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EDITORIAL

IEEE ACCESS SPECIAL SECTION: ANTENNA AND PROPAGATION FOR 5G AND BEYOND

5G is not just the next evolution of 4G technology; it is a paradigm shift. "5G and beyond" will enable bandwidth in excess of 100s of Mb/s with a latency of less than 1 ms, in addition to providing connectivity to billions of devices. The verticals of 5G and beyond are not limited to smart transportation, industrial IoT, eHealth, smart cities, and entertainment services, transforming the way humanity lives, works, and engages with its environment.

"5G and beyond" is an enormous opportunity, but the widespread deployment of 5G still faces many challenges including reliable connectivity, a wide range of bands to support ranging from the 600 MHz UHF band to the mm-Wave 60-GHz V-band, dynamic spectrum sharing, channel modelling and wave propagation for ultra-dense wireless networks, and price pressures. In addition to other required features, the choice of an antenna system will be a critical component of all the node end devices. Choosing the right antenna for an application presents a key design challenge. Creating effective antenna performance requires engineers to examine several factors, from what is needed to what is possible, including antenna size, antenna shape, and placement. As consumer electronic modules continue to shrink and incorporate more wireless technologies, making space for antennas is becoming an increasingly significant challenge. Thus, antenna designers face the restrictions of maintaining reasonable performance in ever-shrinking footprints and under extreme interference conditions. Since high-frequency bands are expected to be used in beyond 5G, the propagation characteristics such as propagation loss and multipath characteristics must be evaluated for mm-Wave frequencies and beyond. Therefore, new radio propagation modeling and prediction techniques need to be developed to cover the new frequency bands for future 5G and beyond wireless systems.

This Special Section consists of 32 contributions including two survey articles covering a variety of topics in line with the Call for Papers.

In the article "On the impact of the radiation pattern of the antenna element on MU-MIMO indoor channels," by Pérez and Torres, an analysis of the effect of the radiation pattern of the base station antenna array elements on the multiuser multiple-input multiple-output (MU-MIMO) channels has been presented. The analysis focuses on the uplink. The use of more or less directional antennas as elements of the base station array influences the coherence bandwidth, and the orthogonality of the subchannels between the multiple users and the base station for a MU-MIMO system. Based on an experimental analysis using both omnidirectional and directional antennas in the 3–4 GHz band, conclusions are drawn on how these two parameters are affected, and their influence on the spectral efficiency.

In the article "A high gain and wideband narrow-beam antenna for 5G millimeter-wave applications," by Ullah and Tahir, a wideband antenna with a high gain and narrow beamwidth for future 5G communication systems is presented. The antenna operates in 28 GHz 5G band with a large 35.53% bandwidth ranging from 23.41 to 33.92 GHz. The array has four elements arranged in a linear fashion to attain a high gain of 10.7 dBi. It radiates along its end fire direction and provides a beamwidth of 14.6° in its H-plane and attains radiation efficiencies of more than 90% throughout its operating frequency range.

In the article "A novel snowflake fractal antenna for dual-beam applications in 28 GHz band," by Ullah and Tahir, a wideband snowflake antenna for 28 GHz millimeter-wave communications is proposed. The antenna has a size of 8×5 mm^2 and is fabricated on ultra-thin 0.254 mm substrate. It consists of four small hexagons surrounding a bigger hexagon in order to attain broadband characteristics. The impedance bandwidth of the antenna is from 25.28 to 29.04 GHz (13.43% @ 28 GHz), having 3.12 dBi gain and more than 80% of radiation as well as total efficiency. The proposed dual-beam antenna and its array have been modelled on thin Rogers substrate to show that its application in millimeter-wave communication equipment is viable.

In the article "UHF RFID handset antenna design with slant polarization for IoT and future 5G-enabled smart cities applications using CM analysis," by Yan *et al.*, a compact antenna design for UHF RFID handset with angle-adjustable linear polarization is presented. The design is carried out using a characteristic mode analysis and consists of a multi-orientation dipole partially printed on three sides of C shaped F4B substrate, and an internal ground behind the handset screen, to provide both vertical and horizontal polarizations. The dipole is connected with the internal ground using two metal shorting strips to adjust the polarization angle, and a suitable feeding position is selected to get the radiation pattern with slant polarization. It covers the whole US UHF RFID band ranging from 902 to 928 MHz. A prototype antenna with 45-degree linear polarization angle is fabricated and characterized as a proof of concept demonstration. These results pave the way to use a typical android phone-sized handheld reader as a terminal device for future IoT applications ranging from consumer terminal devices to infotainment solutions.

In the article "Hand palm local channel characterization for millimeter-wave body-centric applications," by Zhao *et al.*, results from attempts to characterize the hand palm local channel through experimental measurements are presented. The body-centric wireless channel characterization mostly utilizes whole body models. However, localized channels for body parts consistently interacting with the wireless device have their own importance and are the focus of this article. The experiments are carried out at three millimeter-wave frequency bands of 27–28 GHz, 29–30 GHz, and 31–32 GHz, for five human subjects. Net body loss is found to be 3dB for different subjects with subject-specific, and varying palm shape size is found to be the primary affecting source. The repeatability of the on-body propagation measurements has been within 10% of variance.

In the article "A Dipole sub-array with reduced mutual coupling for large antenna array applications," by Jamshed *et al.*, a design for a four-element printed dipole sub-array with reduced MC for S-band has been presented. A balanced transmission line structure has been designed with two dipole arms on the opposite side of the substrate. The proposed array exhibits good impedance matching with a reflection coefficient of −45 dB and resonates at the center frequency of 2.8 GHz. Isolation of −20 dB has been achieved for each element in a 2 × 2 planar array structure using out of band, parasitic elements, and planar shift, by distributing the separation between the elements. The reduced coupling achieved in this can be useful for large array antennas in multiple-input-multiple-output (MIMO) systems.

In the article "Empirical characterization of the indoor radio channel for array antenna systems in the 3–4 GHz frequency band," by Pérez *et al.*, characterization of the wideband indoor radio channel is presented. The measurement setup consists of a virtual vertical uniform array at the receiver side of the link that remains at a fixed position, whereas the transmitter side, which is equipped with a single antenna, is placed at different positions in the environment under analysis. The measurement setup emulates the uplink of a multiuser multiple-input multiple-output (MIMO) system, and allows obtaining the broadband parameters of the multiple channels that are established between the transmitter and each one of the antennas of the receiver array. The results and conclusions about the path loss, temporal dispersion, and coherence bandwidth are included, along with an analysis of the spatial correlation between wideband channels when one of the antennas is an array.

In the article, "Synthesis of linear and planar arrays via sequential convex optimizations," by Qi *et al.*, an iterative procedure for the synthesis of sparse arrays radiating focused beampattern is presented. In this scheme, the prescribed pattern response in the mainlobe is cast as a multiconvex problem at each step that the nonconvex lower bound constraint is relaxed while including a reweighted l1-norm minimization based on the magnitudes of the elements. Thus, a sparse array with fewer elements (compared to other methods) and a better performance of beam pattern (e.g., narrower 3-dB beamwidth, lower maximum sidelobe level) has been produced. Examples concerning the design of linear and planar arrays show relevant savings of array elements with respect to conventional array techniques.

In the article, "Compact liquid crystal polymer based tri-band flexible antenna for WLAN/WiMAX/5G applications," by Du *et al.*, a compact coplanar waveguide (CPW)-fed liquid crystal polymer (LCP) based tri-band antenna is presented and fabricated for WLAN, WiMAX, and 5G systems. The antenna, which is printed on a 0.1-mm-thick LCP substrate, combines two strips with the main radiation rectangular patch and a CPW ground and has a small overall dimension of 20mm×32mm×0.1mm. It has three operating bandwidths, including 2.38–2.79 GHz, 3.27–4.05 GHz, and 4.80–8.44 GHz, with reasonable gains and good radiation characteristics in all the operating bands. To test the flexibility of the antenna, it is simulated and measured in bent configurations for radii of 10 and 50 mm. The antenna is attached to different parts of the human body to test the integration effect in wearable equipment. The performance of the antenna remains reliable under bending conditions and the specific absorption ratio (SAR) value meets the European Union (EU) standard—making it suitable for integration in flexible electronic devices.

In the article, "A dual-band dual-polarised base station antenna using a novel feeding structure for 5G communications," by Hua *et al.*, the authors present a dual-band dual polarised base station antenna for the fifth-generation (5G) mobile system. The proposed antenna covers the frequency bands from 3.3 to 3.8 GHz (the lower band) and from 4.8 to 5.0 GHz (the upper band), with good isolation between its ports ($\geq$ 20 dB). In this design, parts of the dipole antenna structure are used as the feeding lines, and it is found that using one arm of the dipole to feed the whole antenna can improve impedance matching. The dual-band performance is achieved by integrating a small oval-shaped loop within the large oval-shaped loop without increasing the size of the radiating patch. The antenna has an average realized gain of 7.56 dBi in the lower band and 7.42 dBi in the higher band. Meanwhile, for both bands, the radiation pattern is stable, and the half-power beamwidth is within $65° \pm 5°$. Both simulated and measured results demonstrate that the antenna is a very good candidate for 5G mobile base stations.

In the article "Custom-designed electrically small Huygens dipole antennas achieve efficient, directive emissions into air when mounted on a high permittivity block," by Ziolkowski, Huygens radiating systems are shown to provide a unique solution to high permittivity substrate problems, both analytically and numerically. Custom-designed electrically small Huygens dipole antennas that lie on the interface between air and a high permittivity block are reported, which efficiently emit the majority of their radiated power into the air region rather than into the dielectric. System-on-Chip (SoC) applications include embedded systems and mobile computing platforms. SoC plays a major role in fifth generation (5G) wireless systems, notably with the many associated IoT (Internet of Things) devices. Their wireless functions are enabled, for example, by on-chip antennas (OCAs), that is, the system elements that connect them to devices in their external environments. These antennas generally reside on a high permittivity dielectric, such as silicon, which unfortunately causes most of their emitted power to be directed into the dielectric rather than into free space. This feature is quite detrimental, that is, it leads to severe degradation of an OCA's radiation efficiency as a transmitter of information to an external receiver and similarly to its poor performance as a receiver since little of its pattern resides in free space, severely limiting its ability to capture power from an external transmitter. Similar issues exist for sensors and communication devices residing on a human body. While many integrated antenna styles have been developed in attempts to deal with these issues, their complexities and remaining inefficiencies remain a bottleneck to their widespread adoption.

In the article "A dual-polarised magneto-electric dipole antenna for application to N77/N78 band," by Sun *et al.*, the authors present a novel dual-polarised magnetoelectric dipole antenna, developed for 5G wireless communications. The operating frequency band of this antenna is from 3.05 to 4.42 GHz with VSWR $\leq$ 1.5, covering the entire N77/N78 band for sub-6GHz 5G wireless communications. The measured gain varies from 7.09 to 9.36 dBi with high front-to-back ratios, alongside very stable half-power beamwidths in both the principal planes, within the frequency band of interest for the two polarisations. The proposed antenna is a candidate for sub-6 GHz 5G wireless communication applications.

In the article "Unmanned aerial vehicle-to-wearables indoor radio propagation channel measurements and modelling," by Kachroo *et al.*, off-body ultra-wide band (UWB) channel characterization and modeling is presented, with communication occurring between an unmanned aerial vehicle (UAV) and a human subject. The wearable antenna was patched at nine different body locations on a human subject during the experiment campaign. The prime objective of this work was to study and evaluate the distance and frequency dependent path loss factors for different bandwidths corresponding to various carrier frequencies, and also look into the time dispersion properties of such unmanned aerial vehicle-to-wearables systems. The environment under consideration was an indoor warehouse with highly conductive metallic walls and roof. Best fit statistical analysis using Akaike Information Criteria revealed that the log-normal distribution was the best fit distribution to model the UWB fading statistics. This study will serve as a road map for future development of enhanced retail, remote health-care monitoring, and ambient diagnostic systems.

In the article "Electromagnetic scattering of two-dimensional electronic systems," by Abbas *et al.*, the surface equivalence theorem and boundary conditions to develop a set of integral equations to study the electromagnetic scattering from thin material sheets are presented. The proposed scheme is well-suited for electromagnetic investigation of 2-D materials that are increasingly becoming key components in the development of terahertz (THz) frequency devices. The electronic properties of 2-D materials that control the EM scattering are also discussed, out of which existence of plasma waves at THz frequencies is most significant. The article also presents the far-field scattering response for infinitesimally thin 2-D materials.

In the article "An FSS-based multiband MIMO system incorporating 3-D antennas for WLAN/WiMAX/5G cellular and 5G Wi-Fi applications," by Saleem *et al.*, a compact 3-D dual-element, multiband antenna for MIMO applications is proposed. Folding techniques are used for miniaturization in a grid of frequency selective surface (FSS) patch-based decoupling structures, to achieve measured isolation of more than 30 dB between antenna ports. In addition to this decoupling structure, a meandered line-based defected ground plane configuration provides the multiband response while maintaining the optimum isolation performance. This 3-D MIMO antenna is fabricated and measured for its performance in different bands of WLAN, WiMAX, 5G cellular, and 5G Wi-Fi, estimating various MIMO performance parameters.

In the article "Compact base station antenna based on image theory for UWB/5G RTLS embraced smart parking of driverless cars," by Sharif *et al.*, the authors present a compact base station antenna with improved gain for ultra-wideband (UWB) /5G, real-time location systems (RTLS) based smart parking of driverless cars. This antenna consists of an antipodal dipole printed on the Rogers 4350 substrate, and a metal plate carefully designed using image theory, to increase directivity in a selected direction. The advantage of the antipodal configuration is to avoid baluns for impedance matching. This antenna operates from 6 to 7.25 GHz, for use in UWB or 5G-based RTLS systems.

In the article "Design of compact mm-wave tunable filtenna using capacitor loaded trapezoid slots in ground plane for 5G router applications," by Mahmoud and Montaser, the authors present a compact millimeter-wave tunable filtenna, with defected ground-plane structure (DGS) for 5G applications. The proposed filtenna demonstrates good reflection coefficient, lower than -25 dB and a realized gain over 9 dB, in each of the frequency bands. Numerical studies carried out using Matlab-based FDTD code and CST Microwave studio are demonstrated to have good agreement with measurements. A circular array consisting of 16 antenna elements is designed for 5G router devices. Different scenarios have been considered to show the performance capability of the array. Finally, the scan pattern with the coverage efficiency is presented to illustrate the capability of the designed array as a key piece of future 5G routers.

In the article "Eight element multiple-input multiple-output (MIMO) antenna for 5G mobile applications," by Abdullah *et al.*, the authors present a systematic design of high performance eight-element antenna array for a 5G mobile terminal operating at 2.6/3.5 GHz bands. The impedance bandwidth of this array covers from 2.4 to 3.6 GHz, including the two allocated bands of 2400–2600 MHz and 3400–3600 MHz, for 5G cellular communication systems. The envelope correlation coefficient (ECC) is noted to be less than 0.2 for any two antenna elements, surpassing the required standard of less than 0.5. This is further complemented with the mean effective gain (MEG) ratio of any two antenna elements, at par with the required standard of less than 3 dB, for power balance and optimal diversity performance. This compact antenna array can be easily used for integration into future smartphones with minimal thickness, leveraging on the conductive sheet (or so-called "chassis"). The effect of human hands on the antenna array, estimating real-time handling of hand-held devices, is also studied in this article.

In the article "Tri-focal configuration of three-dimensional metallic waveguide-array lens antennas of Rotman lens concept for multi-beam applications," by Chou *et al.*, the authors present a design methodology of a 3-D passive metallic waveguide-array lens antenna (MWALA) by implementing the Rotman lens concept (RLC) for collinear multi-beam radiations on the same angular plane. The RLC methodology extends the original concept of two-dimensional (2-D) trifocal Rotman lens, into a 3-D one in free space. Thus, the MWALA has a planar aperture facing boresight direction to resemble a planar phased array of waveguide antennas and also has a curved focal surface profile (CFSP) on the opposite side to receive the illumination by the radiations of feed antennas. The three coplanar focal points are specified to define a circular focal arc (CFA) for multiple feed placement to radiate multi-beams through this MWALA. The boundary formed by the CFSP and CFA resembles the shape of Rotman lens, equivalently realized in free space. In addition, the shortage of freedoms in a conventional MWALA design limited to dual-focus configurations and resulting in narrow scan angles is relaxed by adopting the phase velocities inside the waveguides as an additional freedom to realise a trifocal configuration and broaden the scan angles of multibeam radiation. Theoretical foundation and design guidelines are summarised, with numerical and experimental examples presented to validate the feasibility.

In the article "Realization of a tapered slot array as both decoupling and radiating structure for 4G/5G wireless devices," by Ikram *et al.*, an integrated design is proposed as a combination of a microwave MIMO antenna system and a millimeter-wave antenna array, to provide multiband operation, high port isolation, and high antenna gain for 4G/5G wireless devices. An array of tapered slots is used as a decoupling structure at microwave frequency band, and as an antenna array at millimeter-wave frequency band. The proposed geometry consists of a dual-band monopole MIMO antenna system operating at 2.6 GHz (for 4G applications), and at 3.5 GHz (for 5G applications). Port isolation of more than 25 dB is achieved by introducing a tapered slot array structure. One of the key design features is the utilisation of these slots as an antenna array with a peak realised gain of 15 dBi at 28 GHz, making this array versatile and thus well-suited for compact 4G/5G handheld devices.

In the article, "4-Port 2-element MIMO antenna for 5G portable applications," by Chattha, a low-profile four-port two-element MIMO antenna is presented for 5G and Internet of Things (IoT) applications. The antenna structure contains two identical antennas where each antenna element has two feeding plates placed at a right angle to each other, making them cross-polarized for exploiting polarization diversity. The frequency range covered by the four ports of this MIMO antenna is from around 2.7–3.6 GHz, thus covering expected future 5G band (3300–3600 MHz).

In the article "An ultra-wideband circularly polarized asymmetric-S antenna with enhanced bandwidth and beamwidth performance," by He *et al.*, the authors present an ultra-wideband circularly polarized (CP) asymmetric-S antenna with wide axial ratio beamwidth (ARBW) for C-band applications. Compared with the symmetric-S antenna, the proposed antenna demonstrates much wider AR bandwidth and wider ARBW over a broader frequency range. The proposed antenna has a wide impedance bandwidth (VSWR < 2) of 70.2% (3.58–7.46 GHz) and a wide 3-dB AR bandwidth of 84.8% (2.7–6.8 GHz).

In the article "Millimeter-wave beam steering reflectarray antenna based on mechanical rotation of array," by Abbasi *et al.*, the authors present the design and analysis of a beam-steering reflectarray antenna, designed at 26 GHz, based on the mechanical rotation of the array. A beam steering range of more than $\pm 60°$ has been demonstrated by varying the tilt angle from $+30°$ to $-30°$. The designed 20×20 element array provided a maximum gain of 26.47 dB at 0°, which reduced to 19.8 dB at 61.9° in the elevation plane. The reflectarray antenna demonstrated a maximum bandwidth of 13.1% with a minimum sidelobe level of -25.9 dB.

In the article "Compact four-element phased antenna array for 5G applications," by Ishfaq *et al.*, the authors present a four-element compact phased planar antenna array for 6-GHz beamforming applications. The mutual coupling being the severe performance degrading factor, three mutual coupling reduction techniques are employed to reduce the mutual coupling below -19 dB in the operational bandwidth of 5.7–6.4 GHz. The peak gain obtained by the proposed phased array is 8.36 dBi.

In the article "Millimeter-wave broadband antennas with low profile dielectric covers," by Baba *et al.*, the authors present a low-profile broadband antenna for 60 GHz applications. The proposed antenna consists of a single-layer dielectric superstrate and an aperture type feed, which are separated by an air cavity. The simulated total efficiency of the antenna is greater than 88% over the entire operating band (55.2 GHz-65 GHz). A measured peak gain of 19.5 dBi is obtained. The proposed antenna provides broadside directed radiation patterns with cross-polarization in the order of −30 dB over the entire operating band.

In the article "Low-profile independently and concurrently tunable quad-band antenna for single chain sub-6GHz 5G new radio applications," by Asif *et al.*, the authors present a quad-band frequency-agile antenna, with independent and concurrent frequency tunability in each band, for a tunable, concurrent, quad-band single chain radio receiver for 5G New Radio (NR). The antenna comprises four planar slots etched in a ground plane and fed through a single microstrip feedline, without any impedance matching network. The four slots resonate around the 830 MHz, 1.8 GHz, 2.4 GHz, and 3.4 GHz frequency bands, which are independently tuned to achieve tuning ranges of approximately 64%, 66%, 27%, and 33%, respectively.

In the article "MIMO antenna system for multi-band millimeter-wave 5G and wideband 4G mobile communications," by Al Abbas *et al.*, the authors present a multiple-input multiple-output (MIMO) antenna system for 5G and 4G mobile communication. The proposed design serves triple bands at mm-Wave (28, 37, and 39 GHz) for 5G in addition to the 2-GHz band (1.8–2.6) for 4G. Each MIMO element consists of a slot-based antenna fed by two microstrip feeders. The overall volume of each MIMO antenna element is $0.21\times0.10\times0.003\,\lambda^3$, where λ is the wavelength of the lowest operating frequency.

The article "Compact metamaterial based 4 × 4 Butler matrix with improved bandwidth for 5G applications," by Karimbu Vallappil *et al.*, proposes a novel compact 4 × 4 Butler matrix (BM) with improved bandwidth based on open-circuit coupled-lines and interdigital capacitor unit-cell, to develop composite right-/left-handed (CRLH) transmission-line (TL) metamaterial structure. The BM is implemented by the combination of compact 3-dB quadrature hybrid couplers, 0dB crossover, and 45° phase shifter on a single FR4 substrate. It covers the frequency range of 3.2–3.75 GHz. The phase differences of −45°, 135°, −135°, and +45° are achieved with a maximum average phase tolerance of 5°.

In the article "Compact circularly polarized microstrip ring antenna using capacitive coupling structure for RFID readers," by Wu *et al.*, the authors present a compact circularly polarized microstrip antenna for radio-frequency identification (RFID) readers. The dimensions of the proposed antenna are reduced by etching a cross slot in the radiation patch and loading four grounded coupling patches on the four corners of the radiation patch. The measured bandwidth, 3-dB axial ratio bandwidth, and maximum gain are 872–1095 MHz, 888–933 MHz, and 5.52 dBi, respectively, at 922 MHz frequency. The overall dimension of the proposed antenna is $0.36\ \lambda g\times\ 0.36\ \lambda g\times\ 0.05\ \lambda g$. The proposed antenna has a small size with good overall performance and is suitable for compact RFID devices.

In the article "Design of wideband beamforming metasurface with alternate absorption," by Ur Rahman *et al.*, the authors present a periodic structure that is capable of alternating between absorption and radiation mode. The designed periodic structure consists of an array of 6 × 6 square-shaped unit cells. Each unit cell consists of a multilayered structure, with dimensions of $0.5\lambda\times0.5\lambda$. The proposed metasurface structure achieves broadband radiation, with low RCS and high gain in the propagation direction, whereas broadband absorption is achieved when it is exposed to a free space plane wave.

In the article "Internet of Things (IoT) for next-generation smart systems: A review of current challenges, future trends and prospects for emerging 5G-IoT scenarios," by Shafique *et al.*, the authors present IoT technology from a bird's eye view, covering its statistical/architectural trends, use cases, challenges, and future prospects. The article also presents a detailed and extensive overview of the emerging 5G-IoT scenario. This article discusses the new emerging use cases of 5G-IoT driven by the advances in artificial intelligence, machine and deep learning, ongoing 5G initiatives, quality-of-service (QoS) requirements in 5G, and its standardization issues. Finally, the article discusses challenges in the implementation of 5G-IoT due to high data rates requiring both cloud-based platforms and IoT device-based edge computing.

In the article "A wideband tunable power divider for SWIPT systems," by Ilyas *et al.*, the authors present a two-way tunable power divider for Simultaneous Wireless Information and Power Transfer (SWIPT). The power divider divides the incoming power in such a way that maximum power is utilized for energy harvesting purposes and the rest of the power is used for information decoding purposes. The tunable power divider is designed and fabricated at 2.4 GHz. The bandwidth measured is 3.2 GHz, and an isolation better than 12 dB is achieved between the output ports. The designed power divider may be used for future 5G wireless networks.

The Editors hope that this Special Section will benefit the scientific community and contribute to the knowledge base. The Editors would like to take this opportunity to applaud the author contributions to this Special Section. The Reviewers' efforts to enhance the quality of the manuscripts are also much appreciated.

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