What will 5G Antennas and Propagation Be?

FIFTH-GENERATION wireless technology, denoted as "5G" by the global wireless communications industry, seeks to accomplish multi-fold increases in key aspects of wireless communication. In conjunction with conventional microwave frequencies, millimeter-wave (mmWave) and THz frequencies and technologies are being investigated by major research institutions and industry. Deliberations are underway by regulatory officials around the world to authorize mmWave and sub-THz spectrum for 5G fixed and mobile applications. In the development of 5G communication systems, new propagation phenomena, novel multi-antenna transmitting architectures, and new mmWave operating frequency bands using much wider channel bandwidths than ever before are proving to be extremely effective ways to dramatically increase the communication data rate of future mobile communication networks. The papers in this special issue offer extensive insights and promising results that address many of the technical challenges that must be solved to usher in the 5G era.

Over the past few decades, mmWave and Terahertz communications and sensing have grown into popular research topics, and the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION (TAP) has published four special issues (*Antennas and Propagation at mm- and Sub mm-Waves* in April 2013, *Antennas and Propagation Aspects of 60-90GHz Wireless Communication* in October 2009, *Optical and Terahertz Antenna Technology* in November 2007, and *Millimeter Wave Antennas and Propagation* in July 1970) discussing different aspects of mmWave and Terahertz designs and applications.

This special issue was motivated by the global race to 5G wireless communications, even though 5G is not yet defined. As demonstrated in this special issue, there are a wide range of new results and emerging antenna and propagation concepts developed by industry and academia that will influence the emergence of mobile communications to the mmWave spectrum and beyond. A wide range of competing wireless architectures, antenna technologies, and propagation studies and models are presented here by authors from 17 countries, and while today it remains difficult to accurately know exactly what 5G will be, one can readily glean from this compilation of papers that 5G will introduce numerous unprecedented challenges to the mobile communications field, with some very promising technological developments available for making multi-gigabit per second mobile devices possible. This special issue was conceived to serve as a catalyst to present promising early work, and to initiate lively technical discussions within the IEEE AP-S community on the following perspective: "How would 5G affect aspects related to antennas and propagation, and how should we respond?"

A. Contents of the Special Issue

This special issue consists of 53 peer-reviewed papers from academic institutions, government laboratories, and industry research centers from around the world. Introducing this special issue are three invited papers which respectively provide extensive insight and a comprehensive overview on key perspectives of 5G, with an emphasis on propagation models, multi-beam antenna technologies, and mmWave antennas for mobile terminals. The remaining 50 papers are then categorized into 7 distinctive categories based on the technical focus of each submitted manuscript that was received through the open call: Antennas (10 papers), Antenna-in-Package (5 papers), Phased-Arrays (6 papers), Propagation and Channel Modeling for 5G (13 papers), MIMO systems and characterization (9 papers), Enhancement Techniques (5 papers), and Communications papers (2 papers).

B. Invited Papers (3 papers)

The first invited paper titled "**Overview of Millimeter Wave Communications for Fifth-Generation (5G) Wireless Networks - with a focus on Propagation Models**" by **Rappaport *et al.*** provides an overview of the evolution of cellular and Wi-Fi networks from the fourth generation (4G) to future fifth generation (5G) networks, and highlights new spectrum allocations and illustrates the new features and applications of 5G being developed for use in the mmWave frequency bands. Early results and key concepts of 5G networks are presented, and detailed propagation channel models and channel modeling standardization efforts of many international groups for both licensed and unlicensed applications are described in detail. The second invited paper by **Hong *et al*.** titled "**Multi-Beam Antenna Technologies for 5G Wireless Communications**" provides an overview of the existing multibeam antenna technologies which include passive multibeam antennas based on quasi-optics components and beamforming circuits, multi-beam phased array antennas enabled by various phase shifting methods, and digital multibeam antennas with different system architectures. The suitability of these multibeam antennas for future 5G massive MIMO wireless systems as well as the associated challenges are presented. The third invited paper titled "**Millimeter-wave 5G Antennas for Smartphones: Overview and Experimental Demonstration**" by **Hong *et al.*** provides an overview of mmWave 5G antennas for cellular handsets. Practical design considerations and solutions related

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to the integration of mmWave phased-array antennas with beam switching capabilities are investigated and exhaustively analyzed.

C. Antennas (10 papers)

The first regular topic focuses on how 5G will affect key aspects of antenna elements, including the design methodologies, topologies and characterizations of antennas. The need for high radiation efficiency while maintaining a low-profile becomes one of the highest priorities at mmWave frequencies and above. The first paper by **Guo *et al.*** presents two new planar aperture antennas (PAAs) with high gain and high aperture efficiency. Each antenna is composed of an opening cavity and differentially fed by the grounded coplanar waveguides (GCPWs) at two parallel edges. This work is followed by the paper of **Ahmad *et al.*** which introduces a novel radiating structure based on a 3-D metallized molded plastic part which is soldered onto a thin, single-layer circuit board and fed by a microstrip line of 50 Ohms impedance. The 3-D structure is free of indentations, and simple to manufacture. The 10 dB return loss bandwidth is wider than the 57 GHz – 64 GHz license-exempt frequency band.

Multiple polarizations and multi-frequency antennas will be required for 5G communication systems. **Hsu *et al.*** present a novel design of a compact dual-polarized MIMO antenna with end-fire radiation for mmWave wireless applications. The low-cost printed circuit board (PCB) process serves as the basis for the design, fabrication, and measurement of the proposed dual-polarized quasi Yagi-Uda antenna. A novel tunable tri-band antenna that is able to provide three concurrent, independently tunable operating bands covering a frequency range from 600 MHz to 2.7 GHz. is presented by **Bai *et al.***

Efficient feeding networks featuring low insertion loss are imperative for 5G antenna array structures. **Zhu *et al.*** propose a substrate-integrated-waveguide-fed array antenna with 57 – 71 GHz bandwidth. The antenna covers a relative bandwidth of 38.7% from 50 to 74 GHz with an average gain of 8.7 dBi. The four-way broad wall coupler is applied for the 2×2 sub-array, which suppresses the cross-polarization of a single element. This method is used to expand up to an 8×8 array antenna with a peak gain of 26.7 dBi, and the radiation efficiency is over 80% within the matching band. **Potelon *et al.*** present a high-gain, broadband and low-profile Continuous Transverse Stub (CTS) antenna array in E-band. This array comprises 32 long slots excited in parallel by a uniform corporate parallel-plate-waveguide (PPW) beamforming network combined to a pillbox coupler. The radiating slots and the corporate feed network (CFN) are built in aluminum, whereas the pillbox coupler and its focal source are fabricated in PCB technology.

Antenna design methods that offer improved antenna element topologies enable the formulation of innovative beam synthesis. **Li *et al.*** propose a mmWave dual-feed square loop antenna (DFA). Direct on-antenna power combining is achieved by eliminating the lossy power combining network between the transmitter and antenna. The DFA is designed and characterized at two potential 5G bands, 38.5 GHz and 73.5 GHz. A low profile antenna for mmWave body-centric applications is presented by **Ur-Rehman *et al.*** The performance of the antenna is evaluated in off-body, on-body and body-to-body communication scenarios using a realistic numerical phantom and verified through measurements. **Chu *et al.*** describe a novel printed log-periodic dipole array antenna for 5G mobile and wireless communication. The gain of the antenna is enhanced by using parasitic cells comprised of several bow-tie directors and bow-tie parasitic patches. The addition of bow-tie directors is based on the principles of the quasi-Yagi and bow-tie antennas. This section concludes with work by **Tang *et al.*** who focus on two 28 GHz, planar, electrically small Huygens source antennas. This paper integrates an electric Egyptian axe dipole (EAD) with magnetic capacitively-loaded loop (CLL) near-field resonant parasitic (NFRP) elements with a coax-fed dipole radiator to demonstrate linearly polarized (LP) and circularly polarized (CP) systems. The design is exhaustively studied using numerous experiments, and the specific absorption rate (SAR) values of both the LP and CP Huygens source antennas are evaluated and found to be very low.

D. Antenna-in-Package (5 Papers)

Packaging aspects will be intertwined with antenna design methodologies for 5G communications. The following manuscripts meticulously describe potentially efficient and economic methods for 5G antenna-in-packages. The first paper by **Zhang *et al.*** discusses a low-cost multilayer antenna-in-package (AiP) solution, using the conventional PCB process at the 60 GHz spectrum. The design procedure focuses on overcoming the fabrication restrictions while realizing a low-cost, broadband, compact and reliable package solution. An aperture coupled patch antenna using a compact fan-shaped feeding network and a vertical quasi-coaxial via transition is proposed, fabricated and measured. Based on the single antenna, a 16-element antenna package is realized in the dimension of 14 mm $\times$ 14 mm $\times$ 0.925 mm. **Vahdati *et al.*** present the design of a 90-GHz phased-array transmitter front-end on low temperature co-fired ceramic (LTCC) technology. The DC and differential hybrid IF signals are provided to the flip-chipped components through the bias and IF lines designed on the LTCC. A 1×4-patch antenna array is designed for the transmitter and fabricated on the LTCC, where the DC and IF signal pads on the LTCC are soldered to PCB pads for measurements. **Liu *et al.*** introduce a practical Ka-band antenna-in-package (AiP) structure and discuss antenna element design and implementation trade-offs. The AiP design is based on multi-layer organic buildup substrates that are suitable for phased array module integration, and supports both horizontal and vertical polarizations. This work is followed by a ball grid array-module with an integrated shaped lens for 5G backhaul/fronthaul communications in F-band by **Bisognin *et al.*** A 2×2 array of aperture-coupled patch antennas is designed in the $7\times7\times0.362$ mm^3 BGA module as the feed antenna of the lens. This approach achieves a 7.8 dBi realized gain, broadside polarization purity above 20 dB, and over 55% total efficiency from 110 GHz to 140 GHz (20% bandwidth). A plastic elliptical lens 40 mm in diameter and 42.3 mm in height is placed on top of the BGA module, achieving a return loss better than 10 dB and a 28 dBi realized gain from 114 to 140 GHz. This section concludes with a paper by **Mak *et al.*** which describes a novel frequency beam-scanning slotted leaky wave magneto-electric (ME) dipole antenna array suitable for 5G applications. The proposed antenna has eighteen elements of slots and electric dipoles, and is built on a two-layer PCB that has a conventional slotted substrate integrated waveguide (SIW) leaky wave antenna (LWA) at the lower level. In the upper layer, electric dipoles are attached to the design. The antenna operates with wide bandwidth and a peak gain of 16.55 dBi with less than 3 dB gain variation throughout the frequency range from 27 GHz to 32 GHz.

E. Phased-Array (6 Papers)

This section comprises of state-of-the-art research activities focused on 5G phased-arrays. **Briqech *et al.*** devise a 55 – 65 GHz 16-element beam steering array with a low-cost piezoelectric transducer (PET) controlled phase shifter that is fabricated on a single low-cost PCB substrate. An ultra-wideband antenna element is designed to achieve symmetric E- and H-plane radiation patterns. The array is fed with an amplitude taper wideband Y-junction power divider including an electromagnetic band gap (EBG) structure surrounding the feeding network. The phased array integrated with EBG structure reduces the coupling between feed lines and surface waves, which shows a clear reduction of sidelobe levels. A planar switchable 3D-coverage phased array for 28 GHz mobile terminal applications is introduced by **Zhang *et al.*** In order to realize 3D-coverage beam scan with a simple planar array, chassis surface waves are efficiently excited and controlled by three identical slot subarrays. Three subarrays switch their beams to three distinct regions. User effects on the switchable array are also studied in both data mode and talk mode (voice) at 28 GHz. This work is followed by **Li *et al.*** who discuss a modified topology of the two-dimensional (2-D) multi-beam antenna array fed by a passive beamforming network. The new array structure can be conveniently integrated into multi-layered planar substrates, which offer advantages of low loss characteristics, ease of realization, and low fabrication cost for mmWave applications. A 4×4 multi-beam antenna array that can generate sixteen radiation beams is then designed, fabricated and measured in order to demonstrate the efficacy of the proposed topology.

The densification of cellular networks and the impending move to much higher operational frequencies are forcing new topological considerations in 5G networks. In particular, networks that enable extreme spatial discrimination are being considered as a means to significantly increase data capacity by realizing spatial-spectral channels that offer frequency re-use without co-channel or adjacent-channel interference. **Prather *et al.*** introduce the design and initial demonstration of both transmit (Tx) and receive (Rx) array systems that are used in tandem to form a down-/up-link for the purpose of characterizing both array and link performance in future narrowbeam mmWave systems.

Hossain *et al.* present design, prototyping and characterization of a radiation pattern reconfigurable antenna (RA) that targets 5G communications. The reconfigurable parasitic structure is similar to a hexagonal prism, where the top/bottom bases are formed by a hexagonal dome structure. The surfaces of the parasitic structure house electrically-small metallic pixels with various geometries. The adjacent pixels are connected by PIN diode switches to change the geometry of the parasitic surface, thus providing reconfigurability in the radiation pattern. In the last paper of the section, **Imbert *et al.*** introduce design, LTCC fabrication, and full experimental verification of novel dielectric flat lens antennas for the mmWave spectrum. The planar lenses allow full 2-D beam-scanning of high-gain radiation beams. A time-domain spectroscopy system is used to evaluate the permittivity profile achieved with the LTCC manufacturing process to confirm the viability of fabricating inhomogeneous flat lenses in a mass-production technology.

F. Propagation and Channel Modeling for 5G Wireless (13 Papers)

Understanding radio propagation mechanisms that impact mobile antennas near the human body, mobile handoffs, beam steering, and MIMO for frequencies above 10 GHz are paramount for 5G. The first paper in this section by **Rappaport *et al.*** offers insights into mmWave channel behavior for handoff, antenna, and air interface design. Omnidirectional and directional small-scale spatial fading of wideband (1 GHz channels) received voltage amplitudes are shown to exhibit log-normal and Ricean distributions, respectively, where fade depths are shown to be dependent upon pointing angle and bandwidth. Small-scale spatial autocorrelations of wideband (1 GHz channels) received voltage amplitudes are shown to fit sinusoidal exponential and exponential functions for line-of-sight (LOS) and non-line-of-sight (NLOS) environments, respectively, with small decorrelation distances of 0.27 cm to 13.6 cm (smaller than the size of a handset) that are favorable for spatial multiplexing. Local area measurements were conducted using cluster and route scenarios to study path loss during channel transitions from LOS to NLOS locations, and various diffraction models are shown to accurately predict human shadowing near an antenna as well as common indoor and outdoor building obstacles. A map-based channel model for evaluation of 5G is discussed by **Kyösti *et al.*** The described model covers frequency bands from typical cellular frequencies up to mmWave in a variety of different environments, with emphasis on the outdoor urban channel. A comparison to a corresponding geometry based stochastic model (GSCM) is performed in the urban outdoor environment with the second moment distributions of propagation parameters and the multi-user (MU) MIMO sum rate capacity. The simulations indicate substantial differences in MU-MIMO performance between the different channel models. **Neil *et al.*** consider channel models and measurements across a wide range of candidate bands for 5G wireless networks. Motivated by the different propagation and spatial characteristics between different bands, and channel models within a band, the authors investigate how key channel modeling and spatial parameter differences impact various antenna topologies in terms of sum rate, channel eigenvalue structure, effective degrees of freedom (EDOF), channel connectivity and massive MIMO convergence. The work by **Raghavan *et al.*** focuses on understanding mmWave channel properties that have an important bearing on the feasibility of mmWave systems in practice and which impact physical (PHY) layer design. The paper first studies large-scale properties such as path loss and delay spread across different carrier frequencies in various real-world scenarios. The authors also seek to understand the feasibility of outdoor-to-indoor coverage, where material measurements corresponding to mmWave reflection and penetration are studied, and significant notches in signal reception spread over a few GHz are reported. Implications of these measurements on system design are discussed, and multiple solutions are proposed to overcome the channel impairments.

Zhao *et al.* focus on the effect of a user's body on channel characteristics for single user downlink transmission in an urban scenario for 5G by using ray-tracing at 15 GHz and 28 GHz. Three different designs of user equipment (UE) antennas are fabricated and integrated into a mobile phone prototype, and their 3D radiation patterns are measured both with and without a user. The user remains in Cellular Telephone Industries Association (CTIA) standard data mode and talking mode during measurements. **Ling *et al.*** attempt to address the challenge of the imperfections in existing 5G channel sounding and data processing approaches, which can impact the fidelity of future channel models. This paper describes measurement campaigns in a lecture hall and laboratory using steerable beam antennas for characterizing 13-17 GHz channels. The Space-Alternating Generalized Expectation-maximization (SAGE) algorithm is applied to estimate the multipath components (MPCs) in delay and angle of arrival domains. These estimated MPCs are further grouped into clusters via five approaches, i.e. K-means, threshold-based, Gaussian-mixture model, hierarchical and spectral methods.

Millimeter-wave transceivers will feature massive phased-array antennas whose pencil beams can be steered towards the angle-of-arrival of the propagation path having the maximum power, exploiting the high gain to compensate for the greater path loss witnessed in the first meter of propagation at much higher frequencies. For this reason, maximum-power path-loss models, in contrast to conventional ones based on the integrated power from an omnidirectional antenna, may be more relevant. The analysis of E-band path loss and propagation mechanisms in the indoor environment is presented by **Senic *et al.*** The authors compare both model types at 83.5 GHz for four indoor environments typical of hotspot deployments in LOS and NLOS conditions up to a range of 160 m. **Hejselbæk *et al.*** describe how a user's proximity affects the performance of a 5G handset mock-up. The user impact is studied by channel sounding in an indoor scenario, with and without the presence of different users. The mock-up handset has a uniform linear array of receive (Rx) antennas operated at 21.5 GHz. A dual-polarized horn antenna with a wide beamwidth is used as the transmit (Tx) antenna in a channel sounder, allowing for the recording of dynamic and realistic channels. **Xu *et al.*** present different measurement schemes to investigate the possibilities and limitations of scalar and vector-based measurement systems for RF EMF compliance assessments of 5G mobile communication user equipment (UE). The accuracy of different measurement schemes is assessed using numerical simulation. Measurements aimed at verifying the simulations are carried out in a semi-anechoic chamber. In work by **Syrytsin *et al.,*** the user effects on mobile terminal antennas at 28 GHz are statistically investigated with the parameters of body loss, coverage efficiency, and power when shadowed. The data are obtained from measurements of 12 users in data and talk modes, with the antenna placed on the top and bottom of the mobile terminal chassis. In the measurements, the users hold the phone naturally. The radiation patterns and shadowing regions are also studied. A detailed numerical dosimetry study is performed by **Guraliuc *et al.*** for a terminal with a 60-GHz antenna module for several representative human body exposure scenarios within 5G small cells. Numerical considerations are made regarding the user terminal and human body modeling, followed by analysis of the user exposure levels in the near field for phone call and browsing scenarios.

The advent of 5G technologies has motivated massive interest in body-centric communications (BCC), especially at mmWave frequencies. As a result, the portable/handheld terminals are becoming more and more "intelligent", but not without the cost of being less secure. Improved authentication measures need to be explored, as effective identity authentication is the first level of security in these devices. **Zhao *et al.*** present a novel keyless authentication method exploiting wireless channel characteristics. A detailed channel model using data acquisition from the real environment and an empirical approach is adopted to evaluate the usability of this method.

Sulyman *et al.* present analytical and empirical data documenting the effects of solar radio noise on outdoor propagation path loss at 60 GHz bands. Both LOS and NLOS scenarios are considered. Based on the measurement data collected in sunny weather with intense solar activities, the authors develop a large-scale propagation path loss models at 60 GHz, where the effects of solar radio noise on the path loss data are considered.

G. MIMO Systems and Characterizations (9 Papers)

5G systems utilizing high carrier frequency and multiple-input multiple-output (MIMO) antennas face challenges for efficient and cost effective design. Wave propagation and practical hardware tradeoffs at higher frequency ranges provide new boundary conditions for implementations. **Tuovinen *et al.*** address system performance boundaries and analysis method towards multibeam communications at mmWave. The authors combine analysis from antennas and propagation, and include RF transceiver specifications and beamforming requirements. Realistic propagation models and antenna implementations are used to generate beam-specific path gains for a wide variety of user scenarios. This paper is followed by the work of **Jo *et al.*** who report a complete mmWave wireless system which coherently utilizes polarization diversity, Multi-Input Multi-Output (MIMO), and beamforming technologies applicable for 5G wireless smart terminals. Using an interdisciplinary approach across the antennas, RF architecture and digital modem, the polarization of the presented mmWave beamforming antenna system dynamically adapts to the channel environment and MIMO transmission modes. **Wallace *et al.*** study the case of co-located 4×4 MIMO antennas at 2.55 and 24 GHz for two university buildings consisting of classrooms and offices. Measurements show that link gains in hallways and connected labs appear similar at the two frequencies when the effect of lower effective receive antenna aperture with increasing frequency is removed. NLOS propagation through a wall or around hallway corners exhibits approximately 5-20 dB (11 dB on average) greater loss beyond the 20 dB aperture loss at 24 GHz compared to that at 2.55 GHz. **Park *et al.*** describe a performance comparison of 2×2 MIMO antenna arrays with different configurations and polarizations in a reverberation chamber (RC) at 28 GHz. Eight types of antenna arrays are proposed, according to different configurations and polarizations. The measured results of the antenna arrays show that they have similar antenna performance with respect to the same array size, except for polarization. Based on these measurements, the authors propose twelve cases of 2×2 MIMO antenna arrays with dual-separated polarizations between the top and bottom sides.

A two concentric slot loop connected array MIMO antenna system for 4G/5G terminals is devised by **Sharawi *et al.*** The proposed design contains a 2-element slot-based connected MIMO antenna system for 4G and a connected antenna array (CAA) 2-element MIMO antenna system for a candidate 5G band. Two rectangular loops are etched on the periphery of the ground plane. The top and bottom portions of the thin loops act as the two 4G MIMO antennas, while parts of their sides serve as 5G arrays. **Murata *et al.*** propose a novel analog eigenmode transmission technique suitable for a short-range multiple-input multiple-output (SR-MIMO) system consisting of arbitrary power-of-two number of antennas, utilizing the idea of orbital angular momentum (OAM). In this paper, the operating principle of the proposed technique is discussed from the viewpoint of linear algebra, and some example network configurations are presented with determination of the DFT-matrix weight. Numerical analyses confirm the important features of the proposed technique. **Taniguchi *et al.*** present MIMO measurements in the 20 GHz band and evaluate the basic performance of massive MIMO systems when considering 100 elements at a base station and 7 user equipment (UE) devices. It is shown that zero forcing is essential as a transmission scheme in massive MIMO systems, whereas the maximum-ratio combining method cannot reduce interference effectively in such systems. In addition, it is shown that analog-digital hybrid beamforming can be used to reduce the calculation complexity and improve hardware implementation.

Massive MIMO is considered to be a promising key technology for 5G. Various studies analyze the impact of the number of antennas, relying on channel properties assuming uniform antenna gains in very large arrays. **Chen *et al.*** investigate the impact of mutual coupling and edge effects on the gain pattern variation in a massive MIMO array. The authors' analysis focuses on the comparison of patch antennas versus dipoles, representative for the antennas typically used in massive MIMO experiments. The section concludes with the paper by **Yang *et al.*** that focuses on the realization of a compact tapered slot antenna array for 5G mmWave massive MIMO systems. The antenna element is fed by a substrate integrated waveguide (SIW), which can be directly integrated with the mmWave circuits.

H. Enhancement Techniques (5 Papers)

This section focuses on research aimed at enhancing existing antenna methodologies. The first paper by **Wu *et al.*** discusses reducing the mutual coupling among antenna elements for large-scale antenna arrays. The authors propose a new concept, called array-antenna decoupling surfaces (ADS), for reducing the mutual coupling between antenna elements in a large-scale array antenna. An ADS is a thin surface that is composed of a plurality of metal reflection patches and is placed in front of the array antenna. The partially reflected waves from the ADS can be controlled to cancel the unwanted coupled waves. A multimode decoupling technique with independent tuning characteristic for mobile terminals is examined by **Xu *et al.*** The authors present a novel idea of achieving stability of the boundary conditions of decoupling elements to solve the mutual effect problem by adopting a metal boundary to realize stability. One distinguished feature of the proposed technique is that the independent tuning characteristic can be maintained even if the number of decoupling elements increases. **Oliveri *et al.*** introduce a new single-objective integer-coded genetic algorithm to simultaneously synthesize the antenna element (a spline-shaped patch embedded in a finite array model) and the overall irregularly clustered-array layout through a multi-objective antenna-shape-optimization combined with a sub-arraying technique. This method is supplemented with numerical examples to demonstrate the advantages and effectiveness of the proposed strategy for future large-scale 5G base station antennas.

In order to estimate the electromagnetic exposure under multi-antenna transmitters installed in portable devices working in LTE and mmWave bands, **Li *et al.*** generalize a low-order model and extend it to higher orders based on the Fourier series expansion for a fast and accurate evaluation and prediction of electromagnetic absorption (EA) as a function of the phase difference among multiple transmitters. The presented higher-order model can be used to improve the bio-electromagnetic performance of multi-antenna portable devices when combined with other communication technologies. The final paper of this section studies the quantitative comparative analysis of electromagnetic exposure and heating induced by 60-GHz body-mounted antennas. In this paper by **Leduc *et al.,*** the near-field interaction between representative antenna arrays for off-body communications with three feeding topologies and human body are compared in terms of matching and radiation, as well as in terms of user exposure. Interestingly, the presence of a ground plane results in exposure reduction by more than 70 and 8 times the peak and averaged levels, respectively.

I. Communications (2 Papers)

Two papers comprise the Communications section. The first paper is authored by **Dussopt *et al.*** which discusses a V-band, switched-beam, linearly-polarized transmit-array antenna enabling self-pointing point-to-point communication systems. The design and characterization of the unit-cells and the transmit-array demonstrate an experimentally realized gain of 33.4 dBi, an aperture efficiency of 48% and a 3-dB bandwidth of 15.4%. This section is concluded by an investigation of a cavity backed dual slant polarized and low mutual coupling antenna array panel. Operating from 4.9 GHz – 6 GHz, **Komandla *et al.*** analyze the aforementioned topology for MIMO antenna 5G applications. The authors use numerical simulations to verify the beamforming capability in the digital domain for both 4×4 and 16×16 panel arrays.

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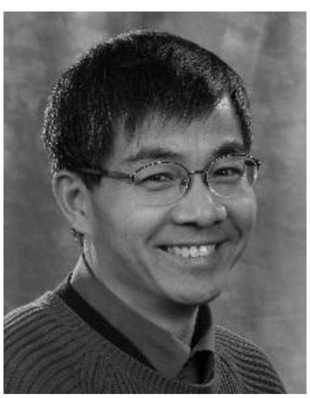

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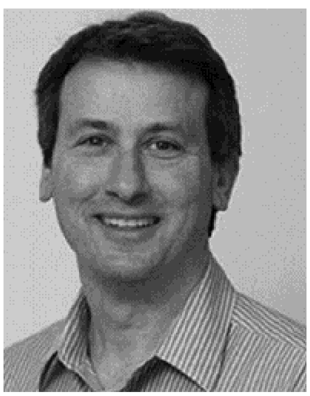
He is currently an Assistant Professor with the Department of Electrical Engineering, Pohang University of Science and Technology, Pohang, South Korea. From 2009 to 2016, he was with Samsung Electronics Co., Ltd., Suwon, South Korea, as a Principal and Senior Engineer, where he was involved in participating and leading extensive research and development tasks for upcoming wireless applications including MIMO, wireless power transfer, and millimeter-wave wireless solutions. He has well over a decade of extensive research and development experience with primary interest in future wireless communication antennas and RF circuits, mesoscale and nanoscale transparent electronics, and 3-D packaging. His patented invention on optically invisible microwave antennas for Wi-Fi and GPS in 2016 and 2017 has led to over three million commercialized productions as of 2017. He has authored or co-authored over 50 peer-reviewed journals, conference papers, and two book chapters. He has invented over 60 patent inventions.

Dr. Hong a member of the Technical Committee of the IEEE MTT-6 Microwave and Millimeter-Wave Integrated Circuits. He was a recipient of numerous recognitions, including the Outstanding Researcher of the Year Award, the Outstanding Mentor of the Year Award, the Major Achievement Award, the Annual Inventor Award, and the Samsung Best Paper Award during his tenure at Samsung. He was also awarded several fellowships and scholarships including the Samsung Scholarship Award for Graduate Studies, the Rappaport Wireless Scholarship, the NASA Summer Under-graduate Research Fellowship, the A. F. Welch Scholarship, and the Donald McQuinn Scholarship. He is currently serving as an Associate Editor for the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION and a Guest Editor for the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION Special Section on *Antennas and Propagation Aspects of 5G Communications*. He has served as an Invited Lecturer and a Speaker in over 50 international research symposiums, government, and industry sessions held around the world.



Theodore S. Rappaport (S'83–M'84–SM'91–F'98) received the B.S., M.S., and Ph.D. degrees in electrical engineering from Purdue University, West Lafayette, IN, USA, in 1982, 1984, and 1987, respectively.

He founded major wireless research centers with the Virginia Polytechnic Institute and State University (MPRG), The University of Texas at Austin (WNCG), and NYU (NYU WIRELESS) and founded two wireless technology companies that were sold to publicly traded firms. He is an Outstanding Electrical and Computer Engineering Alumnus and a Distinguished Engineering Alumnus from Purdue University. He is currently the David Lee/ErnstWeber Professor of Electrical and Computer Engineering with the New York University Tandon School of Engineering, New York University (NYU), Brooklyn, NY, USA, and the Founding Director of the NYU WIRELESS Research Center. He also holds professorship positions with the Courant Institute of Mathematical Sciences and the School of Medicine, NYU. He is a highly sought-after technical consultant having testified before the U.S. Congress and having served the ITU. He has advised more than 100 students, has more than 100 patents issued and pending, and has authored or co-authored several books, including the best seller *Wireless Communications: Principles and Practice*–Second Edition (Prentice-Hall, 2002). His latest book *Millimeter Wave Wireless Communications* (Pearson/Prentice-Hall, 2015) was the first comprehensive text on the subject.

Cyril Luxey (M'05–SM'09–F'17) was born in Nice, France in 1971. He received the Ph.D. degree in electrical engineering from the University Nice-Sophia Antipolis, Nice, France, in 1999. During his thesis, he worked on several antenna concepts for automotive applications like printed leaky-wave antennas, quasi-optical mixers and retrodirective transponders.

From 2000 to 2002, he was with Alcatel, Mobile Phone Division, Colombes, France, where he was involved in the design and integration of internal antennas for commercial mobile phones. In 2003, he was recruited as an Associate Professor at the Polytechnic School of the University Nice Sophia-Antipolis. Since 2009, he is a Full Professor at the IUT Réseaux et Télécoms in Sophia-Antipolis. He is doing his research in the Polytech'Lab. In October 2010, he was appointed as a Junior Member of the Institut Universitaire de France (IUF) institution for five years. He has authored or co-authored more than 300 papers in refereed journals, in international and national conferences and as book chapters. He has given more than 15 invited talks. His current research interests include the design and measurement of Millimeter-wave antennas, antennas-in-package, plastic lenses and organic modules for mm-wave and sub-mm wave frequency bands. He also works on electrically small antennas, multi-antenna systems for diversity and MIMO techniques.

Prof. Luxey was an Associate Editor for *IEEE Antennas and Wireless Propagation Letters* from May 2012 to May 2017, a reviewer for the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, the *IEEE Antennas and Wireless Propagation Letters*, the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, the *IEEE Microwave and Wireless Conference Letters*, the *IET Electronics Letters*, the *IET Microwave Antennas and Propagation* journals and several European and US conferences in the field of microwave, microelectronics and antennas. He and his students received the H. W. Wheeler Award of the IEEE Antennas and Propagation Society for the best application paper of the year 2006. He is also the co-recipient of the Jack Kilby Award 2013 of the ISSCC conference, the best paper of the EUCAP2007 Conference, the best-paper award of the International Workshop on Antenna Technology (iWAT2009), the best paper award at LAPC 2012, the best student paper at LAPC 2013 (3rd place), the best paper of the ICEAA 2014 Conference, and the best paper of the innovation contest of the iWEM 2014 conference (2nd place). He is the recipient of the University Nice-Sophia Antipolis Medal in 2014 and the recipient of the University Côte d'Azur medal in 2016. He was the General Chair of the Loughborough Antennas and Propagation Conference 2011, the Award and Grant Chair of EuCAP 2012, and the Invited Paper Co-Chair of EuCAP 2013 and the TPC Chair of EuCAP 2017 Conference in Paris. Since 2015, he is a member of the IEEE AP-S Education Committee.

Wei Hong (M'92–SM'07–F'12) received the B.S. degree from the University of Information Engineering, Zhengzhou, China, in 1982, and the M.S. and Ph.D. degrees from Southeast University, Nanjing, China, in 1985 and 1988, respectively, all in radio engineering.

Since 1988, he has been with the State Key Laboratory of Millimeter Waves and serves as the Director of the lab since 2003, and is currently a Professor and the Dean of the School of Information Science and Engineering, Southeast University. In 1993, 1995, 1996, 1997, and 1998, he was a short-term Visiting Scholar with the University of California at Berkeley and at Santa Cruz, respectively. He has been engaged in numerical methods for electromagnetic problems, millimeter wave theory and technology, antennas, RF technology for wireless communications etc. He has authored and co-authored over 300 technical publications with over 9000 citations, and authored two books. He was twice awarded the National Natural Prizes, thrice awarded the first-class Science and Technology Progress Prizes issued by the Ministry of Education of China and Jiangsu Province Government, etc. In addition, he also received the Foundations for China Distinguished Young Investigators and for "Innovation Group" issued by NSF of China.

Dr. Hong is a Fellow of IEEE and CIE, the Vice President of the CIE Microwave Society and Antenna Society, the Chair of the IEEE MTT-S/AP-S/EMC-S Joint Nanjing Chapter, and was an elected IEEE MTT-S AdCom Member during 2014 to 2016. He served as the Associate Editor of the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES from 2007 to 2010.