Guest Editorial Millimeter-Wave Networking

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I. Introduction

DUE to the increasing density of wireless devices, the ever-growing demands for extremely high data rates, and the spectrum scarcity at the sub-6 GHz bands, making use of the spectrum-rich millimeter-wave (mmWave) frequencies is among the most important technology trends for future wireless networks. The major commercial potential of mmWave networks has led to mmWave being considered a key element for 5G-and-beyond mobile cellular networks, as well as for emerging Gbps-speed Wi-Fi networks based on the IEEE 802.11ad and draft IEEE 802.11ay standards. Despite this intense interest in mmWave communications from both the research community and industry, much fundamental research is still needed, especially at the higher layers of the networking stack.

Compared to traditional wireless communication systems, the special propagation features and hardware constraints of mmWave systems introduce many new challenges in the design of efficient and robust medium access control (MAC), routing, and transport protocols [1], [2]. Pioneering research efforts in the past decade have largely focused on the PHY layer and key component technologies, thus demonstrating the feasibility of mmWave links. However, there remain a great number of challenging problems in the upper layers of the protocol stack that must be tackled before mmWave networks can become a reality. Communication at such high frequencies suffers from high attenuation and signal absorption as well as high penetration loss, requiring the use of highly directional antennas. This move from conventional omnidirectional networks to directional, blockage-prone mmWave connectivity marks a true paradigm shift for mmWave networking, affecting the design of all aspects of network control and resource management. The extremely high data rates achievable at mmWave come at the price of high coordination overhead. This in turn requires a radical rethinking of the design of all aspects of network coordination and resource management, including cell-discovery and initial access, mobility management, routing, coordination, scheduling, user association, resource allocation, and network planning. For these reasons, the topic of the proposed special issue is of extreme relevance and timeliness to wireless networking.

Prior special issues on the IEEE Journal on Selected Areas in Communications (JSAC) and the IEEE Journal of Selected Topics in Signal Processing have focused on mmWave channel characterizations, signal processing, and the physical layer aspects of communications, such as antenna and transceiver design, waveform design, and channel coding. This special issue takes a new perspective by focusing on the many less-explored and open problems that are critical for enabling mmWave networks, including efficient beam-steering and tracking algorithms, network planning and optimization, mobility management and seamless handover, coexistence and integration with other microwave and mmWave technologies, efficient low latency transport, and data-driven approaches for resource allocation, scheduling, and directional MAC for mmWave deployments.

In this JSAC special issue, we received 68 submissions and have accepted 14 high quality papers, leading to an acceptance rate of about 20%. We have grouped the accepted papers into the following categories:

- Architecture and Network Capacity;
- Medium Access Control;
- Applications.

In the following, we give a summary of the accepted papers.

II. Summary of Research Contributions in This Special Issue

A. Architecture and Network Capacity

mmWave cellular networks will likely need to be significantly more dense than current networks to compensate for

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the relatively short communication range. Dense deployments are also needed to provide macro-diversity [3] for blockage.

A key operational issue in network deployments is backhaul and site acquisition. The paper "Joint user association and beamforming design for millimeter wave UDN with wireless backhaul" by Kwon and Park [4] considers joint user association and beamforming in ultra-dense networks from an optimization perspective. Importantly, the optimization includes time-sharing for integrated access and backhaul in the formulation. This work is complemented by the paper "Millimeter wave integrated access and backhaul in 5G: Performance analysis and design insights" by Saha and Dhillon [5] which provides an analytical framework for a two-tier heterogeneous network with integrated access and backhaul and compares two different resource allocations mechanisms, one with a static partitioning of access and backhaul resources, and one with a dynamic reallocation of resource between access and backhaul. This analysis provides insights into the impact of traffic offloading and small base station density. Furthermore, the paper "SCAROS: A scalable and robust self-backhauling solution for highly dynamic millimeter-wave networks" by Ortiz *et al.* [6] proposes a more extensible multihop backhaul architecture, where direct fiber connectivity is only available to a limited number of base stations (BS), and other BSs connect to the Internet via the multihop relaying. The contribution lies in a learning algorithm design that can achieve low end-to-end latency as well as high network robustness under adverse network dynamics, such as channel variations and link failures.

A further key network aspect is an architecture that improves robustness and delay performance in the presence of handovers, which are likely in mmWaves cellular networks. The paper "Fast inter-BS ring (FIBR): A new millimeter wave cellular network architecture" by Koutsaftis *et al.* [7] presents a timely study about such a new architecture. The essential idea proposed in the paper is to group base stations that are in close proximity and interconnect them to form a "bi-directional buffer insertion ring network" using a fiber-based architecture. The proposed architecture allows for both single BS and multi BS connectivity to improve the robustness to blockage and thus reduce the handover delays, which is particularly useful for URLLC networks. This is an important function not present in 3GPP-like transport architectures, which are affected by significant control signalling overhead during the handover procedures. The paper analyses control plane and data plane latency during handover as well link failure probabilities and compares them with existing 3GPP solutions.

While mmWave networks imply high spatial reuse by using directional communication (in contrast with the omini-directional communication at lower-frequency WiFi or LTE), interference is still not negligible for increasing deployment density. The paper "Interference management and capacity analysis for mm-wave picocells in urban canyons" by Marzi and Madhow [8] performs a capacity analysis for the dense BS deployment scenario, where both intra- and inter-cell interference are taken into account. The analysis leads to a promising estimation that "1000-fold increase relative to conventional LTE cellular networks is indeed feasible", when the interference is successfully managed by the proposed cross-layer approach.

The use of massive MIMO mmWave phased arrays in 5G creates new opportunities for capacity gains, while posing new challenges for resource allocation due to the huge decision space. The paper "Heterogeneous-QoS driven resource allocation over MmWave massive-MIMO based 5G mobile wireless networks in the non-asymptotic regime" by Zhang *et al.* [9] tackles such problems under stringent QoS constraints. The authors optimize the effective capacity under the heterogeneous delay-bounded and error-rate bounded QoS constraints. Both simulation and analytical models demonstrate remarkable performance gains over existing schemes.

B. Medium Access Control

A key challenge in mmWave networks is the directional nature of the transmissions and the need to perform beam search on both ends to find the optimal link configuration. Multiple directions of transmission also enable spatial dimensional multiaccess (SDMA), a key feature for high data rates in mmWave systems. Several papers in this issue develop beam search and spatial multiplexing protocols and study their interactions with high layers.

The paper "Multi-user multi-stream mmWave WLANs with efficient path discovery and beam steering" by Ghasempour *et al.* [10] presents a novel method for fast beam search, leveraging both channel sparsity and fast sampling to rapidly locate optimal beams. The algorithm is validated on a 60-GHz testbed with 802.11ay nodes to demonstrate robustness to blockage.

The paper "Beam acquisition and training in millimeter wave networks with narrowband pilots" by Zhou *et al.* [11] studies joint beam acquisition and tracking among multiple mmWave access points and mobile devices. The authors propose a system-level narrowband training protocol and frame structure and consider different codebooks and channel estimation methods. A system-level optimization is performed to select the frame length, training time and bandwidth that minimize the training overhead in the presence of blockage and user mobility. Simulation results show that the training overhead of the proposed solution is typically around 5% but may exceed 10% in cases of high traffic load or high mobility with frequent blockages.

The paper "Multi-beam transmissions for blockage resilience and reliability in millimeter-wave systems" by Aykin *et al.* [12] proposes SmartLink, a protocol that enables a multibeam link between the base station and a user. SmartLink relies on a logarithmic-time search algorithm called multilobe beam search (MLBS), which probes several directions simultaneously, using multilobe beam patterns, to discover the dominant angular clusters, and selects the multilobe beam pattern that maximizes the average data rate under blockage for data transmission. The protocol is evaluated using trace-based simulation with channel traces obtained from phased arrays operating at 29 GHz.

The paper "Towards efficient medium access for millimeter-wave networks" by Zhao *et al.* [13], investigates a MAC protocol that handles beam alignment, transmission scheduling, and beam tracking. The beam alignment is for both transmitter and receiver, and is multilevel in the sense that it uses a range of beam width from coarse to fine grained. Such an alignment method is based on a channel estimation that exploits the block structure of the mmWave channel. The MAC handles both delay-tolerant users, and a resource allocation based on a weighted rate maximization of the users with delay constraints. The beam tracking handles disconnections for dynamic mobile environments. The performance of the MAC protocol is numerically evaluated in terms of training overhead and network throughput in different SNR, user speed and number of users and antennas. The authors show that the MAC provides high gains in terms of training overhead and network performance compared to other algorithms from the literature and the standards such as IEEE 802.11ad.

Hybrid beamforming is a core technology in 5G NR which harnesses the multiplexing/diversity gains from both MIMO and phased array beamforming. Existing literature on hybrid beamforming has heavily focused on the signal processing algorithm design. The paper "Hybrid-beamforming-based millimeter-wave cellular network optimization" by Liu and Bentley [14] tackles the cross-layer design challenges through a network optimization framework. The authors consider the congestion control as well as scheduling issues on top of a hybrid beamforming PHY layer. The solutions translate into simplified network protocols, with provable utility and delay performance.

C. Applications

Unmanned Aerial Vehicles (UAVs) are a very promising application area that can benefit from the high data rates of mmWave communications and two papers address this topic. The paper "MmWave UAV networks with multi-cell association: Performance limit and optimization" by Liu *et al.* [15] assumes a two-tier cellular architecture: a tier of UAV base stations using the mmWave frequency band forms the data plane and a tier of ground base stations using the UHF frequency band forms the control plane. The paper proposes a three-dimensional location distribution model of the UAVs using stochastic geometry and uses it to explore the performance limits of this architecture.

In "Coverage analysis for energy-harvesting UAV-assisted mmWave cellular networks" by Wang and Gursoy [16], the authors study UAV-assisted mmWave networks, where each UAV acts as a base station serving the users within its range. The work addresses the problem of downlink simultaneous wireless information and power transfer (SWIPT) and uplink information transmission, where constraints are imposed both by the energy harvesting process as well as the requirement to serve the users.

Finally, the paper "Modeling and analysis of MmWave V2X networks with vehicular platoon systems" by Yi *et al.* [17] considers the application of mmWave networks in an advanced V2X scenario of vehicular platoon systems (VPSs), instead of independent individual vehicles. The authors formulate rigorous models for the mmWave V2X in VPSs and derive closed-form solutions, which provides interesting insights, for example, that platoons outperform individual vehicles in terms of road spectral efficiency.

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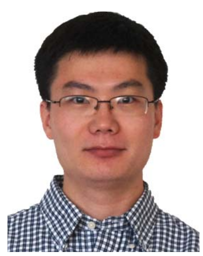

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