MmWave Massive-MIMO-Based Wireless Backhaul for the 5G Ultra-Dense Network

ZHEN GAO, LINGLONG DAI, DE MI, ZHAOCHENG WANG, MUHAMMAD ALI IMRAN, AND MUHAMMAD ZEESHAN SHAKIR

Abstract

The ultra-dense network (UDN) has been considered as a promising candidate for future 5G networks to meet the explosive data demand. To realize UDN, a reliable, gigahertz bandwidth, and cost-effective backhaul connecting ultra-dense small-cell BSs and macrocell BS are prerequisite. Millimeter-wave can provide the potential gigabit-per-second traffic for wireless backhaul. Moreover, mmWave can easily be integrated with massive MIMO for improved link reliability. In this article, we discuss the feasibility of mmWave massive-MIMO-based wireless backhaul for 5G UDN, and the benefits and challenges are also addressed. In particular, we propose a digitally controlled phase shifter network (DPSN)-based hybrid precoding/combining scheme for mmWave massive MIMO, whereby the low-rank property of the mmWave massive MIMO channel matrix is leveraged to reduce the required cost and complexity of a transceiver with a negligible performance loss. One key feature of the proposed scheme is that the macrocell BS can simultaneously support multiple small-cell BSs with multiple streams for each small-cell BS, which is essentially different from conventional hybrid precoding/combining schemes, typically limited to single-user MIMO with multiple streams or multi-user MIMO with single stream for each user. Based on the proposed scheme, we further explore the fundamental issues of developing mmWave massive MIMO for wireless backhaul, and the associated challenges, insight, and prospects to enable mmWave massive-MIMO-based wireless backhaul for 5G UDN are discussed.

Zhen Gao, Linglong Dai, and Zhaocheng Wang are with Tsinghua University.

De Mi and Muhammad Ali Imran are with the University of Surrey.

Muhammad Zeeshan Shakir is with Texas A&M University at Qatar.

This work was supported in part by the International Science & Technology Cooperation Program of China (Grant No. 2015DFG12760), the National Natural Science Foundation of China (Grant Nos. 61201185 and 61271266), the Beijing Natural Science Foundation (Grant No. 4142027), and the Foundation of Shenzhen government.

Introduction

The explosive traffic demand is challenging current cellular networks, including the most advanced fourth generation (4G) network. It has been the consensus that future 5G networks should realize the goals of 1000-fold system capacity, 100-fold energy efficiency, and 10-fold lower latency. To realize such an aggressive 5G version, the ultra-dense network (UDN) has been considered as a promising system architecture to enable gigabit-per-second user experience, seamless coverage, and green communications [1].

In UDN, as shown in Fig. 1, macrocell base stations (BSs) with large coverage usually control user scheduling and resource allocation, and support high-mobility users, while many ultra-dense small-cell BSs with much smaller coverage provide high data rate for low-mobility users. Due to ultra-dense small-cell BSs, better frequency reuse can be achieved, and energy efficiency can also be improved substantially due to the reduced path loss in small cells [1].

To enable UDN, a reliable, cost-effective, gigahertz bandwidth backhaul connecting the macrocell BS and the associated small-cell BSs is prerequisite. It has been demonstrated that backhaul with 1~10 GHz bandwidth is required to effectively support UDN [2]. Conventional optical fiber enjoys large bandwidth and reliability, but its application to UDN as backhaul may not be an economical choice for operators due to the restriction of deployment and installation. Hence, wireless backhaul, especially millimeter-wave (mmWave) backhaul, is more attractive to overcome the geographical constraints. The advantages of mmWave backhaul are:

- *A large amount of underutilized band* in mmWave can be leveraged to provide the potential gigahertz transmission bandwidth, which is different from scarce microwave band in conventional cellular networks [3].
- *A large number of antennas* can easily be employed for mmWave communications due to the small wavelength of mmWave, which can improve the signal directivity (reduce the co-channel interference) and link reliability (mitigate the large path loss) for mmWave backhaul [4].

This article combines mmWave with a large number of antennas, which is also referred to as mmWave massive multiple-input multiple-output (MIMO), to provide wireless backhaul for future 5G UDN. The contributions of this article are listed as follows:

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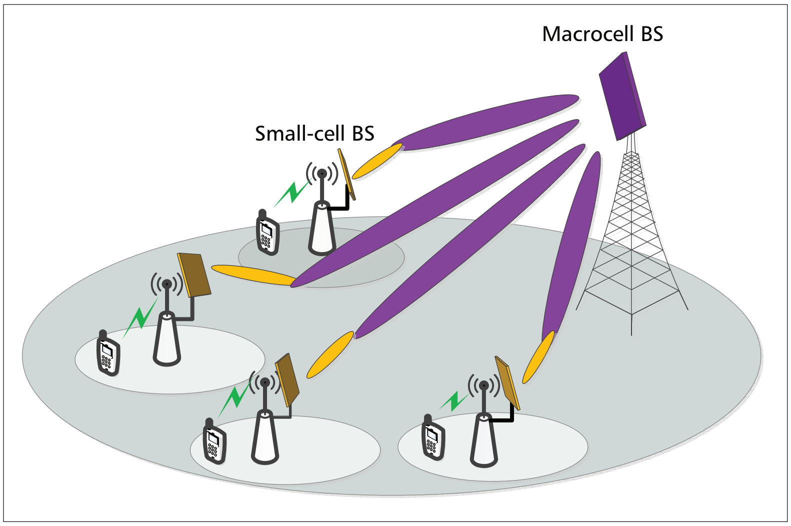

Figure 1. MmWave massive-MIMO-based wireless backhaul for 5G UDN.

- We discuss the feasibility and challenges of the mmWave massive-MIMO-based backhaul for UDN, where its advantages, and differences compared with conventional massive MIMO working at sub-3~6 GHz for the radio access network (RAN) are also addressed. Moreover, the sparsity of mmWave massive MIMO channels is stressed.
- We explore key issues and potential research directions of the cost-effective mmWave massive MIMO for UDN backhaul. In particular, a digitally controlled phase shifter network (DPSN)-based hybrid precoding/combining and the associated compressive sensing (CS)-based channel estimation is proposed.
- We address the benefits of the wireless backhaul for 5G UDN with the technique of mmWave massive MIMO, which may provide a viable approach to realize the novel backhaul network topology, scheduling strategy, and efficient in-band backhaul in mmWave.

Feasibility and Challenges of MmWave Massive MIMO for Wireless Backhaul in 5G UDN

In UDN, small cells are densely deployed in hotspots (e.g., office buildings, shopping malls, residential apartments) with high data rate to provide traffic offload from macrocells, since the large majority of traffic demand comes from these hotspots. Hence, the backhaul between the macrocell BS and the associated small-cell BSs should provide large bandwidth with reliable link transmission. Besides, power efficiency and deployment cost are also key considerations for operators.

MmWave Is Suitable for Wireless Backhaul in 5G UDN

Traditionally, mmWave is not used for RAN in existing cellular networks due to its high path loss and expensive electron components. However, mmWave is especially suitable for backhaul in UDN due to the following reasons.

High-capacity and inexpensive: The large amount of underutilized mmWave including unlicensed V-band (57–67 GHz) and lightly licensed E-band (71–76 GHz and 81–86 GHz) (the specific regulation may vary from country to country) can provide potential gigahertz transmission bandwidth [3]. For example, more than 1 Gb/s backhaul capacity can be supported over a 250 MHz channel in E-band [2].

Immunity to interference: The transmission distance comfort zone for E-band is up to several kilometers due to rain attenuation, while that for V-band is about 500–700 m due to both the rain and oxygen attenuation. Due to high path loss, mmWave is suitable for UDN, where improved frequency reuse and reduced inter-cell interference are expected. It should be pointed out that rain attenuation is not a big issue for mmWave used in UDN. If we consider very heavy rainfall of 25 mm/hr, the rain attenuation is only around 2 dB in E-band if we consider the distance of a backhaul link is 200 m in typical urban UDN [3].

Small form factor: The small wavelength of mmWave implies that massive antennas can easily be equipped at both macro and small-cell BSs, which can improve the signal directivity and compensate severe path loss of mmWave to achieve larger coverage in turn [4]. Hence, the compact mmWave backhaul equipment can easily be deployed with low-cost sites (e.g., light poles, building walls, bus stations) and short installation time.

MmWave Massive MIMO Is Different from Microwave Massie MIMO

Inheriting the advantages of conventional microwave massive MIMO, mmWave massive MIMO has flexible beamforming, spatial multiplexing, and diversity. Hence, mmWave massive MIMO brings not only the improved reliability of the backhaul link, but also new architecture of a backhaul network including a flexible network topology and scheduling scheme, which will be further detailed later. However, compared to conventional microwave (sub-3~6 GHz) massive MIMO used for RAN, the implementation of mmWave massive MIMO also brings challenges as follows.

•First, the cost and complexity of a transceiver, including high-speed analog-digital converters (ADCs) and digital-analog converters (DACs), synthesizers, mixers, and so on in mmWave communications are much larger than those in conventional microwave communications. Hence, massive low-cost antennas but a limited number of expensive baseband (BB) chains can be an appealing transceiver structure for mmWave massive MIMO, which, however, challenges conventional precoding/combining schemes.

•Second, the number of antennas in mmWave at both macro and small-cell BSs can be much larger than that in conventional microwave massive MIMO due to the much smaller wavelength of mmWave. This implies the challenge that channel estimation in mmWave massive MIMO can be more difficult even when time-division duplex (TDD) leveraging the channel reciprocity is considered. Even for TDD-based mmWave communications, the synchronization and calibration error of radio frequency (RF) chains to guarantee the channel reciprocity are not trivial [5].

• Third, since single-antenna users are typically considered in microwave massive MIMO due to the limited form factor, only channel state information at the transmitter (CSIT) is required for precoding. However, for mmWave massive MIMO, where each small-cell BS can be equipped with massive antennas, precoding in the uplink and combining in the downlink at small-cell BSs are also necessary, since precoding/combining can effectively support multiple streams and directional transmission for the improved link reliability. Therefore, channel state information at the receiver (CSIR) is also required for mmWave massive MIMO, which indicates another challenge that channel estimation acquired in the uplink by leveraging the channel reciprocity should also be fed back to small-cell BSs.

MmWave Channel Characteristics

As discussed above, the mmWave massive-MIMO-based backhaul is apt for the transceiver with a limited number of BB chains. Compared to microwave massive MIMO using full digital precoding, precoding/combining with the smaller number of BB chains than that of antenna elements can make mmWave massive MIMO suffer from a certain performance loss, which is largely dependent on the propagation condition of mmWave massive MIMO channels.

MmWave Channels with Spatial/Angular Sparsity

Extensive experiments have shown that mmWave massive MIMO channels exhibit the obviously spatial/angular sparsity due to its high path loss for non-line-of-sight (NLOS) signals, where only a small number of dominant multipath components (typically, 3~5 paths in realistic environments [6]) consist of mmWave MIMO multipath channels. If we consider the widely used uniform linear array (ULA), the point-to-point mmWave massive MIMO channel can be modeled as [6]

$$\mathbf{H}=\sqrt{\frac{N_T N_R}{\rho}}\sum_{l=1}^{L}\alpha_l \mathbf{a}_T(\theta_l)\mathbf{b}_R^*(\varphi_l) =\sqrt{\frac{N_T N_R}{\rho}}\mathbf{A}_T\mathbf{D}\mathbf{B}_R^*, \quad (1)$$

where N_T and N_R are the numbers of transmit and receive antennas, respectively, ρ is the average path loss, L is the number of paths, α_l is the complex gain of the lth path, and $\theta_l \in [0, 2\pi]$ and $\varphi_l \in [0, 2\pi]$ are azimuth angles of departure or arrival (AoD/AoA). In addition,

$$\mathbf{a}_T(\theta_l)=\frac{1}{\sqrt{N_T}}\left[1, e^{j2\pi d\sin(\theta_l)/\lambda}, \cdots, e^{j2\pi(N_T-1)d\sin(\theta_l)/\lambda}\right]^{\mathrm{T}}$$

and

$$\mathbf{b}_R(\varphi_l)=\frac{1}{\sqrt{N_R}}\left[1, e^{j2\pi d\sin(\varphi_l)/\lambda}, \cdots, e^{j2\pi(N_R-1)d\sin(\varphi_l)/\lambda}\right]^{\mathrm{T}}$$

are steering vectors at the transmitter and receiver, respectively,

$$\mathbf{A}_T=\left[\mathbf{a}_T(\theta_1)|\mathbf{a}_T(\theta_2)|\cdots|\mathbf{a}_T(\theta_L)\right],$$
$$\mathbf{B}_R=\left[\mathbf{b}_R(\varphi_1)|\mathbf{b}_R(\varphi_2)|\cdots|\mathbf{b}_R(\varphi_L)\right],$$

and the diagonal matrix $\mathbf{D}$ = diag $\{\alpha_1, \alpha_2, \ldots, \alpha_L\}$, where λ and d are wavelength and antenna spacing, respectively.

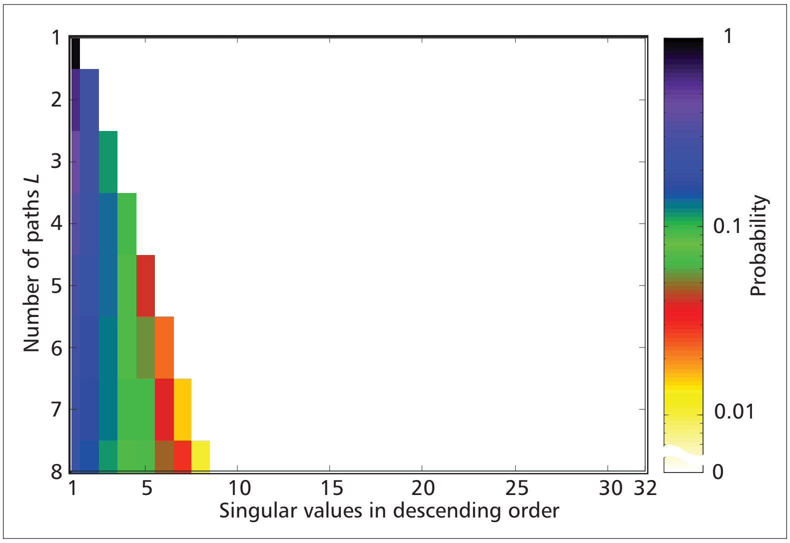

Figure 2. Energy probability distribution of singular values in descending order of the mmWave massive MIMO channel matrix vs. different Ls, where N_T = 512 and N_R = 32.

Low-Rank Property of MmWave Massive MIMO Channels

The spatial/angular sparsity of mmWave channels with small L (e.g., 3~5) and massive MIMO channel matrix with large N_T, N_R (dozens or even hundreds) implies that the mmWave massive MIMO channel matrix has the low-rank property [7]. For example, Fig. 2 provides the energy probability distribution of singular values of $\mathbf{H}$ with descending order against different Ls, where N_T = 512, N_R = 32, and path gains follow the independent and identically distributed (i.i.d.) complex Gaussian distribution. It can be observed that the mmWave massive MIMO channel matrix has the obvious low-rank property. If we consider single-user (SU) MIMO with CSIT for precoding and CSIR for combining, the low-rank channel matrix indicates that the number of effective independent streams that can be exploited is small. Theoretical analysis has shown that the capacity of MIMO systems over sparse mmWave channels appears to have the ceiling effect with the increased number of BB chains [7]. Hence, we can leverage the finite number of BB chains to maximize the backhaul through-

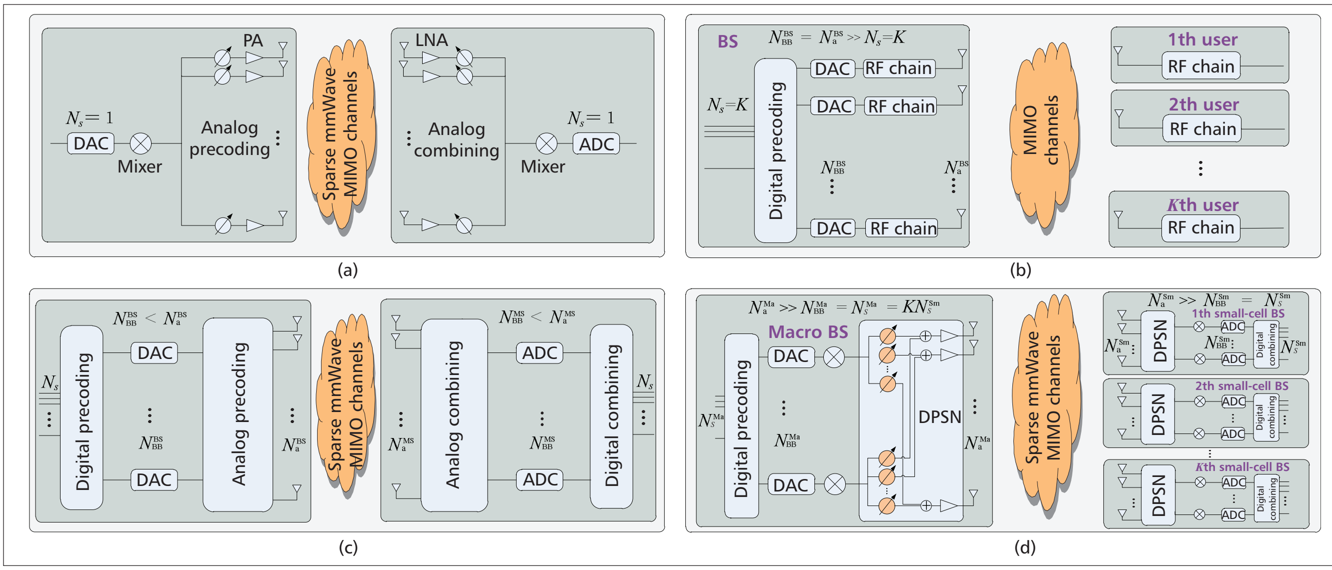

Figure 3. Comparison of precoding/combining schemes, where PA denotes power amplifier and LNA denotes low-noise amplifier: a) analog precoding/combining scheme in mmWave multi-antenna systems; b) digital precoding in microwave massive MIMO for RAN; c) conventional hybrid precoding/combining in mmWave massive MIMO for RAN; d) proposed DPSN-based hybrid precoding/combining for mmWave massive MIMO in UDN backhaul.

put over sparse mmWave channels, where the number of BB chains can be as small as the effective rank of the mmWave massive MIMO channel matrix.

Key Issues of Designing MmWave Massive MIMO for 5G UDN Backhaul

Hybrid Precoding/Combining Design

In order to realize the reliable point-to-multipoint (P2MP) backhaul link, mmWave massive MIMO for UDN backhaul should exploit the flexible beamforming and spatial multiplexing to simultaneously support multiple small-cell BSs and provide multiple streams for each small-cell BS, which challenges conventional precoding/combining schemes.

Overview of Existing Precoding/Combining Schemes: Conventional mmWave multi-antenna systems utilize a single RF chain and analog (e.g., ferrite-based) phase shifters for precoding/combining as shown in Fig. 3a, but are limited to SU-MIMO with a single stream. Full digital precoding in microwave massive MIMO, as shown in Fig. 3b, can simultaneously support multiple single-antenna users (i.e., multi-user [MU]-MIMO), but it requires one specific RF chain to be connected to each antenna, which can be unaffordable in mmWave communications [7]. Recently, the hybrid precoding/combining scheme consisting of analog and digital precoding/combining, as shown in Fig. 3c, has been proposed for mmWave massive MIMO with the reduced cost and complexity of the transceiver. However, state-of-the-art hybrid precoding/combining schemes are usually limited to SU-MIMO with multiple streams or MU-MIMO with a single stream for each user [4, 6–8].

Proposed DPSN-Based Hybrid Precoding/Combining: Multi-User and Multi-Stream:To support multi-user and multi-stream, we propose the DPSN-based hybrid precoding/combining scheme as shown in Fig. 3d, which can effectively reduce the cost and complexity of the transceiver. Specifically, consider the macrocell BS has $N_{\mathrm{a}}^{\mathrm{Ma}}$ antennas but $N_{\mathrm{BB}}^{\mathrm{Ma}}$ BB chains, where $N_{\mathrm{a}}^{\mathrm{Ma}} \gg N_{\mathrm{BB}}^{\mathrm{Ma}}$, while each small-cell BS has $N_{\mathrm{a}}^{\mathrm{Sm}}$ antennas but $N_{\mathrm{BB}}^{\mathrm{Sm}}$ BB chains, where $N_{\mathrm{a}}^{\mathrm{Sm}} \gg N_{\mathrm{BB}}^{\mathrm{Sm}}$. The number of simultaneously supported small-cell BSs is K. $\mathbf{H}_k \in \mathbb{C}^{N_{\mathrm{a}}^{\mathrm{Ma}} \times N_{\mathrm{a}}^{\mathrm{Sm}}}$ with $N_{\mathrm{a}}^{\mathrm{Ma}} > N_{\mathrm{a}}^{\mathrm{Sm}}$ denotes the mmWave massive MIMO channel matrix associated with the macrocell BS and the kth small-cell BS, and it can be expressed as follows according to singular value decomposition (SVD):

$$\mathbf{H}_k = \left[\mathbf{U}_k^1 | \mathbf{U}_k^2\right] \begin{bmatrix} \mathbf{\Sigma}_k^1 & \mathbf{0} \\ \mathbf{0} & \mathbf{\Sigma}_k^2 \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \left(\mathbf{V}_k^1\right)^* \\ \left(\mathbf{V}_k^2\right)^* \end{bmatrix} \approx \mathbf{U}_k^1 \mathbf{\Sigma}_k^1 \left(\mathbf{V}_k^1\right)^*, \tag{2}$$

where both $[\mathbf{U}_k^1 | \mathbf{U}_k^2] \in \mathbb{C}^{N_{\mathrm{a}}^{\mathrm{Ma}} \times N_{\mathrm{a}}^{\mathrm{Ma}}}$ and $[\mathbf{V}_k^1 | \mathbf{V}_k^2]^* \in \mathbb{C}^{N_{\mathrm{a}}^{\mathrm{Sm}} \times N_{\mathrm{a}}^{\mathrm{Sm}}}$ are unitary matrices, $\mathbf{\Sigma}_k^1 \in \mathbb{C}^{R_k \times R_k}$ and $\mathbf{\Sigma}_k^2 \in \mathbb{C}^{(N_{\mathrm{a}}^{\mathrm{Sm}} - R_k) \times (N_{\mathrm{a}}^{\mathrm{Sm}} - R_k)}$ are diagonal matrices whose diagonal elements are singular values of $\mathbf{H}_k$, and R_k is the effective rank of $\mathbf{H}_k$. The approximation in Eq. 2 is due to the low-rank property of $\mathbf{H}_k$ with $\mathbf{\Sigma}_k^2 \approx \mathbf{0}$, so $\mathbf{U}_k^1 \in \mathbb{C}^{N_{\mathrm{a}}^{\mathrm{Ma}} \times R_k}$ and $(\mathbf{V}_k^1)^* \in \mathbb{C}^{R_k \times N_{\mathrm{a}}^{\mathrm{Sm}}}$.

Equation 2 indicates that $N_{\mathrm{BB}}^{\mathrm{Ma}}$ and $N_{\mathrm{BB}}^{\mathrm{Sm}}$ can be reduced to R_k in SU-MIMO due to only $N_s = R_k$ effective independent streams. Moreover, we can use the precoding matrix $\mathbf{P}_k = (\mathbf{U}_k^1)^*$ and the combining matrix $\mathbf{C}_k = \mathbf{V}_k^1$ to effectively realize the independent multi-stream transmission [9]. To achieve this goal, we can use the emerging low-cost silicon-based SiGe and complementary metal oxide semiconductor (CMOS)-based programmable DPSN [10] to realize partial precoding/combining in the analog RF. With the cascade of the digital precoding matrix $\mathbf{P}_{d,k} \in \mathbb{C}^{R_k \times R_k}$ (or combining matrix $\mathbf{C}_{d,k} \in \mathbb{C}^{R_k \times R_k}$) and analog precoding matrix $\mathbf{P}_{a,k} \in \mathbb{C}^{R_k \times N_a^{Ma}}$ (or combining $\mathbf{C}_{a,k} \in \mathbb{C}^{N_a^{Sm} \times R_k}$), we can use $\mathbf{P}_{d,k}\mathbf{P}_{a,k}$ (or $\mathbf{C}_{a,k}\mathbf{C}_{d,k}$) to approximate $\mathbf{P}_k$ (or $\mathbf{C}_k$). Consider the precoding; for instance, we can use the following iterative approach to acquire $\mathbf{P}_{d,k}$ and $\mathbf{P}_{a,k}$ that can minimize $\|\mathbf{P}_k - \mathbf{P}_{d,k}\mathbf{P}_{a,k}\|_F$ with the constraint that elements in $\mathbf{P}_{a,k}$ are constant modulus. We initialize that $\widetilde{\mathbf{P}}_k \leftarrow \mathbf{P}_k$. Then we perform the following operations iteratively until $\mathbf{P}_{a,k}$ and $\mathbf{P}_{d,k}$ converge:

1. Every element of $\mathbf{P}_{a,k}$ has the same phase as the corresponding element of $\widetilde{\mathbf{P}}_k$.
2. $\mathbf{P}_{d,k} \leftarrow \mathbf{P}_k (\mathbf{P}_{a,k})^\dagger$.
3. $\widetilde{\mathbf{P}}_k \leftarrow (\mathbf{P}_{d,k})^\dagger \mathbf{P}_k$.

Note that $\mathbf{P}_{a,k}$ always meets the constraint of constant modulus, and $(\ )^\dagger$ is the Moore-Penrose pseudoinverse. Similarly, we can acquire $\mathbf{C}_{d,k}$ and $\mathbf{C}_{a,k}$ according to $\mathbf{C}_k$ with the same approach. Besides, some power allocation strategies such as waterfilling can be integrated in the digital baseband precoding/combining to further improve the achievable throughput

Furthermore, consider the downlink MU-MIMO, where the channel matrix between a macrocell BS and K small-cell BSs can be denoted as $\mathbf{H} \in \mathbb{C}^{N_a^{Ma} \times KN_a^{Sm}}$, and it can be represented as $\mathbf{H} = [\mathbf{H}_1 | \mathbf{H}_2 | \ \dots \ | \mathbf{H}_K]$ with $\mathbf{H}_k \approx \mathbf{U}_k^1 \mathbf{\Sigma}_k^1 (\mathbf{V}_k^1)^*$ for $1 \le k \le K$ according to Eq. 2. Hence, $\mathbf{H}$ can be further expressed as

$$\mathbf{H} \approx \left[\mathbf{U}_1^1 | \mathbf{U}_2^1 | \cdots | \mathbf{U}_K^1\right] \times \mathrm{diag}\left\{\mathbf{\Sigma}_1^1, \mathbf{\Sigma}_2^1, \cdots, \mathbf{\Sigma}_K^1\right\} \times \mathrm{diag}\left\{\left(\mathbf{V}_1^1\right)^*, \left(\mathbf{V}_2^1\right)^*, \cdots, \left(\mathbf{V}_K^1\right)^*\right\}, \quad (3)$$

where $\mathbf{H}_k$ for $1 \le k \le K$ are assumed to share the same effective rank $R_k = R$. For precoding/combining in the proposed MU-MIMO system, the analog precoding matrix at the macrocell BS is $\mathbf{P}_a = [\mathbf{P}_{a,1}^T | \mathbf{P}_{a,2}^T | \ \dots \ | \mathbf{P}_{a,K}^T]^* \in \pounds^{KR \times N_a^{Ma}}$, and the analog and digital combining matrices for the kth small-cell BS can be $\mathbf{C}_{a,k}$ and $\mathbf{C}_{d,k}$, respectively. To further eliminate the multi-user interference, digital precoding $\mathbf{P}_d = (\mathbf{P}_a \mathbf{U}^{\theta/0})^{-1}$ is proposed at the macrocell BS, where $\mathbf{U}^{\theta/0} = [\mathbf{U}_1^1 | \mathbf{U}_1^2 | \ \dots \ | \mathbf{U}_K^1]$. The precoding/combining in the uplink of mmWave massive-MIMO-based backhaul is similar to the downlink, which will not be detailed in this article owing to the space limitation.

The proposed precoding/combining scheme can diagonalize the equivalent channel $\mathbf{P}_d\mathbf{P}_a\mathbf{H}\mathrm{diag}\{\mathbf{C}_1, \mathbf{C}_2, \ \dots\ , \mathbf{C}_K\}$ with $\mathbf{C}_k = \mathbf{C}_{a,k}\mathbf{C}_{d,k}$ to realize multi-user and multi-stream transmission, which is essentially different from existing schemes. Moreover, thanks to the obvious low-rank property of the mmWave massive MIMO channel matrix as shown in Fig. 2, the proposed precoding/combining with the reduced number of BB chains only suffers from a negligible performance loss, which is shown later.

CSI Acquisition for mmWave Massive MIMO

To effectively realize the proposed DPSN-based hybrid precoding/combining scheme, a reliable CSI acquisition scheme with low overhead is another challenge.

Challenging Channel Estimation for MmWave Massive MIMO: As discussed earlier, mmWave massive MIMO may suffer from the prohibitively high overhead for channel estimation, and calibration error of RF chains as well as synchronization are also not trivial in TDD. Additionally, due to the much smaller number of BB chains than that of antennas, the effective dimensions that can be exploited for channel estimation will be substantially reduced although massive antennas are employed. Furthermore, channel estimation in the digital baseband should consider the characteristics of phase-shifter networks at both macrocell BS and small-cell BSs, which can make it more complex. Finally, due to the strong signal directivity of mmWave, reliable channel estimation requires sufficient received signal power, which means at least partial CSIT is necessary to ensure beamforming at the transmitter to match mmWave MIMO channels.

Overview of Existing Channel Estimation Schemes: Wireless local area networks (WLANs) (IEEE 802.11ad) relies on beamforming training to compensate the large path loss in 60 GHz [7]. The specific training consists of three phases:

- Sector-level sweep is to select the best transmit and optionally receive antenna sector.
- Beam refinement is used for fine adjustment of beamforming.
- Beam tracking can adjust beamforming during data transmission.

In wireless personal area networks (WPANs) (IEEE 802.15.3c), a codebook is designed in scenarios of indoor communications with the small number of antennas [7], where the beamforming protocol is similar to that in IEEE 802. 11ad. However, both of them only consider the analog beamforming (precoding). Reference [6] proposed a hierarchical multi-resolution codebook-based channel estimation for hybrid precoding/combining scheme. However, the proposed scheme may suffer from destructive interference between the path gains when multiple paths are summed up in the earlier stages of the proposed algorithm [6].

Proposed CS-Based Channel Estimation for mmWave Massive MIMO: Some unique features of mmWave massive MIMO channels can be leveraged to alleviate the challenging problem of channel estimation:

- Due to the fixed BS locations, mmWave massive MIMO channels used for backhaul stay almost unchanged for a long time. This long coherence time of channels indicates that channels do not need to be estimated very frequently compared to that in RAN.
- The low-rank property of the mmWave massive MIMO channel matrix indicates that although the dimension of the matrix can be huge, its effective degrees of freedom (DoF) can be small. This inspires us to reconstruct

Small cells in future UDN can provide the Gbps user experience, which requires large transmission bandwidth. To realize mmWave massive-MIMO-based backhaul, the cost of conventional high-speed ADC with high resolution can be unaffordable, while low-resolution ADC with low hardware cost is appealing.

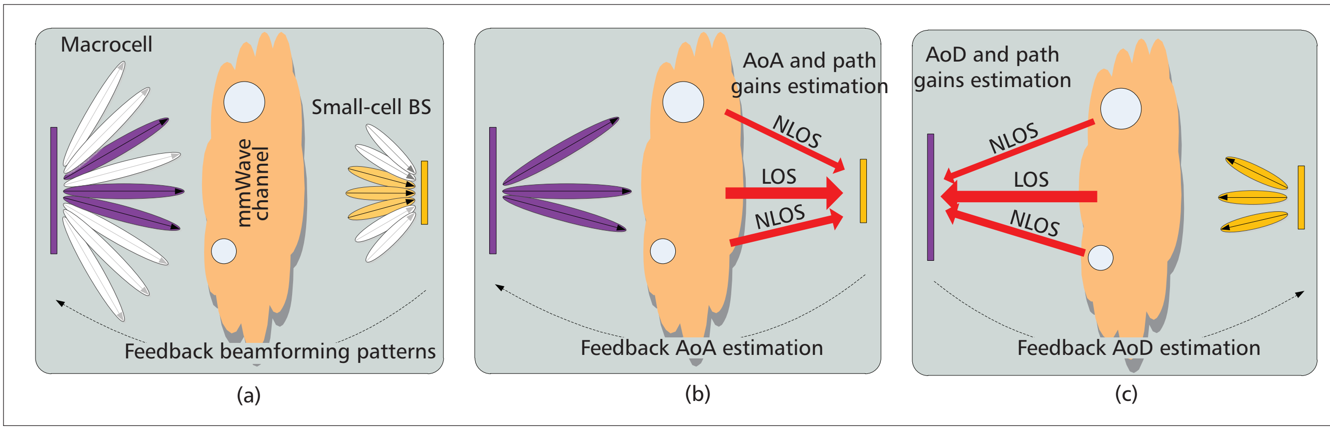

Figure 4. CS-based channel estimation for mmWave massive-MIMO-based UDN backhaul: a) Coarse channel estimation; b) AoA and path gains estimation at small-cell BS; c) AoD and path gains estimation at macrocell BS.

the channel matrix with significantly reduced measurements (sub-Nyquist sampling) under the framework of CS [11].

By leveraging these features, we propose a CS-based channel estimation scheme as illustrated in Fig. 4, which consists of the following three phases.

Phase 1: coarse channel estimation, as illustrated in Fig. 4a, aims to acquire partial CSIT to generate the appropriate beamforming patterns for the following fine channel estimation with improved received signal power. Specifically, the macrocell BS sequentially broadcasts L_{Ma} predefined beamforming patterns in L_{Ma} successive time slots, while in every time slot, each small-cell BS sequentially receives signals with L_{Sm} combining patterns in L_{Sm} successive sub-time slots. Then each small-cell BS feeds back the indices of several optimal beamforming/combining patterns to the macrocell BS.

Phase 2: channel estimation at small-cell BS, as shown in Fig. 4b, aims to estimate AoA and path gains at each small-cell BS. The macrocell BS performs beamforming according to the feedback, while the kth small-cell BS estimates AoA and path gains by exploiting the finite rate of innovation (FRI) theory (analog CS) [11]. With the aid of the predefined training signals $\mathbf{S} \in \mathbb{C}^{T^{\mathrm{Sm}}_{\mathrm{gain}} \times N^{\mathrm{Ma}}_{\mathrm{BB}}}$, the received signals at the small-cell BS is $\mathbf{S}\mathbf{P}_d\mathbf{P}_a\mathbf{A}_T\mathbf{D}\mathbf{B}^*_R\mathbf{C}_a\mathbf{C}_d$ according to Eq. 1, where the index k is omitted, $T^{\mathrm{Sm}}_{\mathrm{gain}}$ is the time overhead. Since DPSN can disable some phase-shifters to set some elements of $\mathbf{C}_a$ to be zeros, the AoA and path gains estimation can be solved by the specific algorithms of FRI theory, e.g., estimating signal parameters via rotational invariance techniques (ESPRIT) algorithm [11].

Phase 3: channel estimation at macrocell BS, as shown in Fig. 4c, aims to estimate AoD and path gains at the macrocell BS. The specific procedure is similar to *Phase 2*, where the kth small-cell BS transmits training signal while the macrocell BS estimates channels.

The FRI theory [11] can be used to accurately acquire the super-resolution estimation of AoA/AoD to effectively distinguish multiple paths with small angular difference, which can also relax the required resolution of the beamforming patterns in coarse channel estimation. According to the estimated parameters and Eq. 1, both macrocell BS and small-cell BSs can acquire the complete CSI for the following precoding/combining.

Other Issues of Channel Estimation: There still remains some problems to be investigated further, such as the optimal beamforming/combining patterns in coarse channel estimation [6, 7], training signals for AoA/AoD and path gains estimation [8], low-complexity high-accuracy CS-based channel estimation algorithms, effective channel feedback scheme, dynamic channel tracking to combat sudden blockage or slow channel changes. For instance, the microwave control link with only limited resource can be used to feedback the estimated parametric AoA/AoD, since the number of AoA/AoD is typically 3~5 [6]. Regarding the CS-based channel estimation algorithm, in addition to FRI theory, other CS approaches such as low-rank matrix reconstruction are expected to be tailored for mmWave massive MIMO with low complexity [11]. Besides, the proposed channel estimation scheme (including the coarse channel estimation and the following estimation of AoA/AoD and path gains) is used to initially build the UDN backhaul link, where the latency can be negligible. Once the backhaul link is built, only the estimation of AoA/AoD and path gains is required to track the channels and then adjust the corresponding precoding/combining, where the training sequences and data can be multiplexing in the time domain, so the latency can also be negligible.

Low-Complexity Hybrid Precoding/Combining for mmWave Massive 3D MIMO

For UDN in an urban area, the precoding/combining scheme for mmWave massive 3D MIMO can exploit both azimuth and elevation to achieve improved performance for backhaul link. Hence, the ULA-based hybrid precoding/combining scheme and the associated channel estimation proposed in this article should be extended to mmWave massive 3D MIMO in the future. Additionally, SVD and waterfilling may impose higher computational complexity on the

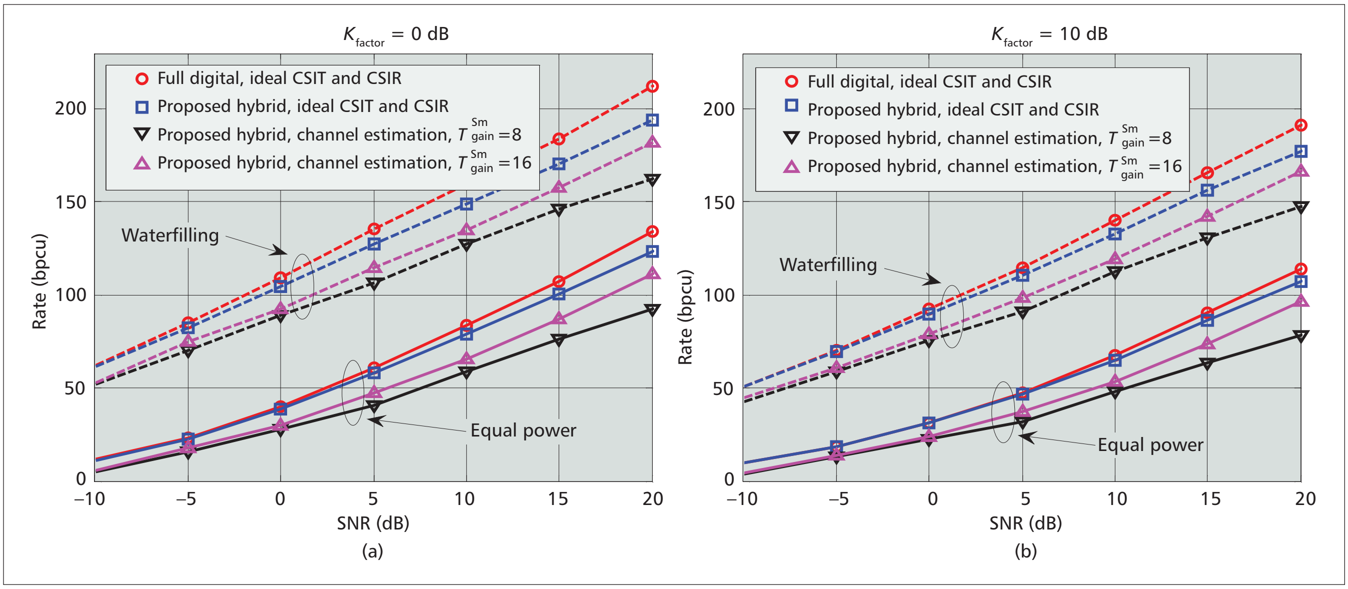

Figure 5. Comparison of the achievable rates between the proposed hybrid precoding/combining scheme and the optimal full digital one: a) $K_{\text{factor}} = 0$ dB; b) $K_{\text{factor}} = 10$ dB.

hybrid precoding/combining in the 3D MIMO. Therefore, low-complexity hybrid precoding/combining schemes are desired for practical system design. For instance, the spatial/angular sparsity of mmWave massive MIMO channels and the geometric structure of mmWave massive 3D MIMO may be exploited to reduce the complexity of SVD, while other sub-optimal power allocations can be considered to approach the performance of waterfilling with much lower complexity.

Sampling with Low-Resolution ADC

Small cells in future UDN can provide gigabit-per-second user experience, which requires large transmission bandwidth. To realize mmWave massive-MIMO-based backhaul, the cost of conventional high-speed ADC with high resolution can be unaffordable, so low-resolution ADC with low hardware cost is appealing. So far, 1-bit ADC-based signal detection and precoding/combining have been investigated for mmWave massive MIMO [7, 12]. However, further efforts are still needed to generalize the associated results of 1-bit to more general cases, and constellation mapping, channel estimation, training signals, and so on may need to be reconsidered if low-resolution ADC is adopted.

Performance Comparison

Figure 5 compares the achievable rates (bit per channel use, bpcu) of the proposed DPSN-based hybrid and optimal full digital precoding/combining schemes in the downlink, where both the waterfilling power allocation and equal power allocation are investigated. In simulations, ULA is considered at both macro and small-cell BSs, the working frequency is 60 GHz, $K = 4$, $N_a^{Ma} = 512$, and $N_a^{Sm} = 32$. For the optimal full digital scheme, $N_{BB}^{Sm} = N_a^{Sm}$ and $N_{BB}^{Ma} = N_a^{Ma}$, where the ideal CSIT and CISR are assumed as the upper bound of rate. In the proposed scheme, $N_{BB}^{Sm} = 4$ and $N_{BB}^{Ma} = 16$, where cases of ideal CSI known by transceiver and nonideal CSI acquired by the proposed CS-based channel estimation scheme are considered. For mmWave massive MIMO channels, L in the simulations follows the discrete uniform distribution $\mathcal{U}_d[2, 6]$, and AoA/AoD follow the continuous uniform distribution $\mathcal{U}_c[0, 2\pi)$. For path gains, we consider Rican fading consisting of one LOS path and $L - 1$ equal-power NLOS paths, where path gains follow the mutually independent complex Gaussian distribution with zero means, and K_{factor} denotes the ratio between the power of the LOS path and the power of the NLOS path.

Figure 5 shows that the proposed hybrid scheme with ideal CSIT and CSIR suffers from a negligible rate loss compared to the optimal full digital scheme, although the proposed scheme only uses a much smaller number of BB chains. This is because the proposed scheme exploits the low-rank property of the mmWave massive MIMO channel matrix, where capacity exhibits a ceiling effect when the number of BB chains are sufficiently large. Moreover, with the increased $T_{\text{gain}}^{\text{Sm}}$, the rate of the proposed scheme with CS-based channel estimation approaches that with ideal CSI. This is because the increased number of measurements can improve channel estimation performance. Besides, schemes with waterfilling power allocation outperform those with equal-power allocation, which indicates that waterfilling or other power allocations should be considered in practical system design for improved backhaul throughput.

Benefits and Opportunities of mmWave Massive-MIMO-Based Backhaul Network

Point-to-Multipoint Backhaul

In a conventional wireless backhaul network, point-to-point (P2P) and P2MP are two typical network topologies. A general consensus is that

The proposed scheme can guarantee the macrocell BS to simultaneously support multiple small-cell BSs with multiple streams for each small-cell BS. This is essentially different from conventional hybrid precoding/combining used for RAN.

P2MP has a lower total cost of ownership than that of P2P [2]. So far, P2P has been widely used in both microwave and mmWave backhaul systems, while P2MP has been implemented in sub-6 GHz licensed band. However, there are no satisfactory P2MP-based backhaul solutions in mmWave, which is urgently desired by industry. In this article, the proposed mmWave massive-MIMO-based wireless backhaul enables a macrocell BS to simultaneously support multiple small-cell BSs, which can provide a viable approach to realize the P2MP backhaul in mmWave.

Beam-Division-Multiplex-Based Scheduling

Time-division multiplex (TDM)-based scheduling has been proposed for mmWave-based backhaul [2]. However, this scheme may suffer from latency, since backhaul links between different small-cell BSs and a macrocell BS multiplex in different time slots. In this article, the proposed mmWave massive-MIMO-based backhaul network can realize beam-division multiplexing (BDM)-based scheduling due to the flexible spatial multiplexing and hybrid beamforming. In a practical backhaul network, according to the backhaul load, the macrocell BS can flexibly combine TDM and BDM to support more small-cell BSs. For instance, links with heavy load or without the LOS paths can be assigned more beam resources, while multiple links with light load can multiplex in the time domain. Additionally, TDM-based in-band mmWave backhaul was recently proposed for reduced cost, where backhaul and RAN share the same frequency band [2]. Obviously, with the proposed mmWave massive MIMO scheme, BDM-based scheduling may be another competitive solution for the in-band mmWave backhaul with lower latency.

TDD is Suitable for MmWave Backhaul Network

For frequency-division duplex (FDD)-based mmWave backhaul, the uplink and downlink have to use different bands. However, the regulation in mmWave may be different in different countries. This indicates that one single device may not be suitable in various countries. In contrast, the uplink and downlink in TDD share the same band. Hence, a single device can be employed in various countries. Moreover, since different operators will employ UDN in the same areas, the mutual interference of backhaul networks must be considered. Compared to FDD with different uplink/downlink channels, TDD makes it easier to find clean spectrum and avoid interference. Moreover, since asymmetric traffic is dominant in a backhaul network, TDD can flexibly adjust the ratio of time slots in the uplink and downlink according to the traffic requirement [5]. For a practical TDD mmWave massive-MIMO-based backhaul, adaptive interference management is desired to avoid mutual interference of different operators' UDN, and automated configuration solutions are expected for the plug-and-play backhaul network, especially for unlicensed V-band. For licensed E-band, spectrum regulation needs to be further improved.

Conclusions

This article discusses a promising wireless backhaul based on mmWave massive MIMO for future 5G UDN. We have explored the fundamental issues of the implementation of mmWave massive MIMO for wireless backhaul. Especially, by leveraging the low-rank property of the mmWave massive MIMO channel matrix, we propose a DPSN-based hybrid precoding/combining scheme and the associated CS-based channel estimation scheme. The proposed scheme can guarantee that the macrocell BS simultaneously supports multiple small-cell BSs with multiple streams for each small-cell BS. This is essentially different from conventional hybrid precoding/combining used for RAN. The proposed scheme can provide a viable approach to realize the desired P2MP backhaul topology and novel BDM-based scheduling, and it may also facilitate the in-band backhual in mmWave. Additionally, some potential research directions to enable mmWave massive-MIMO-based wireless backhaul are highlighted, which may become active research topics in near future.

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Biographies

Zhen Gao (gao-z11@mails.tsinghua.edu.cn) is currently working toward his Ph. D. degree in electronic engineering at Tsinghua University, Beijing, China. His research interests include sparse signal processing, massive MIMO, millimeter-wave communications, and others.

Linglong Dai [M'11, SM'14] (daill@tsinghua.edu.cn) received his B.S. degree from Zhejiang University in 2003, his M.S. degree (with the highest honor) from the China Academy of Telecommunications Technology (CATT) in 2006, and his Ph.D. degree (with the highest honor) from Tsinghua University in 2011. From 2011 to 2013, he was a postdoctoral fellow at the Department of Electronic Engineering, Tsinghua University, and then in July 2013, he became an assistant professor with the same department.

His research interests are in wireless communications with emphasis on multi-carrier modulation, multiple antenna systems, and multiple access techniques. He has published over 60 international journal and conference papers. He has received the IEEE RADIO Young Scientists Award in 2015, *IEEE Transactions on Broadcasting* Best Paper Award in 2015, IEEE ICC Best Paper Award in 2014, URSI Young Scientists Award in 2014, National Excellent Doctoral Dissertation Nomination Award in 2013, IEEE ICC Best Paper Award in 2013, Excellent Doctoral Dissertation of Beijing in 2012, and Outstanding Ph.D. Graduate of Tsinghua University in 2011. He currently serves as a Co-Chair of the Special Interest Group (SIG) on Signal Processing Techniques for 5G of IEEE ComSoc.

DE MI (d.mi@surrey.ac.uk) received his B.Eng. degree in information engineering from Beijing Institute of Technology, China, in 2011. In 2012 he received his M.Sc. degree in communications and signal processing from Imperial College London, United Kingdom. Currently, he is working toward his Ph.D. degree at the Institute for Communications Systems (ICS), University of Surrey, United Kingdom. His research interests include channel estimation, RF impairment, massive MIMO, and millimetre-wave communications.

ZHOUCHENG WANG (zcwang@tsinghua.edu.cn) received his B.S., M.S., and Ph.D. degrees from Tsinghua University in 1991, 1993, and 1996, respectively. From 1996 to 1997, he was a postdoctoral fellow of Nanyang Technological University, Singapore. From 1997 to 1999, he was with OKI Techno Centre (Singapore) Pte. Ltd., where he was first a research engineer and later a senior engineer. From 1999 to 2009, he was with Sony Deutschland GmbH, where he was first a senior engineer and later a principal engineer. He is currently a professor with the Department of Electronic Engineering, Tsinghua University, and serves as director of the Broadband Communication Key Laboratory, Tsinghua National Laboratory for Information Science and Technology. He has authored or coauthored over 90 international journal papers (SCI indexed) and is the holder of 34 granted U.S./EU patents. He co-authored two books, one of which, *Millimeter Wave Communication Systems*, was selected for the IEEE Series on Digital & Mobile Communication and published by Wiley-IEEE Press. His research areas include wireless communications, visible light communications, millimeter-wave communications, and digital broadcasting. He is a Fellow of the Institution of Engineering and Technology. He has served as an Associate Editor of *IEEE Transactions on Wireless Communications* (2011–2015) and *IEEE Communications Letters* (2013–present), and Technical Program Committee Co-Chair of various international conferences.

MUHAMMAD ALI IMRAN [M'03, SM'12] (m.imran@surrey.ac.uk) received his M.Sc. (Distinction) and Ph.D. degrees from Imperial College London in 2002 and 2007, respectively. He is currently a reader in communications (associate professor) in the ICS (formerly known as CCSR) at the University of Surrey and an adjunct associate professor at the University of Oklahoma. He has led a number of multimillion international research projects encompassing the areas of energy efficiency, fundamental performance limits, sensor networks, and self-organizing cellular networks. He is also leading the new physical layer work area for the 5G innovation center at Surrey. He has a global collaborative research network spanning both academia and key industrial players in the field of wireless communications. He has supervised 21 successful Ph.D. graduates and published over 200 peer-reviewed research papers including 22 *IEEE Transactions* … papers. He has been awarded IEEE ComSoc's Fred Ellersick award 2014 and FEPS Learning and Teaching award 2014, and was twice nominated for Tony Jean's Inspirational Teaching award. He is a shortlisted finalist for The Wharton-QS Stars Awards 2014 for innovative teaching and VC's learning and teaching award at the University of Surrey. He is a Senior Fellow of the Higher Education Academy (SFHEA), United Kingdom.

MUHAMMAD ZEESHAN SHAKIR [M'03] (muhammad.shakir@qatar.tamu.edu) received his B.E. degree in electrical engineering from NED University of Engineering and Technology, Karachi, Pakistan, in 2002, and his M.Sc. degree in communications, control, and digital signal processing (with distinction), and his Ph.D. degree in electronic and electrical engineering from the University of Strathclyde, Glasgow, United Kingdom, in 2005 and 2010, respectively. From 2006 to 2009, he was a teaching assistant to undergraduate and graduate students with the Department of Electronic and Electrical Engineering, University of Strathclyde. From November 2009 to June 2012, he was a research fellow with the Communication Theory Laboratory, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia. From September to December 2010, he was a visiting researcher with the Center for Communication System Research (CCSR), University of Surrey, Guildford, United Kingdom. Since July 2012, he has been with the Wireless Research Group, Department of Electrical and Computer Engineering, Texas A&M University at Qatar (TAMUQ), Doha, where he is currently an assistant research scientist. He has mentored several undergraduate and graduate students at TAMUQ and CCSR. Since January 2012, he has been an Elected Secretary to the IEEE DySPAN 1900.7 Working Group, where he is involved in standardization of the project "Radio Interface for White Space Dynamic Spectrum Access Radio Systems Supporting Fixed and Mobile Operation." He is the author of more than two dozen technical journal and conference papers, and has contributed to five books. His research interests include performance analysis of wireless communication systems, including heterogeneous small-cell networks, massive multiple-input–multiple-output systems, and cooperative and cognitive communications networks. He has been a member of the Technical Program Committees of several IEEE flagship conferences, such as IEEE WCNC Conference 2012, IEEE ICC 2012, and IEEE GLOBECOM 2012 and 2013. He received an industrial research scholarship jointly sponsored by the University of Strathclyde and Picsel Technologies Ltd., and a Collaborative Travel Fund from the KAUST Global Collaborative Research initiative to start bilateral collaboration with foreign universities.