Key enabling technologies for 5G: Millimeter-Wave and Massive MIMO

Narcis Cardona, Luis M. Correia, and Daniel Calabuig

5G wireless networks are expected to operate with orders of magnitude higher performance than the current 4G deployments. The demand for 5000 times higher data rates leads to the necessity of finding new techniques to increase spectral efficiency and of exploring new frequency bands above 6 GHz.

It has been proved that from UHF up to C band, a significant increase in system spectral efficiency can be reached through various techniques, such as Coordinated Multi-Point (CoMP), Massive Multiple-Input-Multiple-Output (MIMO), and interference management and cancellation; still, the resulting performance will not cope with the full expectations of IMT-2020 and 5G-PPP requirements for 5G networks, mainly in terms of offering 10 Gbps peak data rates with connection densities of 100 k to 1 M devices/km^2. To overcome this limitation, the future architecture of such 5G networks is being defined to be deployed on small cells and to use higher frequency bands, such as super high frequency (SHF, 3-30 GHz) or extremely high frequency (EHF, 30-300 GHz), also referred as to centimeter and millimeter wave bands, respectively.

The drawback of high propagation losses in mm-wave bands is expected to be compensated by using large blocks of continuous spectrum, which makes possible in early deployments to trade off spectral efficiency for bandwidth, where high data rates are achieved even with low-order modulation schemes requiring lower powers, lower complexity, and lower cost. The World Radiocommunications Conference in 2015 (WRC15) identified some candidate frequency bands for 5G mobile radio services, ranging between 24 GHz to 86 GHz, with significant bandwidths up to 10 GHz in the 66-76 GHz band.

Developing models for mm-wave propagation is crucial for the development of 5G radio access technologies, as such models are used for the definition and test of physical and higher layer components, link and system level feasibility studies, and spectrum management and regulatory issues. Although there are many published works about cm- and mm-wave propagation and radio channel modelling, like the COST IC1004 models published in “Cooperative Radio Communications for Green and Smart Environments” (River Publishers), or the specific models for mm-wave channels compiled in “Channel Measurements and Modeling for 5G Networks in the Frequency Bands above 6 GHz“ (IC1004 white paper), there are still open challenges for the development of technologies in such bands for 5G, being of outmost importance the appropriate measurements and models for 5G scenarios, including indoor, outdoor, and vehicular environments.

In this sense, ITU recommendations contain detailed information on gaseous and rain attenuation, mainly in ITU-R P.676-10 and ITU-R P.530-16, but the channel path loss coefficients and wideband parameters, like the RMS delay spread, are very briefly stated in the reports on propagation data and prediction methods for the planning of outdoor short-range radio-communication systems (ITU-R P.1411-8) and radio local area networks in the frequency range 0.3-100 GHz (ITU-R P.1238-8).

Most of the propagation and channel modelling studies published so far for mm-wave bands were made for static or quasi-static environments, and were aimed to determine the path-loss, the angle of arrival and the delay-spread of the radio channel. Among those parameters, the angle of arrival is of special interest, as getting the angular information allows to optimize beamforming, one of the key enabling technologies for 5G.

In addition to the above-mentioned advantage of having available large continuous blocks of spectrum, at cm- and mm-wave bands the wavelength, and consequently the antenna elements, are smaller, which facilitates the implementation of large antenna arrays. On this basis, Massive MIMO has been identified as one of the pillars of future 5G radio access networks. Massive MIMO uses configurations with hundreds of antenna elements, which enables the use of the spatial dimension via e.g., beamforming, reaching high antenna gains and spatial multiplexing capability, compensating for the severe propagation losses, and significantly improving system performance.

The implementation of Massive MIMO has been widely studied under two possible approaches: fully digital and hybrid analog-digital configurations. Fully digital massive MIMO requires a large-scale digital signal processing unit and one digital-to-analog converter per antenna element. High power consumption, and implementation and computational costs of fully digital configurations are balanced with the high flexibility that these configurations offer. The alternative of hybrid analog-digital systems, which combine analog beamforming and digital MIMO signal processing, reduces the number of digital-to-analog converter elements. Hybrid beamforming may be of full connection type or subarray type, in which the latter can reduce the complexity of RF circuits while reasonably maintaining performance compared to the former one.

For this special issue of the International Journal of Wireless Information Networks, three works presented in the IEEE PIMRC 2016 Symposium were selected, which have been extended and reviewed for this purpose. The three papers deal with the key aspects of 5G radio access networks in mm-wave bands: propagation modelling and massive MIMO implementation.

The paper “Channel Sounding System for mm-Wave Bands and Characterization of Indoor Propagation at 28 GHz”, by Wei Fan et al., describes a measurement campaign in an indoor environment preformed at 26-30 GHz, using both a directional horn antenna and a virtual uniform circular array at the same time. This allows for comparative studies of measured channels with two different antennas in a simultaneous way, conducted in both line-of-sight and non-line-of-sight scenarios. The measurements show good agreement between the measurement data collected with the horn antenna and the data collected with the uniform circular array, and the paper gives details on how propagation environment was found to be sparse both in delay and angular domains for the given scenario.

In the paper “Millimeter-Wave Beam Multiplexing Method Using Subarray Type Hybrid Beamforming of Interleaved Configuration with Inter-subarray Coding”, by Masahiko Shimizu et al., the challenges related to mm-wave beam multiplexing methods using hybrid beamforming configurations of interleaved subarray type is studied, and a solution based on sub-array coding is proposed. The method can reduce inter-beam interference and create multiple beams of a theoretical maximum gain that an array antenna can generate. As shown in detail in the paper, the channel capacity of the interleaved configuration with inter-subarray coding is larger than that of the localized configuration, with even better performance in high user density environments.

Finally, the work entitled ‘‘Performance Evaluation of NL-BMD Precoding over Analog-Digital Hybrid Beamforming for High SHF Wide-Band Massive MIMO in 5G’’, by Hiroshi Nishimoto et al., focuses on multi-user Massive MIMO systems and evaluates the performance of nonlinear block multi-diagonalization precoding, an intermediate solution between the conventional linear precoder and nonlinear precoder, for analog-digital hybrid beamforming. Their simulation results in an indoor scenario show that the nonlinear block multi-diagonalization precoding has a better performance than linear precoder and around half the complexity of nonlinear precoder.

We would like to thank all our colleagues who have helped in the papers review process, and the authors for their contribution and efforts to complete the papers with a very high quality. Finally, we express our gratitude to Dr. Kaveh Pahlavan for initiating this special issue and inviting us to undertake this rewarding activity.

	**Narcis Cardona:** M.Sc. (1990), Ph.D. (1995), Prof. (2001). Since October 1990 he is with the Communications Department of the Polytechnic University of Valencia (UPV), currently Full Professor on Signal Theory and Communications. Prof. Cardona is Director of the Research Institute of Telecommunications and Multimedia Applications (iTEAM), with 150 researchers including assistant professors & research fellows. Additionally, he is the Director of the Mobile Communications Master Degree (since 2006). Prof. Cardona has led National research projects and European projects, Networks of Excellence and other research forums in FP6, FP7 and H2020, always in Mobile Communications aspects. At European scale, he has been Vice-Chairman of COST273 Action (2003-2006), Chairman of the EU Action COST IC1004 (2011-2015), coordinator of the National Network of Excellence ARCO5G since January 2015, Vice-Chairman of the COST Action IRACON from March 2016, member of the Steering Board of METIS (7FP; 2011-2015), METIS2 (H2020 5GPPP; 2015-2017), and WIBEC (H2020 ITN; 2016-2019). He has organized and participated to the Committees of international conferences, being General Chair of IEEE ISWCS 2006 and IEEE PIMRC 2016, and TPC Chair of IEEE VTC 2015 His current research topics are Radio wave propagation, Planning and Optimization of Mobile Access Networks, Digital Multimedia Broadcasting, Dynamic Spectrum Management and Wireless Body Environment Communications
	**Luis M. Correia** was born in Portugal, in 1958. He received the Ph.D. in Electrical and Computer Engineering from IST (University of Lisbon) in 1991, where he is currently a Professor in Telecommunications, with his work focused in Wireless/Mobile Communications in the areas of propagation, channel characterization, radio networks, traffic, and applications, with the research activities developed in the INOV-INESC institute. He has acted as a consultant for Portuguese mobile communications operators and the telecommunications regulator, besides other public and private entities, and he has been in the Board of Directors of a telecommunications company. Besides being responsible for research projects at the national level, he has participated in 31 projects within the European frameworks of COST, RACE, ACTS, IST, ICT and H2020, where he also served as evaluator and auditor, having coordinated 4 of them and taken leadership responsibilities at various levels in many others. He has supervised more than 160 M.Sc. and Ph.D. students, having edited 6 books, contribute to European strategic documents, and authored more than 400 papers in international and national journals and conferences, for which he has served also as a reviewer, editor, and board member. At the international level, he has been part of 28 Ph.D. juries, and evaluated research projects and institutions for funding agencies in 8 countries and the European Commission. He has been the Chairman of Conference, of the Technical Programme Committee and of the Steering Committee of several major conferences,

	besides other several duties. He was a National Delegate to the COST Domain Committee on ICT. He was active in the European Net!Works platform, by being an elected member of its Expert Advisory Group and of its Steering Board, and the Chairman of its Working Group on Applications, and was also elected to the European 5G PPP Association.
	**Daniel Calabuig** received the M.Sc. and Ph.D. degrees in telecommunications from the Universitat Politècnica de València (UPV), Valencia, Spain, in 2005 and 2010, respectively. In 2005, he joined the Institute of Telecommunications and Multimedia Applications (iTEAM), UPV. During his Ph.D., he participated in some European projects and activities, such as NEWCOM, COST2100, and ICARUS, where he was involved in radio resource management in heterogeneous wireless systems and Hopfield neural networks optimization. In 2009, he visited the Centre for Wireless Network Design, University of Bedfordshire, Luton, U.K. In 2010, he received the Marie Curie Fellowship from the European Commission to research on Cooperative Multipoint Transmissions. He visited the Department of Systems and Computer Engineering, Carleton University, Ottawa, Canada, from 2010 to 2012. During 2012, he also visited the TOBB Ekonomi ve Teknoloji Üniversitesi, Ankara, Turkey. In 2012, he returned to the iTEAM and was involved inside the European projects Mobile and Wireless Communications Enablers for the Twenty-twenty Information Society (METIS) and METIS-II, whose main objective is laying the foundation of 5G, the next generation mobile, and wireless communications system.