Performance Analysis of Hybrid Beamforming Techniques in Large MU MIMO Systems

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Abstract. Massive multiple input multiple output (MIMO) at mmWave frequency is one of the primary suggestions for next-generation networks in order to support this large mobile data load. The large number of antennas at the base station (BS) allows multiple users (MU) to share the same time-frequency resources and concentrate energy in a smaller area. As a result, massive MIMO can significantly enhance spectrum and energy efficiency. However, because of the needed number of RF chains per antenna element, fully digital beamforming is undesirable when the number of antennas at the BS becomes very large, resulting in excessive complexity and high power consumption. In this work, we evaluate the performances of hybrid beamforming techniques in downlink MU mmWave large MIMO systems. Specifically, we consider, hierarchical singular value decomposition (SVD) and two-stage iterative MU hybrid beamforming algorithms to alleviate the optimization complexity on finding optimal analog and digital precoding matrices. First, based on the mmWave system and channel model, we formulate the spectral efficiency expression and theoretical analysis is done. Then, the proposed hybrid beamforming algorithms are formulated and numerical simulation are done to evaluate the spectral efficiency and computational complexity of the algorithms. The results reveal that fully-connected hybrid beamforming techniques outperform partially-connected hybrid beamforming techniques in terms of spectrum efficiency.

Keywords: Energy efficiency · Hybrid beamforming techniques · Large MIMO · mmWave · Spectral efficiency

1 Introduction

According to information theory, there are three main techniques to increase the capacity of a wireless communication system: ultra-densification of networks, operating at mmWave bands, and using numerous antennas at the base station. [1,2]. Ultra-dense networks (UDNs) deployment reduces the pathloss due

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to shorter line of sight path but the interference is high when the access point is closer. Increasing the operating spectrum to mmWave bands (i.e. frequencies of 30–300 GHz) provides significant improvement on network capacity. mmWave frequencies, in example, can be used for outside point-to-point backhaul or indoor high-speed wireless applications. Most notably, because mmWave frequencies have exceptionally short wavelengths, a huge number of antenna elements may be packed into a tiny area, allowing for enormous multiple input multiple output (MIMO) at the base station and consumers. The third method for increasing wireless communication capacity is to use a high number of antennas, known as massive MIMO, at the base station and users to improve the system's spectral efficiency. Massive MIMO improves the system's overall performance, especially the possible sum rate, because the BS can communicate with several users at the same time using the same time-frequency resources. Furthermore, huge MIMO increases energy efficiency, reduces signal processing complexity, and generates channel hardening, allowing small scale fading and random noise to be averaged out. To ensure sufficient received signal power in mmWave systems, massive antenna arrays must be deployed at both the BS and the consumers. mmWave large MIMO systems are the result of this nomenclature. This method is predicted to result in a wireless platform made up of small cells with a high capacity. Although mmWave bands have the aforementioned benefits due to their higher frequency, they are unable to pass through buildings and other impediments and are absorbed by plants and rain. As a result, it has a significant propagation loss and a short symbol time, necessitating the use of complex equalization algorithms. Multipath from practically co-incident signals can also produce significant small-scale alterations in the channel's frequency response.

At mmWave bands, the wave length reduces by a factor of 10 to 20 times. Small wavelength enables thousands of antennas to be packed in a small space to focus the power along one direction. Within a very small dimension, it is possible to encompass very large number of antenna elements there by enabling massive MIMO. Besides, in mmWave bands the number of cluster which provides the angle of arrival for different rays are also significantly less compared to sub $6GHz$ band and this helps to make the beam more directional [3,4]. As a result, mmWave massive MIMO with beamforming technology may properly assess directions of arrival, alter beam patterns to reduce interference, and capture the desired signal. However, to drive the growing number of antennas, a high number of RF chains are necessary, considerably increasing system complexity, power consumption, and hardware cost. A viable solution to solve this problem is to offload part of the precoding/processing to the analog domain via analog precoding or combining.

Beamforming techniques with large antenna array makes the propagation between BS and users more directional [5,6]. Beamforming with a larger antenna results in reduced interference and lower energy usage, allowing for higher capacity. Fully - connected and partially connected structures are the two most common hybrid beamforming techniques. Before transmission through the antenna, the beamformer in fully connected hybrid beamforming integrates all of the antennas and RF signals from the RF chains. Signal attenuation and power losses can occur when using additional components to combine RF signals. Separate antenna arrays are used for RF beamforming of each RF chain in partially-connected hybrid beamforming. This leads to wide beam-width, less directivity and strong interference from other chains [7–9]. In this work, we study and evaluate the performances of full-connected and partially-connected hybrid beamforming techniques for downlink MU mmWave massive MIMO systems. Two novel hybrid beamforming algorithms such as hierarchical singular value decomposition (SVD) and two-stage iterative MU hybrid beamforming algorithms are proposed to alleviate the optimization complexity on finding optimal analog and digital precoding matrices. We evaluate the spectra efficiency, energy efficiency of computational complexity of these algorithms.

The rest of the paper is organized as follows. In Sect. 2, review of related work is stated. The system and channel model for downlink mmWave massive MIMO is presented in Sect. 3. Hybrid precoding algorithm for MU mmWave massive MIMO systems is formulated in Sect. 4. Numerical results are discussed in Sect. 5 and conclusions are drawn in Sect. 6.

Notations: Vectors and matrices are expressed in lower and upper case boldface letters, accordingly. $\mathbf{A}^{\mathrm{H}}$, $\mathbf{A}^{\mathrm{T}}$, $\mathbf{A}^{*}$ and $\mathbf{A}^{-1}$ to represent conjugate transposition , transpose, conjugate and inverse of matrix $\mathbf{A}$, respectively. $\mathrm{Tr}(\mathbf{A})$ denotes the trace of a square matrix $\mathbf{A}$. $\mathbf{x} \sim \mathcal{CN}(\mu, \sigma^2\,\mathbf{I})$ represents circular symmetric complex Gaussian distributed random variable $\mathbf{x}$ with mean μ and variance σ^2. $\mathbb{E}\{.\}$ is the expectation operator and $\|.\|$ is the Euclidean norm.

2 Related Works

Hybrid beamforming has been studied in the last decades for single user (SU) and multiuser (MU) massive MIMO systems. The authors in [10] proposed beamforming and multi-stream precoding in SU systems with large mmWave antenna arrays at both transmitter and receiver. The beamforming algorithm is constructed by explicitly accounting for the features of large antenna arrays in settings with little dispersion. The authors in [11] proposed hybrid beamforming for fully connected SU-MIMO systems. The mathematical formulas based on the input parallel data streams are used to construct the best beamforming methods. They show that hybrid beamforming approach significantly reduces the complexity of the systems. In [12] for SU mmWave vast MIMO systems with partially-connected hybrid precoding structures, the author developed a sequential interference cancellation (SIC). They break down the non-convex attainable rate optimization problem into a succession of simple sum-rate optimization problems, each with only one sub-antenna array to consider. This method attempted to maximize the possible sum-rate of each antenna array until the last antenna array was analyzed. The sumrate optimization issue aids in obtaining a precoding vector that is sufficiently close to the ideal unconstrained solution. This approach minimizes the computational complexity by eliminating the need for single SVD and matrix inversion.

Xiaoyong Wu et al. in [8] optimized the beamforming matrices for hybrid analog and digital precoding architectures. In MU large MIMO systems, they presented two-stage iterative methods for fully coupled hybrid beamforming structures. Maximizing the capacity of the baseband channel with proper analog precoding/combining is done in the first analog stage, which aids in achieving optimal capacity in the next step. A sum-rate maximization is performed in the second digital step. Due to the reduced gap between its performance and that of the capacity-reaching strategy, the suggested scheme is better suited to Rayleigh channels than mmWave channels. The authors in [13] proposed a joint design of analog and digital beamformers based on matching pursuit for fully-connected hybrid beamforming techniques that rely on the sparse nature of mmWave channels in the angular domain. By evenly sampling the beam steering space, the recommended precoders may be efficiently quantized, and the precoding method is well-suited for restricted feedback systems. Kilian Roth et al. in [14] compared the spectral and energy efficiency of hybrid beamforming and digital beamforming structures under practical system constraints like effects of channel estimation, transmitter impairments and multiple simultaneous users for mmWave channel.The impacts of transmitter impairments, channel estimate errors, and mixed analog to digital converter (ADC) resolutions are also taken into account. The findings reveal that for MU scenarios, digital beamforming systems with low resolution ADC are more energy efficient and yield a greater attainable rate than hybrid beamforming systems. The authors in [15] proposed a coordinated hybrid beamforming scheme for fully connected structure supporting multiple-stream transmissions for downlink MU massive MIMO systems at mmWave frequencies.They used the generalized low rank approximation of matrices (GLRAM) algorithm to divide the beamforming design into two pieces. The authors next suggest an efficient modified GLRAM algorithm that has no dimensionality constraint, converges in three or four iterations, and takes use of BS and user collaboration. They use the block diagonalization technique to take advantage of the multiplexing gain. The proposed system outperforms equal gain transmission and is nearly as good as the completely digital beamforming technology, according to the author.

In [16,17] fully-connected hybrid structure at the BS and analog-only combining at the MS is proposed for MU large MIMO systems at mmWave bands. The goal is to increase the system's attainable pace with minimal training and feedback. To obtain the analog precoder and combiner, a two-stage iterative technique based on a codebook is provided. To minimize the error between the preamble transmitted by the BS and the estimated received data at the MS, they use a zero forcing (ZF) and Kalman filter based baseband precoder. The authors in [7] For fully connected and partially connected hybrid approaches, analyze the spectral and power efficiency of downlink mmWave large MIMO systems. To facilitate multi-stream transmission, they explore hybrid beamforming at the BS and entirely digital beamforming at the MS. They use a phase shifter with a power amplifier in the analog precoder to regulate the amplitude and phase of the signal at the same time. The proposed model results in a significant overhead associated with the information exchange alignment of the BS and MS beams. The beam-width is limited when high gain is required, making hardware limitations, channel gathering, and continuous alignment of the best beams in a dynamic environment challenging. The authors in [18] study downlink mmWave system with hybrid beamforming at the BS and analog-only combining at the MS. By decoupling analog and digital beamformers at each connection, the effort hopes to reduce complexity and overhead. They demonstrate that the proposed technique works for both partially and fully-connected structures. When channel station information is excellent at the BS, the results show that fully connected design outperforms partially connected architecture. According to the preceding assessment, there are only a few studies that discuss both fully-connected and partially connected hybrid beamforming structures in MU mmWave big MIMO systems. As a result, the goal of this paper is to investigate and assess the performance of these hybrid beamforming algorithms in downlink MU mmWave large MIMO systems. The suggested hybrid beamforming techniques' performance is assessed by looking at their spectral efficiency, energy efficiency, and computational complexity.

3 The System and Channel Model for mmWave Massive MIMO Systems

3.1 the mmWave Large MIMO System Model

We consider a single cell downlink MU mmWave massive MIMO system shown in Fig. 1 where the BS adopts hybrid precoding to support U active users at the MS that deploy only analog combining receiver architectures. The BS is equipped with A_{BS} number of antennas and each user is equipped with A_{MS} number of antennas. The number of concurrent users served at MS is thought to be equal to the total number of data streams, allowing the BS to communicate with all users in the cell using a single data stream. In the same way, the number of RF chains in the BS must be more than or equal to the number of beams in order for the BS to communicate with the MS via multiple beams. Therefore, the number of RF chain in the BS is equal with the number of users in MS as $B_{\mathrm{RF}} = U$ [7]. Let the input data stream to hybrid precoding at the BS be $\mathbf{s} = [s_1, s_2, s_3, \cdots, s_U]^T \in \mathbb{C}^{U\times 1}$ with $\mathbb{E}\{\mathbf{s}s^T\} = \frac{P}{U}\mathbf{I}_U$ where P is the average total transmitted power and $\mathbf{I}_U$ is a $U \times U$ identity matrix. At the BS, the precoder is composed of analog precoder and baseband digital precoder. The BS first performs a $U \times U$ baseband digital precoding that apply to all B_{RF} chains. The baseband digital precoding matrix is expressed as [7]

$$\mathbf{P}_{\mathrm{BB}} = [\mathbf{p}_1^{\mathrm{BB}}, \mathbf{p}_2^{\mathrm{BB}}, \mathbf{p}_3^{\mathrm{BB}}, \cdots, \mathbf{p}_U^{\mathrm{BB}}] \in \mathbb{C}^{U\times U} \tag{1}$$

For fully connected hybrid precoding technique, the analogue precoding is performed over A_{BS} path per RF chain and added together before being transmitted at each antenna element. Thus, in fully connected hybrid precoding techniques, the analogue precoding matrix P_{RF} is expressed as

$$\mathbf{P}_{\mathrm{RF}} = [\mathbf{p}_1^{\mathrm{RF}}, \mathbf{p}_2^{\mathrm{RF}}, \mathbf{p}_3^{\mathrm{RF}}, \cdots, \mathbf{p}_U^{\mathrm{RF}}] \in \mathbb{C}^{A_{\mathrm{BS}}\times U}. \tag{2}$$

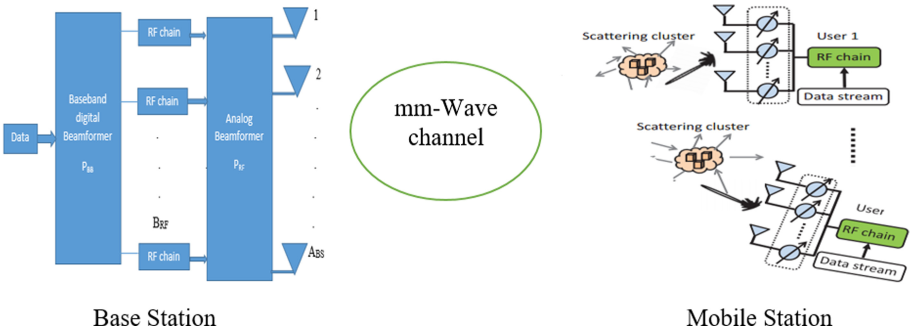

Fig. 1. Hybrid beamforming architecture for MU mmWave large MIMO systems.

It is noteworthy that in fully connected hybrid precoding techniques, RF precoder has full beamforming matrix and its entries are constant modulus with normalized non-zero elements that satisfy $|\mathbf{p}_u^{\mathrm{RF}}(m)|^2 = \frac{1}{A_{\mathrm{BS}}}$ [18]. Each vector contains $\mathbf{p}_u^{\mathrm{RF}} \in \mathbb{C}^{A_{\mathrm{BS}} \times 1}$ where $\mathbf{p}_u^{\mathrm{RF}}$ is the analog weighting vector for the mth array antenna and whose element have the same amplitude but different phase as the RF precoder is realized as analog phase shifter.

For partially connected hybrid precoder techniques, all antenna arrays are divided into $A_{\mathrm{BS}}/B_{\mathrm{RF}}$ number of subarrays and each subarray of antenna is connected to a single RF chain via a phase shifter. The RF precoding is performed over $A_{\mathrm{BS}}/B_{\mathrm{RF}}$ RF paths in each RF chain. Hence, the RF precoder vector consists of a block diagonal beamforming matrix $P_{\mathrm{RF}} \in \dfrac{A_{\mathrm{BS}}}{B_{\mathrm{RF}}} \times U$ which is expressed as [7,18,19]

$$\mathbf{P}_{\mathrm{RF}} = \begin{bmatrix} \mathbf{p}_1^{\mathrm{RF}} & 0 & \dots & 0 \\ 0 & \mathbf{p}_2^{\mathrm{RF}} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \mathbf{p}_U^{\mathrm{RF}} \end{bmatrix} \tag{3}$$

where $\mathbf{p}_u^{RF} \in \mathbb{C}^{\frac{A_{\mathrm{BS}}}{B_{\mathrm{RF}}} \times 1}$ is the analog weighting vector for the mth subarray antenna and whose element have the same amplitude but different phase. Due to the constraint at the analog phase shifters, the entries of each RF precoder has constant modulus that normalize to satisfy $|\mathbf{p}_u^{\mathrm{RF}}(m)|^2 = \frac{1}{A_{\mathrm{BS}}/B_{RF}}$. To simplify our analysis, we assume equal power allocation among users for both hybrid precoding techniques. As a result, normalization is used to enforce the total power constraint. P_{BB} such that $\|\mathbf{P}_{\mathrm{BB}}\mathbf{P}_{\mathrm{RF}}\|_F^2 = U$.

3.2 The mmWave Massive MIMO Channel Model

Diffraction, reflection, and scattering affect the gain of the wireless channel as the signal transmitted from the BS approaches the MS. In mmWave communication, the number of clusters which provide the angle-of-arrival (AOA) for different rays are significantly less as compared to sub 6 GHz bands in the same propagation environment. To build the limited number of clusters in mmWave bands, geometric-based stochastic channel models are used. Every electromagnetic ray that is emitted from the BS to the MS is taken into consideration by the geometrically based stochastic channel model. Individual ray gain will be a function of the BS antenna gain, the mmWave channel gain, and the MS antenna gain, which will be modeled using electromagnetic wave propagation fundamental equations. Thus, by using the geometric based sparse channel model, the mmWave channel model between the BS and MS is expressed as [20,21]

$$\mathbf{H}_u = \sqrt{\frac{A_{\mathrm{BS}} A_{\mathrm{MS}}}{P_u}} \sum_{p=1}^{L_u} \alpha_{u,p} a_{\mathrm{MS}}(\theta_{u,p}^{\mathrm{MS}}, \phi_{u,p}^{\mathrm{MS}}) a_{\mathrm{BS}}^{*}(\theta_{u,p}^{\mathrm{BS}}, \phi_{u,p}^{\mathrm{BS}}) \tag{4}$$

where L_u is the number of effective channel paths corresponding to the number of multipath channel, $\alpha_{u,p}$ is the pth path complex gain including pathloss of the wireless channel between the BS and MS. The variable $(\theta_{u,p}^{\mathrm{MS}}, \phi_{u,p}^{\mathrm{MS}}) \in [0, 2\pi]$ is the pth path's AoA of emanating from the MS and $(\theta_{u,p}^{\mathrm{BS}}, \phi_{u,p}^{\mathrm{BS}}) \in [0, 2\pi]$ is the pth path's angle-of-departure (AoD) launched in BS. a_{MS} $(\theta_{u,p}^{\mathrm{MS}}, \phi_{u,p}^{\mathrm{MS}})$ and a_{BS} $(\theta_{u,p}^{\mathrm{BS}}, \phi_{u,p}^{\mathrm{BS}})$ are the antenna array response gain at each user and the BS, respectively.

The array response vectors for transmit and receive antennas depends on the structure of antenna arrays (such as uniform linear array(ULA) or uniform plannar array(UPA)) rather than the antenna element properties. In mmWave large MIMO systems, UPA geometry has a number of advantages over ULA. We assumed that the MS is aware of the antenna array geometry for the purposes of evaluation and analysis. The directional spread or angular spread of signals arriving at the MS would be substantially less in mmWave bands because to the lower number of clusters compared to other scenarios. For each multipath channel, the gain associated with the BS and MS becomes a complex number with Gaussian distributions for the real and imaginary components. As a result, this complex number's amplitude repose has a Rayleigh distribution. The Rayleigh distance, which separates the near- and far-field portions of an antenna array, can be calculated as a function of the antenna array's maximum physical dimension and wavelength. λ.

By using the precoding matrices in (2) and (3), and the channel model in (4), the received signal at the uth user is given by

$$r_u = \mathbf{H}_u \mathbf{P}_{\mathrm{RF}} \mathbf{p}_{\mathrm{BB}}^{u} s_u + \mathbf{H}_u \sum_{n \neq u}^{U} \mathbf{P}_{\mathrm{RF}} \mathbf{p}_{\mathrm{BB}}^{n} s_n + n_u \tag{5}$$

where $\mathbf{P}_{\mathrm{BB}}^{u}$ is the uth column of $\mathbf{P}_{\mathrm{BB}}$, s_n is the nth element of $\mathbf{s}$ and n_u is the noise at user u with zero mean and variance σ^2. Since the MS employ only analog combining $c_{\mathrm{RF}}^{u} = c_u$, after the combining process, the estimated symbol of the uth MS can be expressed as

$$\tilde{s_u} = c_u^* \mathbf{H}_u \mathbf{P}_{\mathrm{RF}} \mathbf{p}_{\mathrm{BB}}^u s_u + c_u^* \mathbf{H}_u \sum_{n \neq u}^{U} \mathbf{P}_{\mathrm{RF}} \mathbf{p}_{\mathrm{BB}}^n s_n + c_u^* n_u. \tag{6}$$

Thus, the achievable rate of the uth user is given by [7,17,18]

$$R_u = \log_2 \left(1 + \frac{\frac{P}{U} \| c_u^* \mathbf{H}_u \mathbf{P}_{\mathrm{RF}} \mathbf{p}_{\mathrm{BB}}^n \|^2}{\frac{P}{U} \sum_{n \neq u} \| c_u^* \mathbf{H}_u \mathbf{P}_{\mathrm{RF}} \mathbf{p}_{\mathrm{BB}}^n \|^2 + \sigma^2} \right). \tag{7}$$

Finally, the achievable sum rate of the proposed MU mmWave large MIMO system is expressed as

$$R_s = \sum_{u=1}^{U} \log_2 (1 + R_u) \tag{8}$$

4 Hybrid Precoding Algorithms for MU mmWave Large MIMO Systems

The main aim here is to find the optimal baseband precoder matrix $\mathbf{P}_{\mathrm{BB}}$, analog precoder matrix $\mathbf{P}_{\mathrm{RF}}$ at the BS and analog combiner $\mathbf{C}_{\mathrm{RF}}$ at the MS that maximize the achievable rate of each user with affordable hardware and signal processing complexity while providing near-optimal performance. In this paper, we apply hierarchical decomposition and two-stage iterative MU hybrid beamforming methods to solve the proposed system's generic optimization problems. In a two-stage iterative technique, optimization is accomplished by separating the precoder's computation into two parts. This method eliminates the need for explicit channel estimation. Whereas for hierarchical decomposition approach, each of the optimal baseband precoder $\mathbf{P}_{\mathrm{BB}}$, analog precoder $\mathbf{P}_{\mathrm{RF}}$ and analog combiner $\mathbf{C}_{\mathrm{RF}}$ can be determined independently using singular value decomposition (SVD). This method necessitates a thorough understanding of each user's channel. In two-stage iterative based hybrid beamforming algorithm, we can compute the optimal analog combining vector,$\mathbf{c}_u$ for each MS and hybrid analog and baseband precoding matrices, $\mathbf{P}_{\mathrm{RF}}$ and $\mathbf{P}_{\mathrm{BB}}$ at the BS iteratively for both fully and partially connected architectures. The details of this approach is shown in Algorithm 1 [17]. In hierarchical decomposition hybrid beamforming algorithm, we compute the analog combining vector, c_u for each MS and the hybrid analog and digital precoding matrices, P_{RF} and P_{BB} at the BS by using singular value decomposition. The details of this approach is shown in Algorithm 2 [18].

5 Simulation Results and Analysis

The proposed hybrid beamforming techniques for single cell downlink MU mmWave big MIMO systems are evaluated in this section. First, we use the

Algorithm 1. Two-stage iterative based hybrid beamforming algorithms for fully and partially connected MU mmWave large MIMO systems.

Stage 1: Optimal RF precoder and combiner design

1. For each user, compute analog precoder $\mathbf{P}_{\mathrm{RF}}$ and analog combiner $\mathbf{c}_u$ jointly.
2. Choose the appropriate beam-steering path that maximizes the effective channel gain as
$\{\mathbf{o}_u^*, \mathbf{b}_u^*\} = \underset{\mathbf{o}_u \in \mathbf{W}, \mathbf{b}_u \in \mathbf{F}}{\arg\max} \|o_u \mathbf{H}_u \mathbf{b}_u\|$.
3. Set $\mathbf{c}_u = \mathbf{o}_u^*$ for each users at MS.
4. For fully connected hybrid structure, set the full matrix $\mathbf{P}_{\mathrm{RF}} = [\mathbf{b}_1^*, \mathbf{b}_2^*, \cdots, \mathbf{b}_U^*]$ at the BS.
5. For partially connected hybrid structure, set the diagonal matrix
$$\begin{pmatrix} \mathbf{b}_1^* & 0 & \dots & 0 \\ 0 & \mathbf{b}_2^* & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \mathbf{b}_U^* \end{pmatrix}$$
at the BS.

Stage 2: MU optimal baseband precoder design

1. Estimate the effective channel $\mathbf{H}_u^{\mathrm{eff}} = \mathbf{c}_u^* \mathbf{H}_u \mathbf{P}_{\mathrm{RF}}$ for each user at MS.
2. Quantize $\mathbf{H}_u^{\mathrm{eff}}$ using a codebook $\mathbf{H}_{\mathrm{qua}}$ for all users at MS.
3. Calculate and sends back the quantized channel matrix, $\mathbf{H}_u^{\mathrm{quindx}} = \arg\max \|\mathbf{H}_u^{\mathrm{eff}*} \mathbf{H}_u^{\mathrm{quindx}}\|$ to BS.
4. Estimate $\mathbf{P}_{\mathrm{BB}}$ at the BS by using Zero-Forcing (ZF), Minimum Mean Square Error (MMSE) and Maximum Ratio Transmitter (MRT) based baseband precoder.
5. Normalize $\mathbf{P}_{\mathrm{BB}}$ to ensure the power constraint

Output: $\mathbf{P}_{\mathrm{RF}}^*$, $\mathbf{P}_{\mathrm{BB}}$, $\mathbf{c}_u^*$

SNR to assess the algorithms' attainable rate. The effects of the number of BS and users on the spectral efficiency are then analyzed. In addition, a comparison of the performance of hybrid beamforming algorithms with digital beamforming methods is shown.

5.1 Simulation Parameters

For the simulation, we assume single cell downlink system that the users are distributed uniformly in a circular cell of radius $r_c = 500$ m except for an exclusion zone ($r_h \leq 35$ m) near the BS. We use Matlab with the optimization solver to simulate the system. The simulation is run for 1000 Monte-Carlo realizations where in each snapshot, the users are distributed randomly in the cell. Part of the simulation parameters used for the performance analysis is shown in Table 1.

Algorithm 2. Hierarchical decomposition based hybrid beamforming algorithms for fully and partially connected MU mmWave large MIMO systems.

1. Express the SVD of the channel matrix as $\mathbf{H}_u = \mathbf{U\Sigma V}^H$
2. Each c_u sets as the normalized singular vector which corresponds to the largest singular value as $c_u = \frac{1}{\sqrt{A_{\text{MS}}}} e^{ju_m}$ where $m \in A_{\text{MS}}$ and u_m is the phase of the $A_{\text{MS}}^{\text{th}}$ element in u
3. For each MS u, denote $t_u = c_u^H \mathbf{H}_u$.
4. For fully connected hybrid structure, with an element-wise normalization, the BS sets the full matrix $\mathbf{P}_{\text{RF}} = \frac{1}{\sqrt{A_{\text{BS}}}} e^{j(\ a_m^t)}$, where $m \in A_{\text{BS}}$ and a_m is the phase of the mth element in the vector t_u.
5. For partially-connected hybrid structure, with an element-wise normalization the BS sets block-diagonal matrix $\mathbf{p}_{\text{RF}} = \frac{1}{\sqrt{\frac{A_{\text{BS}}}{B_{\text{RF}}}}} e^{j(a_n^t)}$, where $n = (\ u-1)\frac{A_{BS}}{B_{RF}} + m$, $m \in \frac{A_{\text{BS}}}{B_{\text{RF}}}$ and a_n is the phase of the nth element in the vector t_u.
6. Obtain the effective channel $\mathbf{H}_{\text{eff}} = \mathbf{C}_{\text{RF}}^H \mathbf{H} \mathbf{P}_{\text{RF}}$.
7. At the BS, design the baseband precoder based on $\mathbf{H}_{\text{eff}}$ and by using ZF, MMSE and MRT baseband precoder.
8. Normalize $\mathbf{P}_{\text{BB}}$ to ensure the power constraint.

Output: $\mathbf{P}_{\text{RF}}^*$, $\mathbf{P}_{\text{BB}}$, $\mathbf{c}_u^*$.

5.2 Analysis of the Achievable Rate of the Proposed Algorithms

Here, we analyze the spectral efficiency of downlink massive MU-MIMO system in mmWave channel model and linear precoding techniques. Figure 2 shows the spectral efficiency of hybrid beamforming with two-stage iterative algorithm. The results suggest that boosting the SNR improves the system's spectral efficiency. In addition, the results reveal that fully connected hybrid beamforming with MMSE precoding outperforms other linear precoding strategies.

However, when it comes to partially connected hybrid beamforming, ZF precoding performs the worst. The rationale for this is that the MMSE technique is superior to the ZF and MRT techniques in terms of noise reduction, as MMSE considers both noise and signal variance, ensuring that noise is not magnified as in the ZF technique. At low SNR, MRT performs similarly to MMSE, but at high SNR, it lags behind. For all linear precoding approaches, we observe

Table 1. Part of the simulation parameters

Parameters	Values and assumptions
Number of cell	Single cell
Maximum distance between user and BS	≥400 m
System deployment	Hybrid precoder at the BS and analog only combining at the MS.
Number of data stream	Equal to the number of RF chain of the BS.
Number of RF chain at the BS	Equal to the number of users: $B_{\text{RF}} = U$.
Channel model	Geometric based stochastic channel model
Hybrid precoder techniques	Fully-connected and partially-connected hybrid beamforming structure.
Channel State Information	BS has perfect effective channel knowledge and MS perfectly knows its channel H_u.
Propagation scenario	Limited multipath channel
Antenna array geometry	Uniform planar array (UPA)
RF beam-steering vectors P_{RF} and P_{RF}	Takes continuous value
Azimuth (AoAs, AoDs)	Emanating in $\in [0, 2\pi]$
Elevation (AoAs, AoDs)	Emanating in $\in [\frac{-\pi}{2}, \frac{\pi}{2}]$
Propagation scenarios	Based on Rayleigh criterion non-line of sight paths
Number of Monte-Carlo realizations	1000

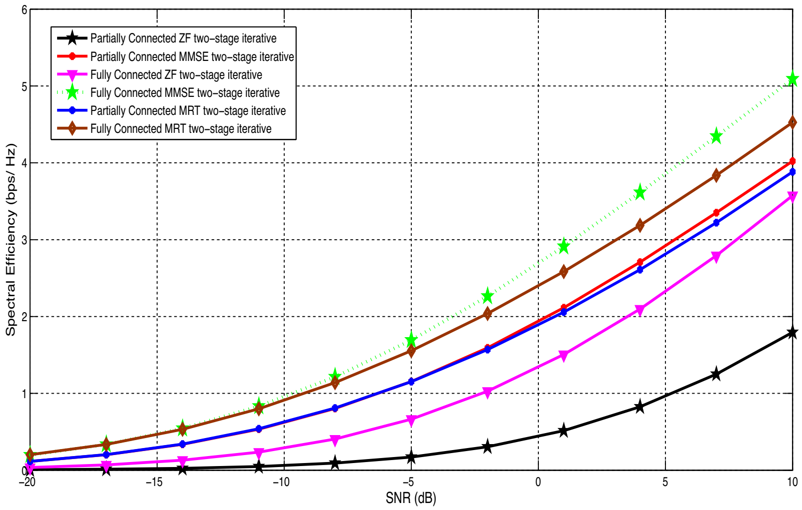

Fig. 2. Spectral efficiency of fully connected and partially connected hybrid beamforming with two-stage iterative algorithms. We assume $A_{\text{BS}} = 64$, $U = 8$, $A_{\text{MS}} = 4$, and $P = 5$.

that partially connected hybrid beamforming schemes perform worse than fully connected hybrid beamforming schemes. We also plot the spectral efficiency of hierarchical decomposition based hybrid beamforming as shown in Fig. 3. The SNR for ZF and MMSE precoding methods is used to show the spectral efficiency of completely and partially linked hybrid beamforming algorithms.

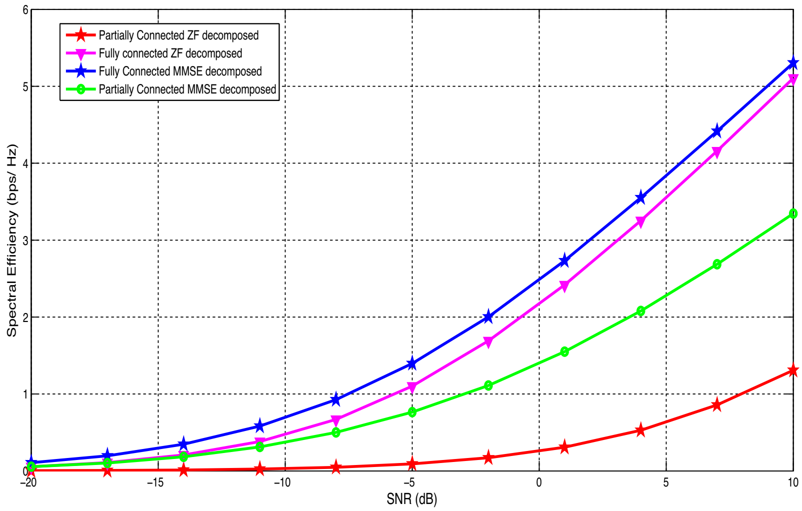

Fig. 3. Spectral efficiency of fully connected and partially connected hybrid beamforming with hierarchical decomposition algorithm. We assume $A_{\mathrm{BS}} = 64$, $U = 8$, $A_{\mathrm{MS}} = 4$, and $P = 5$.

Joint analog combiner and RF precoder design are used in a two-stage iterative based hybrid beamforming technique to jointly select the normalized eigenvectors and analog precoders that maximize the effective analog channel gains with limited feedback and information exchange. The analog combiner and the RF precoders are designed separately for hierarchical decomposed SVD based hybrid beamforming approaches. As can be seen from Fig. 2 and Fig. 3, When compared to hierarchical decomposed methods, the two-stage iterative based hybrid beamforming algorithm performs better since to enhance the effective channel gain, the RF precoder and RF convolution are intended to work together, whereas hierarchical decomposed algorithms employ separate designs.

5.3 Impact of Number of BS Antennas on Spectral Efficiency

Figure 4 and Fig. 5 present the impact of number of BS for fixed number of users ($u = 4$), number of channel path ($P = 5$), and SNR value ($SNR = 5dB$)

for iterative two-stages and hierarchical decomposed algorithm respectively. One can observe from Fig. 4 that the achievable rates of MMSE, ZF, and MRT are increased by increasing the number of antennas. Specially, in down-link large MIMO systems where the number of antennas at the BS is large the performance increases dramatically. As A_{BS} goes to very large, the channel becomes more or less deterministic, means the diagonal element in the effective analog channel gain all having the same power, and the rest of the non-diagonal elements are zero so that do not be affect by channel variability. Thus, by increasing the number of antenna elements in the BS, the capacity increases linearly, and the appropriate spectral efficiency can be achieved. A_{BS}.

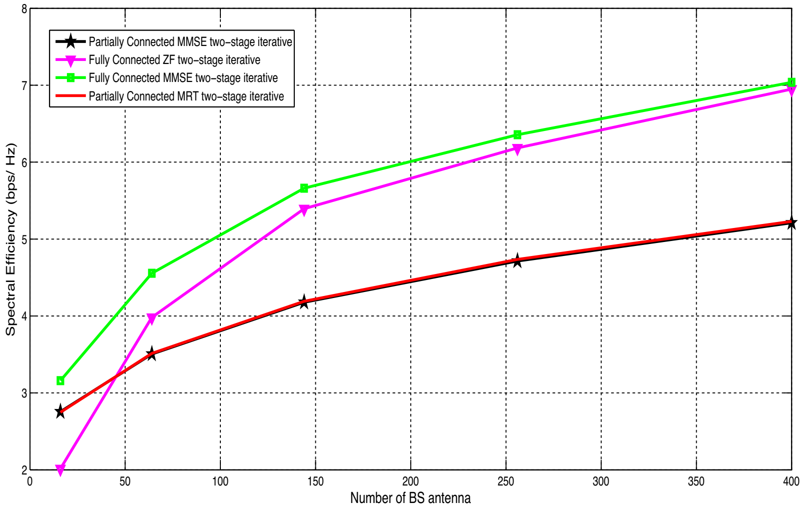

Fig. 4. Impact of varying the number of antenna at the BS for two-stage iterative algorithms $SNR = 5$dB, $u = 4$, $A_{MS} = 4$, and $P = 5$

Fully connected MMSE and MRT deliver full beamforming advantages compared to partially connected hybrid beamforming approaches when the number of antennas at the BS increases to a very large value. A large number of antenna elements at the BS, in general, improves spectral efficiency performance.

The performance loss induced by partially connected hybrid beamforming techniques can be compensated by increasing the number of antenna elements at the BS. At SNR of 7 dB with 64 antenna element in partially MMSE hierarchical decomposed hybrid beamforming algorithm there is 2.6 bps/Hz achievable rate but by fixing and reducing the SNR value to 5dB and increasing the number of antenna elements at the BS to 144 we can get 4.135 bps/Hz achievable rate . The performance gap for fully connected MMSE hierarchical decomposed is grater than 2.064 compared with partially connected MMSE decomposed techniques at $A_{BS} = 400$. When the number of antennas at the BS grows to between 256

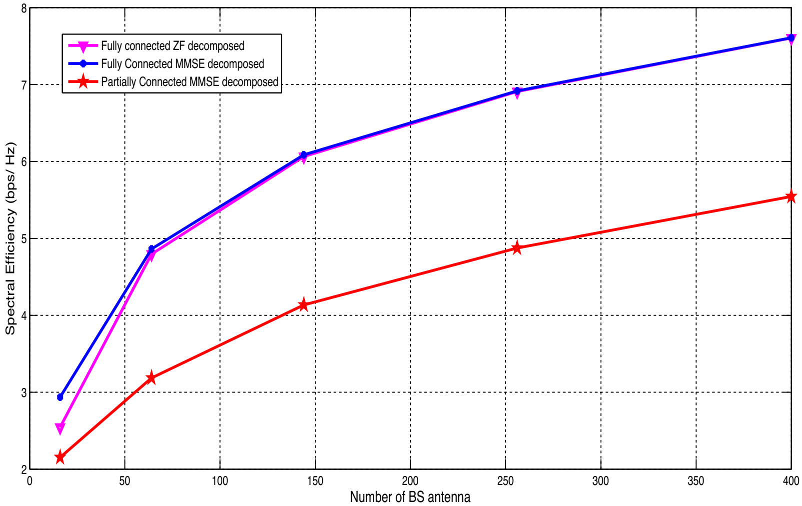

Fig. 5. Impact of varying the number of antenna at the BS for hierarchical decomposed hybrid beamforming algorithms $SNR = 5$dB, $u = 4$, $A_{MS} = 4$, and $P = 5$

and 400, the hierarchical decomposed based hybrid beamforming algorithm outperforms the iterative two-stage based hybrid beamforming algorithm in terms of spectral efficiency.

From the spectral efficiency versus number of BS antenna shown in Fig. 4 and Fig. 5, we can observe that in hierarchical decomposed SVD based hybrid beamforming algorithm the analog precoder matrices P_{RF} is matched with the channel. Then, the arbitrary beams are created based on the particular cluster realization of the channel. As a result, exact matching precoder matrices can be obtained from the channel. In the iterative two-stage codebook-based hybrid beamforming algorithm, there are predetermined matrices from which one is chosen as the best for a given realization. As the number of antenna elements at the BS approaches 256, we can have much more control over the types of beams we can form and match more closely to the channel with the SVD decomposed algorithm, whereas with the iterative codebook based two-stage hybrid beamforming algorithm, we have much more options to choose from the predefined codebook that will match very closely to the channel.

5.4 Spectral Efficiency for Various Number of Users

In this section, we evaluate the impact of the number of users in the MS on the proposed system's performance. We assumed that the number of users at the MS is similar to the number of data streams to be transferred and the number of RF chains at the BS in the proposed system model. ($S = B_{RF} = U$).

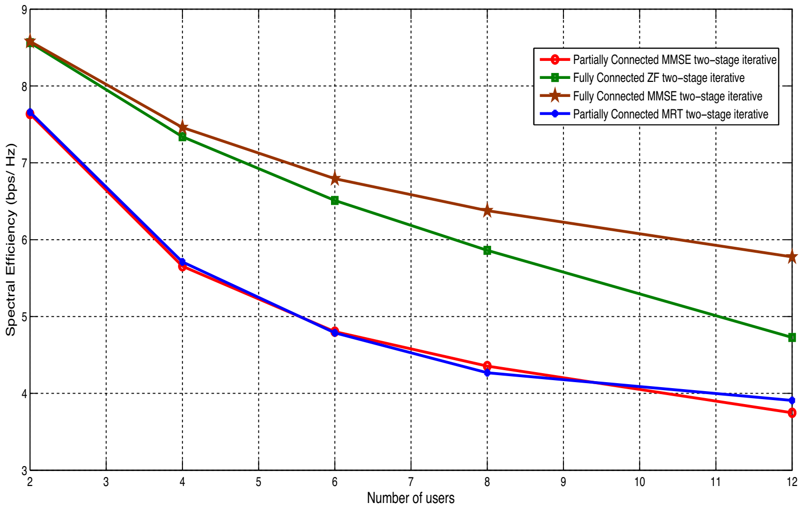

Fig. 6. Impact of varying the number of users at the MS for two-stage iterative algorithms $SNR = 5\text{dB}$, $A_{BS} = 144$, $A_{MS} = 4$, and $P = 5$

The performance of two-stages iterative hybrid beamforming algorithms and the hierarchical decomposed hybrid beamforming algorithm are respectively shown and evaluated in Fig. 6 and Fig. 7 by varying the number of users. One can observe from the results that varying the number of users in the range of 2 to 12 while the number of antenna elements, number of channel path, and the transmitting power are fixed enhance the achievable rate performance because of increased number of independent data streams. The partially connected MRT and MMSE hybrid precoder presents almost the same performance gap until the number of user reaches beyond 10 as shown in Fig. 7.

When the number of users is larger than 10, however, the performance of the MRT partly connected precoder improves. MRT is ideal for high SNR regions because it maximizes SNR at the MS. When the number of users is increased, the ZF fully connected precoder performs the worst. This is because the ZF precoder is unable to eliminate the growing interference caused by a rise in the number of users, resulting in a limited beamforming gain. In general, Co-channel interference, which is introduced by improper cross-correlation features of random spreading sequences across users, causes a reduction in spectral efficiency when the number of users drastically increases.

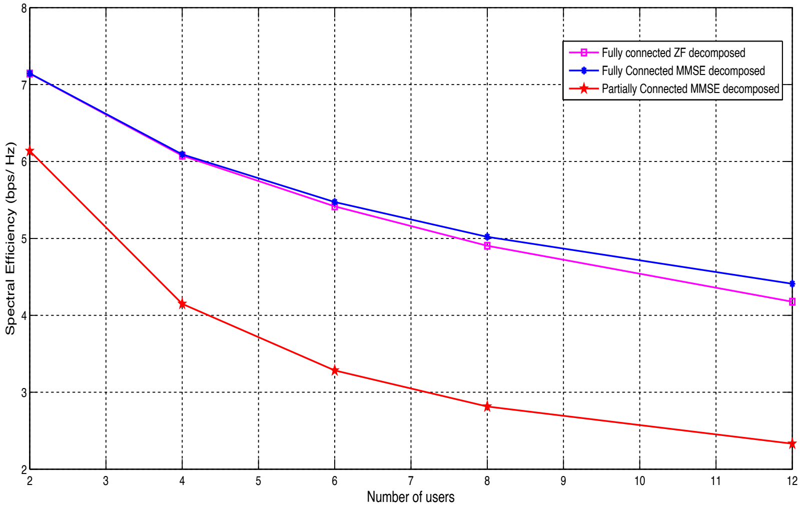

Fig. 7. Impact of varying the number of users at the MS for hierarchical decomposed algorithms $SNR = 5$dB, $A_{BS} = 144$, $A_{MS} = 4$, and $P = 5$

5.5 Spectral Efficiency for Hybrid Beamforming with Digital and Analog Beamforming Approaches

The spectral efficiency by varying SNR with eight number of users, and five number of channel paths for hierarchical decomposed hybrid beamforming algorithms is shown in Fig. 8 and The outcome is compared to SU and merely analog beamsteering. The fact that numerous users can communicate over the same spectrum at the same time improves the system's performance. MU-MIMO networks, on the other hand, are subject to significant inter-user interference, which is not the case with single-user MIMO. For partially and fully connected Hybrid Beamforming systems, ZF and MMSE precoder algorithms are used to overcome the problem of interference in MU-MIMO systems.

A single RF chain is used to transmit a single data stream and generate a single signal beam in analog beamforming. When SNR is low, analog beamforming outperforms partially connected ZF hybrid precoding, and when SNR is 4dB, partially connected ZF precoding performs approximately identically to analog beamforming. In comparison to analog only beamforming, partially ZF precoding achieves the maximum spectral efficiency when SNR is more than 4 dB. To achieve the multiplexing advantage, the ZF precoder requires a high SNR. The performance of the MMSE precoder is close to optimal. As a result,

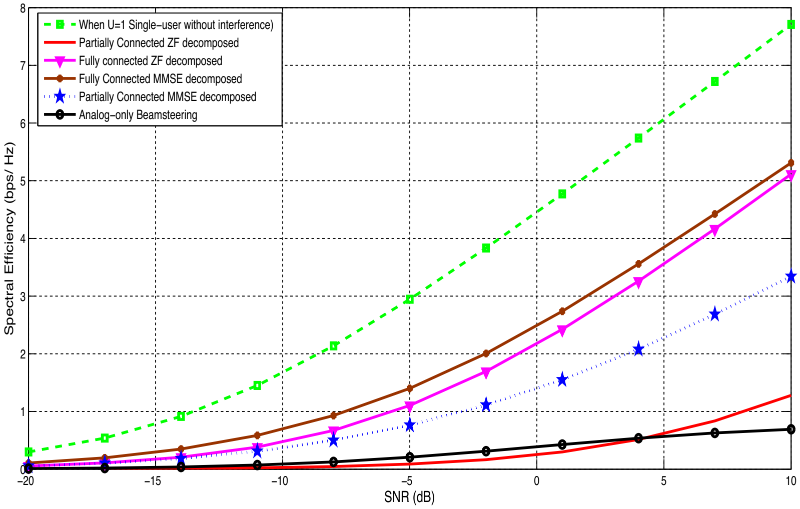

Fig. 8. Hybrid beamforming techniques compared with Analog only beamforming and single user by varying SNR $P = 5$, $A_{BS} = 64$, A_{MS} =16, and $U = 8$

in multi-user hybrid precoding scenarios, an interference management system is required. In addition, we evaluate the performance of fully digital beamforming techniques along with partially and fully connected two-stages iterative hybrid beamforming algorithms by varying the SNR values as shown in Fig. 9.

The fully digital bemforming with ZF and MMSE precoding schemes in the digital baseband yields better spectral efficiency due to the RF chain B_{RF} is behind each antenna element at the BS compared to the fully and partially connected hybrid beamforming techniques. The fully connected MMSE iterative technique near fully digital beamforming capability from –20dB to –5dB SNR region. Beyond –5dB SNR range it can be seen that a small performance gab between fully digital and fully connected hybrid beamforming techniques occurred. One can look at also the performance of both hybrid techniques are inferior to that of the fully digital one, but fully connected based on iterative two-stages algorithm is optimal compared with partially connected hybrid beamforming techniques.

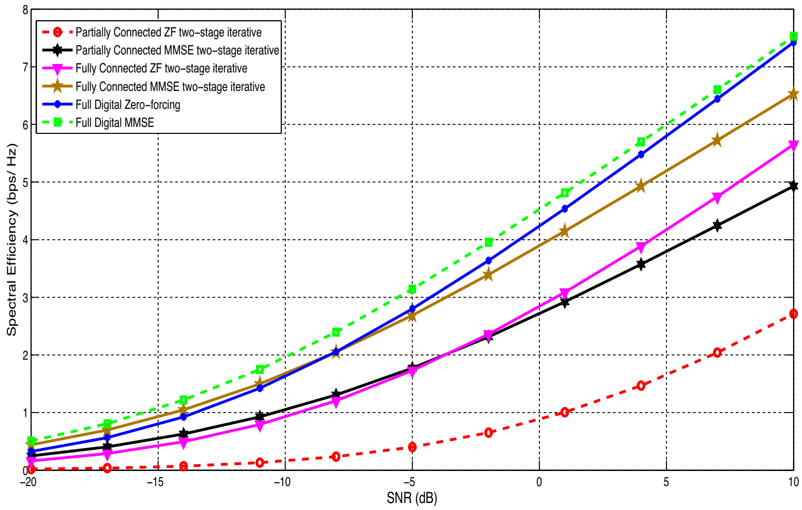

Fig. 9. Hybrid beamforming techniques compared with full digital beamforming techniques by varying SNR $P = 5$, $A_{BS} = 64$, $A_{MS} = 16$, and $U = 8$

6 Conclusion

The work's general conclusion is that, in response to the growing demand for increased data rates and dependability in wireless communication systems, hybrid beamforming for large MIMO systems in the mm-Wave scenario has emerged and attracted a lot of study attention. The performance of MU hybrid beamforming algorithms in mm-Wave large MIMO systems was evaluated in this paper, and hybrid beamforming was compared to fully digital and analog beamforming in terms of spectral efficiency. As discussed from the obtained results fully digital beamforming requires number of RF chains which is equal to the number of transmit antennas, which incur a significant increase in the power consumption, especially when the number of antenna element array in the BS goes to very large.

Hybrid beamforming techniques are an emerging technique for large MIMO systems because they can achieve the performance of traditional fully digital beamforming schemes with far less hardware implementation complexity and power consumption due to the use of a small number of RF chains in hybrid beamforming techniques. With much less RF chains, the fully-connected MMSE hybrid precoder approach can reach spectral efficiency close to that of the ideal fully-digital solution. With more hardware and computational complexity, fully digital beamforming provides improved performance. Analog beamforming, on the other hand, is a simple and cost-effective approach with limited versatility. In addition it is observed that iterative two-stages based on codebooks and hierarchical SVD based decomposition algorithms achieve near optimal solutions to the generic non-convex optimization problem. Because just the codebook indices of the selected array propagation vectors must be provided to the MS in the proposed multi-user downlink system, the complexity and feedback overhead of the iterative based two-stages technique is lower than that of hierarchical SVD based decomposition.

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