective channel matrix could be rank deficient, which degrades the performance of the system.

Considering the aforementioned practical constraints and challenges, a summary of the contributions of this thesis is listed below:

1. A new set of solutions are proposed for HB that approaches the performance of a fully digital beamformer in terms of MIMO multiplexing gains, by taking careful

consideration of the matrix of the effective channel, appropriately selecting independent columns of the analog precoder, calculating the least squares solution for the digital precoder, and selecting its digital gain based on the selected columns of the RF precoder and the effective channel.

2. An effective solution for reducing the complexity and power consumption of hybrid beamforming systems is using the partially or sub connected architecture. This design works by connecting only a subset of the antennas to each RF chain. The objective of this study is to maintain a high rank effective channel with independent beams sending data streams to the receiver. Researchers have studied HB, assuming optimal antenna implementation, ideal environment, and full rank effective channel. However, the rank of the effective channel matrix could be deficient due to implementation limitations and other factors, which would degrade the performance of the system. When the weights of the RF beamformer are properly selected, the structure of the multipath propagation channel will be exploited by the transmitted beams, which maximize the system capacity.

3. The performance of hybrid precoding with finite resolution phase shifters (PSs) at the RF is investigated. For a feasible application of HB, the design of a phase shifter network plays an important role in the complete precoder operation because it necessitates accurate components for realizing precise phases, and that can be costly. Low resolution phase shifters are a good alternative because they need simpler hardware implementation compared to high resolution PSs. However, the degradation of performance of a MIMO system with very low-resolution PSs is significant. Although recent studies suggest adding extra RF chains to substitute for the accuracy of the PSs, it is complex, expensive and not energy efficient. This thesis demonstrates that HB with low resolution PSs can realize a high performance without increasing the number of RF chains. Our proposed solution relies on a proper selection of the weights of the RF

beamformer, hence exploiting the structure of the multipath propagation channel to maximize the system capacity. We also show that separating antennas from each other by sufficient distance, results in a less correlated channel, and thus, a minimal loss in the capacity, and the antenna gains are assured.

1.3 MIMO Wireless Communication

What does MIMO mean? The abbreviation stands for multiple input multiple output [35, 36, 40, 71, 104]. The term defines the communication paradigm that means having multiple antennas at the transmitter and multiple at the receiver. This paradigm has been used for the last 20 years. The term “MIMO” has been around for years, but now it merely refers to the system with multiple transmit and receive antenna with all kind of signal processing that can be used, with the use of different approaches at the transmitter and receiver and all those under the MIMO umbrella [33]. Having these antennas, current algorithms need to be revisited, the signal processing, as well as how we design the transmit signal. It also changes the performance of those algorithms, the rate that can be achieved, the reliability, and the system design since it changes the tradeoff that we want to make. Even though MIMO has been around for a long time, it is still a subject of intense research, because more freedom exists nowadays in a wireless system that can be used for capacity, for reliability, and for dealing with interference [55].

1.4 Millimeter Wave Band for 5G

Due to the continued evolution of cellular standards, the objectives for higher data rates, lower network latency, and implementations that are more energy efficient have become clear. Greater bandwidth systems are necessary because of higher data rates, and the current bandwidth through 6GHz does not accommodate these demands [20]. As a result, the operating frequency bands have reached into the 6 to 100 GHz area for future wireless communication structures as well as broadband standard 5G [3, 66]. Although this frequency range contains the lower centimeter wave range, it is still referred to as millimeter Wave (mmWave). Because of the spectrum and accessibility of consumer grade systems at mmWave, research in both academic and industry has grown exponentially. Nevertheless, in order to efficiently use the spectrum and maintain power efficiency, the baseband and radio front-end architectures must change significantly from the existing state of the art cellular devices.

Data traffic for each smartphone is increasing in every region, while at the same time showing big differences in patterns of data consumption related to networks, markets, and subscribers [69]. The highest usage is found in North America, with 5.1 Gigabyte per month for each smartphone predicted for the end of the current year, which is an increase of approximately 40% from 2015 [1]. That is nearly twice as large as the second highest monthly use of 2.7 GB per user in Western Europe. By the year 2022, North America is still expected to lead the world in highest monthly usage (25GB) [1]. The reasons for this increased use include a higher number of LTE subscriptions, better device capabilities and data plans, and more data-intensive content.

4G-LTE connections in the world are expected to reach 2.8 billion by 2020, compared to 500 million at the end of 2014 [1]. Because 4G users create much more data than 3G users, a huge increase in traffic is expected to occur in the next six years. The Cisco VN14 estimate for South Korea claims that mobile traffic should reach 13GB per month per user by 2019 [2]. The increasing need for higher data rates and more subscriber capacity dictates more efficient use of the spectrum. Therefore future 5G wireless systems are predicted to use a mmWave band, because of its wider bandwidth.

A mmWave standard communication system consists of an isotropic radiator and a receive antenna. According to Friis' equation [73]

$$P_{rx} = (\frac{P_{tx}}{4\pi R^2})(\frac{\lambda^2}{4\pi}) \Rightarrow P_{rx} = G_{rx}G_{tx}(\frac{P_{tx}}{4\pi R^2}), \tag{1.1}$$

as the frequency gets higher, while the antenna gets smaller and the receiver gets less power, where λ is the wavelength and P_{tx} and P_{rx} are the transmit and receive power. Thus, it leads to the general belief that the smaller the wavelength, the lower the received power. However, if the size of the antenna is constant, the same amount of power can be collected as in lower frequency. It can be done by using the transmit and receive array gain as in (1.1), where G_{tx} and G_{rx} are the transmit and receive antenna gains [73]. Alternatively, if the aperture size increases, the amount of energy captured at the receiver increases, which means the dependence on wavelength can be canceled. In theory, by having a large aperture, communication in higher frequency is the same as with lower frequency; it would become frequency-independent [73].

Another issue at mmWave is that the noise bandwidth is larger. The reason behind choosing a wideband channel, such as 500 MHz, a GHz or 2 GHz channels instead of 5 or 10 MHz channels, is the need to get more power received and higher data rates. When noise power spectral density is constant, a larger bandwidth results in larger amount of received noise power. The additional noise power that exists in the mmWave noise bandwidth must be overcome. It can be done by achieving gain at the transmitter and receiver that can improve our received power and help us overcome the noise power.

Now, a natural question is, how do we achieve gain from the transmitter and receiver? Additional gain can be achieved through the use of antenna arrays or adaptive antennas [51]. By collecting a whole bunch of antenna elements together and co phasing their signals, effectively, directional antennas can be implemented to have a large amount of gain. This forms the connection to the MIMO communication. Therefore, there are antennas allocated at the transmitter and receiver. This array gain can be exploited to overcome the effects of frequency dependence, overcome the noise power, and even get more gain [73].

5G networks use large sized antenna arrays to diminish the transmission loss in the mmWave band; however, these designs have their own problems [44]. The wavelength in the mmWave band is quite a bit smaller, compared to today's wireless systems, and it becomes less cost effective to provide one transmit and receive unit for each antenna, even though the smaller wavelength permits an array to hold more elements with the same physical measurements [4].

Current wireless communication devices use spatial multiplexing to improve the data input and output in a scatter rich environment. Each data flow can be recovered with the aid of precoding and combining weights which are derived from the channel information. The weights comprising magnitude and phase terms are usually employed in the digital field. Shorter wavelengths at higher frequency bands allow applications with more antennas per system with small form factors. Unfortunately, challenges in signal path and propagation connected with operating at higher frequencies are also increased. These losses may be counterbalanced with the use of spatial signal processing techniques such as intelligent array design and beamforming [34, 98]. This processing is facilitated by very large MIMO arrays is used to deliver higher link-level advances to overcome path loss and interference. To maintain more control with beamforming in an active array, having independent weighting control over each element of the antennas is advantageous [34, 98]. Such control necessitates a transmit and receive model for each element. Building array sizes that are common for a huge MIMO system is very difficult and expensive and limited by space and power. For example, a system with a high-performance ADC and DAC for every channel along with the supporting components can overrun the cost and power beyond most design budgets. In addition, the system costs may be increased by having variable gain amplifiers in the RF chain for each channel.

A high beamforming gain may be achieved by building an array with a larger number of antenna elements [57]. The beam, which is highly directive, assists in offsetting the high path loss at higher frequencies, as beams are guided in a specific direction [99]. The gains from larger antennas must be weighed against the fact that MIMO systems depends highly on scattering environments and broader beam to maximize channel capacity [3]. With mmWave systems, the area of the antenna array is reduced in proportion to the size of the wavelength. To illustrate, at millimeter wave frequencies, an antenna array can be up to 100 times smaller than an array made for microwave frequencies [3]. The most customary array shape is the flat antenna array with a uniform spacing between antennas. For a large element antenna in the 20 GHz band, the antenna spacing can be set to be equal half the wavelength (7.5 mm), which makes it possible to stack 256 elements in an area about 12 cm square [87]. In that same area, when using higher frequency bands with shorter wavelengths, the number of antennas that can be mounted may increase significantly. As frequency becomes higher, the distance of the beam becomes shorter. The elements grow and costs rise as frequency increases. Therefore, finding ways to reduce the costs in massive MIMO systems has become high priority in 5G multi-antenna technology research [87].

1.5 MmWave Precoding Constraints

Precoding at low frequencies is different from MIMO precoding/combining in mmWave systems [8]. One cause is the different hardware constraints; i.e., although mmWave signals with their small wavelength allows a large number of antennas being placed in a small area, the high power consumption and cost of mixed signal components, such as high-resolution analog-to-digital converters make it difficult to earmark a separate radio frequency chain for each antenna [77]. In fact, the conventional design of current cellular systems is no longer feasible. Other differences are that MIMO systems in mmWave make use of a large number of antennas, which affects the complex nature of important signal processing functions, such as equalization, channel estimation, precoding, and combining. Finally, mmWave channels use a large bandwidth, which means that broadband channel equalization is still required. As a result of hardware constraints, the large number of antenna arrays, different channel conditions, and the larger channel bandwidth, the innovative MIMO transceivers are needed for mmWave components [8].

Current transceiver structural design will be affected by the imposition of more hardware restrictions caused by operating in mmWave frequencies with wide bandwidths; therefore, changes must be made in these designs to accommodate budgets and reduce costs of application. These changes will impose new constraints on the mmWave precoding architecture. First, mixed signal devices, such as high-bandwidth, high-resolution ADCs, cost too much and use too much power. Second, as the number of ADCs grows, the baseband digital processing grows in complexity; therefore, performing analog beamforming or combining is desirable [8]. Finally, the phase shifters are the cause of other constraints with regard to implementation; that is, a quantized angle and a fixed amplitude [8]. Consequently, transceiver design which takes these hardware limitations into consideration must be developed.

Because less power is captured by a smaller antenna aperture at high frequencies, larger antenna arrays must be positioned at both the transmitter and receiver to deliver necessary beamforming gains and received power [31]. Moreover, it seems feasible to have up to 256 antennas and 16 antennas at a base station a mobile station, respectively [8]. But the design with large scale MIMO systems requires that both the transmitter and receiver create large precoding and combining matrices. The complexity and costs due to large scale also increases associated with traditional precoding and channel estimation algorithms, as conventional MIMO channel estimation practices depend on calculating approximately the entries of the channel matrices, and that necessitates high training overhead for large MIMO systems [8, 102]. Therefore, the necessity exists to develop precoding with low complexity for mmWave systems.

The primary motivation for changing cellular communication to mmWave bands is to use the large bandwidth obtainable at high frequencies. Users will be then assigned a large communication bandwidth which can send high data rates. This bandwidth, however, affects the mmWave cellular system and precoding transceiver structures. For example, large channel bandwidth before beamforming gives rise to high noise power and low received SNR, which makes functions such as channel estimation random access, and beam training difficult to implement [8]. Additionally, in broadband channels, a high channel delay spread makes equalization at the receiver necessary. On the other hand, hardware problems will make it difficult to preform the required equalization processing completely in the baseband as is done in conventional cellular systems, and new architectures and algorithms are necessary in mmWave channels, to account for the large arrays, channel characteristics, and hardware constraints [8].

Compared to lower frequency channels, the mmWave with its propagation traits in potential bands may be more suitable for cellular usages. To illustrate, mmWave channels in the angular domains are expected to be sparse [12, 32, 76, 103], with only a few scattering clusters, with different laws for path loss for line-of-sight (LOS) and non-line-of-sight (NLOS) signals, i.e., LOS signals are similar to free space, but with weaker NLOS signals [8]. Less delay spread occurs with mmWave compared to lower frequency systems. When designing any mmWave structure, the characteristics of mmWave channels must be taken into account. That is, the system must be so robust that it works in both LOS and NLOS situations. Construction in the channel, for example, sparsity, may be manipulated to reduce complexity as well as training overhead [7, 15, 65]. More work is needed on channel models to better exemplify the available sparsity, to account for blockage effects and to include different mobility settings [8].

1.6 Massive MIMO precoding Techniques

1.6.1 Digital Precoding

Special multiplexing can improve the data input and output of wireless communication devices. Each data flow can be recovered with the aid of precoding and combining weights which are derived from the channel matrix. The weights comprise magnitude and phase terms are employed digitally. To maintain the most control and flexibility with beamforming in an active array, having independent weighting control over each element of the antennas is advantageous. Such control necessitates a transmit and receive model for each element which is the case in fully digital precoding designs. According to [84, 85], the optimal way to perform precoding in a fully digital MIMO system is by applying singular value decomposition (SVD) and using the waterfilling solution for power allocation. The digital precoder works by sending data streams along the dominant eigen-modes of the MIMO channel and the growth of the capacity is proportional to the number of data streams at high SNR [65]. This processing is capable of delivering higher link-level advances to overcome path loss and unwanted interference causes. However, building array sizes that are common for a huge MIMO system is very difficult and expensive and limited by space and power. For example, having a high-performance ADC and DAC for every channel (along with the supporting components) increase the cost and power beyond most design budgets. In addition, the system costs may be increased by having variable gain amplifiers in the RF chain for each channel.

1.6.2 Analog Beamforming

The big difference between lower frequency and higher frequency is related to power consumption of mixed signal devices [47]. Surely, these analog to digital converters consume a lot of power, but those RF chains can consume a lot of power as well. The first mmWave commercial system which is the 11ad/WiGig and the wireless HD use analog beamforming model [73]. In this model, instead of having each antenna connected to a complete baseband, mixed signal chain, RF, and all the processing done in digital, everything is done in the analog domain, so the radio sees what looks like only one RF chain as in Figure (1.1). The same signal is sent to all of these different antennas but is phase shifted. Phase shifters are merely a minor delay element. By controlling all of these phases, different beam patterns can be created and steered to different radios. Therefore, analog beamforming is a single stream MIMO communication since it can send only one data stream [81]. It cannot get the spatial multiplexing gains for MIMO; it is hard to extend this to multi-stream and multi-user. It is generally made to have a reasonable low power solution. A lot of worthy research is related to this technology. Scholarly works explain how the beamforming is designed and know where to point and how to point the receiver.

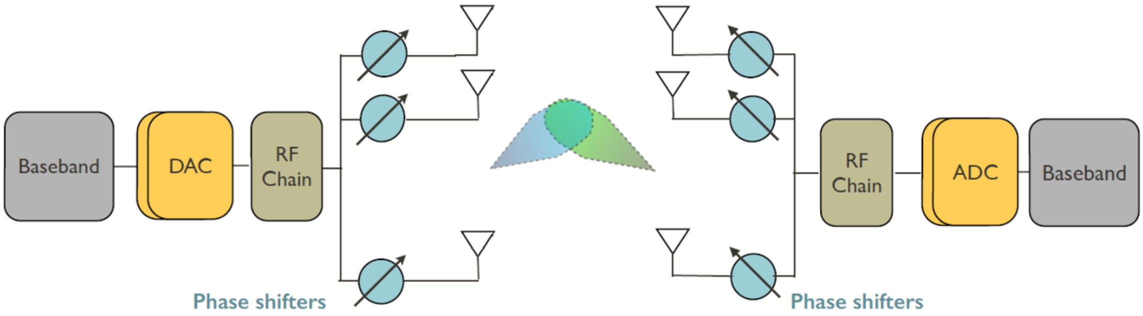


Fig. 1.1 Analog Beamforming [73]

1.6.3 Hybrid Beamforming

Researchers specializing in wireless network have been exploring new technologies and methods that enable to maintain more users reliably communicate at the higher data rates while saving energy. MmWave cellular systems can attain the data rates of a gigabit per second due to the large available bandwidth of mmWave frequencies, as Shannon's theorem claims [7, 22, 64, 65]. Unfortunately, signals in mmWave systems are more likely to face path loss compared to microwave signals that are now employed in cellular systems [65]. To prevent path loss and to increase beamforming gain in mmWave systems, antenna arrays should be large which is possible thanks to the short wavelength in mmWave channel. Beamforming with several streams of data, commonly named precoding, can ensure even higher performance [7, 65, 73, 89]. Traditionally, beamforming, as well as precoding, is performed at baseband in microwave systems. However, due to the costliness of RF and mixed-signal chains, working with analog domains and baseband is more reasonable in mmWave systems. Such hardware limitations present additional requirements to precoder design.

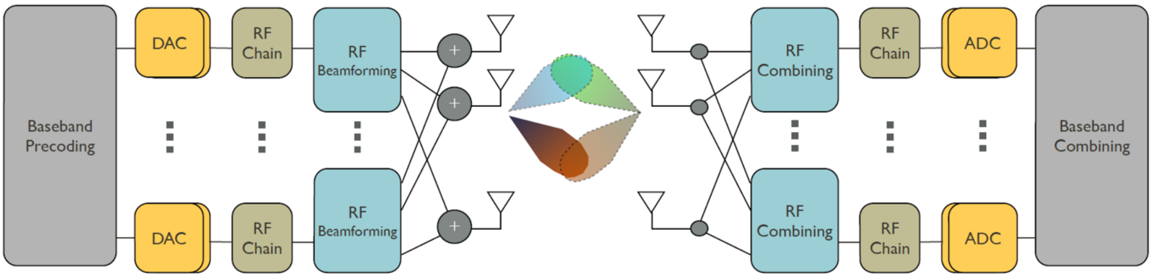


Fig. 1.2 Hybrid Beamforming [73]

Now one of promising ideas is the idea of hybrid beamforming which is a precoding model that consists of two stages, a digital layer at the baseband followed by an analog one as illustrated in Figure (1.2). The analog layer in the hybrid precoding is responsible for assigning different beams to different users, while more complex tasks such as interference management are to be processed in the digital layer [8]. It seems that limiting MIMO systems to two mixed signal devices and two analog to digital converter is extreme. So maybe four or eight can be employed, especially at the base station, it should be able to tolerate little bit of extra power [54]. Therefore, the hybrid beamforming model is where there are multiple output streams, each connected to an RF beamformer that has phase shifters and then each output gets summed in the antennas [73]. Therefore, we can imagine sending two pieces of information, each on its own beam. This is why it is called second order spatial multiplexing. It can be used for supporting multiple data streams to one user or multiple data streams to multiple users and the idea works for both the transmitter and receiver. It is interesting because all this receive processing should have some sort of joint optimization between what is done in analog and what is done in digital and it creates a lot of complexity. For instance, how to measure the channel? When is the channel estimated? Since analog limitations are corrected by the digital layer in the hybrid beamforming, the latter can perform closer to optimal beamforming.

Precoding has the same fundamentals without dependence on the carrier frequency [65]. A number of serious constraints exist for signal processing with the use of mmWave systems. For instance, the common MIMO processing is usually conducted digitally at baseband; it allows to control the amplitude and signal phase. Nevertheless, digital processing needs special RF hardware and baseband for every antenna element. Unfortunately, such a transceiver arrangement is impossible in large scale systems because of the costliness and high energy consumption of mmWave mixed-signal hardware.

1.6.4 Advantages and Drawbacks of Hybrid Beamforming

Hybrid precoding allows to gain at performance and maintain hardware complexity at the same time. It allows using fewer complete RF chains than antennas, which saves cost and power. Hybrid precoding allows more freedom in developing precoding matrices than analog beamforming due to its additional digital layer. Therefore, hybrid precoding can fulfill more complicated processing, in addition to supporting multiuser transmission, as well as multi-stream multiplexing. Furthermore, the additional digital layer makes the operation of mmWave systems with broadband channels more robust, for instance, to fulfill frequency-domain equalization for space time [8]. The number of RF chains limits the performance of hybrid precoding or combining unlike that of fully digital baseband solutions. For example, the required number of RF chains needed for an HB structure to be as efficient as a fully digital beamforming should be at least twice the number of data streams [8]. However, in mmWave systems, it is expected that the channels in the angular domain are sparse. It can be demonstrated that when the rank of the channel is equal to the number of RF chains, hybrid precoding can provide the same level of performance as optimal digital precoding [8, 89].

1.6.5 Existing Techniques of Hybrid Beamforming

Researchers examine precoding insight and propose to develop solutions remembering three problems: precoding with the limitations of RF hardware, using vast antenna arrays, and the restraints of the scattering specificity of mmWave channels [65]. Precoding techniques have been developed using practical architecture of a transceiver where a limited amount of transmit or receive chains drive a vast array of antenna [96]. In this technique, transmitters can use high-dimensional RF precoders and implement them through analog phase shifters [65]. In addition, small digital precoders (low-dimensional) are used at baseband. A realistic clustered channel model can be chosen, which can capture limited scattering at high frequency, as well as the antenna correlation that exists in tightly-packed arrays of antenna [65]. It has been demonstrated that the cooperation between practical architectures of hardware and realistic channel models help form simple precoding solutions with near optimal spectral efficiency. The mmWave channels, particularly their sparse-scattering structure, can be used to define hybrid precoders design as a matrix reconstruction problem constrained by sparsity.

Researchers present the problem of mmWave precoding and demonstrate that, instead of merely maximizing the data rate, hybrid precoders of near-optimal type can be formed through an optimization that is similar to the simultaneously sparse approximation problem in which the recovery of sparse signals can be optimized by multiple measurement vectors. Scholars also present an algorithmic solution related to precoding and based on the idea of orthogonal matching pursuit [7, 17, 65, 89]. In this algorithm, an optimal precoder with no constraints is taken as input and then approximated as a linear combination of beam steering vectors, which can be used at RF and connected digitally at baseband [65].

Furthermore, researchers expand this approach of sparse precoding to the processing of receiver side. They demonstrate that developing the combiners of hybrid minimum mean-square error can be seen as a simultaneous sparse approximation problem and solved through basis pursuit [65]. Scholars claim that the proposed framework not only provides practical near-optimal precoders but also is responsible for the limitations of the feedback operation. Therefore, it can go further than genie-aided systems [65]. It is possible to compress the generated precoders efficiently with the use of simple scalar quantizers, as well as low-dimensional Grassmannian subspace quantizers: the former for the arguments related to the beam steering vectors and the latter for quantizing the baseband precoder [7, 17, 65, 89].

Early work on hybrid precoding solutions imposes high complexity. This thesis provides a new set of solutions for HB that approaches the performance of a fully digital beamformer in terms of MIMO multiplexing gains, by taking careful consideration of the complexity of the system, appropriately reducing it while keeping the same level of quality of service.

1.6.6 Hybrid Precoding With Low Resolution Phase Shifters

The previously mentioned existing hybrid beamforming designs usually presume the use of infinite resolution phase shifter for analog beamformers; therefore, the elements of RF beamformers may possess some random phase angles. On the other hand, the components necessary for realizing precise phase shifters can be costly [43, 82]; therefore, low resolution phase shifters are commonly used in practice because they are more cost effective. It has been shown that the extra number of RF chains are often used to substitute for the accuracy of the phase shifters [43, 82]. The number of phase shifters in hybrid structure is relative to the number of antennas; consequently, infinite resolution phase shifter assumption may not be reasonable for large antenna array systems [90].

The design of beamformers is a well-researched problem. In theory, because the set of feasible RF beamformers is infinite, all realistic choices may be searched comprehensively; however, because the number of practicable RF beamformers is exponential in the resolution of the phase shifters and the number of antennas, that practice is impractical for systems with large numbers of antennas [90]. Another uncomplicated approach for finding the practical solution is first to solve the problem under the assumption of the infinite resolution phase shifter, and then quantize the parts of the phase shifters to the nearest points in the finite set [90]. One should note that accounting for the impact of phase quantization is most crucial when low resolution phase shifters are utilized, because in those cases the number of possible selections for each element of the RF beamformer is small, and the one-dimensional exhaustive search is not demanding computationally [91]. The degradation of performance of a MIMO system with very low-resolution phase shifters is significant when compared to the infinite resolution situation, and it can be decreased by increasing the number of RF chains. Moreover, the number of RF chains is used to make up for the accuracy of phase shifters in the hybrid beamforming design [90].

Moreover, in practical situations, phase shifters is not a simple circuit in the RF band [59, 70], and the resolution of PSs must be finite, which makes it difficult to steer the beams precisely. More PSs resolution means more power consumption [74]. To reduce the cost of hardware, hybrid precoding with low resolution phase shifters was studied in [21, 90], and [85]. A customary way to achieve hybrid precoding while using low resolution PSs is to create a hybrid precoding design without the constraint of phase quantization, then rounding the analog precoder to the nearest phase in the set [19]. The aforementioned studies have demonstrated that hybrid precoding with finite-resolution PSs may approximate the performance of the ideal continuous PSs.

With up to 256 antenna components, the designs of the RF codebook in the current literature require more than 8 bits resolution to accomplish near optimal performance in terms of spatial multiplexing gain [38]. Over the past few years, especially following the works in [6, 8, 65], many papers have been published suggesting various structures for hybrid beamforming [38]. In [65], utilizing compressed sensing, the authors recommend a greedy algorithm titled orthogonal matching pursuit (OMP) for the sparsity nature of the mmWave channel [38]. It has been shown that the attainable problem of maximizing the spectral efficiency can be solved approximately by the minimization of the Frobenius norm of the difference between the optimal fully digital unconstrained SVD based precoding and the hybrid precoder. The high performance of the OMP algorithm is achieved when very large numbers of antennas are used at both ends. The previously mentioned hybrid beamforming algorithm may reach ideal unconstrained operation with only high-bit resolution for executing the analog phase shifters; that is, resolution must be greater than or equal to $log_2(N)$, where N is the number of antennas [38]. Yet, the parts necessary for attaining correct phase shifters with high bit resolution are generally expensive; therefore, more cost effective low bit resolution phase shifters are desirable [38].

The functioning of hybrid beamforming is contingent on the resolution of the phase shifters. The common theme found in the literature is the use of high resolution phase shifters; very few papers have taken into account the finite phase shifter resolution, except [90]. With regard to feasible application of HB, the phase shifter network design plays an important role in the complete precoder operation because it necessitates accurate components that can be costly [43]. Finite resolution phase shifters are good solutions because they are simpler to implement in hardware than those with infinite resolution.

With a low resolution phase shifter at MIMO systems, the phase shifter may reduce the antenna array gain; therefore, the role of antenna arrays is essential at mmWave [79]. Antenna array arrangements can be utilized to obtain high gain characteristics, in order to overcome the high propagation loss. In a multi-path channel, intelligent beamforming algorithms are successful in searching for and identifying propagation links between a set of directional antennas. Among a designated number of smart antenna procedures, mmWave-phased-arrays are one of the most effective and well-known methods that attain adaptive and real-time beamforming that is accurate. Nevertheless, because of challenges associated with complex execution and high costs, finite numbers of phase shifting angles are usually used [16]. As a result, the quantization error of the low resolution phase shifter may have a direct effect on the benefit of mmWave beamforming in some situations. This challenge is made worse, especially for mobile applications that employ a limited number of antennas, due to an essential small form factor and power use restrictions.

1.7 Effect of Antenna Coupling on MIMO Systems

MIMO technology is one that improves the error performance and capacity of wireless communication systems and radars for some time. To get good results from MIMO systems, channels between transmission and reception antennas should ideally be independent and distributed identically (i.i.d.); therefore, antennas must be distant from each other [62]. MIMO studies often overlook the influence of antennas on each other and on MIMO function; however, recently, because of the popularity of smaller and lighter communication devices, characteristics of antenna radiation and mutual coupling have become important factors in arrays, and antennas must be placed near each other. The consideration of mutual coupling is even more crucial in MIMO studies because it not only influences antenna efficiency but also alters the correlation to make the channel between antennas correlated, and correlation in MIMO channels may degrades the capacity and the diversity gain [62].

The independent and identically distributed (i.i.d.) property of the channels between transmission and reception antennas is typically accomplished by placing the antennas sufficiently far apart. In practice, however, due to the sizes of devices, the distance among the antennas is generally small, which makes the channel between antennas correlated. This correlation reduces both the capacity and the diversity gains of the MIMO system [101].

The effects of antenna coupling on multi-antenna systems were researched in [37] and [93], and the study in [92] demonstrated that mutual coupling decreases the correlation between antennas. In addition, mutual coupling results in an extra power penalty when two antennas are placed too near each other [14]. In [101], the blended effects of additional mutual coupling through the outage capacity of the MIMO channels were studied. The study showed that mutual coupling added more degradation to the outage capacity of the MIMO systems.

CHAPTER 2

GENERALIZING HYBRID BEAMFORMING SOLUTIONS FOR MASSIVE MIMO SYSTEMS

Hybrid beamforming using both analog precoding at RF and digital precoding is an effective solution to reduce the complexity and power consumption of massive MIMO systems. Extensive work has determined that HB can achieve the performance of the optimal precoder, assuming optimal antenna implementation, ideal environment, and full rank effective channel. However, depending on the implementation techniques adopted for the RF precoder and other system parameters, such as the number of active RF chains, the limited distance between antennas, and the geometric placement of both ends of wireless systems, the effective channel matrix could be rank deficient, which degrades the performance of the system. This paper provides a new and complete set of solutions for HB that approaches the performance of a fully digital beamformer in terms of MIMO multiplexing gains, by taking careful consideration of the matrix of the effective channel, appropriately selecting independent columns of the analog precoder, calculating the least squares solution for the digital precoder, and selecting its digital gain based on the selected columns of the RF precoder and the effective channel.

The millimeter wave spectrum with massive multiple-input multiple-output antennas could enable wireless communications at rates over tens of Gbps [65, 73, 91]. To compensate for the high path loss in the mmWave frequencies, beamforming (or precoding) [65, 73] is often used in such systems. It has been found that many constraints exist for signal processing in mmWave systems [29]. For instance, MIMO precoding/processing is typically conducted digitally at baseband, giving the system full control of the signal amplitude and phase. Such a transceiver architecture is often impractical for large-scale MIMO systems because of its high energy consumption and high cost.

Consequently, extensive research has studied hybrid beamforming that employs a combination of RF precoding (analog processing) and digital precoding, resulting in a lower number of active RF chains than the number of antennas [78, 88]. Work in this area has explored HB system architectures that achieve as high a multiplexing gain as the fully digital beamformer. In such systems, the number of RF chains must be optimized based on the effective channel, to achieve the minimum rank [83], which is crucial because the rank has a great influence on the system spatial degrees of freedom [11]. However, depending on the number of antennas and other system parameters, such as the limited distance between antennas and the geometric placement of both ends of the wireless system, the effective channel could be rank deficient [30, 105]. Low rank channel is even more common in mmWave systems due to the limited scattering [6] and the high sensitivity to small changes in placement and alignment of antenna arrays and the environment [30].

Existing work on HB for massive MIMO systems assumes that the effective channel matrix has a full rank. The rank of the effective channel can be optimized based on the number of active RF chains. the rank of the RF precoder (i.e., optimizing the number of active RF chains). Thus, the rank of the RF precoder matches the rank of the effective channel and can be used to determine the rank of the effective channel. The rank of the effective channel (i.e. the rank of RF precoder) can be obtained by applying SVD. Singular values of the effective channel that are above certain threshold can determine the rank of the effective channel [105]. It is difficult to implement a mmWave system that can stay at certain and optimal design parameters. Any changes in the environment or placement of the antennas might cause changes in the rank of the effective channel. Additionally, system parameters, such as the number of active RF chains and the number of transmit antennas, as well as the correlation among the large number of antennas might result in an effective channel matrix that has eigenvalues of zero or very small values, so the rank of the effective channel will be deficient. The system performance will be dominated by the weaker eigenvalues of the spatial channels [105]. Again, it is difficult to implement a mmWave system that can stay at certain and optimal design parameters. The large number of antennas and the limited distance between them cause high spatial correlation which might result in an effective channel that has eigenvalues with zero or very small values, so the rank of the effective channel (i.e. rank of RF precoder) will be deficient. Even the range in between the transmitter and receiver can cause changes in the eigenvalues of effective channel. The system performance will be dominated by the weaker eigenvalues or the spatial channels [105].

Existing work on HB for massive MIMO systems assumes that the RF precoding matrix has a full rank, or full column rank since it has a larger number of rows than the number of columns. For example, design via the orthogonal matching pursuit algorithm [65] could result in a HB system that achieves the same performance as the fully digital beamformer when the RF precoder has a full rank. Furthermore, in ideal circumstances, HB with its analog and digital precoders can not only reach the performance of the unconstrained (high number of RF chains) digital precoder, but can also perform well with the number of RF chains that is much smaller than the number of transmit antennas [75]. The HB design contains two stages, a digital precoder for inter-user interference management, followed by an RF precoder for phase control. Implementation of the analog precoder primarily uses phase shifters, which only allow the analog precoding matrix to have constant-modulus entries. This constraint could complicate the signal processing in the systems and restrict the potential means to obtain solutions for the sum-rate maximization problem of MIMO systems

[48]. However, removing the constant-modulus constraint could result in a reduction of the rank of RF precoding matrix [48]. Therefore, the implementation for the RF precoder (which places practical constraints on the precoder) and system parameters such as the number of active RF chains and the number of transmit antennas as well as the correlation among the large number of antennas could all lower the rank of the RF precoding matrix which results in a rank deficient effective channel.

This thesis provides a new set of solutions for HB that approaches the performance of a fully digital beamformer in terms of MIMO multiplexing gains, by taking careful consideration of the effective channel, appropriately selecting independent columns of the analog precoder, calculating the least squares solution for the digital precoder and selecting its digital gain based on the selected columns of the RF precoder and the effective channel. Our objective is to have a high rank effective channel transmitting the desired data streams and maximizing the system capacity.

2.1 Hybrid Precoding Background

2.1.1 System Model

A single user MIMO system is considered, where the transmitter is equipped with N transmit antennas that send N_s data streams to a receiver equipped with M antennas. Note that N_t also represents the number of transmitter RF chains, with $N_s \leq N_t < N$. In the Hybrid beamforming design, $\mathbf{A} \in \mathbb{C}^{N \times N_t}$ is the RF/analog precoder and $\mathbf{V} \in \mathbb{C}^{N_t \times N_s}$ is the digital precoder, both at the transmitter. Similarly, at the receiver, there are the RF/analog combiner $\mathbf{W}_\mathrm{a}$ and the digital combiner $\mathbf{W}_\mathrm{d}$. For simplicity, we focus here on the transmitter side, while the same observations and principles can be applied at the receiver side. Notably, the baseband precoder is able to modify and control the signal amplitude and phase, but the phase shifters based RF precoder enables only phase modifications [53]. Thus, entries of the analog precoder **A** are normalized to satisfy $|\mathbf{A}^{(i,j)}| = \frac{1}{\sqrt{N}}$ where $|\mathbf{A}^{(i,j)}|$ is the (i, j) th element of the amplitude of **A**.

The Rician MIMO channel considered in this chapter is described by

$$\mathbf{H} = \sqrt{\frac{K}{1+K}}\mathbf{H}_{\mathrm{LOS}} + \sqrt{\frac{1}{1+K}}\mathbf{H}_{\mathrm{NLOS}}, \tag{2.1}$$

where **H** is the $M \times N$ channel matrix, and K is the Rician factor which is the power ratio of the LOS component to the NLOS component. The severity of fading is measured by the K factor, with $K = 0$ representing the Rayleigh fading, the most severe case, and $K = \infty$ is the Gaussian channel. In mmWave wireless channels, the LOS component dominates with a K factor typically ranging from 6 to 15 dB in practical environments [58].

In this hybrid precoding design, the estimated signal that is obtained by the receiver can be expressed as

$$\mathbf{y} = \mathbf{W}_{\mathrm{d}}^{H}\mathbf{W}_{\mathrm{a}}^{H}(\mathbf{HAVs} + \mathbf{n}), \tag{2.2}$$

where **n** is an i.i.d. noise vector with distribution $\mathbf{n} \sim \mathscr{CN}(0, \sigma_n^2)$, and the vector $\mathbf{s} \in \mathbb{C}^{N_s \times 1}$ represents the N_s symbols that will be sent to the receiver. Note that $\mathbf{H}_{\mathrm{e}} = \mathbf{HA}$ is the effective channel for the baseband digital precoder, which can be expressed as [61]

$$\mathbf{H}_{\mathrm{e}} = \mathbf{H}\begin{bmatrix} (\mathbf{a}^{11}) & (\mathbf{a}^{12}) & \cdots & (\mathbf{a}^{1N_t}) \\ (\mathbf{a}^{21}) & (\mathbf{a}^{22}) & \cdots & (\mathbf{a}^{2N_t}) \\ \vdots & \vdots & \ddots & \vdots \\ (\mathbf{a}^{N1}) & (\mathbf{a}^{N2}) & \cdots & (\mathbf{a}^{NN_t}) \end{bmatrix}. \tag{2.3}$$

Note that the elements of the $\mathbf{H}_{\mathrm{e}}$ matrix represent a channel gain of every single RF chain in the system [61]. Our objective is to have a high rank effective channel transmitting the desired data streams and maximizing the system capacity. We aim to carefully select the best columns of the RF precoder to maximize the sum of the squares of singular values of the effective channel, then to obtain the baseband digital precoders by applying the singular value decomposition SVD on the effective channel [84].

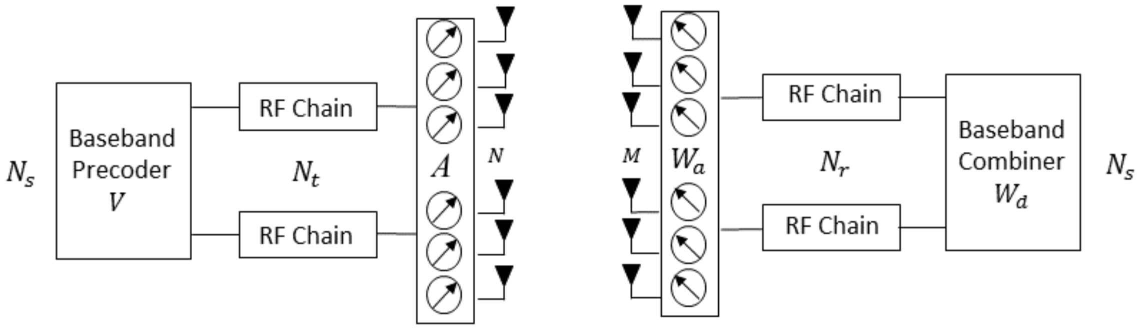


Fig. 2.1 Hybrid beamforming design for a massive MIMO system.

2.1.2 Hybrid Precoding Model

One of the main motivations of designing a massive MIMO is to maximize the data rate. In such a case, one might start by finding a solution for the sum-rate maximization problem of MIMO systems

$$R = \log_2\left(\left|\mathbf{I}_M + \frac{1}{\sigma^2}\left(\mathbf{W}_d^H\mathbf{W}_a^H\mathbf{W}_a\mathbf{W}_d\right)^{-1}\mathbf{W}_d^H\mathbf{W}_a^H\mathbf{H}\mathbf{A}\mathbf{V}\mathbf{V}^H\mathbf{A}^H\mathbf{H}^H\mathbf{W}_a\mathbf{W}_d\right|\right). \quad (2.4)$$

However, such a problem has no general solutions when the analog precoder uses constant-modulus phase shifters [48, 65]. An alternative to directly maximizing the data rate in (2.4) is to achieve high capacity performance by applying Zero forcing precoding on the baseband precoder for inter-user interference management followed by phase shifter based RF precoder for phase control. The capacity of our system can be represented as [105]

$$C = \log_2 \det\left(\mathbf{I}_{N_s} + \frac{\rho}{N_s}\mathbf{H}_{\mathrm{e}}^H\mathbf{H}_{\mathrm{e}}\right) \quad (2.5)$$

where $\mathbf{I}_{N_s}$ and ρ denote the $N_s \times N_s$ identity matrix and the average SNR at the receiver, respectively.

The analog precoder at the RF domain simply works by performing phase only modification by extracting phases of the conjugate transpose of the downlink channel from the base station to all users [50], assuming perfect channel state information which is achievable by the time division duplex (TDD) training method. Finally, the low dimension zero forcing precoding is applied at the baseband to the effective channel to ensure orthogonality among different users.

In comparison to the optimal unconstrained digital precoder $\mathbf{B} \in \mathbb{C}^{N \times N_s}$ which works by sending data streams along the dominant eigen-modes of the MIMO channel $\mathbf{H}$ [65], our Hybrid precoding, with its analog component $\mathbf{A}$ and digital $\mathbf{V}$, can achieve the performance of the optimal precoder $\mathbf{B}$ assuming optimal antenna implementation and full rank effective channel. The kth column of the digital precoder, $\mathbf{V}^{(k)}$, is designed as [91]

$$\mathbf{v}^{(k)} = [\mathbf{0}^H \; v_{2k-1} \; v_{2k} \; \mathbf{0}^H]^H \tag{2.6}$$

with zero elements to ensure successful inter-user interference cancellation at the effective channel and non-zero elements to feed the data streams with digital gain. For $\mathbf{AV} = \mathbf{B}$, we need to find an $N_t \times N_s$ matrix $\mathbf{V}$ such that it has the following two properties:

(a) it satisfies the equation $\mathbf{AV} = \mathbf{B}$, and

(b) it has the given pattern of 0s $\begin{bmatrix} \mathbf{0}^H & v_{2k-1} & v_{2k} & \mathbf{0}^H \end{bmatrix}^H$.

Case 1: Suppose $\mathbf{A}$ has full column rank, i.e., rank $(\mathbf{A}) = N_t$ and $\mathbf{A}(\mathbf{A}^H\mathbf{A})^{-1}\mathbf{A}^H\mathbf{B} = \mathbf{B}$ and $(\mathbf{A}^H\mathbf{A})^{-1}\mathbf{A}^H\mathbf{B}$ has the given pattern of 0s. Then $\mathbf{V} = (\mathbf{A}^H\mathbf{A})^{-1}\mathbf{A}^H\mathbf{B}$ is the digital precoder for our hybrid precoding design and it satisfies properties (a) and (b).

Case 2: Suppose $\mathbf{A}$ has full column rank and $\mathbf{A}(\mathbf{A}^H\mathbf{A})^{-1}\mathbf{A}^H\mathbf{B} = \mathbf{B}$ and $(\mathbf{A}^H\mathbf{A})^{-1}\mathbf{A}^H\mathbf{B}$ does not have the given pattern of 0s. Then there *is no* matrix $\mathbf{V}$ that has properties (a) and (b).

Case 3: Suppose $\mathbf{A}$ has full column rank and $\mathbf{A}(\mathbf{A}^H\mathbf{A})^{-1}\mathbf{A}^H\mathbf{B} \neq \mathbf{B}$. Then there *does not exist* any matrix $\mathbf{V}$ that satisfies property (a).

2.1.3 Number of RF Chains and Phase Shifters in HB

Furthermore, in ideal circumstances, such as in *case 1*, hybrid precoding can not only reach the performance of the unconstrained (high number of RF chains) digital precoder, but it can also perform highly with an efficient number of RF chains that is much fewer than the number of transmit antennas $N_t << N$. For the hybrid precoding $\mathbf{AV}$ matrix to realize the optimal precoder $\mathbf{B}$ with a fewer number of RF chains, the rank of $\mathbf{AV}$ should not exceed the number of RF chains N_t and since rank ($\mathbf{B} = N_s$), then $N_s \leq N_t$ to satisfy $\mathbf{AV} = \mathbf{B}$. This result $N_s \leq N_t$ is significant because the number of RF chains needs to scale according to the number of data streams and not the number of transmitter antennas.

However, N_t needs to be properly optimized, based on the effective channel $\mathbf{H}_\mathrm{e}$ in (2.3) to achieve the minimum rank (i.e. rank $(\mathbf{H}_\mathrm{e}) \geq N_s$ to support transmitting N_s data stream), which is crucial because the rank has a great influence on the system spatial degrees of freedom. The rank of the effective channel is obtained by optimizing the rank of the RF precoder (i.e., optimizing the number of active RF chains). Thus, using the result $N_s \leq N_t$, the rank of the RF precoder rank $(\mathbf{A}) = N_t$ matches the rank of the effective channel $\mathbf{H}_\mathrm{e} = \mathbf{HA}$ because $N_t < N$.

Phase shifters in the RF precoder play an important role in reducing the number of RF chains in Hybrid systems. To analyze this mathematically, the analog precoder $\mathbf{A}^{(i,j)} = \frac{1}{\sqrt{N}} e^{j\phi_{i,j}}$ where $\phi_{i,j}$ denotes the phase of the (i,j)th element of the conjugate transpose of the aggregate downlink channel. The hybrid system $\mathbf{AV}$ using phase shifters at the RF and the digital precoder in (2.6) can be denoted as

$$\mathbf{A}^{(i,j)}\mathbf{V}^{(i,j)} = v_{i,j} e^{j\phi_{i,j}}. \tag{2.7}$$

The optimal fully digital precoder can also be represented as a gain and a phase shift

$$\mathbf{B}^{(i,j)} = |b_{i,j}| e^{j\angle b_{i,j}}. \tag{2.8}$$

Due to the pattern of 0s in the digital precoder, $\mathbf{AV} = \mathbf{B}$ can be formulated by using Eq. (2.7) and (2.8)

$$v_{2k-1} e^{j\phi_{i,2k-1}} + v_{2k} e^{j\phi_{i,2k}} = |b_{i,k}| e^{j\angle b_{i,k}}, \forall i, k. \tag{2.9}$$

As stated earlier, in ideal circumstances such as in *case 1*, and depending on so many assumptions and parameters, such as the number of active RF chains and the number of transmit antennas, as well as the correlation among the large number of antennas, the digital gain v_{2k-1} and v_{2k} might reach the gain of the optimal precoder $\mathbf{B}$. The problem in Eq. (2.9) has many solutions [91], but by setting

$$\phi_{i,j} = \begin{cases} \angle b_{2k-1} - \cos^{-1}(|b_{2k-1}|) & \text{for } \phi_{i,2k-1} \\ \angle b_{2k} + \cos^{-1}(|b_{2k}|) & \text{for } \phi_{i,2k} \end{cases} \tag{2.10}$$

it implies that $\phi_{i,2k-1}$ and $\phi_{i,2k}$ are identical except for a phase shift and since $v_{2k-1} = v_{2k} = |b_{i,k}|$, the number of RF chains can be reduced to N_s instead of $2N_s$ as in previous hybrid precoding papers, because the digital gain of data streams is being used twice in the RF domain by phase shifting them [91]. This means that N_s RF chains and $2N_s$ phase shifters are sufficient to produce high digital gain and to harvest the large antenna arrays as in the optimal case [85].

2.2 Solutions for Optimal Hybrid Precoding

The hybrid precoding method discussed above can achieve high capacity performance assuming optimal antenna implementation and full rank effective channel. An optimal placement of antennas will result in an orthogonal $\mathbf{H}_{\mathrm{LOS}}$ and full rank effective channel [68]. However, the rank of the effective channel is sensitive to the antenna placement of both ends of MIMO system and the number of transmit antennas, as well as the correlation among the large number of antennas. Additionally, system parameters, such as the number of active RF chains, as well as the range in between the transmitter and receiver might result in an $\mathbf{H}_{\mathrm{e}}$ matrix that has eigenvalues with zero or very small values, so the rank of $\mathbf{H}_{\mathrm{e}}$ will be deficient. The system performance will be dominated by the weaker eigenvalues or the spatial channels [105].

The placement and orientation of antennas was studied in [30]. And the sensitivity of LOS MIMO systems to deviations from the optimal antenna separation was analyzed. It has been shown that it is difficult to implement a mmWave system that can stay at certain and optimal design parameters. Any changes in the environment or placement of the antennas may affect the elements of the $\mathbf{H}_{\mathrm{e}}$ matrix (i.e. channel gain from RF chains), which may decrease the large array gain and the rank of $\mathbf{H}_{\mathrm{e}}$. Additionally, system parameters such as the number of active RF chains and the number of transmit antennas as well as the correlation among the large number of antennas could all lower the rank of $\mathbf{H}_{\mathrm{e}}$. In this section, considering the aforementioned practical constraints and environmental challenges, we provide a set of solutions to hybrid precoding massive MIMO systems that can approach the performance of optimal digital precoding and can maximize the capacity of the system as well as the array gain, taking careful consideration of the matrix of the effective channel and the hybrid precoders.

The problem of interest is to obtain $\mathbf{AV}$ that can optimize the system capacity in (2.5) and manage the inter-(user/chain) in the effective channel in (2.3) under the aforementioned circumstances. The main idea of our solution is to simply select columns of $\mathbf{A}$ that are independent (i.e. to avoid the deficient columns) to maximize the sum of the squares of singular values of $\mathbf{H}_\mathrm{e}$, then calculate the least squares solutions for the digital precoder and obtain its digital gains by applying the singular value decomposition SVD on $\mathbf{H}_\mathrm{e}$.

The entries and columns of the hybrid $\mathbf{AV}$ and the unconstrained optimal $\mathbf{B}$ matrices can be written as $\mathbf{A} = \begin{bmatrix} a_{ij} \end{bmatrix}_{N \times N_t} = \begin{bmatrix} \mathbf{a}_1 & \mathbf{a}_2 & \dots & \mathbf{a}_{N_t} \end{bmatrix}$, $\mathbf{B} = \begin{bmatrix} b_{ij} \end{bmatrix}_{N \times N_s} = \begin{bmatrix} \mathbf{b}_1 & \mathbf{b}_2 & \dots & \mathbf{b}_p \end{bmatrix}$, $\mathbf{V} = \begin{bmatrix} v_{ij} \end{bmatrix}_{N_t \times N_s} = \begin{bmatrix} \mathbf{v}_1 & \mathbf{v}_2 & \dots & \mathbf{v}_{N_s} \end{bmatrix}$. The entries of $\mathbf{A}$ and $\mathbf{B}$ are assumed to be known, whereas the nonzero entries $v_1, \dots, v_{N_s}$ of $\mathbf{V}$ are unknown and must be solved for. The first step is to choose two columns of $\mathbf{A}$ at a time and select the desired columns to find a solution for $\mathbf{V}$. To do this, we introduce more notation. For $k = 1, \dots, N_s$, define:

$$\begin{aligned} \mathbf{A}^{(k)} &= \begin{bmatrix} \mathbf{a}_{2k-1} & \mathbf{a}_{2k} \end{bmatrix} \text{ (an } N \times 2\text{matrix)} \\ \mathbf{v}^{(k)} &= \begin{bmatrix} v_{2k-1} \\ v_{2k} \end{bmatrix} \text{ (a } 2 \times 1 \text{ column vector)} \end{aligned}$$

Observe that $\mathbf{AV} = \mathbf{B}$ if and only if $\mathbf{AV}_k = \mathbf{b}_k$ for all $k = 1, \dots, N_s$. Because of the pattern of 0s in $\mathbf{V}$, as in the kth column of the digital precoder,

$$\mathbf{v}^{(k)} = [\mathbf{0}^H \; v_{2k-1} \; v_{2k} \; \mathbf{0}]^H, \tag{2.11}$$

we see that $\mathbf{AV}_k = \mathbf{A}^{(k)}\mathbf{v}^{(k)}$. There is a matrix $\mathbf{V}$ that satisfies the equation $\mathbf{AV} = \mathbf{B}$ and the pattern of 0s in (2.11) if and only if, for all $k = 1, \dots, N_s$, there are vectors $\mathbf{v}^{(k)}$ that satisfy $\mathbf{A}^{(k)}\mathbf{v}^{(k)} = \mathbf{b}_k$.

Therefore Given an $N \times 2$ matrix $\mathbf{A}^{(k)}$ and the $N \times 1$ vector $\mathbf{b}_k$, we want to find a 2×1 vector $\mathbf{v}^{(k)}$ that satisfies the equation $\mathbf{A}^{(k)}\mathbf{v}^{(k)} = \mathbf{b}_k$. The first requirement to find a solution for $\mathbf{v}^{(k)}$ is for $\det\{\mathbf{A}^{(k)^H}\mathbf{A}^{(k)}\} \neq 0$ to ensure invertibility of $\mathbf{A}^{(k)^H}\mathbf{A}^{(k)}$ and $\mathbf{A}^{(k)}[\mathbf{A}^{(k)^H}\mathbf{A}^{(k)}]^{-1}\mathbf{A}^{(k)^H}\mathbf{b}_k = \mathbf{b}_k$ for all $k = 1, \dots, N_s$.

Moreover, in terms of the quantities v_j of the digital precoder $\mathbf{V}$, we need to analyze every possible scenario the columns of the analog precoder $\mathbf{A}$ might have. Define:

$$\begin{aligned}
K_{00} &= \{k : \mathbf{a}_{2k-1} = \mathbf{0}, \mathbf{a}_{2k} = \mathbf{0}\} \\
K_{01} &= \{k : \mathbf{a}_{2k-1} = \mathbf{0}, \mathbf{a}_{2k} \neq \mathbf{0}\} \\
K_{10} &= \{k : \mathbf{a}_{2k-1} \neq \mathbf{0}, \mathbf{a}_{2k} = \mathbf{0}\} \\
K_{110} &= \{k : \mathbf{a}_{2k-1} \neq \mathbf{0}, \mathbf{a}_{2k} \neq \mathbf{0}, \det\{\mathbf{A}^{(k)^H}\mathbf{A}^{(k)}\} = 0\} \\
&= \{k : \mathbf{a}_{2k-1} \neq \mathbf{0}, \mathbf{a}_{2k} = c\mathbf{a}_{2k-1} \text{ for some } c \neq 0\} \\
K_{111} &= \{k : \det\{\mathbf{A}^{(k)^H}\mathbf{A}^{(k)}\} \neq 0\}.
\end{aligned}$$

The sets $K_{00}, K_{01}, K_{10}, K_{110}, K_{111}$, form a partition of $\{1, ..., N_s\}$.

Given these sets, the optimal precoder $\mathbf{b}_k$ in the equation $\mathbf{A}^{(k)}\mathbf{v}^{(k)} = \mathbf{b}_k$ has to be

$$\begin{aligned}
&\mathbf{b}_k = \mathbf{0} \text{ for all } k \in K_{00}, \text{ and} \\
&\det\{\begin{bmatrix} \mathbf{a}_{2k} & \mathbf{b}_k \end{bmatrix}\} = 0, \forall k \in K_{01}, \text{and} \\
&\det\{\begin{bmatrix} \mathbf{a}_{2k-1} & \mathbf{b}_k \end{bmatrix}\} = 0 \forall k \in K_{10}, \text{and} \\
&\det\{\begin{bmatrix} \mathbf{a}_{2k-1} & \mathbf{b}_k \end{bmatrix}\} = 0 \forall k \in K_{110}, \text{and} \\
&\mathbf{A}^{(k)}[\mathbf{A}^{(k)^H}\mathbf{A}^{(k)}]^{-1}\mathbf{A}^{(k)^H}\mathbf{b}_k = \mathbf{b}_k \forall k \in K_{111}.
\end{aligned}$$

Then $\mathbf{A}^{(k)}\mathbf{v}^{(k)} = \mathbf{b}_k$ has at least one solution; therefore, the original problem $\mathbf{AV} = \mathbf{B}$ has at least one solution. In terms of the quantities v_j, the solutions are:

For $k \in K_{00}$, v_{2k-1} and v_{2k} can be chosen arbitrarily because elements in K_{00} are all zeros.

For $k \in K_{01}$, v_{2k-1} can be chosen arbitrarily because $\mathbf{a}_{2k-1} = \mathbf{0}$. $v_{2k} = b_{ik}/a_{i,2k}$ where i can be chosen to be the row index of any nonzero entry in $\mathbf{a}_{2k}$.

For $k \in K_{10}$, v_{2k} can be chosen arbitrarily because $\mathbf{a}_{2k} = \mathbf{0}$. $v_{2k-1} = b_{ik}/a_{i,2k-1}$ where i can be chosen to be the row index of any nonzero entry in $\mathbf{a}_{2k-1}$.

For $k \in K_{110}$, recall that $\mathbf{a}_{2k} = c\mathbf{a}_{2k-1}$ for some $c \neq 0$. Note that $c = a_{i,2k}/a_{i,2k-1}$ where i is the row index of any nonzero entry in $\mathbf{a}_{2k-1}$. The quantity v_{2k} can be chosen arbitrarily and $v_{2k-1} = (b_{ik} - a_{i,2k}v_{2k}/a_{i,2k-1})$

For $k \in K_{111}$, let $\mathbf{v}^{(k)} = [\mathbf{A}^{(k)^H}\mathbf{A}^{(k)}]^{-1}\mathbf{A}^{(k)^H}\mathbf{b}_k$.

Then $\mathbf{v}^{(k)} = [\mathbf{A}^{(k)^H}\mathbf{A}^{(k)}]^{-1}\mathbf{A}^{(k)^H}\mathbf{b}_k$ is a solution to $\mathbf{A}^{(k)}\mathbf{v}^{(k)} = \mathbf{b}_k$ for all $k = 1, ..., N_s$. This specifies the entries of a unique solution $\mathbf{V}$ to the problem $\mathbf{AV} = \mathbf{B}$. The set K_{111} ensures invariability of $\mathbf{A}^{(k)^H}\mathbf{A}^{(k)}$ and offers a solution for the digital precoder. Thus, the set K_{111} is the best fit to be chosen for the RF precoder because independent non-deficient columns are provided in this set.

The next step is to obtain the baseband digital precoder by applying SVD to the effective channel. At the transmitter, given the RF precoder and assuming perfect channel state information, the effective channel $\mathbf{H}_\mathrm{e}$ using SVD can be decomposed as

$$\mathbf{H}_\mathrm{e} = \mathrm{U}_\mathrm{e}\Lambda_\mathrm{e}\mathrm{V}_\mathrm{e}^H \tag{2.12}$$

The left and right singular vectors of $\mathbf{H}_\mathrm{e}$ are represented by the unitary matrices $\mathbf{U}_\mathrm{e}$ and $\mathbf{V}_\mathrm{e}$ respectively, where the diagonal of singular values of $\mathbf{H}_\mathrm{e}$ is represented by Λ_e. The baseband precoder $\mathbf{V} = \begin{bmatrix} v_{ij} \end{bmatrix}_{N_t \times N_s} = \begin{bmatrix} \mathbf{v}_1 & \mathbf{v}_2 & \dots & \mathbf{v}_{N_s} \end{bmatrix}$ can be obtained by selecting the first N_s columns of $\mathbf{V}_\mathrm{e}$ and using the water filling solution for power control [84].

2.3 Simulation

In this section, simulated spectral efficiencies over 100 channel realizations of the proposed hybrid precoding were obtained and compared with that of the unconstrained optimal fully digital precoding and the fully analog precoding. The analog precoding works by creating different beam patterns for the transmitted signal and steering the beam to different radios. Implementation of the analog precoder mainly uses phase shifters, which only allow the analog precoding matrix to have constant-modulus entries which places practical constraints on the system. These constraints can complicate the signal processing in the systems and restrict the potential means to obtain the spatial multiplexing gains for MIMO. Analog beamforming is generally made to have a reasonable low power solution.

We consider 64×16 and 128×32 MIMO systems in a 60GHz mmWave band. The antenna spacing is assumed to be half of the wavelength. The channel matrix is generated as described in section 2.1.1 with 10dB K-factor [105]. Signal-to-noise ratio (SNR) is set to be $\mathrm{SNR} = P/\sigma^2$, where P is the signal transmit power and σ^2 is the noise power.

In Figure 2.2 a single user MIMO system is considered. The transmitter is equipped with $N = 64$ transmitter antennas that sends to a receiver equipped with $M = 16$ antennas $N_s = 4$ data streams. Furthermore, $N_t = 4$ is the number of transmitter RF chains. We observed that the proposed hybrid precoding achieves near optimal performance along the low and high SNR regime. The capacity gap between the optimal precoder and the proposed one does not exceed 1 bits/s/Hz throughout the SNR range. Furthermore, the capacity gap between the proposed precoding method and the analog precoding increases dramatically as the SNR increases.

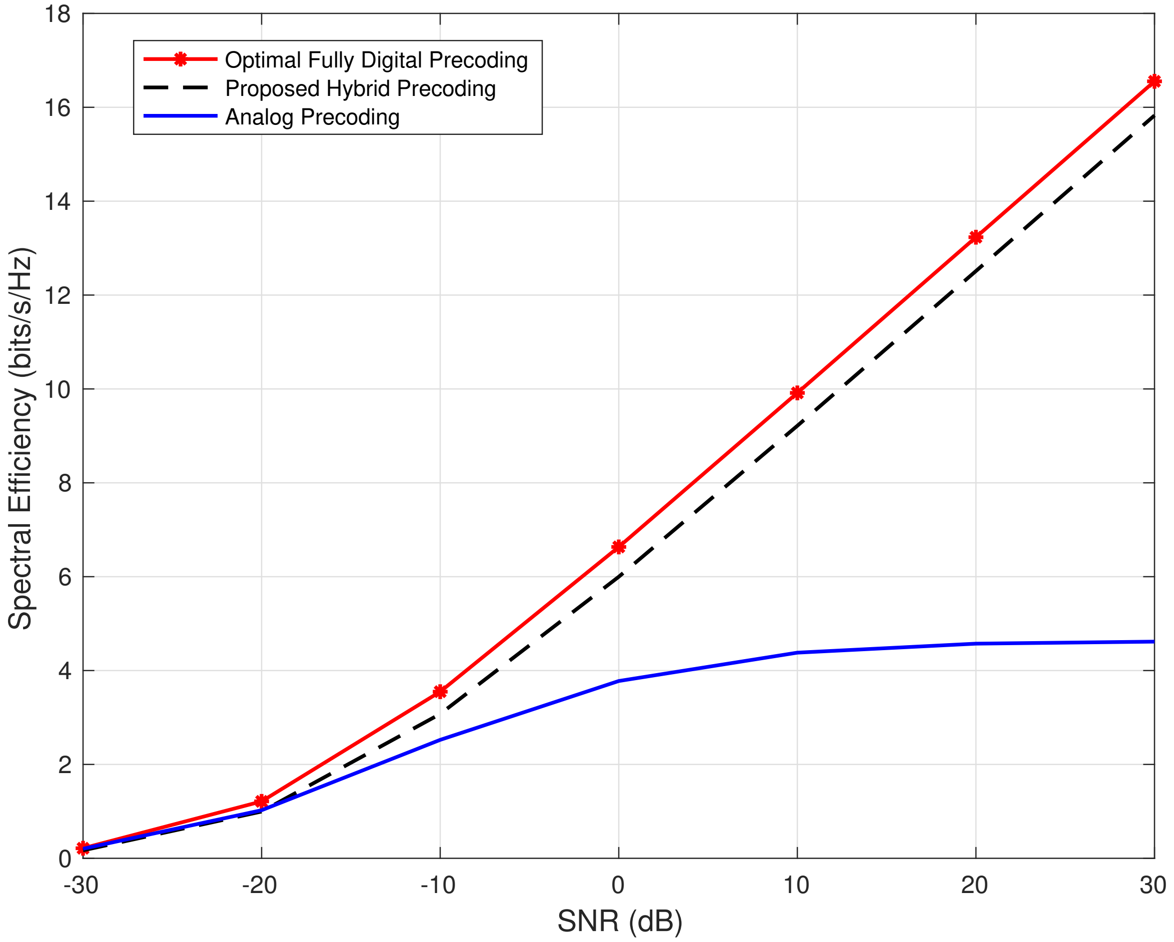


Fig. 2.2 Comparison of spectral efficiencies achieved for a 64 x 16 massive MIMO system.

In Figure 2.3 a single user MIMO system is considered. The transmitter is equipped with $N = 128$ transmitter antennas that send to a receiver equipped with $M = 32$ antennas $N_s = 8$ data streams. Furthermore, $N_t = 8$ is the number of transmitter RF chains. Similar observation as in Figure 2.2 can be found but with slightly higher capacity performance.

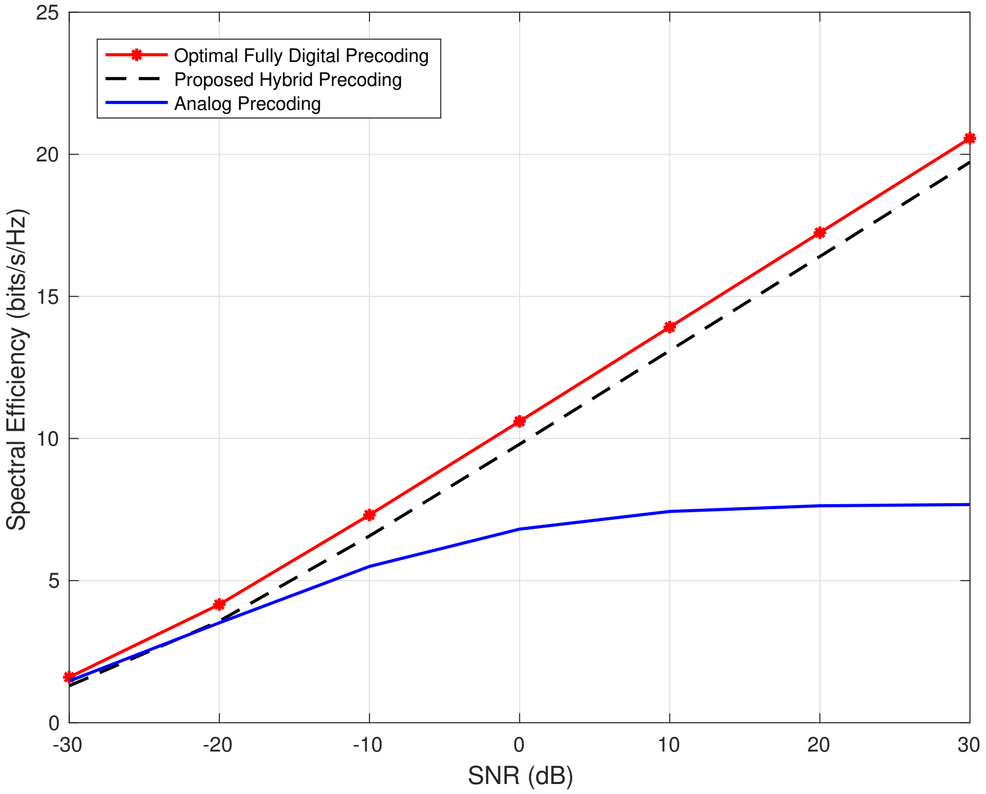


Fig. 2.3 Comparison of spectral efficiencies achieved for a 128 x 32 massive MIMO system.

Comparing these two figures, we can conclude that increasing the number of RF chains and the number of antennas at both ends of the system increases the spatial multiplexing gain, which is expected.

2.4 Conclusion

The purpose of this chapter has been to provide new solutions for HB, by carefully considering the effective channel matrix and selecting appropriate columns of the analog precoder. In addition, the least square solution for the digital precoder and selection of its digital gain were obtained. Simulation results show that the hybrid precoding achieves a near-optimal performance.

CHAPTER 3

SUBARRAY HYBRID PRECODING FOR MASSIVE MIMO CAPACITY MAXIMIZATION

An effective solution for reducing complexity and power consumption of massive MIMO systems is hybrid beamforming using analog precoding at RF and digital precoding at the baseband. Researchers have studied HB, assuming optimal antenna implementation, ideal environment, and full rank effective channel. However, the rank of the effective channel matrix could be deficient due to implementation limitations and other factors, which would degrade the performance of the system. The objective of the study in this chapter is to maintain a high rank effective channel with independent beams sending data streams to the receiver. When the weights of the RF beamformer are properly selected, the structure of the multipath propagation channel will be exploited by the transmitted beams, which maximize the system capacity.

There are many constraints for signal processing in millimeter wave systems. For example, the system has full control of the signal amplitude and phase when MIMO precoding/processing is conducted digitally at baseband [60]. Because of energy consumption and cost are both high with such a design, it is often not practical for large-scale MIMO systems [65, 73, 91]. Beamforming (or precoding) [65, 73] is used to compensate for the high path loss in the mmWave frequencies. To reach high multiplexing gains, it is critical to optimize the number of RF chains based on the effective channel to reach its minimum rank [78, 83, 88]. This is necessary because the rank has a high influence on the system spatial degrees of freedom [11].

Most existing studies on HB for massive MIMO systems assume that the effective channel matrix has a full rank. System parameters such as the correlation among many antennas and the number of active RF chains may result in a matrix with zero or very small eigenvalues, which will cause deficiency in the rank of the effective channel. The weaker eigenvalues of the spatial channels will dominate the system performance [105]. Due to scattering and high sensitivity to placement and alignment of antennas and the environment, low rank channel occur frequently in mmWave systems [6, 30]. Moreover, in the best of circumstances, HB can not only perform as well as the unconstrained digital precoder, but also works well when the number of RF chains is much smaller than the number of antennas.

Two common hybrid beamforming architectures are often considered in existing work. The most popular design is the fully connected model in which each RF chain is connected to all the antennas by a network of phase shifters. This model requires the outputs of the RF chains to be phase shifted and then summed prior to transmission by the antennas. The summation of the different RF signals can complicate the signal processing in the systems and can increase the loss of power by the signal combining components [80]. Although this HB version can reach near optimal performance in terms of spatial multiplexing gain and is able to harvest gain of the large antenna arrays because of its connection to all of the antennas, it is complex, expensive and not energy efficient.

The second design, which is the one chosen for this chapter, is known as the partially or sub connected architecture. This design works by connecting only a subset of the antennas to each RF chain. It is an alternative to the fully connected HB structure to save cost and energy by working without some of the signal combining devices that are necessary in the fully connected structure. The technique of connecting the RF chains to a subset of the antennas reduces the complexity, but it may cause issues to the beam and the signal, such as widening the width of the beam which causes signal interference and poor beam directivity [80]. Despite being less expensive than the fully connected one, the sub-connected architecture is not able to provide equally efficient performance, especially in terms of arrays gain because the RF chains do not have access to all of the antennas. It gains on power consumption and hardware complexity.

3.1 Hybrid Precoding Background

3.1.1 System Model

A single user MIMO system is considered, where the transmitter is equipped with N transmit antennas that send N_s data streams to a receiver equipped with M antennas, as shown in Figure 3.1. In the subarray structure for hybrid precoding that is considered for this paper, there are N_t subarrays at the transmitter, each equipped with N/N_t antennas, as shown in Figure 3.1b. Note that N_t also represents the number of transmitter RF chains, where each of them is connected to one of the subarrays, with $N_s \leq N_t < N$. The HB design contains two stages, a digital precoder for inter-user interference management, followed by an RF precoder for phase control. $\mathbf{A} \in \mathbb{C}^{N\times N_t}$ is the RF/analog precoder and $\mathbf{V} \in \mathbb{C}^{N_t\times N_s}$ is the digital precoder, both at the transmitter.At the receiver, there are the RF/analog combiner $\mathbf{W}_\mathrm{a}$ and the digital combiner $\mathbf{W}_\mathrm{d}$. For simplicity, we focus here on the transmitter side, while similar observations and principles can be applied at the receiver side.

Similarly as in the second chapter, the Rician MIMO channel is considered In this hybrid precoding design, the estimated signal in the receiver can be expressed as

$$\begin{aligned} \mathbf{y} &= \mathbf{W}_\mathrm{d}^H \mathbf{W}_\mathrm{a}^H (\mathbf{HAVs} + \mathbf{n}) \\ &= \mathbf{W}_\mathrm{d}^H \mathbf{W}_\mathrm{a}^H (\mathbf{H_e Vs} + \mathbf{n}), \end{aligned} \tag{3.1}$$

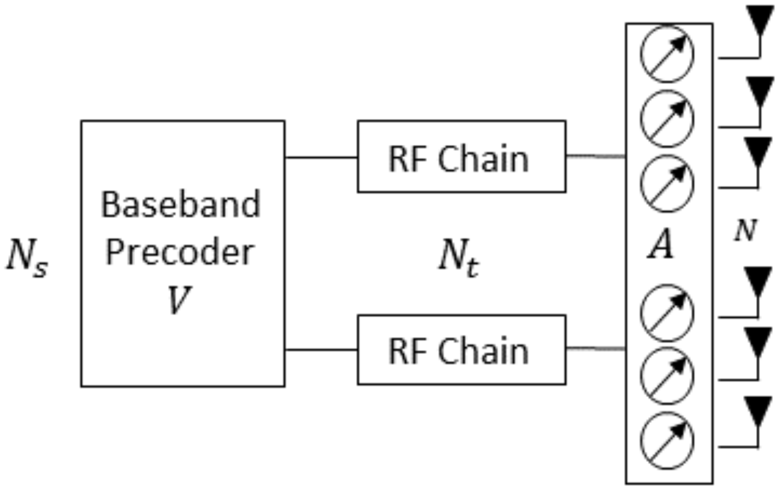
where $\mathbf{n}$ is an i.i.d. noise vector, whose elements have a distribution $\mathscr{CN}(0,\sigma_n^2)$, and the vector $\mathbf{s} \in \mathbb{C}^{N_s \times 1}$ represents the N_s symbols that will be sent to the receiver. Note that $\mathbf{H}_\mathrm{e} = \mathbf{HA}$ is the effective channel for the baseband digital precoder. Due to the HB subarray structure chosen, the matrix of the analog precoding is a diagonal matrix [84]. Thus, the effective channel can be expressed as

$$\mathbf{H}_\mathrm{e} = \mathbf{H}\begin{bmatrix} (\mathbf{a}^1) & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & (\mathbf{a}^2) & \cdots & \mathbf{0} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0} & \mathbf{0} & \cdots & (\mathbf{a}^{N_t}) \end{bmatrix} \tag{3.2}$$

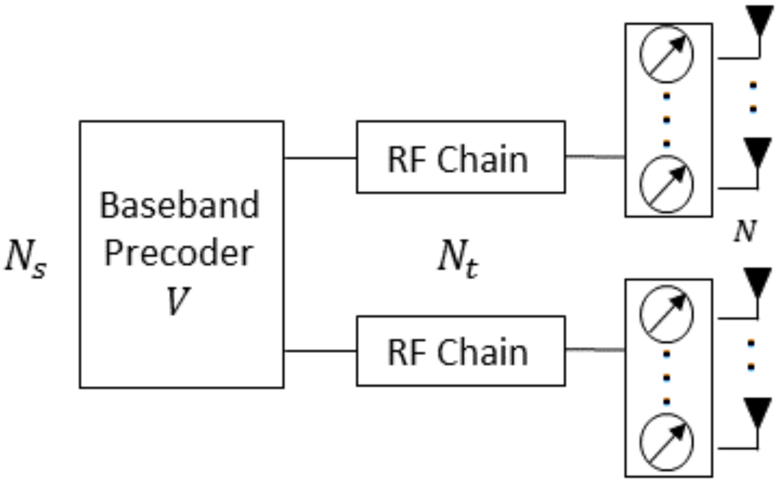
with one nonzero block in each column representing channel gain of every single RF chain in the system [61]. Entries of the analog precoder $\mathbf{A}$ are normalized to satisfy $|\mathbf{A}^{(i,j)}| = \frac{1}{\sqrt{N}}$, where $|\mathbf{A}^{(i,j)}|$ is the amplitude of the (i,j)th element of $\mathbf{A}$. This diagonal matrix is an advantage that can reduce complexity and computation time compared to the fully connected HB structure. The subarray structure can also make a difference in power consumption and hardware complexity by working without those signal combining devices that are necessary in the fully connected structure. However, the limited number of RF transceivers and their connection to only a subset of the antennas may cause a loss of performance in terms of spatial multiplexing gain and the antenna gain. Therefore, proper design of the analog precoder that can maximize the sum of the squares of the singular values of the effective channel is necessary for $\mathbf{H}_\mathrm{e}$ to achieve a high rank, transmit the desired data streams and maximize the system capacity.

3.1.2 Hybrid Precoding Model

One of the primary motivations of designing a massive MIMO is to maximize the data rate. In such a case, one might start by finding a solution for the sum-rate maximization



(a) Fully-connected HB structure



(b) Subarray HB structure

Fig. 3.1 Hybrid precoding structures

problem of MIMO systems (2.4). However, such a problem has no general solutions when the analog precoder uses constant-modulus phase shifters [48, 65]. An alternative to directly maximizing the data rate in (2.4) is to achieve a high capacity by optimally selecting the transmit symbol $\mathbf{s}$. The system capacity can be represented as

$$C = \log_2 \det \left(\mathbf{I}_{N_s} + \frac{\rho}{N_s} \mathbf{H}_\mathrm{e} \mathbf{H}_\mathrm{e}^H \right) \tag{3.3}$$

where $\mathbf{I}_{N_s}$ and ρ denote the $N_s \times N_s$ identity matrix and the average SNR at the receiver, respectively [13]. The capacity here can reach a high value, assuming optimal antenna implementation and a full rank effective channel. An optimal placement of antennas will result in an orthogonal $\mathbf{H}_\mathrm{LOS}$ and full rank effective channel. However, the rank of the effective channel is sensitive to the antenna placement of both ends of the MIMO system and the number of transmit antennas, as well as the correlation among the large number of antennas. Additionally, system parameters such as the number of active RF chains, as well as the range between the transmitter and receiver, may result in $\mathbf{H}_\mathrm{e}$ matrix that has zero or very small eigenvalues, so the rank of $\mathbf{H}_\mathrm{e}$ will be deficient. The system performance will be dominated by the weaker eigenvalues of the spatial channels [105]. The placement and orientation of antennas are studied in [30], where the sensitivity of LOS MIMO systems to deviations from the optimal antenna separation is analyzed. It has been shown that it is difficult to implement a mmWave system that can stay at certain optimal design parameters. Any changes in the environment or placement of the antennas may impact the elements of the $\mathbf{H}_\mathrm{e}$ matrix (i.e. channel gain from RF chains), which decrease the large array gain and the rank of $\mathbf{H}_\mathrm{e}$.

3.2 Solutions for Optimal Hybrid Precoding

3.2.1 The Capacity Maximization Problem

Considering the aforementioned practical constraints and environmental challenges, this section aims to maintain a high rank effective channel with independent beams sending data streams to the receiver. The objective is to select the weights of the RF beamformer in an optimal manner to maximize the capacity in (3.3) by exploiting the structure of the multipath propagation channel [94]. Hence, the system capacity can be maximized subject to $|\mathbf{A}^{(i,j)}| = \frac{1}{\sqrt{N}}, \forall i, j$. The capacity problem can be represented as in (2.5) The analog precoder at the RF domain simply works by performing phase only modification by extracting phases of the conjugate transpose of the downlink channel from the base station to all users [50], assuming perfect channel state information, which is achievable by the time division duplex (TDD) training method [28]. The channel $\mathbf{H}$ using SVD can be written as

$$\mathbf{H} = \mathrm{U}\Lambda\mathrm{V}_{\mathrm{e}}^{H}. \tag{3.4}$$

The left and right singular vectors of $\mathbf{H}$ are represented by the unitary matrices $\mathbf{U}$ and $\mathbf{V_e}$, respectively, where the singular values of $\mathbf{H}$ are represented by Λ. Using a similar procedure as in [94], the system capacity in (3.3) becomes

$$C = \log_2 \det \left(\mathbf{I}_{N_s} + \frac{\rho \mathbf{P}}{N_s} \mathrm{U}\Lambda\mathrm{V}_{\mathrm{e}}^{H} \mathbf{A}\mathbf{A}^{H} \mathrm{V}_{\mathrm{e}} \Lambda^{H} \mathrm{U}^{H} \right) \tag{3.5}$$

where $\mathbf{P}$ is added for power control using the water filling solution [84, 95]. It is a diagonal matrix, which allocates power to data streams. We can simplify (3.5) further by using the identity $\det \mathbf{U}\mathbf{U}^{H} = \det \mathbf{I} = 1$ and the identity $\det\,(\mathbf{I} + \Lambda\Lambda^{H}) = (\mathbf{I} + \Lambda^{H}\Lambda)$, and (3.5) becomes

$$C = \log_2 \det\left(\mathbf{I}_{N_s} + \frac{\rho \mathbf{P}}{N_s} \Lambda^H \Lambda \mathbf{V}_{\mathrm{e}}^H \mathbf{A}\mathbf{A}^H \mathbf{V}_{\mathrm{e}}\right). \tag{3.6}$$

For simplicity, the capacity can be rewritten as

$$C = \log_2 \det\left(\mathbf{I}_{N_s} + \frac{\rho \mathbf{P}}{N_s} \tilde{\Lambda}\tilde{\mathbf{A}}\right) \tag{3.7}$$

where $\tilde{\Lambda} = \Lambda^H \Lambda$ and $\tilde{\mathbf{A}} = \mathbf{V}_{\mathrm{e}}^H \mathbf{A}\mathbf{A}^H \mathbf{V}_{\mathrm{e}}$.

Going back to the matrix of the analog precoder $\mathbf{A}$, we need to analyze every possible scenario the columns of $\mathbf{A}$ might have, then pick two columns of $\mathbf{A}$ at a time and select the desired columns to achieve the maximum value of the system capacity. To do this, for $k = 1, ..., N_s$, we define:

$$\mathbf{A}^{(k)} \;\; = \begin{bmatrix} \mathbf{a}_{2k-1} & \mathbf{a}_{2k} \end{bmatrix} \text{ (an } N \times 2 \text{ matrix).}$$

The columns of $\mathbf{A}$ need to be selected in an optimal way to maximize the system capacity. Thus, the sets of columns with all zero in one or two columns will not be good choices, as in

$$\begin{aligned} K_{00} &= \{k : \mathbf{a}_{2k-1} = \mathbf{0}, \mathbf{a}_{2k} = \mathbf{0}\} \\ K_{01} &= \{k : \mathbf{a}_{2k-1} = \mathbf{0}, \mathbf{a}_{2k} \neq \mathbf{0}\} \\ K_{10} &= \{k : \mathbf{a}_{2k-1} \neq \mathbf{0}, \mathbf{a}_{2k} = \mathbf{0}\}, \end{aligned}$$

as well as columns with non-zero elements, but $\det\{\mathbf{A}^{(k)^H} \mathbf{A}^{(k)}\} = 0$, as in

$$\begin{aligned} K_{110} &= \{k : \mathbf{a}_{2k-1} \neq \mathbf{0}, \mathbf{a}_{2k} \neq \mathbf{0}, \} \\ &= \{k : \mathbf{a}_{2k-1} \neq \mathbf{0}, \mathbf{a}_{2k} = c\mathbf{a}_{2k-1} \text{ for some } c \neq 0\}. \end{aligned}$$

However, in the set K_{111} where $\det\{\mathbf{A}^{(k)^H} \mathbf{A}^{(k)}\} \neq 0$, the columns of $\mathbf{A}$ are independent and non-deficient. Thus for the capacity maximization problem, the columns of $\mathbf{A}$ must have the form of the set K_{111}. By considering these columns and using the Hadamard inequality, which indicates that the determinant of a positive semidefinite matrix is bounded by the product of its diagonal entries as follows [94]

$$\det(\mathbf{X}) \leq \Pi_k X_{kk},$$

the equality is attained if and only if the matrix is diagonal. This bound can be applied to our capacity problem as follows [94]

$$C = \log_2 \det\left(\mathbf{I}_{N_s} + \frac{\rho \mathbf{P}}{N_s} \tilde{\Lambda} \tilde{\mathbf{A}}\right) \leq \log_2 \prod \left(\mathbf{I}_{N_s} + \frac{\rho \mathbf{P}}{N_s} \tilde{\Lambda}_k \tilde{\mathbf{A}}_{kk}\right), \tag{3.8}$$

where $\tilde{\Lambda}_k = \Lambda^H \Lambda$ represents the squares of the singular values of $\mathbf{H}$. The inequality in (3.8) indicates that the capacity can achieve maximum as long as the selected columns of $\mathbf{A}$ result in a diagonal matrix of $\tilde{\mathbf{A}} = \mathbf{V}_{\mathrm{e}}^H \mathbf{A} \mathbf{A}^H \mathbf{V}_{\mathrm{e}}$. More importantly, this bound links weights of the Rf beamformer $\mathbf{A}$ with the channel unitary matrix $\mathbf{V}_{\mathrm{e}}$ because $\mathbf{A} = \mathbf{V}_{\mathrm{e}} \tilde{\mathbf{A}} \mathbf{V}_{\mathrm{e}}^H$. This relationship indicates that columns of $\mathbf{V}_{\mathrm{e}}$ are the eigenvectors of the analog precoder $\mathbf{A}$. In addition, the eigenvalues of the diagonal matrix $\tilde{\mathbf{A}}$ are real and non negative because $\mathbf{A}$ is a positive semidefinite and a Hermitian matrix.

3.2.2 Baseband Digital Precoder

The baseband digital precoder can be obtained by selecting the first N_s columns of $\mathbf{V}_{\mathrm{e}}$ which correspond to the right singular vectors of $\mathbf{H}$ from eq. (3.4) [105]. The baseband precoder $\mathbf{V} = \begin{bmatrix} v_{ij} \end{bmatrix}_{N_t \times N_s} = \begin{bmatrix} \mathbf{v}_1 & \mathbf{v}_2 & \dots & \mathbf{v}_{N_s} \end{bmatrix}$ along with the analog precoder can achieve the performance of the optimal precoder $\mathbf{B} \in \mathbb{C}^{N \times N_s}$ which works by sending data streams along the dominant eigen-modes of the MIMO channel $\mathbf{H}$ [65, 72], assuming an ideal environment such as optimal antenna implementation. However, in critical cases where the implementation and the environment are not perfect, the hybrid precoder $\mathbf{AV} \neq \mathbf{B}$.

To realize a matrix $\mathbf{V}$ that satisfies the equation $\mathbf{AV} = \mathbf{B}$, it is necessary to add more notation and assumptions. The kth column of the digital precoder, $\mathbf{V}^{(k)}$, is designed as [91]

$$\mathbf{v}^{(k)} = [\mathbf{0}^H \; v_{2k-1} \; v_{2k} \; \mathbf{0}^H]^H \tag{3.9}$$

with zero elements to ensure successful inter-user interference cancellation at the effective channel and non-zero elements to feed the data streams with digital gain. The entries of $\mathbf{A}$ and $\mathbf{B}$ are assumed to be known, whereas the nonzero entries $v_1, ..., v_{N_s}$ of $\mathbf{V}$ are unknown and need to be solved for. For $k = 1, ..., N_s$, define:

$$\begin{aligned}
\mathbf{A}^{(k)} &= \begin{bmatrix} \mathbf{a}_{2k-1} & \mathbf{a}_{2k} \end{bmatrix} \text{ (an } N \times 2 \text{ matrix)} \\
\mathbf{v}^{(k)} &= \begin{bmatrix} v_{2k-1} \\ v_{2k} \end{bmatrix} \text{ (a } 2 \times 1 \text{ column vector)}
\end{aligned}$$

The entries and columns of the unconstrained optimal precoder $\mathbf{B}$ can be written as $\mathbf{B} = \begin{bmatrix} b_{ij} \end{bmatrix}_{N \times N_s} = \begin{bmatrix} \mathbf{b}_1 & \mathbf{b}_2 & \dots & \mathbf{b}_p \end{bmatrix}$,

Observe that $\mathbf{AV} = \mathbf{B}$ if and only if $\mathbf{AV}_k = \mathbf{b}_k$ for all $k = 1, ..., N_s$. Because of the pattern of 0s in $\mathbf{V}$ as in the kth column of the digital precoder in (3.9), we see that $\mathbf{AV}_k = \mathbf{A}^{(k)}\mathbf{v}^{(k)}$. There is a matrix $\mathbf{V}$ that satisfies the equation $\mathbf{AV} = \mathbf{B}$ and the pattern of 0s if and only if, for all $k = 1, ..., N_s$, there are vectors $\mathbf{v}^{(k)}$ that satisfy $\mathbf{A}^{(k)}\mathbf{v}^{(k)} = \mathbf{b}_k$. Therefore given an $N \times 2$ matrix $\mathbf{A}^{(k)}$ and the $N \times 1$ vector $\mathbf{b}_k$, we want to find a 2×1 vector $\mathbf{v}^{(k)}$ that satisfies the equation $\mathbf{A}^{(k)}\mathbf{v}^{(k)} = \mathbf{b}_k$. The first requirement to find a solution for $\mathbf{v}^{(k)}$ is for $\det\{\mathbf{A}^{(k)^H}\mathbf{A}^{(k)}\} \neq 0$ to ensure invertibility of $\mathbf{A}^{(k)^H}\mathbf{A}^{(k)}$ and $\mathbf{A}^{(k)}[\mathbf{A}^{(k)^H}\mathbf{A}^{(k)}]^{-1}\mathbf{A}^{(k)^H}\mathbf{b}_k = \mathbf{b}_k$ for all $k = 1, ..., N_s$.

Given the set K_{111},, the optimal precoder $\mathbf{b}_k$ in the equation $\mathbf{A}^{(k)}\mathbf{v}^{(k)} = \mathbf{b}_k$ has to be

$$\mathbf{A}^{(k)}[\mathbf{A}^{(k)^H}\mathbf{A}^{(k)}]^{-1}\mathbf{A}^{(k)^H}\mathbf{b}_k = \mathbf{b}_k \forall k \in K_{111}.$$

Then the solution of the quantities v_j using the set K_{111}, which ensures invariability of $\mathbf{A}^{(k)^H}\mathbf{A}^{(k)}$ and provides independent non-deficient columns; however, the other sets contain zero columns, which affect the rank of the matrix:

$$\text{for } k \in K_{111}, \text{let } \mathbf{v}^{(k)} = [\mathbf{A}^{(k)^H}\mathbf{A}^{(k)}]^{-1}\mathbf{A}^{(k)^H}\mathbf{b}_k.$$

Thus, $\mathbf{v}^{(k)} = [\mathbf{A}^{(k)^H}\mathbf{A}^{(k)}]^{-1}\mathbf{A}^{(k)^H}\mathbf{b}_k$ is a solution to $\mathbf{A}^{(k)}\mathbf{v}^{(k)} = \mathbf{b}_k$ for all $k = 1, ..., N_s$. This specifies the entries of a unique solution $\mathbf{V}$ to the problem $\mathbf{AV} = \mathbf{B}$. Assuming $\mathbf{A}$ has full column rank, i.e., rank $(\mathbf{A}) = N_t$ and $\mathbf{A}(\mathbf{A}^H\mathbf{A})^{-1}\mathbf{A}^H\mathbf{B} = \mathbf{B}$ and $(\mathbf{A}^H\mathbf{A})^{-1}\mathbf{A}^H\mathbf{B}$ has the given pattern of 0s as in (3.9). Then $\mathbf{V} = (\mathbf{A}^H\mathbf{A})^{-1}\mathbf{A}^H\mathbf{B}$ is the digital precoder for our hybrid precoding design.

3.3 Simulation

For the hybrid precoding $\mathbf{AV}$ matrix to realize the optimal precoder $\mathbf{B}$ with fewer numbers of RF chains, the rank of $\mathbf{AV}$ should not exceed the number of RF chains N_t and because rank $(\mathbf{B} = N_s)$, then $N_s \leq N_t$ to satisfy $\mathbf{AV} = \mathbf{B}$. This result $N_s \leq N_t$ is significant because the number of RF chains need to scale according to the number of data stream and not the number of transmitter antennas.

Phase shifters in the RF precoder play an important role in reducing the number of RF chains in a hybrid system. To analyze this mathematically, the analog precoder $\mathbf{A}^{(i,j)} = \frac{1}{\sqrt{N}}e^{j\phi_{i,j}}$ where $\phi_{i,j}$ denotes the phase of the (i, j)th element of the conjugate transpose of the aggregate downlink channel. The hybrid system $\mathbf{AV}$ using phase shifters at the RF and the digital precoder in (3.9) can be denoted as

$$\mathbf{A}^{(i,j)}\mathbf{V}^{(i,j)} = v_{i,j}e^{j\phi_{i,j}}. \tag{3.10}$$

The optimal fully digital precoder which can also be represented as a gain and a phase shift

$$\mathbf{B}^{(i,j)} = |b_{i,j}|e^{j\angle b_{i,j}}. \tag{3.11}$$

Due to the pattern of 0s in the digital precoder, $\mathbf{AV} = \mathbf{B}$ can be formulated by using (3.10) and (3.11)

$$v_{2k-1}e^{j\phi_{i,2k-1}} + v_{2k}e^{j\phi_{i,2k}} = |b_{i,k}|e^{j\angle b_{i,k}}, \forall i,k. \tag{3.12}$$

The problem in Eq. (3.12) has many solutions [91], but by setting

$$\phi_{i,j} = \begin{cases} \angle b_{2k-1} - \cos^{-1}(|b_{2k-1}|) & \text{for } \phi_{i,2k-1} \\ \angle b_{2k} + \cos^{-1}(|b_{2k}|) & \text{for } \phi_{i,2k} \end{cases} \tag{3.13}$$

it implies that $\phi_{i,2k-1}$ and $\phi_{i,2k}$ are identical except for a phase shift, and assuming $v_{2k-1} = v_{2k} = |b_{i,k}|$, the number of RF chains can be reduced to N_s instead of $2N_s$ as in previous hybrid precoding papers, because the digital gain of data streams are being used twice in the RF domain by phase shifting them [91]. This means that N_s RF chains and $2N_s$ phase shifters are sufficient to produce high digital gain.

Simulated spectral efficiencies over 100 channel realizations of the proposed hybrid precoding were obtained and compared with that of the unconstrained optimal fully digital precoding. We consider a 64×16 with $N_s = N_t = 4$ and a 128×32 with $N_s = N_t = 8$ in a 60GHz mmWave band. The antenna spacing is assumed to be half of the wavelength. The channel matrix is generated as described in section II with 10dB K-factor [105]. Signal-to-noise ratio (SNR) is set to be $\text{SNR} = P/\sigma^2$, where P is the signal transmit power and σ^2 is the noise power.

Figure 3.2 shows that spectral efficiency gains vary with different numbers of antennas. The analysis behind this variation follows. The analog precoder works by extracting phases of the conjugate transpose of the downlink channel. Mathematically, the entries at the

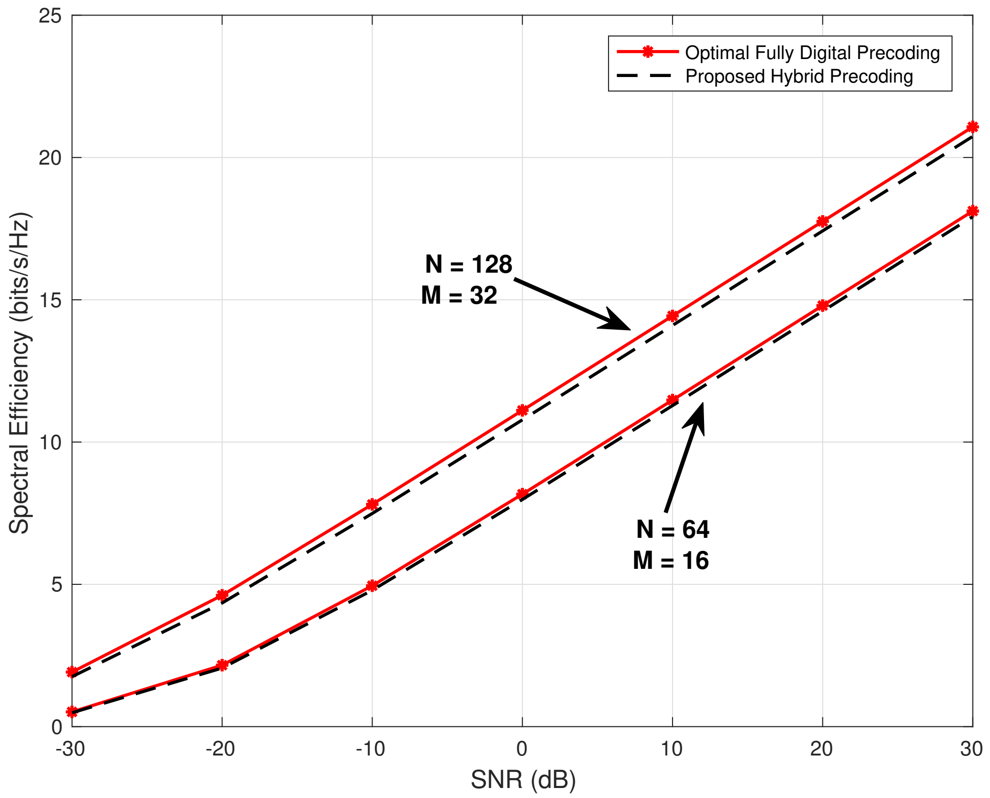


Fig. 3.2 Comparison of spectral efficiencies achieved for 64 x 16 and 128 x 32 massive MIMO systems.

diagonal of the effective channel are $\mathbf{h}_k^H \mathbf{a}_k = \frac{1}{\sqrt{N}} \sum_{i=1}^{N} |h_{i,k}|$ where $h_{i,k}$ is the (i)th element of the (k)th column of $\mathbf{H}$, whereas the off-diagonal entries with a magnitude $|\mathbf{h}_k^H \mathbf{a}_j|$ where $k \neq j$. It has been proven in [53] that with $N \to \infty$, the off-diagonal elements will be negligible compared to the diagonal entries, becuase $\mathbf{h}_k^H \mathbf{a}_k \sim \mathscr{N}(\frac{\sqrt{\pi N}}{2}, 1 - \frac{\pi}{4})$ and $|\mathbf{h}_k^H \mathbf{a}_j|$ has distribution $\mathscr{N}(\frac{\sqrt{\pi}}{2}, 1 - \frac{\pi}{4})$. Thus, the higher the number of antennas, the more dimensions for $\mathbf{H}$, which contributes to orthogonalizing $\mathbf{H}$ to eliminate interference among different channels.

We observe that the proposed hybrid precoding achieves near optimal performance along the low and high SNR regime. The capacity gap between the optimal precoder and the proposed one does not exceed 1 bits/s/Hz throughout the SNR range. Comparing these systems, we can conclude that increasing the number of RF chains and the number of antennas at both ends of the system increases the spatial multiplexing gain, which is expected.

3.4 Conclusion

Considering practical constraints and environmental challenges, this chapter provides a new set of solutions for hybrid beamforming that approaches the performance of a fully digital beamformer in terms of MIMO multiplexing gains. Proper design of the analog precoder results in a high rank effective channel that can maximize the system capacity. Simulation results show that the hybrid precoding achieves a near-optimal performance.

CHAPTER 4

SUBARRAY HYBRID PRECODING WITH FINITE-RESOLUTION PSS FOR MASSIVE MIMO CAPACITY MAXIMIZATION

The addition of analog processing to the digital precoding, known as hybrid beamforming (HB), is an efficient solution for massive MIMO systems, which results in a lower number of active RF chains than antennas. For a feasible application of HB, the design of a phase shifter network plays an important role in the complete precoder operation because it necessitates accurate components for realizing precise phases, and that can be costly [43, 82]. Finite resolution phase shifters (PSs) are good alternatives because they need simpler hardware implementation than those with infinite resolution. However, the degradation of performance of a MIMO system with very low-resolution PSs is significant. Although recent studies suggest adding extra RF chains to substitute for the accuracy of the PSs, it is complex, expensive and not energy efficient. This chapter demonstrates that HB with low resolution PSs can realize a high performance without increasing the number of RF chains. Our proposed solution relies on a proper selection of the weights of the RF beamformer, hence exploiting the structure of the multipath propagation channel to maximize the system capacity. We also show that separating antennas from each other by sufficient distance, results in a less correlated channel, and thus, a minimal loss in the capacity, and the antenna gains are assured.

Because the gain of antenna, and therefore the directivity, improves with the aperture, the only solution to attain a high effective aperture and maintain omni directional coverage is with an antenna array. With mmWave systems, the area of the antenna array is reduced in proportion to the size of the wavelength. To illustrate, at millimeter wave frequencies, an antenna array can be up to 100 times smaller than an array made for microwave frequencies [3]. In that same area, when using higher frequency bands (shorter wavelengths), the number of elements that can be mounted may increase significantly.

5G schemes use large sized antenna arrangements to diminish the serious transmission loss in the mmWave band; however, these designs have their own problems. The wavelength in the mmWave band is quite a bit smaller, compared to today's wireless systems, and it becomes less cost effective to provide one transmit or receive radio frequency chain for each antenna, even though the smaller band permits an array to hold more elements with the same physical measurements. Therefore, finding ways to reduce the costs in massive MIMO has become a high priority in 5G multi-antenna technology research.

The idea of hybrid precoding allows using fewer complete RF chains than antennas. It consists of a digital layer at the baseband followed by an analog phase shifter network at the RF. Over the past few years, especially following the work in [6, 8, 65], many papers have been published suggesting various structures for hybrid beamforming [38]. In [65], and utilizing compressed sensing, the authors recommend a greedy algorithm titled orthogonal matching pursuit (OMP) for the sparsity nature of the mmWave channel [38]. It has been shown that the attainable problem of maximizing the spectral efficiency can be solved approximately by the minimization of the Frobenius norm of the difference between the optimal fully digital unconstrained SVD based precoding and the hybrid precoder [45]. The high performance of the OMP algorithm is achieved when very large numbers of antennas are used at both ends. The previously mentioned hybrid precoding algorithm may reach ideal unconstrained operation with only high-bit resolution for executing the analog PSs. Yet, the parts necessary for attaining correct PSs with high bit resolution are generally expensive; therefore, more cost effective low bit resolution PSs are mandatory [38].

The functioning of HB is contingent on the resolution of the phase shifters. The common theme found in the literature is the use of high resolution phase shifters; very few papers have taken into account the finite phase shifter resolution. Moreover, in practical situations, phase shifters is not a simple circuit in the RF band [70], [59], and the resolution of PSs must be finite, which makes it difficult to steer the beams precisely. More PSs resolution means more power to be used [74]. To reduce the cost of hardware, hybrid precoding with low resolution phase shifters was studied in [21], [90], and [85]. However, the degradation of performance of a MIMO system with very low-resolution PSs is significant when compared to the infinite resolution situation. The aforementioned studies have demonstrated that increasing the number of RF chains to make up for the accuracy of PSs can decrease that degradation[90]. However, it is often not practical for large-scale MIMO systems to add more RF chains along with mixed signal components for the cost and power can exceed most design budgets.

A popular assumption in the study of MIMO systems is that the channels between transmission and reception antennas are independent and identically distributed (i.i.d.), which is accomplished by placing the antennas sufficiently far apart. In practice, however, due to the sizes of devices, the distance among the antennas is generally small, which makes the channel between antennas correlated [101], and having correlated channels in MIMO usages reduces both the capacity and the diversity gain [62]. The effects of antenna coupling on multi-antenna systems were researched in [37] and [93], and the study in [92] demonstrated that mutual coupling decreases the correlation between antennas. In addition, mutual coupling results in an extra power penalty when two antennas are placed too near each other [14]. In [101], the blended effects of mutual coupling through the outage capacity of the MIMO channels were studied. The study showed that mutual coupling added more degradation to the outage capacity of the MIMO systems.

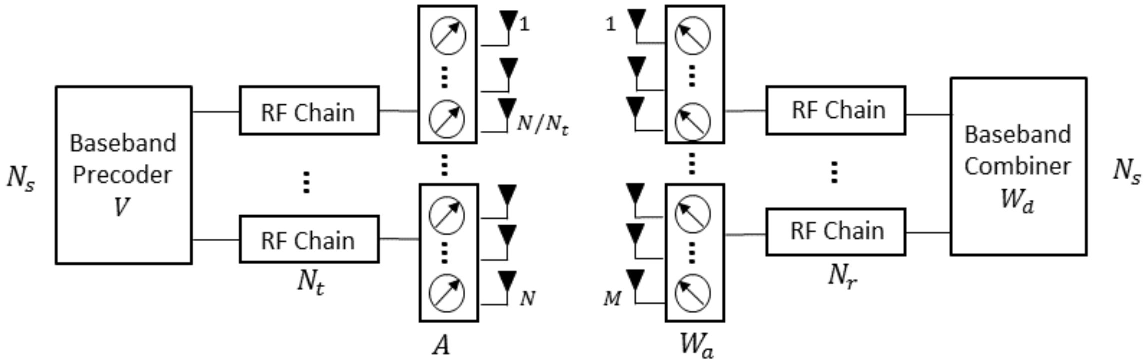


Fig. 4.1 Subarray Hybrid beamforming design for a massive MIMO system.

The objective of this chapter is to maintain a high rank effective channel with independent beams sending data streams to the receiver. When the weights of the RF beamformer are properly selected, the structure of the multipath propagation channel will be exploited by the transmitted beams, which maximize the system capacity. The capacity gap between the optimal precoder and our proposed hybrid precoding with low-resolution PSs can be reduced without increasing the number of RF chains. To get optimum results from MIMO systems while using finite PSs, channels between transmission and reception antennas must be independent and identically distributed (i.i.d.). Furthermore, separating the antennas from each other by sufficient distance results in a less correlated channel, and thus, a minimal loss in the capacity.

4.1 Hybrid Precoding Background

4.1.1 System Model

A high beamforming gain may be achieved by building an array with a larger number of antenna elements [57]. The beam, which is highly directive, assists in offsetting the high path loss at higher frequencies, as beams are guided in a specific direction [99]. The gains from larger antennas must be weighed against the fact that MIMO systems depends highly on scattering environments and broader beam to maximize channel capacity.

To maintain more control with beamforming in an active array, having independent weighting control over each element of the antennas is advantageous [34, 98]. Such control necessitates an RF chain for each element. Building array sizes that are common for a huge MIMO system is very difficult and expensive and limited by space and power. For example, a system with a high-performance ADC and DAC for every channel along with the supporting components can overrun the cost and power beyond most design budgets. In addition, the system costs may be increased by having variable gain amplifiers in the RF chain for each channel.

In this chapter, consider a single-user mmWave MIMO system as shown in Fig. 4.1, where we focus on the transmitter side, while at the receiver side, similar observations and principles can be applied. The system is equipped with N antennas at the transmitter that send N_s data streams to a receiver with M antennas. A subarray hybrid precoding structure is considered, where N_t subarrays are at the transmitter, each containing N/N_t antennas. There are N_t independent RF chains and each of them is connected to one subarray. Moreover, the inter-user interference is managed at the digital precoder $\mathbf{V} \in \mathbb{C}^{N_t \times N_s}$ and the phase control is the RF precoder's $\mathbf{A} \in \mathbb{C}^{N \times N_t}$ responsibility. For the hybrid precoding $\mathbf{AV}$ matrix to realize the fully-digital optimal precoder $\mathbf{B} \in \mathbb{C}^{N \times N_s}$ with fewer numbers of RF chains, the rank of $\mathbf{AV}$ should not exceed the number of RF chains N_t and because rank ($\mathbf{B} = N_s$), then $N_s \leq N_t < N$ to satisfy $\mathbf{AV} = \mathbf{B}$. This result $N_s \leq N_t$ is significant because the number of RF chains is needed to scale according to the number of data stream and not the number of transmitter antennas.

Note that the effective channel for the baseband digital precoder is represented by $\mathbf{H}_\mathrm{e} = \mathbf{HA}$. The analog precoder, due to the subarray structure, is a diagonal matrix [84].

Thus, the effective channel can be written as

$$\mathbf{H}_{\mathrm{e}} = \mathbf{H}\begin{bmatrix} (\mathbf{a}^1) & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & (\mathbf{a}^2) & \cdots & \mathbf{0} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0} & \mathbf{0} & \cdots & (\mathbf{a}^{N_t}) \end{bmatrix}, \tag{4.1}$$

where each column consists of a single nonzero block representing channel gain of every RF chain in the system [61]. The vector $|\mathbf{a}^{(i)}|$ denotes the i-th element of $\mathbf{A}$. This diagonal matrix and the subarray structure have many advantages over the fully-connected HB structure (a common design in the literature) due to its low hardware complexity, power, and computation time, according to [80]. However, the RF transceivers in this design connect to only a subset of the antennas, which may cause a degradation in the antenna gain and spatial multiplexing gain. Therefore, the antennas and the analog precoder must be properly designed in order to minimize the loss in the capacity of the system [25, 26]. Maximizing the sum of the squares of the singular values of the effective channel is necessary for $\mathbf{H}_{\mathrm{e}}$ to achieve a high rank, transmit the desired data streams, and maximize the system capacity.

4.1.2 Hybrid Precoding Model

Maximizing the data rate in 2.4 is a primary motivation when thinking of designing massive MIMO systems. The system capacity can be written as in the previous chapters. An optimal antenna implementation will result in an orthogonal $\mathbf{H}_{\mathrm{LOS}}$; thus, high system capacity can be achieved. Moreover, other factors, such as the range between the transmitter and receiver, as well as the number of active RF chains, may result in a low rank $\mathbf{H}_{\mathrm{e}}$ due to the zero or very small eigenvalues. The weaker eigenvalues of the spatial channels will dominate the performance of the system [105].

The common assumption found in the study of MIMO systems is that channels are independent and identically distributed (i.i.d.) between transmission and reception antennas [41]. However, the distance among the antennas is generally designed to be small, which causes the channel between them to be correlated. This correlation may have a negative impact on both the capacity and the diversity gains of the MIMO system. Therefore, the antennas must be placed sufficiently far apart in order to achieve a high capacity.

4.1.3 Hybrid Precoding With Low Resolution Phase Shifters

Existing hybrid beamforming designs usually presume the use of an infinite resolution phase shifter for employing analog beamformers; therefore, the elements of RF beamformers may possess any random phase angles. On the other hand, the components necessary for realizing precise phase shifters can be costly [43, 82]; therefore, low resolution PSs are commonly used in practice because they are more cost effective.

With regard to feasible application of HB, the phase shifter network design plays an important role in the complete precoder operation because it necessitates accurate components for realizing precise PSs [24, 43]. The number of PSs in hybrid structure is relative to the number of antennas; consequently, infinite resolution phase shifter assumption may not be reasonable for systems with large antenna array terminals. The previously mentioned hybrid precoding algorithm may reach high performance with only high-bit resolution for executing the analog PSs; that is, bit resolution must be greater than or equal to $\log_2(N)$ [38]. Yet, the parts necessary for attaining correct PSs with high bit resolution are generally expensive; therefore, more cost effective low bit resolution PSs are mandatory.

Low resolution PSs are good solutions because they need simpler hardware implementation compared to high resolution PSs. The analog precoder considering the finite resolution option consists of discrete phases; i.e., $\mathbf{A} \in \mathscr{A}$ where $\mathscr{A} = \left\{1, a, a^2, ..., a^{p-1}\right\}$, $a = e^{j\frac{2\pi}{p}}$, and p denotes the number of adjustable discrete phases [90]. A customary way to achieve hybrid precoding while using low resolution PSs is to create a hybrid precoding design without the constraint of phase quantization, then rounding the analog precoder to the nearest phase in the set [19]. In theory, because the set of feasible RF beamformers is infinite, all realistic choices may be searched comprehensively; however, because the number of practicable RF beamformers grows exponentially with the resolution of the phase shifters and the number of antennas, that practice is impractical for systems with large numbers of antennas [90]. Another uncomplicated approach for finding the practical solution is first to solve the problem under the assumption of the infinite resolution phase shifter, and then quantize the parts of the phase shifters to the nearest points [90]. One should note that accounting for the impact of phase quantization is most crucial when low resolution PSs are utilized because the number of possible selections for each element of RF beamformer is small, and the exhaustive search is not demanding computationally [89, 90].

Phase shifters may negatively impact the antenna array gain. Moreover, the role of antenna arrays is essential at mmWave [79]. Antenna array arrangements can be utilized to obtain high gain characteristics in order to overcome the high propagation loss. In a multi-path channel setting, intelligent beamforming algorithms are successful in searching for and identifying propagation links between a set of high-directional antennas. Among a designated number of smart antenna procedures, mmWave-phased-arrays are one of the most effective and well-known methods that attain adaptive and real-time beamforming that is accurate. Nevertheless, because of challenges associated with complex execution and high costs, finite numbers of phase shifting angles are usually used [16]. As a result, the quantization error may have a direct effect on the benefit of mmWave beamforming in some situations. This challenge is made worse, principally for mobile applications that employ a limited number of antennas, due to an essential small form factor and power use restrictions.

Moreover, the insertion of a RF precoder with its phase shifters network in a hybrid system contributes significantly in reducing the number of RF chains. Mathematically, the analog precoder $\mathbf{a}^{(i,j)} = \frac{1}{\sqrt{N}} e^{j\phi_{i,j}}$ where $\phi_{i,j}$ denotes the phase of the (i, j)th element of the conjugate transpose of the aggregate downlink channel. The hybrid system using PSs at the RF **A** and the digital precoder **V** where the *k*th column of the digital precoder, $\mathbf{V}^{(k)}$ is designed as to be

$$\mathbf{v}^{(k)} = [\mathbf{0}^H \; v_{2k-1} \; v_{2k} \; \mathbf{0}^H]^H, \tag{4.2}$$

now **AV** can be denoted as

$$\mathbf{a}^{(i,j)} \mathbf{v}^{(i,j)} = v_{i,j} e^{j\phi_{i,j}}. \tag{4.3}$$

The fully-digital optimal precoder with a gain and a phase shift can be represented as

$$\mathbf{B}^{(i,j)} = |b_{i,j}| e^{j\angle b_{i,j}}. \tag{4.4}$$

Thus, using (4.3) and (4.4) and due to the pattern of 0s in (4.2), $\mathbf{AV} = \mathbf{B}$ can be formulated as

$$v_{2k-1} e^{j\phi_{i,2k-1}} + v_{2k} e^{j\phi_{i,2k}} = |b_{i,k}| e^{j\angle b_{i,k}}, \forall i, k. \tag{4.5}$$

The problem in Eq. (4.5) does not have one solution [89], but by setting

$$\phi_{i,j} = \begin{cases} \angle b_{2k-1} - \cos^{-1}(|b_{2k-1}|) & \text{for } \phi_{i,2k-1} \\ \angle b_{2k} + \cos^{-1}(|b_{2k}|) & \text{for } \phi_{i,2k} \end{cases} \tag{4.6}$$

it implies that $\phi_{i,2k}$ and $\phi_{i,2k-1}$ differ only by a phase shift which also means that the digital gain of data streams is being used twice by phase shifting them in the RF domain [**?**]. In such a case, the system can perform with RF chains equal to N_s instead of $2N_s$ under the assumption $v_{2k-1} = v_{2k} = |b_{i,k}|$. This result concludes that in such a system, it is sufficient to produce high digital gain by using only N_s RF chains and $2N_s$ phase shifters.

4.2 Solutions for Optimal Hybrid Precoding

4.2.1 The Capacity Maximization Problem

The objective of this section is to maximize the system capacity in (2.5) by optimally selecting weights of the RF precoder; thus, independent beams can be generated to send data streams to the receiver. Hence, the capacity maximization problem can be represented subject to $|\mathbf{A}^{(i,j)}| = \frac{1}{\sqrt{N}}, \forall i, j$ as

$$C = \max_{\mathbf{A}} \log_2 \det \left(\mathbf{I}_{N_s} + \frac{\rho}{N_s} \mathbf{H}_{\mathrm{e}} \mathbf{H}_{\mathrm{e}}^H\right), \tag{4.7}$$

where the analog precoder $\mathbf{A}$ must be a positive semidefinite Hermitian matrix, and it adjusts the phase of the signal by extracting phases of the conjugate transpose of the downlink channel from the base station to all users, assuming perfect channel state information [50]. The channel $\mathbf{H}$ using SVD can be written as

$$\mathbf{H} = \mathrm{U} \Lambda \mathrm{W}^H. \tag{4.8}$$

The unitary matrices $\mathbf{U}$ and $\mathbf{W}$ represent the left and right singular vectors of $\mathbf{H}$, respectively, and Λ represents the singular values of $\mathbf{H}$. Therefore, the capacity now after inserting (4.8) into it is

$$C = \log_2 \det \left(\mathbf{I}_{N_s} + \frac{\rho \mathbf{P}}{N_s} \mathrm{U} \Lambda \mathrm{W}^H \mathrm{A} \mathrm{A}^H \mathrm{W} \Lambda^H \mathbf{U}^H \right) \tag{4.9}$$

where $\mathbf{P}$ is a diagonal matrix that allocates power to data streams using the water filling solution [84, 94]. The identity det $\mathbf{U}\mathbf{U}^H$ = det $\mathbf{I} = 1$ and the identity det $(\mathrm{I} + \Lambda\Lambda^H) = (\mathbf{I} + \Lambda^H \Lambda)$ can be used to further simplify (4.9) to

$$C = \log_2 \det \left(\mathbf{I}_{N_s} + \frac{\rho \mathbf{P}}{N_s} \Lambda^H \Lambda \mathrm{W}^H \mathrm{A} \mathrm{A}^H \mathbf{W} \right). \tag{4.10}$$

For simplicity, the capacity can be rewritten as

$$C = \log_2 \det\left(\mathbf{I}_{N_s} + \frac{\rho \mathbf{P}}{N_s} \tilde{\Lambda}\tilde{\mathrm{A}}\right) \tag{4.11}$$

where $\tilde{\Lambda} = \Lambda^H \Lambda$ and $\tilde{\mathrm{A}} = \mathrm{W}^H \mathrm{A}\mathrm{A}^H \mathrm{W}$.

4.2.2 Digital Precoding

The unconstrained digital precoder is represented as a gain and a phase shift $\mathbf{B} \in \mathbb{C}^{N \times N_s} = \mathbf{B}^{(i,j)} = |b_{i,j}|e^{j\angle b_{i,j}}$. The system is equipped with N antennas at the transmitter that send N_s data streams to a receiver with M antennas. According to [67, 84, 85], the optimal way to perform precoding in a fully digital MIMO system is by applying singular value decomposition (SVD) and using the waterfilling solution for power allocation. The channel $\mathbf{H}$ using SVD can be written as $\mathbf{H} = \mathrm{U}\Lambda\mathrm{W}^H$ where the unitary matrices $\mathbf{U} \in \mathbb{C}^{M \times M}$ and $\mathbf{W} \in \mathbb{C}^{N \times N}$ represent the left and right singular vectors of $\mathbf{H}$, respectively, and the diagonal of $\Lambda \in \mathbb{C}^{M \times N}$ represents the singular values of $\mathbf{H}$.

Depending on the number of transmitted data streams, if $N_s \leq \min(N, M)$, then the capacity can be maximized by selecting the first N_s columns corresponding to the right singular of $\mathbf{W}$ [67, 85, 105]. In this case, the digital precoder works by sending data streams along the dominant eigen-modes of the MIMO channel and the growth of the capacity is proportional to N_s at high SNR [65]. The maximum capacity in this fully digital system can be represented as [67, 100]

$$C = \max_{\sum_{n=1}^{N_s} P_{nn} \leq 1} \sum_{n=1}^{N_s} \log_2\left(1 + P P_{nn} \sigma_{nn}^2 / \sigma^2\right), \tag{4.12}$$

where P is the total transmit power, P_{nn} is responsible for power allocation by waterfilling, σ_{nn}^2 and σ^2 represent the ordered eigenvalues of the correlation matrix $\mathbf{HH}^H$ and the variance of an i.i.d. noise vector, respectively. On the other hand, the capacity of a full rank

MIMO channel grows linearly when the transmitter sends $N_s = \min(N, M)$ at high SNR [10]. However, with a rank deficient channel, the transmitter is limited to send a number of data streams equals the rank of the channel.

Hybrid precoding consists of an analog precoder along with a baseband precoder $\mathbf{V} = \begin{bmatrix} v_{ij} \end{bmatrix}_{N_t \times N_s} = \begin{bmatrix} \mathbf{v}_1 & \mathbf{v}_2 & \dots & \mathbf{v}_{N_s} \end{bmatrix}$ can perform similar to the fully digital precoder $\mathbf{B}$. However, the hybrid precoder may not reach the spatial multiplexing gain of the fully-digital precoder, i.e. $\mathbf{AV} \neq \mathbf{B}$ due to implementation constraints and environmental challenges. For the hybrid precoder to reach the spatial multiplexing gain of the fully-digital precoder, i.e. $\mathbf{AV} = \mathbf{B}$, where the entries of $\mathbf{A}$ and $\mathbf{B}$ are assumed to be known and entries of $\mathbf{V}$ are unknown. The kth column of the digital precoder, $\mathbf{V}^{(k)}$, can be designed as

$$\mathbf{v}^{(k)} = [\mathbf{0}^H \ v_{2k-1} \ v_{2k} \ \mathbf{0}^H]^H \tag{4.13}$$

where non-zero elements correspond to digital gains of data streams, while inter-user interference is managed by the zero elements. To solve for the nonzero entries $v_1, \dots, v_{N_s}$ of $\mathbf{V}$ and to realize a matrix $\mathbf{V}$ that satisfies the equation $\mathbf{AV} = \mathbf{B}$, we need to add more notations and assumptions. For $k = 1, \dots, N_s$, define:

$$\begin{aligned} \mathbf{A}^{(k)} &= \begin{bmatrix} \mathbf{a}_{2k-1} & \mathbf{a}_{2k} \end{bmatrix} \text{ (an } N \times 2 \text{ matrix)} \\ \mathbf{v}^{(k)} &= \begin{bmatrix} v_{2k-1} \\ v_{2k} \end{bmatrix} \text{ (a } 2 \times 1 \text{ column vector)} \end{aligned}$$

Note that $\mathbf{AV} = \mathbf{B}$ if and only if $\mathbf{AV}_k = \mathbf{b}_k$ for all $k = 1, \dots, N_s$. Due to the pattern of 0s in the kth column of the digital precoder $\mathbf{V}$, hence $\mathbf{AV}_k = \mathbf{A}^{(k)}\mathbf{v}^{(k)}$. Moreover, the matrix $\mathbf{V}$ to realize the equation $\mathbf{AV} = \mathbf{B}$ if and only if, for all $k = 1, \dots, N_s$, there are $\mathbf{v}^{(k)}$ vectors that satisfy $\mathbf{A}^{(k)}\mathbf{v}^{(k)} = \mathbf{b}_k$. Now, we want to find a 2×1 vector $\mathbf{v}^{(k)}$ that satisfies the equation $\mathbf{A}^{(k)}\mathbf{v}^{(k)} = \mathbf{b}_k$, given an $N \times 2$ matrix $\mathbf{A}^{(k)}$ and the $N \times 1$ vector $\mathbf{b}_k$. To find a solution for $\mathbf{v}^{(k)}$, the first requirement is for $\det\{\mathbf{A}^{(k)^H}\mathbf{A}^{(k)}\} \neq 0$, to ensure invertibility of $\mathbf{A}^{(k)^H}\mathbf{A}^{(k)}$ and $\mathbf{A}^{(k)}[\mathbf{A}^{(k)^H}\mathbf{A}^{(k)}]^{-1}\mathbf{A}^{(k)^H}\mathbf{b}_k = \mathbf{b}_k$ for all $k = 1, ..., N_s$.

The optimal precoder $\mathbf{b}_k$ and the equation $\mathbf{A}^{(k)}\mathbf{v}^{(k)} = \mathbf{b}_k$ given the set K_{111} can be rewritten as

$$\mathbf{A}^{(k)}[\mathbf{A}^{(k)^H}\mathbf{A}^{(k)}]^{-1}\mathbf{A}^{(k)^H}\mathbf{b}_k = \mathbf{b}_k \forall k \in K_{111}.$$

This enables us to find a solution to the quantities v_j, while using the set K_{111} to ensure invariability of $\mathbf{A}^{(k)^H}\mathbf{A}^{(k)}$,

$$\text{for } k \in K_{111}, \text{let } \mathbf{v}^{(k)} = [\mathbf{A}^{(k)^H}\mathbf{A}^{(k)}]^{-1}\mathbf{A}^{(k)^H}\mathbf{b}_k.$$

Hence, $\mathbf{v}^{(k)} = [\mathbf{A}^{(k)^H}\mathbf{A}^{(k)}]^{-1}\mathbf{A}^{(k)^H}\mathbf{b}_k$ is a solution to $\mathbf{A}^{(k)}\mathbf{v}^{(k)} = \mathbf{b}_k$ for all $k = 1, ..., N_s$, where it also represents the entries of a unique solution $\mathbf{V}$ to the problem $\mathbf{AV} = \mathbf{B}$. Finally, assuming rank $(\mathbf{A}) = N_t$, and $(\mathbf{A}^H\mathbf{A})^{-1}\mathbf{A}^H\mathbf{B}$ in $\mathbf{A}(\mathbf{A}^H\mathbf{A})^{-1}\mathbf{A}^H\mathbf{B} = \mathbf{B}$ has the same 0s pattern as in (4.13), the digital precoder for our hybrid precoding is $\mathbf{V} = (\mathbf{A}^H\mathbf{A})^{-1}\mathbf{A}^H\mathbf{B}$.

4.3 Simulation

Recent studies claim that hybrid beamforming can realize a high performance similar to that of the fully digital beamforming. These findings may be a little deceptive because they assume that precisions of analog phase shifters are infinite, when, in reality, they have limited precision and are often grouped by the number of bits used in the phase shifts. To illustrate, within 360 degrees, a phase shifter with 3-bit resolution can represent only 8 distinct angles; hence, including such quantization in the simulation will degrade the performance of the system [5].

To get good results from MIMO systems while using finite PSs, channels between transmission and reception antennas must be independent and identically distributed (i.i.d.); therefore, antennas must be distant from each other. MIMO studies often overlook the influence of antennas on each other and on MIMO function. However, recently, because of the popularity of smaller and lighter communication devices, characteristics of antenna radiation and mutual coupling have become important factors in arrays.

In MIMO systems, the most customary array shape is the flat antenna array with a uniform spacing of half a wavelength between antennas, i.e. $d = \lambda/2$. For example, for a large element antenna in the 60 GHz band, setting the element spacing to half the wavelength (2.5 mm) makes it possible to mount 256 elements in an area less than 10 cm square [87]. With up to 256 antenna components, the designs of the RF codebook in the current literature require more than 8 bits resolution to accomplish near optimal performance in terms of spatial multiplexing gain [38]. Moreover, when applying low-resolution phase shifters in a MIMO system; recent studies suggest adding extra RF chains to substitute for the accuracy of the PSs and to decrease the significant degradation of performance compared to the infinite resolution situation [90].

In this section, simulated spectral efficiencies over 100 channel realizations of the proposed hybrid precoding were obtained and compared with that of the unconstrained optimal fully digital precoding and the performance of the quantized version of the OMP algorithm. The quantized version of OMP creates a hybrid precoding design by solving the problem under the infinite resolution phase shifter assumption first, then quantizes the parts of the RF beamformers to the nearest points among the finite phase set[90]. The channel matrix is generated as described in chapter II with 10dB K-factor [105]. Signal-to-noise ratio (SNR) is set to be SNR $= P/\sigma^2$, where P is the signal transmit power and σ^2 is the noise power.

In Fig. 4.2, we consider a 64×16 with $N_s = N_t = 4$ in a 60 GHz mmWave band. It shows that the proposed method gains in performance when the antennas distanced farther apart in

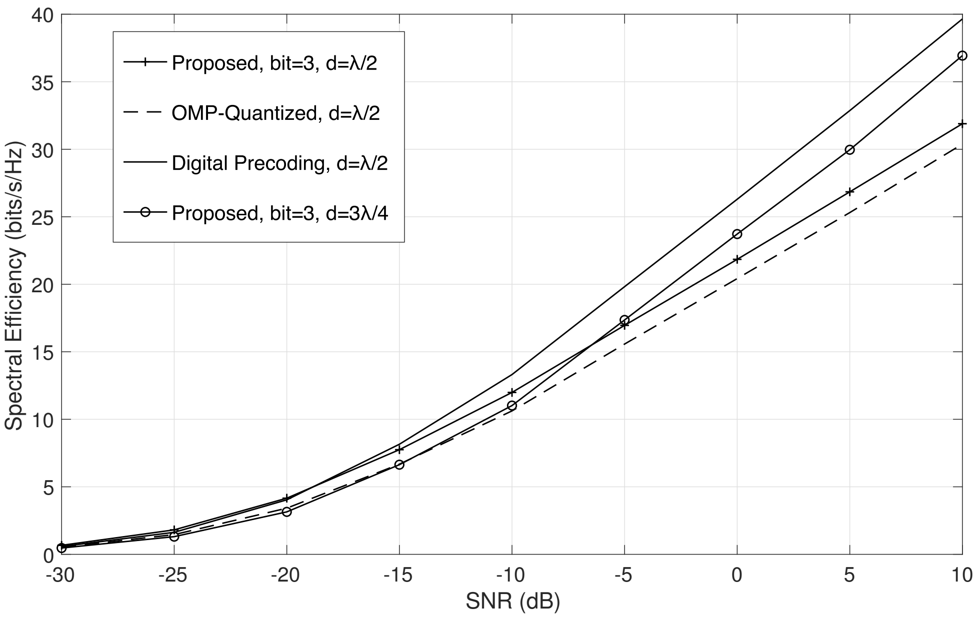


Fig. 4.2 Comparison of spectral efficiencies achieved for 64 x 16 massive MIMO systems.

comparison with the rule of thumb antenna spacing of half a wavelength. This result suggests that this consideration is crucial in MIMO studies because it not only influences antenna efficiency but also alters the correlation to make the channel between antennas correlated, and correlation in MIMO channels may degrades the capacity and the diversity gain [62]. More importantly, when making up for the accuracy of phase shifters, placing the antennas sufficiently far apart is more efficient in terms of power consumption, complexity, and cost than adding more RF chains in a HB design.

The simulation in Fig. 4.3 with similar settings as in Fig. 4.2, but with 128×32 system and $N_s = N_t = 8$ shows that spectral efficiency gains vary with different numbers of antennas. The analysis behind this variation follows. The analog precoder works by extracting phases of the conjugate transpose of the downlink channel. Mathematically, the entries at the diagonal of the effective channel are $\mathbf{h}_k^H \mathbf{a}_k = \frac{1}{\sqrt{N}} \sum_{i=1}^{N} |h_{i,k}|$ where $h_{i,k}$ is the (i)th element of the (k)th column of $\mathbf{H}$, whereas the off-diagonal entries with a magnitude $|\mathbf{h}_k^H \mathbf{a}_j|$ where $k \neq j$. It has been proven in [53] that with $N \to \infty$, the off-diagonal elements

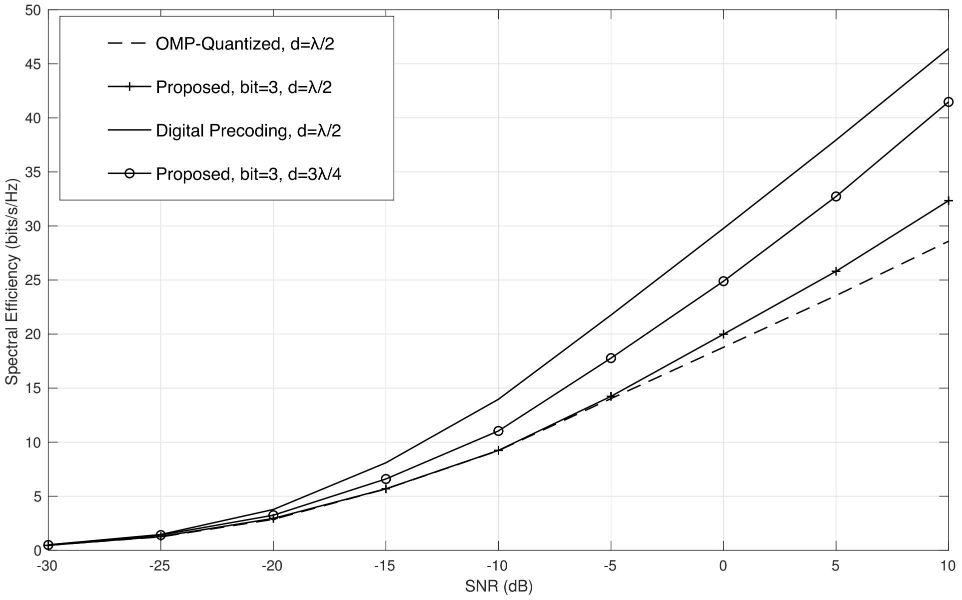


Fig. 4.3 Comparison of spectral efficiencies achieved for 128 x 32 massive MIMO systems.

will be negligible compared to the diagonal entries, becuase $\mathbf{h}_k^H\mathbf{a}_k \sim \mathcal{N}(\frac{\sqrt{\pi N}}{2}, 1-\frac{\pi}{4})$ and $|\mathbf{h}_k^H\mathbf{a}_j|$ has distribution $\mathcal{N}(\frac{\sqrt{\pi}}{2}, 1-\frac{\pi}{4})$. Thus, the higher the number of antennas, the more dimensions for $\mathbf{H}$, which contributes to orthogonalizing $\mathbf{H}$ to eliminate interference among different channels.

4.4 Conclusion

This chapter considers a hybrid precoding scheme with low-resolution PSs in a mmWave MIMO system. It has been shown in recent literature that the extra number of RF chains is often used to substitute for the accuracy of the phase shifters. Increasing the number of RF chains and the number of antennas at both ends of the system increases the spatial multiplexing gain, which is expected. Our simulations show that the proposed hybrid precoding with low-resolution PSs can closely match the optimal performance and other methods along the low and high SNR regime. The capacity gap between the optimal precoder and the proposed one can be reduced without increasing the number of RF chains. Furthermore, since antennas are separated from each other by sufficient distance, hence resulting in a less correlated channel, a minimal loss in the capacity is assured.

CHAPTER 5

CONCLUSION & FUTURE RESEARCH

5.1 Conclusion

The fifth generation mobile cellular communications system (5G) continues to evolve. It promises higher rates of data and lower network latency. The wide bandwidth of mmWave spectrum can be exploited to enable wireless communications at rates over tens of Gbps. Fortunately, the high path loss in the mmWave frequencies can be compensated by beamforming (or precoding). Although mmWave signals have small wavelength which allows for a large number of antennas to be stacked into a small area, the high-power consumption and cost of mixed signal components make it difficult to earmark a separate radio frequency chain for each antenna. The addition of analog processing to the digital precoding, known as hybrid beamforming, is an efficient solution for massive MIMO systems, which results in a number of active RF chains lower than antennas. This dissertation provides a new set of solutions for HB that approaches the performance of a fully digital beamformer in terms of MIMO multiplexing gains. Multiple hybrid precoding schemes are developed and proposed, taking careful consideration of the complexity and power consumption of the system, appropriately reducing them while keeping the same level of quality of service.

Scholarly works show that hybrid precoding can achieve a near-optimal performance, assuming optimal antennas implementation, ideal environment, and full rank effective channel. However, depending on the implementation techniques adopted for the RF precoder and other system parameters, such as the number of active RF chains, the limited distance between antennas, and the geometric placement of both ends of wireless systems, the effective channel matrix could be rank deficient, which degrades the performance of the system. The first part of this dissertation takes careful consideration of the matrix of the effective channel, appropriately selects independent columns of the analog precoder, calculates the least squares solution for the digital precoder, and selects its digital gain based on the selected columns of the RF precoder and the effective channel.

In the second part, a hybrid precoding scheme with low-resolution PSs in a mmWave MIMO system is considered. It has been shown in recent literature that the extra number of RF chains is often used to substitute for the accuracy of the phase shifters. Increasing the number of RF chains and the number of antennas at both ends of the system increases the spatial multiplexing gain. Our simulations show that the proposed hybrid precoding with low-resolution PSs can closely match the optimal performance and other methods along the low and high SNR regime. The capacity gap between the optimal precoder and the proposed one can be reduced without increasing the number of RF chains. Furthermore, since antennas are separated from each other by sufficient distance, hence resulting in a less correlated channel, a minimal loss in the capacity is assured.

Finally, we investigate new ways that allow one to lower the expenses of cost and power of the HB system and keep the performance at a high level at the same time. The idea of connecting the RF chains to a subset of the antennas and spacing those sub-arrays to provide additional diversity gains is one of the approaches that can save money and power. However, this spacing technique cannot be implemented at the receiver side due to its limited size. To reduce power consumption at the receiver, low-resolution analog-to-digital converters

(ADCs) can be implemented. This idea is powerful because with a simple circuit and digital combining based on coarse quantization, it allows to gain at performance,maintaining hardware complexity, and saving energy at the same time. It will be of great interest to implement and develop techniques that can merge the idea of distanced sub-arrays for the uplink between base stations with the low-resolution ADCs on the downlink.

5.2 Future Research

5.2.1 Multiuser MIMO Systems

Most of the hybrid precoding techniques that have been developed recently are for single-user systems. It will be of great interest to implement and develop techniques that can support multi-user systems. Hybrid precoding is freer in developing precoding matrices than analog beamforming due to its additional digital layer [63]. Therefore, hybrid precoding can fulfill more complicated processing, in addition to supporting multiuser transmission, as well as multi-stream multiplexing. A number of serious constraints exist for signal processing with the use of mmWave in multi-user hybrid systems. However, the hybrid approach is powerful because with just one or two extra RF chains, hybrid precoding allows to gain at performance, maintaining hardware complexity, and saving energy at the same time.

5.2.2 Subarray Selection

The idea of subarray selection emerged from the antenna selection technique in which the best subset among a high number of cheap antenna elements are chosen [23, 42]. After that, only a small number of costly RF chains is needed. The problem is how to choose the best subset of antennas from all available options. Researchers suggested that the best subset of antennas are those that can maximize the data exchanged between the transmitter and receiver [42, 86]. In some research works, the use of this approach is claimed to demonstrate the coincidence of the diversity achieved through antenna selection employed in spatial multiplexing systems and the diversity obtained from the use of the whole antenna set [9]. Such an outcome proves that antenna subset selection is beneficial.

The optimization of the MIMO channel capacity in recent literature relies on the assumption that all the antennas in the system are active and being used. In the previous chapters of this thesis, the rank deficiency of the MIMO channel were discussed in which linearly dependent columns in the channel matrix exist. Channel matrix that is rank deficient may have a negative effect on the capacity of the system. Linearly dependent columns in a matrix can be expressed for other columns as a linear combination. These columns will convey redundant information which does not contribute to the system capacity. Thus, deactivating the antennas that relate to the linearly dependent columns and distribute the power on other useful antennas may improve the system capacity [27, 39].

The optimal selection of transmit antennas that can maximize the system capacity were researched in [23]. It has been shown that this selection contributes positively to the rank of the channel matrix. Moreover, authors in [86] proposed a search technique for the best antenna that is computationally efficient and its based on waterpouring method. In [9], the capacity of MIMO systems is analyzed when the best receive antennas are selected. Their idea has the advantage that fewer number of receiver RF chains are active which reduce the complexity and power consumption of the system.

5.2.3 Coupling Between Subarrays and Antennas

Researchers provided a comprehensive investigation of energy-efficient HB designs, yet those designs are not able to provide equally efficient performance as the fully connected HB structure, especially in terms of arrays gain. In the works studying energy-efficient HB designs such as the partially or sub connected HB architecture, the authors usually neglect the distance between the sub-arrays. Increasing the distance between subarrays can provide additional diversity gains to overcome the loss in BF gains caused by the splitting structure of the arrays [52]. The large distance between the sub-arrays can also minimize the correlation between them and their channels. Although this HB version may reach near optimal performance in terms of spatial multiplexing gain and is able to harvest gain of the large antenna arrays, it cannot be implemented at the receiver side due to its limited size.

Another design issue is the distance between antenna elements, which may lead to an undesired coupling effect between them [49]. This effect is referred to as mutual coupling, which can be obtained by a multiplication of the channel and coupling matrices. The design of an antenna array must be optimized based on the mutual coupling to achieve the minimum effect, which is crucial because this correlation between the array elements has a great influence on the array performance as well as the channel matrix [101]. It could also result in a reduction of the array gain and the angle of arrival or the resolution performance as well as the system capacity [62]. If the antenna spacing is assumed to be half of the wavelength, there are no grating lobes exist within the steering directions, which is an advantage in many scenarios. Most existing studies assume that spacing of wavelength/2 between the antenna elements is the optimal. However, It's important to study the the impacts of mutual coupling on such systems, because increasing the spacing of antenna elements may be necessary for mutual coupling mitigation. The effect of a 10% increase in the element spacing may cause grating lobes, but only outside +/-41 degrees [3]. This small change shows clearly the trade off that must be considered when choosing the antenna spacing parameter. Mutual coupling effects and the space between elements in an array are to be traded off against one another [3]. Extensive research has studied the influence of mutual coupling on systems and ways to mitigate those effects, but less work related to mm-wave massive MIMO systems has been done.

5.2.4 Low Resolution ADCs at the Receiver

To reduce power consumption at the receiver, low-resolution analog-to-digital converters (ADCs) can be implemented [8]. Although, high-resolution quantization can fulfill more complicated processing especially at low signal-to-noise ratio (SNR), in some research works, a little rate loss incurred while using low-resolution ADCs at the receiver compared to high-resolution. The idea of low-resolution ADCs is powerful because with a simple circuit and digital combining based on coarse quantization, it allows to gain at performance, maintaining hardware complexity, and saving energy at the same time. It will be of great interest to implement and develop techniques that can merge the idea of distanced sub-arrays for the uplink between base stations with the low-resolution ADCs on the downlink.

In traditional MIMO receiver designs, the ADCs should have high resolution and act as preservers of transparent waveform [8]. In mmWave designs, the larger bandwidth causes the sampling rate of the ADC to increase. Regrettably, high-speed and high resolution ADCs are expensive and use more power [56]. Currently, high-speed and high-resolution ADCs which are commercially available use several watts of power. At the receiver, the higher power consumption of high-resolution ADCs may mean restricted access for mmWave MIMO systems, especially for mobile stations powered by batteries [8]. One possible resolution of the problem would be to reduce either the quantization resolution of ADCs or the sampling rate, or both [8]. Decreasing the sampling rate may be done with different ADC structures.

Very low power consumption is the main advantage of a receiver structure that uses low resolution ADC for each in-phase and quadrature baseband received signal and where a single comparator can be used to implement the ADC [8]. This design also simplifies other areas of circuit complexity. Earlier work has demonstrated that low resolution ADCs in the low and medium SNR regimes may achieve much of the unquantized capacity [8, 46]. Two disadvantages of the low resolution ADC model are that more RF chains are necessary compared to a receiver with high resolution ADCs, and the capacity that can be attained is also limited [8].

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