MILLIMETER-WAVE COMMUNICATIONS FOR 5G: FUNDAMENTALS: PART I

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The widespread availability and demand for multimedia capable devices and multimedia content have fueled the need for high-speed wireless connectivity beyond the capabilities of existing commercial standards. While fiber optic data transfer links can provide multi-gigabit-per-second data rates, cost and deployment are often prohibitive in many applications. Wireless links, on the contrary, can provide a cost-effective fiber alternative to interconnect the outlining areas beyond the reach of the fiber rollout. With this in mind, the ever increasing demand for multi-gigabit wireless applications, fiber segment replacement mobile backhauling and aggregation, and covering the last mile have posed enormous challenges for next generation wireless technologies. In particular, the unbalanced temporal and geographical variations of spectrum usage along with the rapid proliferation of bandwidth-hungry mobile applications, such as video streaming with high definition television (HDTV) and ultra-high definition video (UHDV), have inspired millimeter-wave (mmWave) communications as a promising technology to alleviate the pressure of scarce spectrum resources for fifth generation (5G) mobile broadband.

The current 4G Long Term Evolution (LTE)-Advanced and WiMAX 2 already use sophisticated link adaptation, orthogonal frequency-division multiplexing (OFDM), and multiple-input multiple-output (MIMO) for maximum spectral efficiencies close to theoretical limits measured in bits per second per Hertz per cell. With limited room for further enhancements of the spectral efficiency, one might argue that the trend toward network densification and multi-layer deployments with the aggressive deployment of small cells is a solution to the wireless spectrum shortage; however, co-tier interference between cells in the same layer and cross-tier interference between cells in different layers are a major drawback. In fact, the coexistence between the different layers of a hierarchical network remains an open problem; not to mention that capacity only scales linearly with the number of cells. Small cells alone are incapable of meeting the order of magnitude increase in mobile broadband traffic.

Very recently, the wireless communication community has turned its attention to the millimeter wavelength spectrum. The idea behind mmWave communications is to take advantage of the huge and unexploited bandwidth to cope with future multi-gigabit-per-second mobile, imaging, and multimedia applications. The vision of mmWave communications is to unleash the 30–300 GHz spectrum with the potential of over 100 GHz of new spectrum suitable for mobile broadband. This vision will enable low-cost fiber replacement mmWave mobile backhauls, last mile wireless broadband access, low-interference highly dense mmWave small cells, low-latency uncompressed high-definition media transfers, and wireless access to the cloud. The emergence of mmWave communications has created the need for new signal processing, circuit, antenna, and communication technologies. The convergence of these technologies is almost surely inevitable to cope with the stringent constraints imposed by the high propagation loss.

In the mmWave bands, atmospheric losses due to water vapor and oxygen absorption come into play and can easily exceed the usual free space losses. While signals in the sub-3 GHz spectrum can travel many miles and easily penetrate buildings, mmWave signals can only propagate a few miles and do not generally penetrate solid materials. However, this is not a disadvantage. These fundamental characteristics of low-interference mmWave communications will certainly promote:

- Densely packed communication links for more efficient spectrum reuse
- Privacy and security enhancement of communication transmissions

Recent research and development of radio frequency integrated circuit (RFIC) design and the introduction of relatively inexpensive/power-efficient complementary metal oxide semiconductor (CMOS) processing for semiconductor manufacturing have opened the mmWave bands and sub-mmWave bands for commercial use, as evidenced by IEEE 802.15.3c and IEEE 802.11ad. Despite this significant progress, a complete characterization of the mmWave link for 5G mobile broadband remains elusive. In particular, the coverage, directionality, and reliability of mmWave communications will require new innovations in signal processing, system architectures, and communication technologies that are far from trivial. System designers must increase the transmission range and spatial selectivity in the mmWave bands, especially in non-line-of-sight (NLOS) channels. This necessitates highly directional antennas and steerable antenna beams to compensate for the high propagation loss. Certainly, mmWave transmission is a key enabling technology for future multi-cell large-scale antenna systems where mmWave antennas with small size λ/2 dipoles allow for dense antenna packing in small areas for high beamforming gains. With this in mind, several practical design and implementation issues remain open and their solution will drastically change our understanding of future mmWave radio systems.

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We expect that through this Feature Topic, we can foster new solutions to the design, evaluation, and application of future mmWave radio systems. This Feature Topic brings together leading researchers and developers from diverse disciplines in system, hardware, software, and application design to the forefront of mmWave communications for future 5G. In response to the call for contributions, we received 40 paper submissions. During the review process, each paper was reviewed by at least three experts in the relevant areas through a rigorous two-round review process. Thanks to the courtesy of the Editor-in-Chief of *IEEE Communications Magazine*, Dr. Sean Moore, 13 outstanding papers have been collected for this Feature Topic, covering various aspects of mmWave communications, such as access and backhaul, dense networks, and resource allocation for multimedia applications. In order to present all of these papers, this Feature Topic has been split into two parts. The first part is concerned with the fundamentals of propagation characteristics, path loss, large-scale antenna arrays, coverage, and capacity, whereas the second part will be related to applications such as device-to-device communications and heterogeneous networks, and multimedia transmission. The first set of five articles appear in this issue, with the second part scheduled for publication in January 2015.

The combination of mmWave communications, large-scale multiple antennas, and small cell geometries is a symbiotic convergence of technologies that has the potential to drastically improve wireless access and throughput. The first two articles are related to these technologies. The first article, "Millimeter Wave Massive MIMO: The Next Wireless Revolution?" by A. Lee Swindlehurst *et al.*, outlines the benefits, challenges, and potential design considerations and solutions associated with cellular networks that incorporate these technologies. These issues span the breadth of communication/signal processing design and system/circuit design. From a communication/signal processing perspective, the authors treat a variety of issues related to modulation, equalization, channel estimation, and interference management. From a system/circuit perspective, the authors address issues related to RF transceiver design and antenna front-end integration. The aim is to accommodate orders of magnitude increase in capacity and spectral efficiency for future 5G mobile broadband. In the second article, "Study and Prototyping of Practically Large-Scale mmWave Antenna Systems for 5G Cellular Devices" by Wonbin Hong *et al.*, hardware challenges and important design considerations are presented for realizing a large-scale antenna array in the mmWave frequency bands for future 5G cellular devices. For the first time, a detailed approach is outlined for the implementation of up to 32 highly miniaturized antennas inside a real-life cellular device prototype. Analog beam steering is applied at 28 GHz using this prototype in combination with mmWave RF unit and baseband modem. Clearly, there is an urgent need to bridge the gap, and successfully integrate several diverse but interrelated technologies of large mmWave antenna arrays, RF units, and baseband modems.

The radio propagation characteristics of 5G cellular are fundamentally different from those of the microwave frequencies operating below 6 GHz. Attenuations and environmental losses in the mmWave bands are much higher than their microwave counterparts, making cellular operations over mmWave frequencies a much more challenging task. The next two articles are on the propagation characteristics in the mmWave bands, taking into account various scenarios and applications by addressing issues related to system architecture, coverage, and path loss. In the third article, "Coverage and Capacity of Millimeter Wave Cellular Networks" by Tianyang Bai *et al.*, the most relevant aspects regarding coverage and capacity are described taking into account three important factors affecting the mmWave cellular network: blockage, directional antennas, and co-channel interference. The authors make the important observation that dense mmWave networks can achieve comparable coverage and significantly higher data rates compared to conventional microwave networks. The fourth article, "Outdoor Path Loss Models for 5G Cellular Networks in the 28 GHz and 38 GHz Millimeter Wave Bands" by Ahmed Iyanda Sulyman *et al.*, presents a comprehensive overview of outdoor path loss model 5G cellular network planning in the mmWave bands based on measurement data collected at 28 GHz and 38 GHz in Austin, Texas, and Manhattan, New York. The authors argue that existing path loss prediction models for the microwave bands are inaccurate for predicting the outdoor path loss observed in the mmWave bands. More important, the authors propose two modified models at 28 GHz and 38 GHz that can be used for cellular planning in these frequency bands. Using the proposed models, an effective cell radius of about 200 m is observed. Based on this observation, 5G networks would require at least four times the number of sites for the same coverage as existing 3G and 4G networks.

In the near future, 5G networks will offload high data rate traffic from macrocells to small cells that use mmWave access links and receive data through multihop mmWave backhaul. In the fifth article, "Millimeter-Wave Access and Backhauling: The Solution to the Exponential Data Traffic Increase in 5G Mobile Communications Systems?" by Cedric Dehos *et al.*, the authors present an extensive survey detailing opportunities and challenges for the access and backhaul in the V- and E-bands, taking into account link budget, transceiver architecture, and antenna design.

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 mmWave 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 in 2014, CHINACOM in 2014, and IEEE VTC-Spring in 2013. He received the Exemplary Reviewer Certificate of *IEEE Communications Letters* in 2012.

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