MILLIMETER-WAVE COMMUNICATIONS FOR 5G – PART 2: APPLICATIONS



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In the September 2014 issue of *IEEE Communications Magazine*, the first part of this Feature Topic included five articles that covered the fundamentals of mmWave communications with topics ranging from propagation to coverage, presenting a holistic view of research challenges and opportunities in the emerging area of mmWave radio systems and 5G mobile broadband. The use of this technology is expected to surge in the next few years and to transform the Internet industry in the next 10 years. This part of the Feature Topic will address in more detail many technical and application issues related to beamforming, device-to-device communications, heterogeneous networks, and multimedia transmission.

We start with three articles addressing the challenging problems of coverage, initial access, handover, and hybrid beamforming. The first article, "Multi-Gigabit Millimeter Wave Wireless Communications for 5G: From Fixed Access to Cellular Networks" by Peng Wang *et al.*, explores the potential of the E-band spectrum for future mobile communications by introducing the E-band spectrum and its propagation characteristics. The authors discuss the possible applications over E-band frequencies with emphasis on the network architecture and the air interface design of E-band mobile broadband. Several key techniques are discussed that can potentially solve the coverage problem and provide good link qualities regardless of the locations of the mobile users in the network area. The second article, "Random Access in Millimeter-Wave Beamforming Cellular Networks: Issues and Approaches" by Cheol Jeong *et al.*, explores the random access channel (RACH) in mmWave communications as an important procedure for initial access and handover. Since random access cannot fully benefit from beamforming due to lack of information about the best transmit-receive beam pair, the design of RACH becomes a particularly challenging problem, especially in non-line-of-sight (NLOS) channels. The main problem of random access is that the total duration of RACH should be long to accommodate the multiple preambles transmitted for all transmit and receive beam pairs. To overcome this challenge, the authors propose several potential solutions such as enhanced preamble detection performance, multiple digital chains at the base station (BS), beam reciprocity, and cell planning. The third article, "Large-Scale Antenna System with Hybrid Analog and Digital Beamforming for Millimeter Wave 5G" by ShuangFeng Han *et al.*, explores the optimal design of hybrid analog and digital beamforming in a multi-user scenario. The authors examine the general scenario of N transceivers and M antennas per transceiver, where the energy efficiency (EE) and spectrum efficiency (SE) of the $N \times M$ beamforming structure is analyzed. Several key insights are drawn from the EE-SE relationship at the green point, the point with the highest EE on the EE-SE curve.

Cost-effective and scalable wireless backhaul solutions are therefore essential for realizing the 5G vision of anywhere anytime multi-gigabit-per-second data rates. The backhaul is clearly a fundamental component for supporting network densification in small cell deployments with very low latency inter-BS communication to combat intercell interference. In the fourth article, "Point to Multipoint In-Band mm-Wave Backhaul for 5G Networks" by Rakesh Taori *et al.*, presents an in-band solution to meet the backhaul and inter-BS coordination challenges that come with network densification. The authors argue that in-band wireless backhaul for data backhauling and inter BS-coordination is feasible without significantly hurting the cell access capacities.

Mobile broadband will continue to drive the demands for higher traffic and higher end-user data rates. These demands for very high system capacity and very high end-user data rates can be met using technologies such as ultra-dense networks, device-to-device communications, and heterogeneous networks. The next four articles discuss these important technologies by considering practical issues related to mobility, resource sharing, deployment, and routing. The fifth article, "Ultra-Dense Networks in Millimeter-Wave Frequencies" by Robert Baldemair *et al.*, explores ultra-dense networks as a solution to fulfill the extremely high traffic demands on system capacity and achievable end-user date rate. Ultra-dense networks are networks with distances between access nodes ranging from a few meters in indoor deployments up to roughly 50 m in outdoor deployments. The authors present an extensive survey detailing key requirements and characteristics of ultra-dense networks, taking into account mobility, self-backhauling, and spectrum sharing. The sixth article, "Enabling Device-to-Device Communication in Millimeter Wave 5G Cellular Networks" by Jian Qiao *et al.*, introduces a hybrid system architecture of D2D communications over mmWave 5G cellular networks. The most relevant aspects regarding the propagation characteristics to achieve reliable high-rate communications are discussed, including propagation loss, diffraction and penetration ability, and directional antennas. The authors propose an effective resource sharing scheme that allows non-interfering D2D links to operate concurrently, taking into account neighbor discovery for handoff and network integration for high-rate D2D communications with mobility. The seventh article, "Hybrid Millimeter-Wave Systems: A Novel Paradigm for HetNets" by Hani Mehrpouyan *et al.*, proposes an mmWave heterogeneous architecture, hybrid HetNet, which exploits the bandwidth and propagation characteristics of the V- and E-bands to reduce the impact of interference in HetNets. Two transceiver structures that enable handoffs from the V-band to the E-band, and vice versa are proposed. The eighth article, "10 Gb/s HetSNets with Millimeter-Wave Communications: Access and Networking Challenges and Protocols" by Kan Zheng *et al.*, introduces heterogeneous and small cell networks (HetSNets) in mmWave communications to increase spatial spectrum reusability and efficiency. The authors focus on the network and medium access control layers, taking into account several deployment scenarios for backhaul and user access. The authors discuss issues related to routing, access control, and interference coordination.

Multimedia applications such as on-demand HD video, IPTV, and ultra HDTV demand ultra-high throughput and ultra-low latency. MmWave technologies such as IEEE 802.15.3c and IEEE 802.11ad are ideal candidates to handle the data volumes in wireless multimedia data-intensive applications, in particular to multiple users demanding differentiated quality of service (QoS). MmWave multimedia communications is therefore an important topic, and is addressed in the next two articles. The ninth article, "Millimeter Wave Multimedia Communications: Challenges, Methodology, and Applications" by Dan Wu *et al.*, defines and evaluates several important metrics to characterize the multimedia QoS in mmWave communications and jointly takes into account several technical challenges, including large-scale attenuation, atmospheric absorption, phase noise, and limited gain amplifiers. The authors design a QoS-aware multimedia scheduling scheme to achieve the trade-off between performance and complexity, in which accurate propagation analysis is carried out and suitable countermeasure techniques are pointed out to satisfy the QoS requirements. The final article, "Multimedia Resource Allocation in MmWave 5G Networks" by Sandra Scott-Hayward *et al.*, presents an optimization solution, known as particle swarm optimization (PSO), as an ideal candidate to handle a mixed set of multimedia applications. The authors propose channel time allocation PSO as a reduced execution time solution to successfully optimize the channel time allocation in a mixed multimedia wireless environment, even in scenarios where blockage exists in the mmWave network.

BIOGRAPHIES

MAGED ELKASHLAN (maged.elkashlan@qmul.ac.uk) received his Ph.D. degree in electrical engineering from the University of British Columbia, Canada, in 2006. From 2006 to 2007, he was with the Laboratory for Advanced Networking at the University of British Columbia. From 2007 to 2011, he was with the Wireless and Networking Technologies Laboratory at the Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia. He also held an adjunct appointment at the University of Technology Sydney, Australia, between 2008 and 2011. In 2011, he joined the School of Electronic Engineering and Computer Science at Queen Mary, University of London, United Kingdom, as an assistant professor. His research interests include millimeter wave communications, energy harvesting, cognitive radio, and wireless security. He currently serves as an Editor for *IEEE Transactions on Wireless Communications*, *IEEE Transactions on Vehicular Technology*, and *IEEE Communications Letters*. He received the best paper award at IEEE ICC '2014, the International Conference on Communications and Networking in China (CHINACOM) in 2014, and IEEE Conference VTC-Spring '13. He received an Exemplary Reviewer Certificate for *IEEE Communications Letters* in 2012.

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