Low RF-Complexity Technologies for 5G Millimeter-Wave MIMO Systems with Large Antenna Arrays

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Abstract—Millimeter-wave (mmWave) MIMO with large antenna array has attracted considerable interests from academic and industry, as it can simultaneously provide wider bandwidth and higher spectrum efficiency. However, with hundreds of antennas employed at mmWave frequencies, the number of radio frequency (RF) chains required by mmWave MIMO is also huge, leading to unaffordable hardware cost and energy consumption in practice. In this paper, we review low RF-complexity technologies to solve this bottleneck in mmWave MIMO systems. We first describe the evolution of low RF-complexity technologies from cellular frequencies to mmWave frequencies. Then, we discuss two attractive low RF-complexity technologies for mmWave MIMO systems in detail, i.e., hybrid precoding and beamspace MIMO, including their fundamental principles, application advantages, and design challenges. We compare the performance of these two low RF-complexity technologies to draw some insights about how they should be employed in practical mmWave MIMO systems. Finally, we conclude this paper by highlighting the potential opportunities in this emerging research direction.

I. INTRODUCTION

CURREN 4G wireless communication system is far away to meet the one thousand times increase in data traffic predicted for 5G, which requires us to explore new spectrum bands with wider bandwidth and advanced physical technologies with higher spectrum efficiency [1]. To this end, the integration of millimeter-wave (mmWave) and multiple-input multiple-output (MIMO) has attracted considerable interests from academic and industry [1]. On one hand, mmWave can provide more than 2 GHz bandwidth for communication [2], which is much wider than the 20 MHz bandwidth in current 4G wireless communication system. On the other hand, the short wavelengths associated with mmWave frequencies enable a large antenna array to be packed in a small physical dimension, which means that MIMO with a large antenna array can be easily employed at mmWave frequencies to considerably improve the spectrum efficiency [3]. Therefore, mmWave MIMO with large antenna array has been considered as a promising technique for further 5G wireless communication system [1].

Realizing mmWave MIMO in practice is not a trivial task. One key challenging problem is that each antenna in MIMO systems usually requires one dedicated radio-frequency (RF) chain, including low-noise amplifiers, high-resolution digital-to-analog converters (DACs), and so on [3]. This will result in unaffordable hardware cost and energy consumption in mmWave MIMO systems with large antenna arrays, as the number of antennas is huge and the energy consumption of RF chain is high. For example, due to the high frequency and wide bandwidth of mmWave, the energy consumption of each RF chain at mmWave frequencies (30-300 GHz) is about 250 mW, which is much larger than 30 mW per RF chain at cellular frequencies (sub-6 GHz) [3]. If we consider the base station (BS) in a typical mmWave MIMO system with 256 antennas, the corresponding 256 RF chains will consume 64 Watts, which is much higher than the energy consumption of current 4G micro-cell BS (several Watts) [1]. Therefore, the large number of RF chains with the prohibitively high energy consumption is a bottleneck for mmWave MIMO systems with large antenna arrays in practice [1], [3].

In this paper, we review low RF-complexity technologies for mmWave MIMO systems [1]. We first review the evolution of traditional low RF-complexity technologies from cellular frequencies to mmWave frequencies, including antenna selection [4], spatial modulation [5], and analog beamforming [6]. Then, we explain why these traditional technologies cannot be directly used in mmWave MIMO systems by considering the characteristics of mmWave MIMO channels. After that, we discuss two attractive low RF-complexity technologies for mmWave MIMO systems, including their fundamental principles, application advantages, and design challenges. The first low RF-complexity technology is hybrid analog and digital precoding [7]. Its key idea is to divide the conventional digital precoder into a large-size analog beamformer (realized by a large number of analog phase shifters) to increase the antenna gain and a small-size digital precoder (requiring a small number of RF chains) to eliminate interferences. Thanks to the low-rank characteristics of mmWave channels in the spatial domain [2], a small-size digital precoder is able to achieve the potential spatial multiplexing gain, making hybrid precoding enjoy the satisfying sum-rate performance with only

1The simulation codes are provided to reproduce the results in this paper at: http://oa.ee.tsinghua.edu.cn/dailinglong/
a small number of RF chains. The second low RF-complexity technology is lens antenna array-based beamspace MIMO. By employing a lens antenna array instead of the conventional electromagnetic antenna array, beamspace MIMO can transform the conventional spatial channel into beamspace channel by concentrating the signals from different directions (beams) on different antennas. Since mmWave signals are quasi-optical, the number of effective propagation paths in mmWave communications is limited, occupying only a small number of beams. Therefore, the beamspace channel is sparse, and it is possible to select a small number of dominant beams to reduce the dimension of MIMO system and the number of required RF chains while guaranteeing the near-optimal sum-rate performance. We compare the performance of hybrid precoding and beamspace MIMO in terms of achievable sum-rate and energy efficiency, where we also draw some insights about how they should be employed in practical mmWave MIMO systems. Finally, we point out some potential research opportunities on low RF-complexity technologies for mmWave MIMO systems.

II. TRADITIONAL LOW RF-COMPLEXITY TECHNOLOGIES

In this section, we review several traditional low RF-complexity technologies, including antenna selection, spatial modulation, and analog beamforming. Although these technologies cannot be directly used in mmWave MIMO systems as we will discuss later, they can be regarded as the basis for some recently proposed technologies, such as hybrid precoding and beamspace MIMO.

A. Antenna selection

Antenna selection may be considered as the most classical low RF-complexity technology for MIMO systems. As shown in Fig. 1 (a), the key feature of antenna selection is that there is a selecting network between \( N_{RF} \) RF chains and \( N \) antennas. Based on the channel state information (CSI), the target of antenna selection is to utilize the selecting network to select \( L = N_{RF} \) best antennas out of total \( N \) antennas for data transmission to maximize the achievable sum-rate.

An exciting result of antenna selection is that when the number of RF chains \( N_{RF} \) is larger than the number of transmitted data streams \( N_s \), the performance loss induced by antenna selection is negligible under independent identically distributed (IID) Rayleigh fading channels. However, when channels are highly correlated, the achievable sum-rate of antenna selection will decrease drastically, as antenna selection induces more channel information loss in this case.

B. Spatial modulation

Spatial modulation can be regarded as an evolution of antenna selection, where the key difference is that the spatial index of each antenna can be exploited as an additional source for extra information transmission. As shown in Fig. 1 (b), the transmitted data streams are first divided into two blocks by spatial modulation mapper. The bits in the first block are used to select the antennas which are switched on for data transmission, while the bits in the second block are passed through the baseband signal processing module with conventional constellation modulation, precoding, and so on. Since the signals transmitted by different antennas are expected to experience different propagation channels, at the receiver, we can detect not only the transmitted signals, but also which antennas are active if CSI is known. After that, the transmitted bits in both two blocks above can be recovered simultaneously.

The main advantage of spatial modulation is that it can provide additional increase in sum-rate without any bandwidth expansion. However, as only \( N_{RF} \) out of \( N \) antennas \((N_{RF} < N)\) are active at the same time, the antenna gain achieved by spatial modulation is limited. Moreover, if the channels of active antennas are not sufficiently different, we cannot accurately distinguish which antennas are used at the receiver, and spatial modulation will suffer from an obvious performance degradation.

C. Analog beamforming

The analog beamforming was widely used in the past, and has been reused for point-to-point indoor mmWave communications. As shown in Fig. 1 (c), only one RF chain is employed to transmit single data stream, and the analog beamforming is utilized to control only the phases of original
signals to maximize the antenna gain and effective signal-to-noise ratio (SNR). Building the beamforming vectors requires beam training, which involves an iterative and joint design between the transmitter and receiver. For example, in IEEE 802.11ad, a multi-resolution beamforming codebook is adopted to progressively refine the beams [4]. The advantage of analog beamforming is that it only requires one RF chain, leading to quite low hardware cost and energy consumption [6]. However, since only the phases of signals can be controlled, the performance loss of analog beamforming is obvious. More importantly, analog beamforming can only support single-stream transmission, which is difficult to be extended to multi-stream or multi-user scenarios.

### III. MMWave MIMO Channel Characteristics

In this section, we briefly summarize the main characteristics of mmWave MIMO channels. After that, we answer the question why traditional low RF-complexity technologies including antenna selection, spatial modulation, and analog beamforming discussed above cannot be directly used in mmWave MIMO systems.

#### A. High propagation loss

According to Friis law [1], the free space propagation loss of the electromagnetic signal is proportional to its frequency, which means that the high frequencies at mmWave will lead to more serious propagation loss compared to that at cellular frequencies. Fortunately, thanks to the short wavelengths associated with mmWave frequencies, a much larger antenna array can be employed than the one at cellular frequencies with the same antenna aperture size [1]. Such large antenna array can provide sufficient antenna gain to compensate the excess free space propagation loss via beamforming [3]. Beside the free space propagation, atmospheric gaseous and rain are the other two dominant factors to induce propagation loss [2]. By carefully selecting the frequency for communication, the atmospheric loss and rain attenuation can be neglected. For example, at 28 GHz, the atmospheric loss is only 0.1 dB/km (including vapor and oxygen), while the rain attenuation is about 1 dB/km (moderate rain) [2].

#### B. Clustered multipath

MmWave MIMO channel usually consists of one line-of-sight (LoS) path and several non-line-of-sight (NLoS) clusters, where the cluster is a group of multipath components with the similar propagation angles as they share the same scatter [3]. Generally, the number of NLoS clusters is limited, while the power of each NLoS cluster is also considerably small compared with the LoS path. This is because that wavelengths at mmWave frequencies are small compared to the size of the obstacles encountered during propagation, leading to poor diffraction [3]. Moreover, though scattering occurs due to irregularities and roughnesses of surfaces, the scattering at mmWave frequencies induces additional 15-20 dB attenuation [3], leading to a limited number of NLoS clusters with small power. A study has shown that the average number of NLoS clusters in a 28 GHz outdoor mmWave communications is only 2.4 [2]. This means that the mmWave MIMO channel matrix is expected to have low rank in the spatial domain, and correspondingly enjoys sparse structure in the angular domain.

#### C. Low SNR

The bandwidth at mmWave frequencies is in order of GHz, which is much wider than, for example, 20 MHz for current 4G wireless communication systems at cellular frequencies [11]. The associated wideband noise will lead to SNR degradation. Besides, as we have mentioned above, mmWave communications with large antenna arrays are expected to use beamforming to increase antenna gain. In other words, the antenna gain is limited before the establishment of the transmission link, which means that mmWave signals will suffer from serious path loss. Consequently, low SNR is another characteristic that should be considered in mmWave MIMO systems, especially before the transmission link has been established.

#### D. Can traditional low RF-complexity technologies be used in mmWave MIMO systems?

Based on the discussion above, we know that antenna selection performs well in IID Rayleigh fading channels, but suffers from serious performance loss when channels are highly correlated. Besides, spatial modulation highly relies on the channel differences among antennas, otherwise the receiver cannot distinguish which antennas are active. These features, however, make antenna selection and spatial modulation difficult to be applied in mmWave MIMO systems, since mmWave MIMO channels are highly correlated with a small number of NLoS clusters. Moreover, although analog beamforming is developed for mmWave communications, it can only support single-stream transmission, which cannot fully exploit the potential of mmWave MIMO in spectrum efficiency, as the multiplexing gain cannot be achieved. Above all, we can conclude that traditional low RF-complexity technologies cannot be directly used in mmWave MIMO systems, and new low RF-complexity technologies are required. Next, we will investigate two attractive low RF-complexity technologies for mmWave MIMO systems, i.e., hybrid precoding and beamspace MIMO, in the following Section IV and Section V, respectively.

### IV. Hybrid Precoding

#### A. Principle

Precoding can support multi-user/multi-stream transmission by maximizing desired signal strength and eliminating interferences among users/streams at the transmitter in advance [3], which plays an indispensable role in MIMO systems. However, the conventional digital precoding is not preferred for mmWave MIMO systems, since it requires one dedicated RF chain for each antenna, which brings unaffordable hardware cost and energy consumption as shown in Fig. 2 (a).

Hybrid precoding is a comprise between digital precoding and analog beamforming [7]. The key idea of hybrid precoding is to divide the conventional large-size digital precoder into a large-size analog beamformer (which is usually realized
by a large number of phase shifters) to achieve the antenna gain, and a small-size digital precoder (which requires a small number of RF chains) to eliminate interferences. Fig. 2 (b) and (c) show the typical architectures of hybrid precoding, from which we can observe that the received signal $y$ in the downlink can be presented as

$$y = HADs + n,$$

where $H$, $s$, and $n$ denote the mmWave MIMO channel matrix, transmitted signal vector, and noise vector, respectively. $A$ of size $N \times N_{RF}$ is the analog beamformer realized by phase shifter network, and $D$ of size $N_{RF} \times N_s$ is the digital precoder requiring $N_{RF} < N$ RF chains. It is worth pointing out that hybrid precoding has two architectures, i.e., full-array [7], 9] and sub-array [10], as illustrated in Fig. 2 (b) and Fig. 2 (c), respectively. In the full-array architecture, each RF chain is connected with all $N$ antennas via phase shifters, and the analog beamformer $A$ is a full matrix, while in the sub-array architecture, each RF chain is only connected with a subset of antennas, leading $A$ to be a block diagonal matrix. Obviously, sub-array architecture can reduce the number of phase shifters from $NN_{RF}$ to $N$, together with the associated insertion loss [10]. However, it suffers from a loss in antenna gain by a factor of $1/N_{RF}$ [1].

B. Advantages

Hybrid precoding can achieve a better tradeoff between the hardware cost/energy consumption and the sum-rate performance. The smallest number of required RF chains $N_{RF}$ in hybrid precoding can equal the number of transmitted data streams $N_s$ (i.e., $N_{RF} = N_s$), while this number in conventional digital precoding should be as large as the number of antennas $N$, which is much larger than $N_s$ (e.g., $N = 256 \gg N_s = 4$ [7]). This means that the number of RF chains can be significantly reduced by hybrid precoding, leading to quite low energy consumption. Besides, since the number of NLoS clusters is limited as we have discussed before, the mmWave MIMO channel matrix is usually low-rank [2]. This indicates that the maximum number of data streams that can be effectively transmitted by such channel is limited. Therefore, as long as the number of RF chains is larger than the rank of channel matrix, the small-size digital precoder is still able to fully achieve the multiplexing gain, which enables hybrid precoding with only a small number of RF chains to achieve the performance close to the conventional digital precoding with a large number of RF chains.

C. Challenges and recent results

**Optimal design of hybrid precoder:** Maximizing the achievable sum-rate by designing the hybrid precoder $P = AD$ is usually the main target of hybrid precoding. However, this optimization problem imposes new challenges, as traditional methods for digital precoding cannot be directly used. This is due to the fact that there are several constraints on the analog beamformer $A$ and digital precoder $D$ due to the practical hardware limitations. For example, $\|AD\|_F^2 \leq N_s$ should be satisfied to meet the total transmitter power requirement, and all the nonzero entries of analog beamformer $A$ should share the same amplitude due to the constant modulus constraint on phase shifters. These constraints, however, make the sum-rate optimization problem of hybrid precoding non-convex, which is difficult to be solved. To this end, one feasible way is to approximate the original optimization problem as a convex one to obtain a sub-optimal but low-complexity hybrid precoder.

Following this idea, some advanced hybrid precoding schemes have been proposed recently. In [7], a spatially sparse precoding is proposed for the full-array architecture. The key idea is to approximate the sum-rate optimization problem as the one which minimizes the choral distance between the optimal unconstrained precoder and the hybrid precoder. Then, a variant of orthogonal matching pursuit (OMP) algorithm is developed to obtain the near-optimal hybrid precoder. In [9], hybrid precoding with full-array is extended to multi-user scenarios, where a two-stage multi-user precoding is proposed. In the first stage, the optimal analog beamformer is searched from a pre-defined codebook to maximize the desired signal power of each user. In the second stage, a digital precoder similar to the classical zero forcing (ZF) precoder is designed to cancel multi-user interferences. In [10], we propose a successive interference cancelation (SIC)-based hybrid precoding for the sub-array architecture, which is realized by decomposing the sum-rate optimization problem into a series of simple and convex sub-problems, and each sub-problem only considers one sub-array. Then, inspired by the classical SIC multi-user signal detector, the near-optimal hybrid precoder on each sub-array is obtained in an one-by-one fashion.

**Channel estimation:** The max gain from hybrid precoding can be only achieved with perfect CSI, which is difficult to be obtained for mmWave MIMO systems. First, as we have mentioned above, before the establishment of the transmission link, the SNR of mmWave MIMO systems is quite low. Accurately estimating the high-dimension channel matrix with low SNR is a challenging task. Secondly, the number of RF chains in hybrid precoding is usually much smaller than the number of antennas. Therefore, hybrid precoding cannot directly observe the channel matrix like that in digital precoding. Instead it can only observe a noisy version of the effective channel in the analog domain, which depends on the selected analog beamformer. As a result, the channel estimation in hybrid precoding can be regarded as a general problem of subspace sampling, which cannot be solved by traditional channel estimation schemes. To this end, one feasible way is to exploit the sparsity of mmWave MIMO channels, where the efficient compressed sensing (CS) tools can be used.

Based on this fact, some advanced channel estimation schemes for hybrid precoding have been proposed recently. For example, in [3], the authors propose an adaptive channel estimation scheme, which combines the adaptive CS algorithm with the idea of multi-resolution codebook in traditional analog beamforming [6]. It has been shown in [3] that the proposed adaptive channel estimation scheme can accurately estimate the entries of multipath channel with low SNR. In [11], we extend the narrowband mmWave MIMO systems to broadband, and propose a distributed CS-based channel
estimation scheme. By exploiting the structural sparsity of broadband mmWave MIMO channels, the proposed scheme enjoys satisfying accuracy with reduced pilot overhead.

V. BEAMSPACE MIMO

A. Principle

Different from hybrid precoding, which deals with the low-rank channel in the spatial domain, Beamspace MIMO exploits the sparsity of channel in the beamspace (i.e., angular domain) to reduce the number of required RF chains [3].

As shown in Fig. 3 (a), the conventional channel in the spatial domain can be transformed to the beamspace channel by employing a carefully designed lens antenna array instead of the conventional electromagnetic antenna array [8]. Specifically, such lens antenna array plays the role of a spatial discrete fourier transform (DFT) matrix $U$ of size $N \times N$, which contains the array steering vectors of $N$ orthogonal pre-defined directions covering the entire angular space. Then, the system model of beamspace MIMO can be presented by

$$\tilde{y} = \mathbf{H} \mathbf{D} \mathbf{s} + \mathbf{n} = \tilde{\mathbf{H}} \mathbf{D} \mathbf{s} + \mathbf{n},$$

where $\tilde{y}$, $\mathbf{s}$, and $\mathbf{n}$ denote the received signal vector in the beamspace, transmitted signal vector, and noise vector, respectively. $\mathbf{D}$ of size $N \times N$ is the digital precoder, and the beamspace channel $\tilde{\mathbf{H}}$ is defined as $\tilde{\mathbf{H}} = \mathbf{H} \mathbf{U}$, whose $N$ columns correspond to $N$ orthogonal beams. It is worth pointing out that the beamspace channel $\tilde{\mathbf{H}}$ at mmWave frequencies has a sparse structure due to the limited number of NLoS clusters as we have discussed in Section III. Therefore, as shown in Fig. 3 (b), we can select only a small number of dominant beams to reduce the effective dimension of MIMO system as $\tilde{\mathbf{y}} \approx \mathbf{H}_r \mathbf{D}_s \mathbf{s} + \mathbf{n}$, where $\mathbf{H}_r = \mathbf{H}(:, I)_{l \in B}$ is the dimension-reduced beamspace channel with $B$ denoting the beam set which contains the indices of selected beams, and $\mathbf{D}_s$ of size $|B| \times N_s$ is the corresponding dimension-reduced digital precoder. As the dimension of $\mathbf{D}_s$ is much smaller than that of the original digital precoding matrix $\mathbf{D}$ in [3] (i.e., $|B| \ll N$), beamspace MIMO can significantly reduce the number of required RF chains.

B. Advantages

Similar to hybrid precoding, beamspace MIMO can also achieve the near-optimal sum-rate performance with low hardware cost/energy consumption. This advantage mainly comes from the exploitation of the channel sparsity in mmWave MIMO systems. Since most of the elements of beamspace channel are near to zero, we can significantly reduce the system dimension without obvious performance loss. Moreover, the employment of lens antenna array does not affect the effective channel properties, as it plays the role of a spatial DFT matrix (i.e., $U^H \mathbf{U} = \mathbf{I}$). Therefore, the performance loss induced by lens antenna array is also negligible. Above all, we can conclude that the performance of beamspace MIMO is quite close to that of digital precoding using all RF chains. Another advantage of beamspace MIMO is that it is more suitable for fast time-varying channels. For hybrid precoding, when channel has changed, we need to re-design the optimal analog beamformer and digital precoder jointly, which is complicated and time-consuming. However, this procedure can be decoupled in beamspace MIMO. In the analog domain, we only need to adjust the switches in selecting network. Then, in the digital domain, the digital precoder such as ZF precoder can be easily re-computed according to the updated $\mathbf{H}_r$, leading to low complexity and latency.

C. Challenges and recent results

Optimal design of beam selection: Based on the discussion above, we know that the performance of beamspace MIMO depends on the dimension-reduced beamspace channel, which is determined by beam selection. The target of beam selection is to select $|B|$ beams out of the total $N$ beams to maximize the achievable sum-rate, where $B$ contains the indices of selected beams. The most intuitive beam selection scheme is exhaustive search, which enjoys the optimal performance but involves prohibitively high complexity. For a mmWave MIMO system with $N = 256$ and $|B| = 16$, there will be totally $\binom{256}{16} \approx 1 \times 10^{25}$ possible $B$’s. To this end, more efficient beam selection scheme should be designed to achieve the near-optimal performance.

In [8], a magnitude maximization (MM) beam selection is proposed, where several beams with large power are selected for data transmission. MM beam selection is simple but faces one problem: it only aims to retain the power as much as possible without considering inter-beam interferences, leading to a non-negligible performance loss. In [12], the authors propose a more efficient beam selection scheme by using the decremental algorithm developed from antenna selection. It aims to delete $N - |B|$ beams (i.e., select $|B|$ beams) one by one in a decremental order. In each step, the beam with the smallest contribution to the achievable sum-rate is deleted. In [13], we propose an interference-aware (IA) beam selection scheme. The key idea is to classify all users into two user groups according to the potential inter-beam interferences. For users with small interferences, we directly select the beams with large power, while for users with severe interferences,
a low-complexity incremental algorithm based on sum-rate maximization is proposed to select the optimal beams.

Channel estimation: The channel estimation for beamspace MIMO is different from that for hybrid precoding, since they have quite different hardware architectures. Besides, in beamspace MIMO, we need to estimate the beamspace channel instead of the traditional spatial channel, which enjoys different characteristics as discussed in Section III. As a result, the channel estimation schemes designed for hybrid precoding may not be directly extended to beamspace MIMO. Fortunately, thanks to the sparse structure of beamspace channels, we can still resort to the efficient CS tools to solve this problem.

In [14], a two-step channel estimation scheme is proposed. In the first step, a beam training procedure is required to determine which beams should be used and reduce the dimension of sparse beamspace channel. In the second step, the classical channel estimation scheme such as minimum mean square error (MMSE) is used to estimate the dimension-reduced beamspace channel. In [15], we propose a support detection (SD)-based channel estimation scheme with much lower pilot overhead. Specifically, we first design an adaptive selecting network to replace the traditional selecting network in beamspace MIMO systems as shown in Fig. 4, which can be considered as a bridge between hybrid precoding and beamspace MIMO. The proposed adaptive selecting network can not only realize beam selection like the traditional selecting network, but also obtain the efficient measurements of the beamspace channel for channel estimation. The key difference of the proposed adaptive selecting network from the analog beamformer in hybrid precoding is that only 1-bit phase shifters (i.e., only two phases 0 and \(\pi\)) are controlled by 1 bit are required, leading to significantly reduced cost and energy consumption [10]. Then, based on the adaptive selecting network, the SD-based channel estimation scheme is proposed by utilizing the structural characteristics of beamspace channels. It has been shown in [15] that the proposed SD-based channel estimation scheme enjoys satisfying accuracy with low pilot overhead, even in the low SNR region.

VI. PERFORMANCE COMPARISON

In this section, we compare the performance of hybrid precoding, beamspace MIMO, and the digital precoding using all RF chains. A typical outdoor multi-user mmWave MIMO system where the BS employs \(N = 256\) antennas to simultaneously serve \(K = 16\) single-antenna users is considered. We adopt the widely used Saleh-Valenzuela channel model to capture the characteristics of mmWave MIMO channels [2], where each user has one line-of-sight (LoS) path and two non-line-of-sight (NLoS) clusters. The gain of LoS path is assumed to follow complex Gaussian distribution \(CN(0, 1)\) with zero mean and unit variance, while the gain of NLoS cluster is assumed to follow \(CN(0, 0.1)\). The angles of all paths are assumed to follow the IID uniform distribution within \([-\pi, \pi]\). Finally, the channel is assumed to be perfectly known by the BS.

Fig. 5 shows the comparison of achievable sum-rate. For hybrid precoding (full-array architecture), we use the two-stage multi-user precoding proposed in [9], while for beamspace MIMO, we adopt our proposed IA beam selection [13]. Note that the number of required RF chains is \(N_{RF} = K = 16\) for both schemes. For digital precoding, the classical ZF precoder is employed with \(N_{RF} = N = 256\) RF chains. From Fig. 5, we can observe that, although the number of RF chains is significantly reduced (e.g., from 256 to 16), both hybrid precoding and beamspace MIMO can achieve the sum-rate
performance close to that of digital ZF precoding. This is caused by the fact that hybrid precoding can fully exploit the low-rank characteristics of mmWave channels in the spatial domain, while beamspace MIMO can benefit from the sparse characteristics of mmWave channels in the beamspace (analog domain). Since the lens antenna array in beamspace MIMO plays the role of spatial DFT, the beamspace channel and the spatial channel are essentially equivalent but expressed in different forms, just like the same signal can be expressed in the time domain and equivalently in the frequency domain. Moreover, Fig. 5 also shows that hybrid precoding performs a little better than beamspace MIMO, since the analog beamformer can provide more freedoms than the adaptive selecting network to achieve higher antenna gain.

Fig. 6 shows the comparison of energy efficiency, where the SNR is 30 dB. The energy efficiency $\eta$ is defined as

$$\eta = \frac{R}{P_{\text{total}}} = \frac{R}{P_t + N_{\text{RF}} P_{\text{RF}} + N_{\text{PS}} P_{\text{PS}} \left( \text{bps/Hz/W} \right)},$$

where $R$ is the achievable sum-rate, $P_{\text{total}} \triangleq P_t + N_{\text{RF}} P_{\text{RF}} + N_{\text{PS}} P_{\text{PS}}$ is the total energy consumption, $P_t$ is the transmitted energy, $P_{\text{RF}}$ is the energy consumed by RF chain, $P_{\text{PS}}$ is the energy consumed by phase shifter (including the energy for the excitation and the energy for the compensation of insertion loss), and $N_{\text{PS}}$ is the number of phase shifters, where we have $N_{\text{PS}} = N N_{\text{RF}}$ for both hybrid precoding with full-array and beamspace MIMO with adaptive selecting network. In this paper, we adopt the practical values $P_t = 1W$ (30 dBm) and $P_{\text{RF}} = 250mW$.

For hybrid precoding, we set $P_{\text{PS}} = 5mW$ (5-bit phase shifter), while for beamspace MIMO with adaptive selecting network, we adopt $P_{\text{PS}} = 1mW$ since only 1-bit phase shifters are required. From Fig. 6, we can observe that both hybrid precoding and beamspace MIMO can achieve much higher energy efficiency than digital ZF precoding. In addition, beamspace MIMO performs better than hybrid precoding in energy efficiency, especially when the number of users is not very large (e.g., $K \leq 50$). This is due to the fact that although the sum-rate achieved by beamspace MIMO is a little lower than that of hybrid precoding, it can reduce the energy consumption of phase shifters. However, when the number of users is large, the total energy consumption is dominated by RF chains, and this advantage of beamspace MIMO becomes less pronounced.

Based on the observations in Fig. 5 and Fig. 6, we can further conclude that when the requirement of sum-rate is more important for mmWave MIMO systems, hybrid precoding is more preferred. In contrast, if the energy efficiency is most concerned, beamspace MIMO will be a better choice, especially when the number of users is not very large.

VII. Future Research Directions

Beside the discussions above, there are still many open issues on low RF-complexity technologies for mmWave MIMO systems. In this section, we highlight some potential research opportunities that deserve further efforts.

A. More efficient low RF-complexity technologies

In previous sections, we have introduced two promising low RF-complexity technologies, i.e., hybrid precoding and beamspace MIMO. There should be some other low RF-complexity technologies, which may be more efficient for mmWave MIMO systems in some particular application scenarios. For example, we can employ the low-resolution ADCs instead of the commercial high-resolution ADCs to reduce energy consumption of RF chains (the number of required RF chains remains unchanged). Alternatively, by exploiting the correlation of mmWave channels, we can directly use the transmitted signals on a subset of antennas to compose the signals on remaining antennas to reduce the number of required RF chains. These low RF-complexity technologies, however, require further investigation.

B. Low RF-complexity technologies for frequency-selective broadband mmWave MIMO systems

Most of the existing low RF-complexity technologies are under the assumption of narrowband channel. However, mmWave MIMO systems are expected to be broadband, where the bandwidth of channel is in the order of GHz, much larger than the coherence bandwidth. This implies that the channel will be frequency-selective, which makes the existing schemes inapplicable. Therefore, extending low RF-complexity technologies, e.g., hybrid precoding and beamspace MIMO, to frequency-selective broadband mmWave MIMO systems will be a very interesting topic in the future.

C. Low RF-complexity technologies in fast time-varying channels

In the future, mmWave MIMO is likely to work not only in indoor scenario but also in outdoor scenario, where some users may move fast. This means that the channel will be fast time-varying especially at mmWave frequencies, which imposes new challenges for the transceiver design. Consider hybrid precoding for instance. The existing schemes need to estimate the channel and re-compute the hybrid precoder for each varied channel, leading to high pilot overhead and computational complexity. Therefore, the future research should take the fast time-varying channels into account, and try to exploit the channel temporal correlation to reduce the corresponding pilot overhead and computational complexity.

VIII. Conclusions

Low RF-complexity technology will be an indispensable component for future mmWave MIMO systems, since it can relieve the bottleneck of high hardware cost and energy consumption induced by the huge number of RF chains. In this paper, we first review three traditional RF-complexity technologies, including antenna selection, spatial modulation, and analog beamforming. After that, we discuss two attractive low RF-complexity technologies for mmWave MIMO systems, i.e., hybrid precoding and beamspace MIMO, which can achieve much higher energy efficiency than digital precoding. Performance comparison further shows that hybrid precoding enjoys...
better sum-rate performance, while beamspace MIMO can achieve higher energy efficiency. Future potential opportunities in this emerging research area of low RF-complexity technology include more efficient alternatives to realize low RF-complexity, novel transceiver designs for frequency-selective and time-varying mmWave MIMO channels.

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