Millimeter Wave Communications for Future Mobile Networks (Guest Editorial), Part I

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I. Introduction

FOR the potential of providing rates of multiple Giga-bps in a single channel, millimeter wave (mmWave) communications have recently attracted substantial research interest. While mmWave technology is already being used in stationary scenarios such as indoor hotspots or backhaul, it is challenging to use mmWave frequencies in mobile networks, where transmitting/receiving nodes may be moving, channels may have a complicated structure, and the coordination among multiple nodes is difficult. To fully exploit the high potential rates of mmWave in mobile networks, many significant technical challenges must be tackled. The main objective of this IEEE JSAC Special Issue on "*Millimeter wave communications for future mobile networks*" is to collect the most recent technical advances in mmWave for future mobile networks. The response from the community to the call has been overwhelming. We received 96 submissions with a call period short than 4 months. Many of the submissions are from the most well known research groups in the field. After a strict review process, we decided to accept 38 papers, which will be published in two issues. The papers were selected based on the technical relevance and merits. Unfortunately, due to space limitations, a number of interesting papers were not selected, despite the merits that they had. We sincerely hope those papers can find other publishing venues.

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The first issue contains 19 papers, covering a wide selection of topics as follows.

The first paper, entitled "*Hybrid analog and digital beamforming for mmWave OFDM large-scale antenna arrays,*" studies hybrid analog and digital beamforming for mmWave OFDM large-scale antenna arrays. Hybrid analog and digital beamforming is a promising candidate for large-scale millimeter wave (mmWave) multiple-input multiple-output (MIMO) systems because of its ability to significantly reduce the hardware complexity of the conventional fully digital beamforming schemes while being capable of approaching the performance of fully digital schemes. Most of the prior work on hybrid beamforming considers narrowband channels. However, broadband systems such as mmWave systems are frequency-selective. In broadband systems, it is desirable to design common analog beamformer for the entire band while employing different digital (baseband) beamformers in different frequency sub-bands. This paper considers the hybrid beamforming design for systems with orthogonal frequency division multiplexing (OFDM) modulation. For a single-user MIMO (SU-MIMO) system, the paper shows that hybrid beamforming with a small number of radio frequency (RF) chains can asymptotically approach the performance of fully digital beamforming for a sufficiently large number of transceiver antennas. For systems with a practical number of antennas, the authors propose a unified heuristic design of two hybrid beamforming structures, the fully-connected and the partially connected structures, to maximize the overall spectral efficiency of a mmWave MIMO system. For the multiuser multiple-input single-output (MU-MISO) case, the paper proposes a heuristic hybrid precoding design to maximize the weighted sum rate in the downlink and show numerically that the proposed algorithm with practical number of RF chains can already approach the performance of fully digital beamforming.

The second paper, entitled "*How much spectrum is too much in millimeter wave wireless access,*" quantifies the maximum beneficial bandwidth for mmWave transmission in some typical deployment scenarios where the pilot-based channel estimation penalty is taken into account, assuming a minimum mean square error (MMSE) channel estimator is used at the receiver. The paper shows that, under the independent and identically distributed block fading model with coherence time T_c and coherence bandwidth B_c, for transmitters and receivers equipped with a single antenna, the optimal (rate maximizing) signal-to-noise ratio (SNR) is a constant that only depends on the product B_cT_c, which measures the size of the channel coherence block and equals the average number of orthogonal symbols per independent channel coefficient. That is, for fixed size B_cT_c of the channel coherence block, the optimal bandwidth scales linearly with the received signal power.

The third paper, entitled "*When mmWave communications meet network densification: A scalable interference coordination perspective,*" explores the potential gain of ultra-densification for enhancing mmWave communications from a network-level perspective. By deploying the mmWave base stations (BSs) in an extremely dense and amorphous fashion, the access distance is reduced and the choice of serving BSs is enriched for each user, which are intuitively effective for mitigating the propagation loss and blockages. Nevertheless, co-channel interference under this model will become a performance-limiting factor. To solve this problem, we propose a large-scale channel state information (CSI) based interference coordination approach. Note that the large-scale CSI is highly location-dependent, and can be obtained with a quite low cost. Thus, the scalability of the proposed coordination framework is good. Particularly, using only the large-scale CSI of interference links, a coordinated frequency resource block allocation problem is formulated for maximizing the minimum achievable rate of the users, which is uncovered to be an NP-hard integer programming problem. A greedy scheme with polynomial-time complexity is proposed in the paper by adopting the bisection method and linear integer programming tools. Simulation results demonstrate that the proposed coordination scheme based on only large-scale CSI can offer substantial gains over the existing methods. Moreover, although the proposed scheme is only guaranteed to converge to a local optimum, it performs well in terms of both user fairness and system efficiency.

The fourth paper, entitled "*Adaptive SM-MIMO for mmWave communications with reduced RF chains,*" proposes a novel MIMO transmission scheme, termed as receive antenna selection (RAS)-aided spatial modulation MIMO (SM-MIMO) for mmWave communications. The scheme employs the spatial modulation (SM) concept and the RAS technique to tackle the costs of the multiple radio frequency (RF) chains at both link ends. Moreover, a pair of RAS algorithms for the proposed mmWave RAS-SM scheme based on the capacity maximization (max-capacity) and the bit error rate minimization (min-BER) criteria are proposed. Furthermore, an iterative algorithm is proposed to jointly design the log barrier algorithm and the simplified conjugate gradient method for RAS optimization. The simulation results show that the proposed RAS-SM schemes are capable of achieving considerable performance gains over conventional norm-based and eigenvalue-based schemes in mmWave MIMO channels, while avoiding an overwhelming complexity overhead imposed by exhaustive search.

In the fifth paper, entitled "*Design and optimization on training sequence for mmWave communications: A new approach for sparse channel estimation in massive MIMO*", a channel estimation scheme based on training sequence (TS) design and optimization with high accuracy and spectral efficiency is investigated in the framework of structured compressive sensing (SCS). As a new perspective to optimize the block coherence of the sensing matrix, the auto-coherence and cross-coherence of the blocks are proposed and specified as two key merit factors. In order to optimize the two factors, a specific TS is designed and obtained from the inverse discrete Fourier transform of a frequency domain binary training sequence, and a genetic algorithm is adopted afterwards to optimize the merit factors of the TS. It is demonstrated by the simulation results that the block coherence of the sensing matrix can be significantly reduced by the proposed TS design and optimization method. Moreover, by using the proposed optimized TSs, the channel estimation outperforms the conventional TS design obtained by the brute force search in terms of the correct recovery probability, mean square error, and bit error rate, and can also approach the Cramer-Rao lower bound.

In the sixth paper, entitled "*Coverage analysis for millimeter wave networks: The impact of directional antenna arrays*", using tools from stochastic geometry, the authors carry out a comprehensive investigation of the impact of directional antenna arrays in mmWave networks. A general and tractable framework for coverage analysis with arbitrary distributions for interference power and arbitrary antenna patterns is first given. It is then applied to mmWave ad hoc and cellular networks, where two sophisticated antenna patterns with desirable accuracy and analytical tractability are proposed to approximate the actual antenna pattern. Compared with previous works, the proposed approximate antenna patterns help to obtain more insights into the role of directional antenna arrays in mmWave networks. In particular, it is shown that the coverage probabilities of both types of networks increase as a non-decreasing concave function with the antenna array size. The analytical results are verified to be effective and reliable through simulations, and numerical results also show that large scale antenna arrays are required for satisfactory coverage in mmWave networks.

MmWave communications is an attractive technology for ultra-dense small cells and mobile data offloading. However, ultra-dense nodes and increasing data traffic lead to vast interference. Thus, the seventh paper, entitled "*Low complexity interference alignment for mmWave MIMO channels in three-cell mobile network*", investigates low complexity non-iterative interference alignment (IA) schemes for MIMO interference broadcast channels (IFBC) in mmWave communications. The authors focus on a three-cell mobile network model in which each BS supports no more than two users within its cell. There already exists a closed-form IA solution for the case that one cell has two users while the other two cells have one user in each, which can be denoted as 2,1,1. This paper considers different settings and proposes corresponding IA schemes. First, two IA schemes based on multi-step for the asymmetric setting 2,2,1 are presented, five degrees of freedom (DoF) could be achieved. Then for the symmetric setting 2,2,2, a novel IA solution with lower complexity and a joint method combining IA with non-iterative multi-user MIMO techniques are proposed, they can achieve six DoF. The simulation results indicate that the proposed non-iterative schemes achieve similar sum-rate as the iterative ones in existing work, and the complexity is effectively reduced.

In the eighth paper, entitled "*Low-rank tensor decomposition-aided channel estimation for millimeter wave MIMO-OFDM systems*", the problem of downlink channel estimation for mmWave MIMO-OFDM systems is considered, where both the BS and the mobile station (MS) employ large antenna arrays for directional beamforming. Hybrid analog and digital beamforming structures are employed in order to offer a compromise between hardware complexity and system performance. Different from most existing studies that are concerned with narrowband channels, the authors consider estimation of wideband mmWave channels with frequency selectivity, which is more appropriate for mmWave MIMO-OFDM systems. By exploiting the sparse scattering nature of mmWave channels, a CANDECOMP/PARAFAC (CP) decomposition-based method for channel parameter estimation (including angles of arrival/departure, time delays, and fading coefficients) is proposed, in which the received signal at the MS is expressed as a third-order tensor. The analysis reveals that the uniqueness of the CP decomposition can be guaranteed even when the size of the tensor is small. Hence the proposed method has the potential to achieve substantial training overhead reduction. The authors also derive Cramer-Rao bounds (CRBs) for the channel parameter estimation, and compare the proposed method with a compressed sensing-based method. Simulation results show that the proposed method attains performance that is very close to their associated CRBs, and presents a clear advantage over the compressed sensing-based method.

The ninth paper, entitled "*Wideband circularly polarized antipodal curvedly tapered slot antenna array for 5G applications*", presents and characterizes a novel high gain circularly polarized (CP) antenna array for 5G applications. The array element is an antipodal curvedly tapered slot antenna (ACTSA) generating a circularly polarized field. The CP ACTSA fed by substrate integrated waveguide (SIW) is convenient to integrate with substrates. By introducing two sheet-metals on the two sides of the rectangular Rogers 6002 substrate, an impedance bandwidth of 18.2%, a wide 3-dB axial ratio (AR) bandwidth of 16.9%, and stable gain of 8 ± 0.6 dBic over the operating band are achieved. By employing the proposed CP ACTSA as radiating elements, a 4 high-gain wideband antenna array is proposed for 5G E-band and W-band millimeter-wave applications. Fabrications are carried out using a wire-cutting electrical discharge machine and print circuit board (PCB) process, which have advantages of low cost. The whole feeding network is realized by SIW with low insertion loss at the mmWave band. Benefiting from the wide impedance and AR bandwidth of the new antenna element, good impedance matching, and AR characteristics can be achieved over the whole working frequency band from 81 GHz to 95 GHz by this antenna array. Gain up to 18.5 ± 1.3 dB is also obtained.

In the tenth paper, entitled "*BDMA for millimeter-wave/terahertz massive MIMO transmission with per-beam synchronization*", the authors propose a beam division multiple access (BDMA) method with per-beam synchronization (PBS) in time and frequency for wideband massive MIMO transmission over mmWave/Terahertz (THz) bands. A physically motivated beam domain channel model for massive MIMO is first introduce. The envelopes of the beam domain channel elements tend to be independent of time and frequency when both the numbers of antennas at the BS and user terminals (UTs) tend to infinity. Then PBS for mmWave/THz massive MIMO is proposed and shown that both the effective delay and Doppler frequency spreads of wideband massive MIMO channels with PBS are reduced by a factor of the number of UT antennas compared with the conventional synchronization approaches. Simulation results verify the effectiveness of BDMA with PBS for mmWave/THz wideband massive MIMO systems in typical mobility scenarios.

Thanks to the short wavelength of mmWave radio, massive antenna arrays can be packed into the limited dimensions of mmWave transceivers. Therefore, with directional beamforming (BF), both mmWave transmitters (MTXs) and mmWave receivers (MRXs) are capable of supporting multiple beams in 5G networks. However, for the transmission between an MTX and an MRX, most works have only considered a single beam, which means that they do not make full potential use of mmWave. Furthermore, the connectivity of single beam transmission can easily be blocked. In this context, in the eleventh paper, entitled "*Beamspace SU-MIMO for future millimeter wave wireless communications*", the authors propose a single-user multi-beam concurrent transmission scheme for future mmWave networks with multiple reflected paths. Based on spatial spectrum reuse, the scheme can be described as a MIMO technique in beam-space (i.e., in the beam-number domain). Moreover, this study investigates the challenges and potential solutions for implementing this scheme, including multi-beam selection, cooperative beam-tracking, multi-beam power allocation and synchronization. The theoretical and numerical results show that the proposed beam-space SU-MIMO can largely improve the achievable rate of the transmission between an MTX and an MRX and, meanwhile, can maintain the connectivity.

In the twelfth paper, entitled "*Multi-user precoding and channel estimation for hybrid millimeter wave systems*", the authors develop a low-complexity channel estimation technique for hybrid mmWave systems, where the number of RF chains is much lower than the number of antennas equipped at each transceiver. The proposed mmWave channel estimation algorithm first exploits multiple frequency tones to estimate the strongest angle-of-arrivals (AoAs) at both the BS and user sides for the design of analog beamforming matrices. Then all the users transmit orthogonal pilot symbols to the BS along the directions of the estimated strongest AoAs in order to estimate the channel. The estimated channel is exploited to design the digital zero-forcing (ZF) precoder at the BS for the multi-user downlink transmission. The proposed channel estimation algorithm is applicable to both non-sparse and sparse mmWave channel environments. The analytical and simulation results show that the proposed scheme obtains a considerable fraction of the achievable rate of fully digital systems. Besides, by taking into account the effect of various types of errors, i.e., random phase errors, transceiver analog beamforming errors, and equivalent channel estimation errors, a closed-form approximation for the achievable rate of the considered scheme is derived. The robustness of the proposed channel estimation and multi-user downlink precoding scheme against these system imperfections is shown.

MmWave channel measurements are conducted with different configurations, which may have large impact on the propagation channel characteristics. Also, the comparison of different mmWave bands is far from comprehensive. Moreover, mmWave massive MIMO channel measurements are absent, and new propagation properties caused by large antenna arrays have rarely been studied. Thus, in the thirteenth paper, entitled "*Multi-frequency MmWave massive MIMO channel measurements and characterization for 5G wireless communication systems*", mmWave massive MIMO channel measurement results at 11, 16, 28, and 38 GHz bands in indoor environments are presented. The space-alternating generalized expectation-maximization (SAGE) algorithm is applied to process the measurement data. Important statistical properties such as the average power delay profile (APDP), power azimuth profile (PAP), power elevation profile (PEP), root mean square (RMS) delay spread (DS), azimuth angular spread (AAS), elevation angular spread (EAS), and their cumulative distribution functions (CDFs) and correlation properties are obtained and compared for different bands. New massive MIMO propagation properties, including spherical wavefront, cluster birth-death, and non-stationarity over the antenna array, are validated for the four mmWave bands by investigating the variations of channel parameters. Two channel models are used to verify the measurements. The results indicate that massive MIMO effects should be fully characterized for mmWave massive MIMO systems.

Non-orthogonal multiple access (NOMA), mmWave, and massive MIMO have emerged as key physical-layer technologies for 5G. However, less light has been casted on the combination of the three technologies. Additionally, the rate improvements that can be achieved via this combination remains unclear. In fourteenth paper, entitled "*Capacity analysis of non-orthogonal multiple access with mmWave massive MIMO systems*", an in-depth rate analysis for the integrated NOMA-mmWave-massive-MIMO systems is provided. A simplified mmWave channel model is introduced by extending the uniform random single-path (UR-SP) model with angle of arrival (AoA). Afterwards, the capacity analysis on the low SNR and high SNR regimes based on the dominant factors of signal-to-interference-plus-noise ratio (SINR) is given. In the noise-dominated low SNR regime, the rate analysis carried out using the deterministic equivalent method with the Stieltjes- Shannon transform. In contrast, statistic and eigenvalue distribution tools are invoked for the capacity analysis in the interference-dominated high SNR regime. An exact rate expression and a low-complexity asymptotic rate expression are derived based on the probability distribution function of the channel eigenvalue. Simulation results validate the theoretical analysis and demonstrate that significant rate improvements can be achieved by the integrated NOMA-mmWave massive-MIMO systems.

In mmWave cellular communication, fast and reliable beam alignment via beam training is crucial to harvest sufficient beamforming gain for the subsequent data transmission. In the fifteenth paper, entitled "*Millimeter wave beam alignment: Large deviations analysis and design insights*", fundamental limits in beam-alignment performance under both exhaustive search and hierarchical search is established. Lower and upper bounds on the probability of misalignment for an arbitrary level in the hierarchical search, based on a single-path channel model is established. Using the method of large deviations, the authors characterize the decay rate functions of both bounds and show that the bounds coincide as the training sequence length goes large, and characterize the asymptotic misalignment probability of both the hierarchical and exhaustive search, and show that the latter asymptotically outperforms the former, subject to the same training overhead and codebook resolution. Numerical results show that this relative performance behavior holds in the non-asymptotic regime. Moreover, the exhaustive search is shown to achieve significantly higher worst-case spectral efficiency than the hierarchical search, when the pre-beamforming SNR is relatively low. This hence implies that the exhaustive search is more effective for users situated further from the BSs, as they tend to have low SNR.

Although the benefits of precoding and combining of data signals are widely recognized, the potential of these techniques for pilot transmission is not fully understood. This is particularly relevant for MU-MIMO cellular systems using mmWave communications, where multiple antennas have to be used both at the transmitter and the receiver to overcome the severe path loss. In the sixteenth paper, entitled "*Pilot precoding and combining in multiuser MIMO networks*", the gains of pilot precoding and combining in terms of channel estimation quality and achievable rate is characterized. Three uplink pilot transmission scenarios in a mmWave MU-MIMO cellular system are considered: 1) nonprecoded and uncombined, 2) precoded but uncombined, and 3) precoded and combined. The authors show that a simple precoder that utilizes only the second-order statistics of the channel reduces the variance of the channel estimation error by a factor that is proportional to the number of user equipment (UE) antennas. They also show that using a linear combiner design based on the second-order statistics of the channel significantly reduces multiuser interference and provides the possibility of reusing some pilots. Specifically, in the large antenna regime, pilot precoding and combining help to accommodate a large number of UEs per cell, significantly improve channel estimation quality, boost the SNR of the UEs located close to the cell edges, alleviate pilot contamination, and address the imbalanced coverage of pilot and data signals.

MIMO systems in the lower part of the mmWave spectrum band (i.e., below 28 GHz) do not exhibit enough directivity and selectively, as their counterparts in higher bands of the spectrum (i.e., above 60 GHz), and thus still suffer from the detrimental effect of interference, on the system sum rate. As such systems exhibit large numbers of antennas and short coherence times for the channel, traditional methods of distributed coordination are ill-suited, and the resulting communication overhead would offset the gains of coordination. In the seventeenth paper, entitled "*Sum-rate maximization in sub-28 GHz millimeter-wave MIMO interfering networks*", algorithms for tackling the sum-rate maximization problem are proposed. A lower bound on the sum-rate, a so-called DLT bound (i.e., a difference of log and trace), is found to shed light on its tightness, and highlight its decoupled nature at both the transmitters and the receivers. The authors then show the convergence of the resulting algorithm, max-DLT, to a stationary point of the DLT bound. Extensive simulations of various network configurations are given to establish the fast-converging nature of the proposed schemes, and thus their suitability for addressing the short coherence interval, as well as the increased system dimensions, arising when managing interference in lower bands of the millimeter wave spectrum. The results also suggest that interference management still brings about significant performance gains, especially in dense deployments.

Little is known about mmWave path loss in rural areas with tall antennas, yet, as shown in the eighteen paper, entitled "*Rural macrocell path loss models for millimeter wave wireless communications*" surprisingly long distances (greater than 10 km) can be achieved in clear weather with less than 1 W of power. In the paper, 73 GHz measurements in rural Virginia are used to develop a new RMa path loss model that may be used for frequencies from 0.5 GHz to 100 GHz. The measurement system used here is comparable to a wideband (800 MHz radio frequency (RF) bandwidth) channel sounder with 21.7 dBW EIRP. Comparisons between simulations of existing RMa models and measured data verify the path loss model given here, that uses a novel close-in free space reference distance with a height dependent path loss exponent (CIH model).

Most of the existed investigations in mmWave channel only focus on single-input single-output (SISO) links or MIMO links, whereas the researches of massive MIMO channels mainly focus on a frequency band below 6 GHz. The nineteenth paper, "*On indoor millimeter wave massive MIMO channels: Measurement and simulation*", investigates the channel behaviors of massive MIMO at a mmWave frequency band around 26 GHz. Results from an indoor mmWave massive MIMO channel measurement campaign with 64 and 128 array elements is presented, from which path loss, shadow fading, root-mean-square (RMS) delay spread, and coherence bandwidth are extracted. By calibrating a ray-tracing simulator with the measurement data, extensive ray-tracing simulations with 1024 antenna elements in the same indoor scenario is made, and insights into the variation tendency of mean delay and the RMS delay with different array elements are discussed. It is observed that the measurement and the ray-tracing based simulation results have reached a good agreement.

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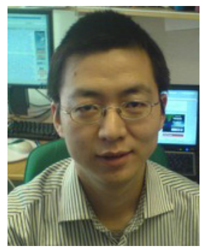

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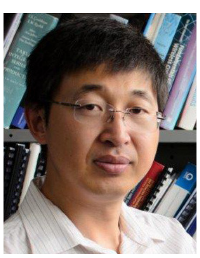

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