Low RF-Complexity Technologies to Enable Millimeter-Wave MIMO with Large Antenna Array for 5G Wireless Communications

Xinyu Gao, Linglong Dai, and Akbar M. Sayeed

ABSTRACT

mmWave MIMO with large antenna array has attracted considerable interest from the academic and industry communities, as it can provide larger bandwidth and higher spectrum efficiency. However, with hundreds of antennas, the number of RF chains required by mmWave MIMO is also huge, leading to unaffordable hardware cost and power consumption in practice. In this article, we investigate low RF-complexity technologies to solve this bottleneck. We first review the evolution of low RF-complexity technologies from microwave frequencies to mmWave frequencies. Then, we discuss two promising low RF-complexity technologies for mmWave MIMO systems in detail, that is PAHP and LAHP, including their principles, advantages, challenges, and recent results. We compare the performance of these two technologies to draw some insights about how they can be deployed in practice. Finally, we conclude this article and point out some future research directions in this area.

INTRODUCTION

Millimeter-wave (mmWave) (30–300 GHz) multiple-input multiple-output (MIMO) with large antenna array has been considered a promising solution to meet the one thousand times increase in data traffic predicted for future 5G wireless communications [1]. On one hand, mmWave can provide nearly 2 GHz bandwidth [2], which is much larger than the 20 MHz bandwidth in current 4G wireless communications without carrier aggregation. On the other hand, the short wavelengths associated with mmWave frequencies enable a large antenna array to be packed in a small physical size, which means that MIMO with a large antenna array is possible at mmWave frequencies to effectively compensate the high path loss induced by high frequencies and considerably improve the spectrum efficiency [3].

However, realizing mmWave MIMO in practice is not a trivial task. One challenging problem is that each antenna in MIMO systems usually requires one dedicated radio-frequency (RF) chain, including digital-to-analog converters (DACs), mixers, and so on [3]. This will result in unaffordable hardware cost and power consumption in mmWave MIMO systems, as the number of antennas is huge (e.g., 256 compared with 8) and the power consumption of the RF chain is high (e.g., 250 mW at mmWave frequencies compared with 30 mW at microwave frequencies) [3]. Therefore, the large number of RF chains with prohibitively high power consumption is a bottleneck for mmWave MIMO with large antenna array in practice [1, 3].

In this article, we investigate low RF-complexity technologies for mmWave MIMO systems. Our contributions can be summarized as follows:

• We provide a review of the evolution of low RF-complexity technologies from microwave frequencies to mmWave frequencies, and highlight two promising technologies proposed recently, that is, phased array based hybrid precoding (PAHP) [4] and lens array based hybrid precoding (LAHP) [5]. We give a detailed overview of these two technologies, including their principles, advantages, challenges, and recent results.

• We propose a novel adaptive selecting network for LAHP with low hardware cost and power consumption. For data transmission, it can select beams such as the traditional one, while for channel estimation, it can formulate the beamspace channel estimation as a sparse signal recovery problem and estimate the beamspace channel with considerably reduced pilot overhead.

• We provide the sum-rate and power efficiency comparisons between PAHP and LAHP in a practical outdoor mmWave MIMO system, where the channel estimation error and inter-cell interference are also included (The simulation codes can be found at http://oa.ee.tsinghua.edu.cn/dailinglong/publications/publications.html). Then, we draw some insights about how these two technologies can be deployed in practice.

TRADITIONAL LOW RF-COMPLEXITY TECHNOLOGIES

We first review two typical low RF-complexity technologies, that is, antenna selection and analog beamforming. Antenna selection may be considered the most classical low RF-complexity technology for microwave MIMO systems. In contrast, analog beamforming is the most widely used low RF-complexity technology for indoor

mmWave MIMO with a large antenna array has attracted considerable interest from the academic and industry communities, as it can provide larger bandwidth and higher spectrum efficiency. However, with hundreds of antennas, the number of RF chains required by mmWave MIMO is also huge, leading to unaffordable hardware cost and power consumption in practice. The authors investigate low RF-complexity technologies to solve this bottleneck.
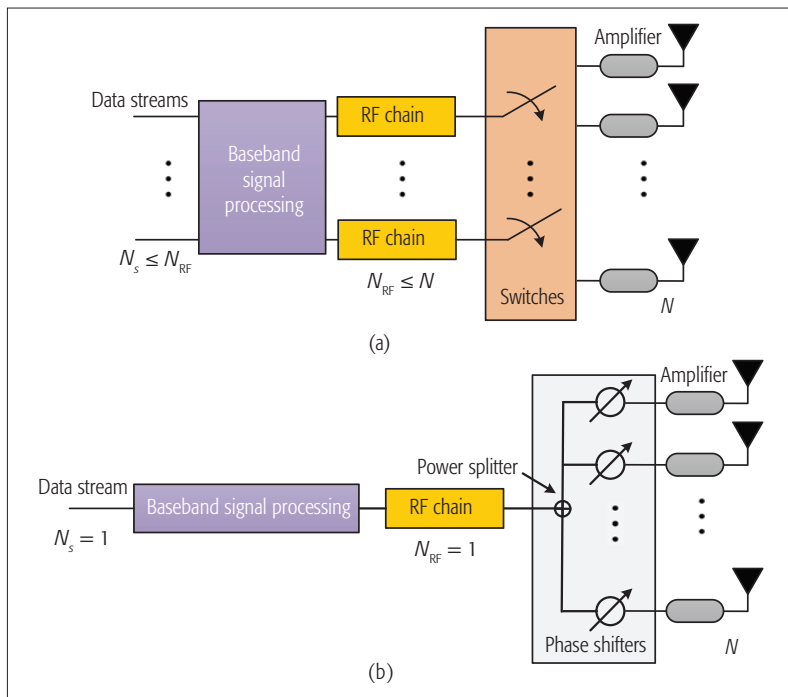
X. Gao and L. Dai (corresponding author) are with the Tsinghua National Laboratory for Information Science and Technology, Tsinghua University; A. Sayeed is with the University of Wisconsin.

Figure 1. Architectures of traditional low RF-complexity technologies: a) antenna selection; b) analog beamforming.

mmWave communications. These two technologies can be regarded as the basics of PAHP and LAHP.

ANTENNA SELECTION

As shown in Fig. 1a, the key feature of antenna selection [6] is that there is one selecting network between N_{RF} RF chains and N antennas. Based on the channel state information (CSI), the target of antenna selection is to select N_{RF} best antennas out of total N antennas for data transmission to maximize the achievable sum-rate [6].

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 [6]. However, when channels are highly correlated, the achievable sum-rate of antenna selection will decrease drastically [6], as antenna selection incurs more channel information loss in this case.

ANALOG BEAMFORMING

As shown in Fig. 1b, the key idea of analog beamforming [7] is to use only one RF chain to transmit a single data stream, and employ the phase shifter network to control the phases of original signals to maximize the array gain and effective signal-to-noise ratio (SNR). Building the beamforming vectors (including the relative amplitudes and phases applied to the different antenna elements to shape the signal strength at a specific direction in the far field) 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 (consisting of several pre-defined beamforming vectors) is adopted to progressively refine the selected beamforming vectors [7].

The advantage of analog beamforming is that it only requires one RF chain, leading to quite low hardware cost and power consumption [7]. However, analog beamforming can only adjust the phases of the signals, which means that all the elements of the beamforming vector have the same amplitude. Such a design constraint will incur some performance loss [3]. More importantly, analog beamforming can only support single-stream transmission, which cannot be used in multi-stream or multi-user scenarios [3].

CAN TRADITIONAL LOW RF-COMPLEXITY TECHNOLOGIES BE USED IN MMWAVE MIMO SYSTEMS?

Note that the outdoor mmWave MIMO channel is significantly different from the one at microwave frequencies. One of the most important differences is that the scattering of outdoor mmWave communications is usually limited, because the wavelengths at mmWave frequencies are quite small compared to the obstacle size, leading to poor diffraction [3]. Moreover, though scattering occurs, it incurs significant 5–20 dB attenuation at mmWave frequencies [2, 5]. A study in New York has shown that the average number of paths in 28 GHz outdoor mmWave communications is only 2.4 [2]. This means that the outdoor mmWave MIMO channel is usually low-rank with high correlation in the spatial domain and sparse in the angular domain [5].

Based on these facts, we know that antenna selection is not appropriate for mmWave MIMO systems [2], since it suffers from serious performance loss with highly correlated channels. Moreover, although analog beamforming is developed for mmWave communications, it can only support single-stream transmission without multiplexing gains. This means that analog beamforming cannot fully exploit the potential of mmWave MIMO in spectrum efficiency [3, 5]. Next, we will investigate two promising low RF-complexity technologies proposed recently for mmWave MIMO systems, that is, PAHP and LAHP.

PHASED ARRAY BASED HYBRID PRECODING

PRINCIPLE

Precoding is used to adjust the weights of transmitted signals to maximize the achievable sum-rate [3]. As shown in Fig. 2a, conventional fully digital precoding can arbitrarily adjust the amplitudes and phases of the original signals. It can achieve multiplexing gains, and enjoys higher design freedom than analog beamforming. However, it requires one dedicated RF chain for each antenna, resulting in unaffordable hardware cost and power consumption when the number of antennas is large. Hybrid precoding can be considered a promising compromise between optimal fully digital precoding and low-cost analog beamforming [4, 5]. Its key idea is to divide the large-size digital precoder into a large-size analog beamformer (realized by the analog circuit) and a small-size digital precoder (requiring a small number of RF chains).

PAHP is one realization of hybrid precoding, where the analog beamformer is realized by phase shifters. Assume there are N_S single-antenna users to be served. As shown in Fig. 2b or Fig. 2c,

the received signal vector **y** for N_s users in the downlink can be presented as

$$\mathbf{y} = \mathbf{HADs} + \mathbf{n}, \qquad (1)$$

where **H** of size $N_s \times N$, **s** of size $N_s \times 1$, and **n** of size $N_s \times 1$ denote the mmWave MIMO channel matrix, transmitted signal vector, and noise vector, respectively, **A** of size $N \times N_{RF}$ is the analog beamformer, and **D** of size $N_{RF} \times N_s$ is the digital precoder. Note that PAHP has two architectures, that is, full-PAHP [4] and sub-PAHP [8], as illustrated in Fig. 2b and Fig. 2c, respectively. In full-PAHP, each RF chain is connected to all N antennas via phase shifters, and the analog beamformer **A** is a full matrix. It can achieve satisfying performance, but usually requires a large number of NN_{RF} phase shifters (e.g., $NN_{RF} = 256 \times 16 = 4096$), together with the complicated power splitters/cominbers and signal/control lines. In contrast, in sub-PAHP, each RF chain is only connected to a subset of antennas, leading **A** to be a block diagonal matrix. Obviously, sub-PAHP can reduce the number of phase shifters from NN_{RF} to N and avoid using power combiners [8]. Therefore, although sub-PAHP suffers from a loss in array gains by a factor of $1/N_{RF}$, it may be preferred in practice [8].

ADVANTAGES

PAHP can achieve a better trade-off between the hardware cost/power consumption and the sum-rate performance. It can significantly reduce the number of required RF chains from N (e.g., $N = 256$) to N_s (e.g., $N_{RF} = N_s = 16$), leading to lower power consumption. In addition, as explained above, the outdoor mmWave MIMO channel matrix is usually low-rank [2]. This indicates that the maximum number of data streams that can be simultaneously transmitted by such a channel is limited. Therefore, as long as the number of RF chains is larger than the rank of the channel matrix, the small-size digital precoder is still able to fully achieve multiplexing gains and obtain near-optimal performance compared to fully digital precoding [4, 8].

CHALLENGES AND RECENT RESULTS

Optimal Design of Hybrid Precoder: Maximizing the achievable sum-rate by designing the hybrid precoder **P** = **AD** is the main target of PAHP. However, this optimization problem imposes new challenges, since there are several non-convex hardware constraints on the analog beamformer **A**. For example, all the nonzero elements of **A** should share the same amplitude due to the constant modulus constraint on the phase shifter. To this end, one feasible way is to approximate the original optimization problem as a convex one to obtain a near-optimal hybrid precoder with low complexity.

Following this idea, some advanced schemes have been proposed recently. In [4], a spatially sparse scheme is proposed for single-user full-PAHP. It approximates the sum-rate optimization problem as the one minimizing the distance between the optimal fully digital precoder and the hybrid precoder. Then, a variant of the orthogonal matching pursuit (OMP) algorithm [9] is developed to obtain the near-optimal
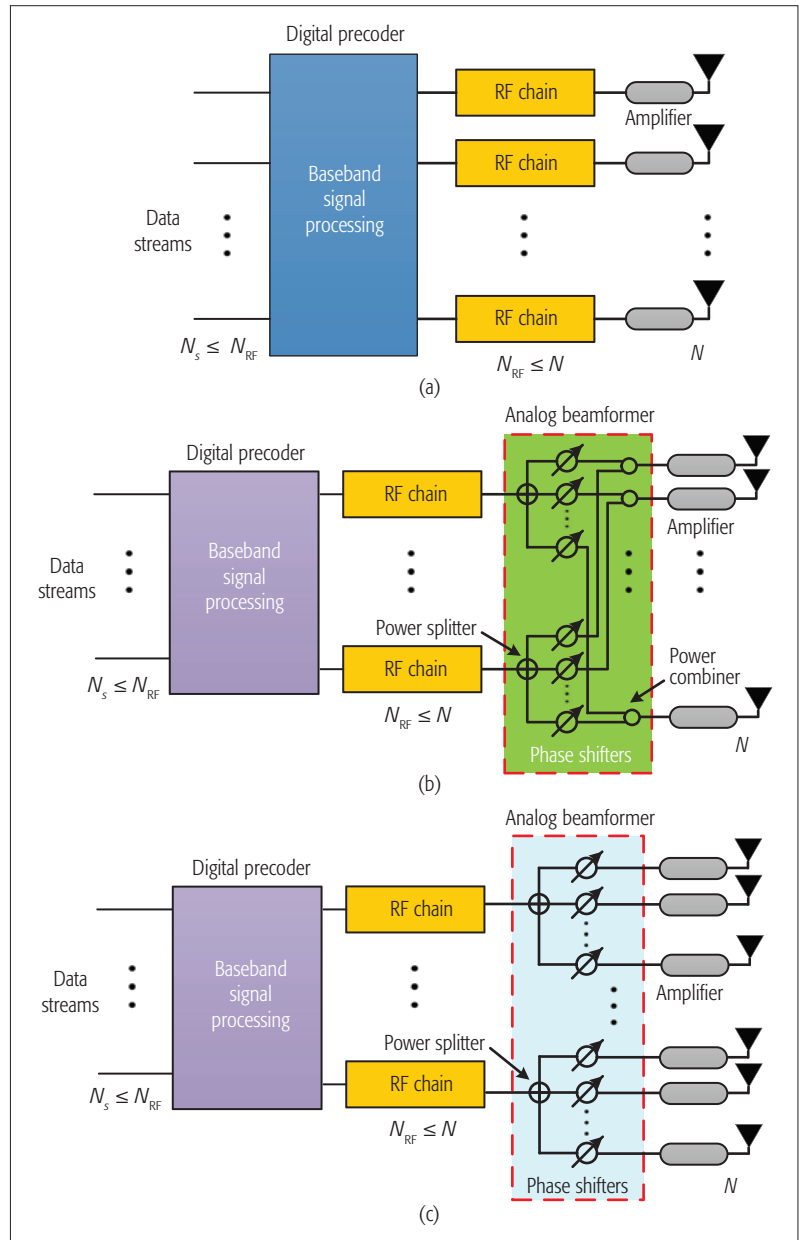

Figure 2. Architecture comparison: a) fully digital precoding; b) full-PAHP; c) sub-PAHP.

hybrid precoder. In [10], full-PAHP is extended to the multi-user scenario, where a two-stage multi-user scheme 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, the classical zero forcing (ZF) precoder is used to cancel multi-user interference. In [8], a successive interference cancelation (SIC)-based scheme is proposed for sub-PAHP. It first decomposes the sum-rate optimization problem into a series of simple and convex sub-problems, each of which only considers one sub-phased array. Then, inspired by the classical SIC multi-user signal detector, the near-optimal hybrid precoder for each sub-phased array is obtained in a one-by-one fashion.

Channel Estimation: The maximum gain of PAHP can only be achieved with perfect CSI, which is difficult to obtain in mmWave MIMO sys-

tems. First, due to the lack of array gains before the establishment of the transmission link, the SNR for channel estimation in PAHP is quite low [3]. Second, the number of RF chains in PAHP is usually much smaller than the number of antennas. Therefore, we cannot directly observe the channel matrix like that in fully digital precoding.

Two typical solutions have been proposed to solve this problem. The first solution divides the channel estimation problem into two steps. In the first step, the BS and users will perform beam training like analog beamforming [7] to determine **A**. In the second step, the effective channel matrix **HA** with smaller size $N_s \times N_{RF}$ ($N_{RF} \ll N$) is estimated by classical schemes, such as least squares (LS). The second solution is to exploit the low-rank characteristic of the mmWave MIMO channel. Instead of estimating the effective channel matrix **HA**, it can directly obtain the complete channel matrix **H** with low pilot overhead. For example, an adaptive compressive sensing (CS) [9] based channel estimation scheme is proposed in [3]. It divides the total channel estimation problem into several sub-problems, each of which only considers one channel path. For each channel path, it first starts with coarse direction grids, and determines the direction of this path belonging to which grid by employing the OMP algorithm. Then, the narrowed direction grids are used, and the direction of this path is further refined. Note that the first solution usually involves low complexity and is easy to implement. In contrast, the second solution can significantly reduce the pilot overhead, but usually involves higher complexity.

Lens Array Based Hybrid Precoding

Principle

Although full-PAHP can achieve near-optimal performance with a reduced number of RF chains, it usually requires a large number of high-resolution phase shifters, together with the complicated power splitters/combiners. Sub-PAHP can partly solve these problems, but it suffers from some performance loss due to the reduced array gains.

These problems can be solved by LAHP [5], another realization of hybrid precoding, where the analog beamformer is realized by lens array and selecting network, as shown in Fig. 3a. By employing a lens array (an electromagnetic lens with directional energy focusing capability and a matching antenna array with elements located in the focal surface of the lens [5]), the signals from different directions (beams) can be concentrated on different antennas, and the spatial channel can be transformed to the beamspace channel. Mathematically, the lens array plays the role of a spatial discrete fourier transform (DFT) matrix **U** of size $N \times N$, whose N columns correspond to the orthogonal beamforming vectors of N pre-defined directions (beams) that cover the whole angular space. The system model of LAHP can be presented by

$$\tilde{\mathbf{y}} = \mathbf{HUDs} + \mathbf{n} = \tilde{\mathbf{H}}\mathbf{Ds} + \mathbf{n}, \qquad (2)$$

where $\tilde{\mathbf{y}}$, **s**, and **n** of size $N_s \times 1$ denote the received signal vector in the beamspace, transmitted signal vector, and noise vector, respectively, **D** of size $N \times N_s$ is the digital precoder, and the beamspace channel $\tilde{\mathbf{H}}$ of size $N_s \times N$ is defined as $\tilde{\mathbf{H}} = \mathbf{HU}$, whose N columns correspond to N orthogonal beams.

Advantages

LAHP can also achieve near-optimal performance with low hardware cost/power consumption. This advantage comes from the fact that the beamspace channel $\tilde{\mathbf{H}}$ at mmWave frequencies is sparse due to the limited scattering [2]. Therefore, similar to antenna selection, we can select only a small number of dominant beams to reduce the MIMO dimension as $\tilde{\mathbf{y}} \approx \tilde{\mathbf{H}}_\mathbf{r}\mathbf{D}_\mathbf{r}\mathbf{s} + \mathbf{n}$, where $\tilde{\mathbf{H}}_\mathbf{r} = \tilde{\mathbf{H}}(:, l)_{l \in \mathcal{B}}$ is the dimension-reduced beamspace channel, $\mathcal{B}$ denotes the set of selected beams, and $\mathbf{D}_r$ of size $|\mathcal{B}| \times N_s$ is the corresponding dimension-reduced digital precoder. As the dimension of $\mathbf{D}_r$ is much smaller than that of **D** in Eq. 2, LAHP can significantly reduce the number of required RF chains without obvious performance loss. Another advantage of LAHP is that the array gains can always be preserved by the low-cost lens array. Therefore, even though the simple selecting network is used, the satisfying performance can still be guaranteed [5].

Challenges and Recent Results

Optimal Design of Beam Selection: The performance of LAHP depends on beam selection, which aims to select $|\mathcal{B}|$ beams out of the total N beams to maximize the achievable sum-rate. The most intuitive beam selection scheme is exhaustive search. It provides optimal performance but prohibitively high complexity, which exponentially increases with the number of selected beams. This means that more efficient beam selection schemes should be designed.

In [5], a magnitude maximization (MM) beam selection scheme is proposed, where several beams with large power are selected for data transmission. The MM beam selection scheme is simple and efficient, but it only aims to preserve power as much as possible without considering interference, leading to some performance loss. In [11], the authors propose a more efficient beam selection scheme by using the incremental algorithm developed from antenna selection. It selects $|\mathcal{B}|$ beams one by one. In each step, the beam with the greatest contribution to the achievable sum-rate is selected. In [12], an interference-aware (IA) beam selection scheme with better performance is proposed. The key idea is to classify all users into two user groups according to the potential interference. For users with small interference, it directly selects the beams with large power, while for users with severe interference, the incremental algorithm is employed to search the optimal beams.

Channel Estimation: The channel estimation for LAHP is a little different from that for PAHP since:
- PAHP and LAHP have different hardware architectures.
- We need to estimate the sparse beamspace channel instead of the conventional low-rank spatial channel [5].

This problem can be solved by following two recently proposed solutions. The first one is to reduce the dimension of the beamspace channel estimation problem. For example, in [13] a
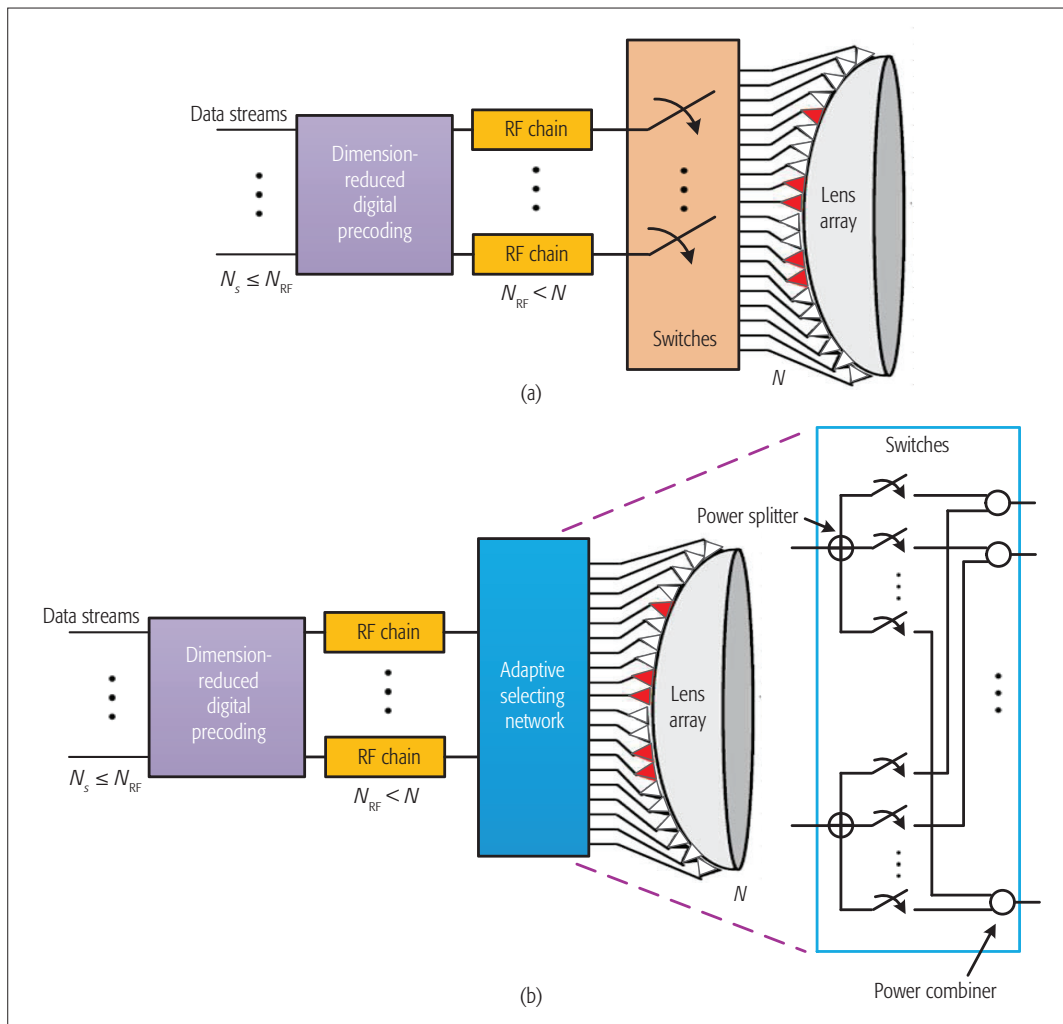
Figure 3. Architectures of LAHP with: a) traditional selecting network; b) proposed adaptive selecting network.

two-step channel estimation scheme is proposed. In the first step, the BS utilizes the selecting network to scan all the beams, and selects several strong beams. In the second step, LS is used to estimate the dimension-reduced beamspace channel. The second solution is to completely estimate the sparse beamspace channel by utilizing CS algorithms. However, if we use the traditional selecting network as shown in Fig. 3a (each RF chain can only select one beam via one switch) to sample the beamspace channel with a reduced number of pilots, the sensing matrix will be rank-deficient and CS algorithms cannot work [9]. To this end, we propose an adaptive selecting network for LAHP as shown in Fig. 3b, where each RF chain is connected to all antennas via switches. For data transmission, it can select beams like the traditional one, while for channel estimation, it can perform as a sensing matrix with randomly selected 0/1 elements, which has full rank [9]. Then, we can estimate the sparse beamspace channel via efficient CS algorithms such as OMP, and considerably reduce pilot overhead.[1] Note that the extra power consumption and hardware cost incurred by the adaptive selecting network is limited, since the switches are easy to implement with low power consumption [15]. Finally, similar to PAHP, the first solution usually involves low

complexity while the second one can considerably reduce pilot overhead.

PERFORMANCE COMPARISON

In this section, we compare the performance of full-PAHP, LAHP with the proposed adaptively selecting network, and fully digital precoding. We first consider an outdoor multi-user mmWave MIMO in a single-cell scenario, where the BS employs $N = 256$ antennas to simultaneously serve $N_s = 16$ single-antenna users. The widely used Saleh-Valenzuela multi-path model is adopted to capture the characteristics of mmWave MIMO channels [2]. Each user has one LoS path and two NLoS paths. The gain of the LoS path is normalized to 1, while the gain of each NLoS path is assumed to follow $\mathcal{CN}(0, 0.1)$. The directions of all paths of users are assumed to follow the IID uniform distribution within $[-\pi/2, \pi/2]$.

Figure 4 shows the comparison of the achievable sum-rate against the SNR for data transmission. For full-PAHP with $N_{RF} = N_s = 16$ RF chains, we use the adaptive CS based channel estimation scheme proposed in [3] (the number of initial direction grids is set as 1024) to estimate the spatial channel, and employ the two-stage multi-user scheme proposed in [10] (4-bit phase shifters are used) to transmit data. For LAHP also with

[1] In practice, the beamspace channel may not be sparse enough due to the power leakage effect, but this can be relieved following the idea in [14].
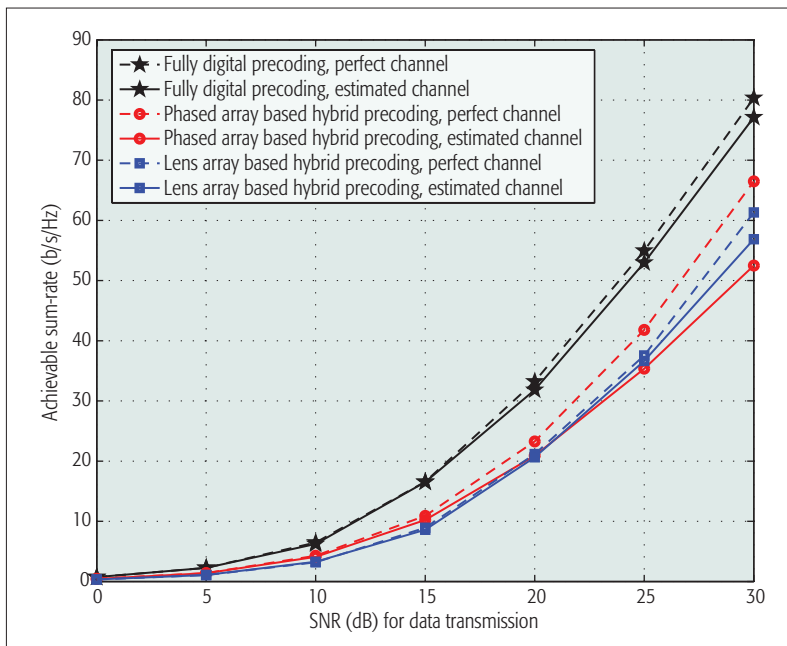
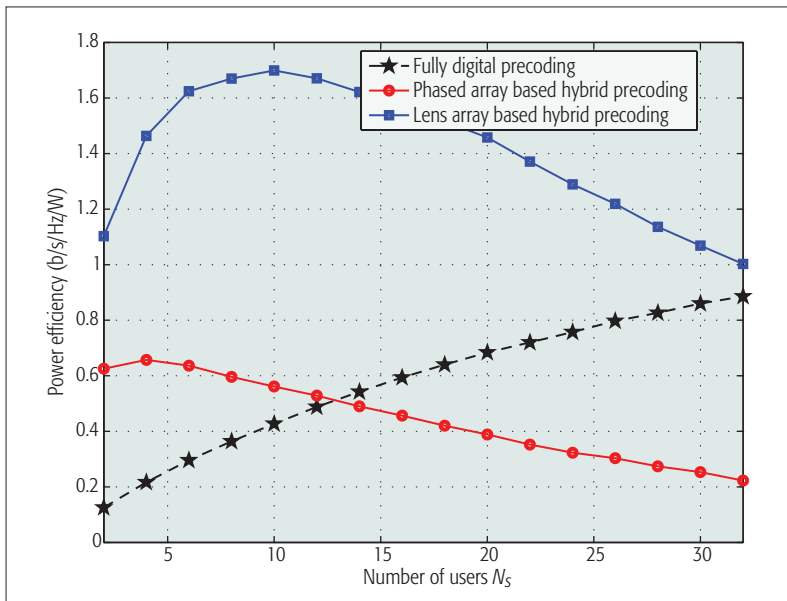**Figure 4.** Comparison of sum-rate against the SNR for data transmission.

Figure 5. Comparison of power efficiency against the number of users N_s.

$N_{RF} = N_s = 16$ RF chains, we utilize the proposed adaptive selecting network to estimate the beam space channel as illustrated above, and adopt the IA beam selection scheme [12] to transmit data. Finally, for fully digital precoding with $N_{RF} = N = 256$ RF chains, the classical LS channel estimation scheme and the ZF precoding scheme are adopted. For fair comparison, we set SNR as 20 dB and use 96 pilots for all three of the adopted channel estimation schemes. From Fig. 4 we observe that although the number of RF chains is significantly reduced, both PAHP and LAHP can achieve sum-rate performance close to that of fully digital precoding. This is due to the fact that PAHP can fully exploit the low-rank characteristic of mmWave channels in the spatial domain, while LAHP can benefit from the sparse characteristic of mmWave channels in the beamspace (angular

domain). Since the lens array 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. 4 also shows that with the perfect channel, PAHP outperforms LAHP by about 2 dB, since the phase shifter has higher design freedom than the switch. Finally, Fig. 4 shows that LAHP is more robust to the channel estimation error, since only the dimension-reduced beamspace channel is effective for data transmission and a slightly inaccurate channel may still achieve satisfying performance.

Figure 5 shows the comparison of power efficiency against the number of users N_s. We define the power efficiency η as $\eta = R/(P_T + P_H)$ [11], where R is the achievable sum-rate, P_T is the transmission power, which can be set as $P_T = 2.5W$ (34 dBm) for outdoor mmWave MIMO in a small cell [2], P_H is the power consumed by hardware architecture. For full-PAHP as shown in Fig. 2b, we have $P_T = NP_A + N_{RF}NP_{PS} + N_{RF}P_{SP} + NP_{CO} + N_{RF}P_{RF}$, where P_A, P_{PS}, P_{SP}, P_{CO}, and P_{RF} are the power consumed by amplifier, phase shifter, power splitter, power combiner, and RF chain, respectively. For LAHP with the proposed adaptive selecting network as shown in Fig. 3b, we have $P_T = NP_A + N_{RF}NP_{SW} + N_{RF}P_{SP} + NP_{CO} + N_{RF}P_{RF}$, where P_{SW} is the power consumed by the switch. Finally, for fully digital precoding as shown in Fig. 2a, we have $P_T = NP_A + NP_{RF}$. In this article, some referenced values[2] are adopted as $P_A = 20mW$ [15], $P_{SP} = P_{CO} = 10mW$ [15], $P_{RF} = 250mW$ [3], $P_{PS} = 30mW$ for a 4-bit phase shifter [15], and $P_{SW} = 5mW$ [15]. Figure 5 shows that both PAHP and LAHP can achieve much higher power efficiency than fully digital precoding when the number of users is not large (e.g., $N_s \leq 8$). However, when $N_s > 12$, LAHP still enjoys high power efficiency, but PAHP performs even worse than fully digital precoding. This can be explained by the fact that as N_s grows, the number of phase shifters required by PAHP increases rapidly. As a result, the power consumption of phase shifters will be huge, even higher than that of RF chains.

Next, we extend the performance comparison to the multi-cell scenario as shown in Fig. 6, where the number of cells is set as 2 for simplicity but without loss of generality. Each cell has one BS with $N = 256$ antennas to serve $N_s = 16$ users with the same transmission power. The channels between the BS and the users in its own cell, and the channels between the BS and the users in the neighbor cell, are generated following the same model as in Fig. 4. We assume that no cooperation between BSs exists, and each BS only knows the channels of the users in its own cell. From Fig. 6, we observe that the achievable sum-rates of all technologies will not grow without bound when the SNR for data transmission increases, because high SNR also incurs high inter-cell interference. However, Fig. 6 still shows that both PAHP and LAHP can achieve near-optimal performance, even in the multi-cell scenario with inter-cell interference.

CONCLUSIONS

In this article, we have introduced two promising low RF-complexity technologies for mmWave MIMO with large antenna array, that is, PAHP

and LAHP, in detail. We have also proposed an adaptive selecting network for LAHP with low hardware cost and power consumption, which can formulate the beamspace channel estimation as a sparse signal recovery problem, and considerably reduce pilot overhead. Finally, we have provided a complete and systematic performance comparison between PAHP and LAHP. It shows that PAHP achieves higher achievable sum-rate than LAHP when the channel is perfectly known, but LAHP is more robust to the channel estimation error. It also shows that LAHP enjoys higher power efficiency than PAHP, since the phase shifter network is replaced by the low-cost lens array and switches.

In addition to the discussions above, there are still some open issues on low RF-complexity technologies for outdoor mmWave MIMO systems. For example, most of the existing low RF-complexity technologies are designed for the narrowband and time-invariant channels. However, due to the large bandwidth and the high frequency, the mmWave MIMO channels are more likely to be broadband and time-varying, which incurs new challenges. Taking PAHP for example, "broadband" means that the analog beamformer cannot be adaptively adjusted according to the frequency, leading to more difficulties in signal processing design, while "time-varying" means that we need to re-estimate the channel and re-compute the hybrid precoder frequently, leading to high pilot overhead and computational complexity. Therefore, designing low RF-complexity technologies for broadband time-varying channels will be an urgent problem to solve.

Figure 6. Comparison of sum-rate in multi-cell scenario.

REFERENCES

[1] S. Mumtaz, J. Rodriguez, and L. Dai, *MmWave Massive MIMO: A Paradigm for 5G*, Academic Press, Elsevier, 2016.
[2] T. S. Rappaport *et al.*, "Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!" *IEEE Access*, vol. 1, May 2013, pp. 335–49.
[3] R. W. Heath *et al.*, "An Overview of Signal Processing Techniques for Millimeter Wave MIMO Systems," *IEEE J. Sel. Top. Signal Process.*, vol. 10, no. 3, Apr. 2016, pp. 436–53.
[4] O. El Ayach *et al.*, "Spatially Sparse Precoding in Millimeter Wave MIMO Systems," *IEEE Trans. Wireless Commun.*, vol. 13, no. 3, Mar. 2014, pp. 1499–1513.
[5] J. Brady, N. Behdad, and A. Sayeed, "Beamspace MIMO for Millimeter-Wave Communications: System Architecture, Modeling, Analysis, and Measurements," *IEEE Trans. Ant. and Propag.*, vol. 61, no. 7, July 2013, pp. 3814–27.
[6] A. F. Molisch and M. Z. Win, "MIMO Systems with Antenna Selection," *IEEE Microwave Mag.*, vol. 5, no. 1, Mar. 2004, pp. 46–56.
[7] S. Hur *et al.*, "Millimeter Wave Beamforming for Wireless Backhaul and Access in Small Cell Networks," *IEEE Trans. Commun.*, vol. 61, no. 10, Oct. 2013, pp. 4391–4403.
[8] X. Gao *et al.*, "Energy-Efficient Hybrid Analog and Digital Precoding for mmWave MIMO Systems with Large Antenna Arrays," *IEEE JSAC*, vol. 34, no. 4, Apr. 2016, pp. 998–1009.
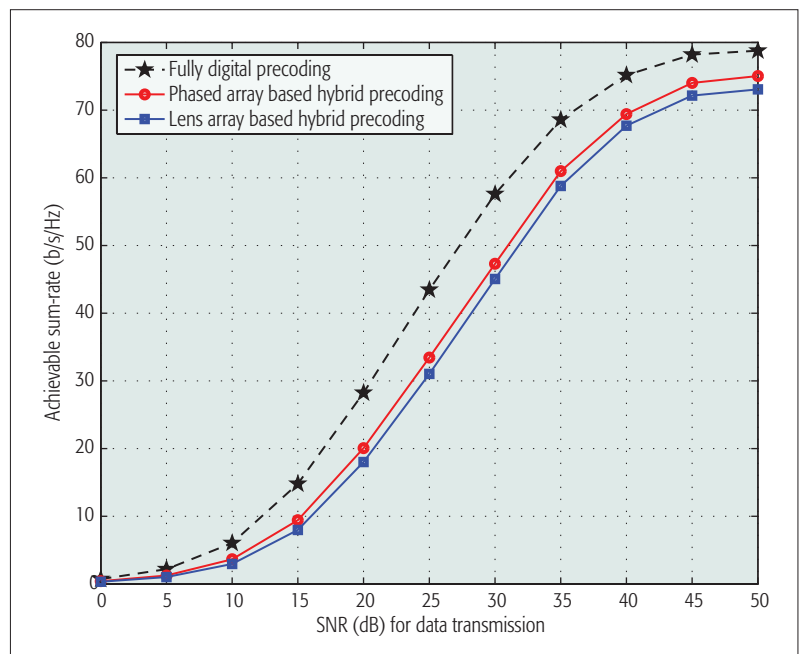[9] W. U. Bajwa *et al.*, "Compressed Channel Sensing: A New Approach to Estimating Sparse Multipath Channels," *Proc. IEEE*, vol. 98, no. 6, June 2010, pp. 1058–76.
[10] A. Alkhateeb, G. Leus, and R. W. Heath, "Limited Feedback Hybrid Precoding for Multi-User Millimeter Wave Systems," *IEEE Trans. Wireless Commun.*, vol. 14, no. 11, Nov. 2015, pp. 6481–94.
[11] P. Amadori and C. Masouros, "Low RF-Complexity Millimeter-Wave Beamspace-MIMO Systems by Beam Selection," *IEEE Trans. Commun.*, vol. 63, no. 6, June 2015, pp. 2212–22.
[12] X. Gao *et al.*, "Near-Optimal Beam Selection for Beamspace mmWave Massive MIMO Systems," *IEEE Commun. Lett.*, vol. 20, no. 5, May 2016, pp. 1054–57.
[13] J. Hogan and A. Sayeed, "Beam Selection for Performance-Complexity Optimization in High-Dimension MIMO Systems," *Proc. CISS*, Mar. 2016, pp. 337–42.
[14] G. Taubock *et al.*, "Compressive Estimation of Doubly Selective Channels in Multicarrier Systems: Leakage Effects and Sparsity-Enhancing Processing," *IEEE J. Sel. Top. Signal Process.*, vol. 4, no. 2, Apr. 2010, pp. 255–71.
[15] R. Méndez-Rial *et al.*, "Hybrid MIMO Architectures for Millimeter Wave Communications: Phase Shifters or Switches?" *IEEE Access*, vol. 4, Jan. 2016, pp. 247–67.

BIOGRAPHIES

XINYU GAO [S'14] received the B.E. degree in communication engineering from Harbin Institute of Technology, Heilongjiang, China, in 2014. He is currently working toward a Ph.D. degree in electronic engineering from Tsinghua University, Beijing, China. His research interests include massive MIMO and mmWave communications. He received the national scholarship in 2015 and the WCSP Best Paper Award in 2016.

LINGLONG DAI [M'11, SM'14] received the Ph.D. degree from Tsinghua University, Beijing, China, in 2011. He is currently an associate professor at Tsinghua University. His current research interests include massive MIMO, millimeter-wave communications, multiple access, and sparse signal processing. He has received five conference Best Paper Awards (IEEE ICC 2013, IEEE ICC 2014, WCSP 2016, IEEE ICC 2017, and IEEE VTC 2017 Fall).

AKBAR M. SAYEED [F'12] received the Ph.D. degree from the University of Illinois at Urbana-Champaign, USA, in 1996. He is a professor of electrical and computer engineering at the University of Wisconsin-Madison. His research interests include wireless communications, statistical signal processing, communication and information theory, wireless channel modeling, time-frequency analysis, and development of basic theory, system architectures, and prototypes for new wireless technologies.