Editorial
Special Article Collection on Antennas and Propagation for Emerging 5G/6G Communications

I. Introduction

WIRELESS communication systems have become key players in enabling highly interactive and context-aware scenarios, with a broad range of applications and sectors, spanning from industry, logistics, healthcare, transportation, or massive telemetry, just to name a few. The need for connectivity has been further spanned by new ways of handling and organizing information, within the framework of the Internet of Things and the evolution towards proactive and predictive environments, such as those foreseen in Cognitive cities. This evolution has led to the need of ever increasingly demanding key performance indicators of wireless communication devices and systems of current 5G and future 6G networks, with transmission rates in the Tbps range, latencies of 100 μs, reliability values of 99.99999%, or device densities of 10^7 devices/km^2, among others. These requirements pose relevant challenges in different domains, which in turn has catalyzed research efforts to meet these stringent demands related with devices, channel and system design and development. In this way, new antenna concepts are proposed, propagation analysis and measurement techniques are explored, and new application scenarios and domains are envisaged. With the emergence of high frequency ranges, large antenna arrays, and metasurfaces for communication systems, the near field boundary definition is becoming increasingly important. As a result of high path losses at mmWave and THz frequencies, the 6G communication systems are anticipated to operate mostly in the near field, where a plane wave approximation can result in a significant phase error during beam steering. This simple conclusion has resulted in re-evaluation of many antenna design principles that were taken for granted during the era of small antenna apertures and sub-6 GHz propagation. This is particularly visible through the analysis of reconfigurable intelligent surfaces (RIS), which are considered in [1]. RIS apertures are large w.r.t. operational frequency and they are expected to operate predominantly in near field, which necessitates the generation of near field codebooks and imaging patterns. The performance of RIS metasurfaces in near field is considered in [2], that involves generation of near field codebooks and imaging patterns.

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Another emerging technology for 6G is the integrated sensing and communication (ISAC), which is characterized by two different approaches: a) same frequency ISAC and b) coexistence of communication with radar. In [3], the direction of arrival (DOA) estimation is performed on the same frequency as the communication, by applying the orthogonal codes to the space-time coding antenna array. However, in [3] radar and communication functions are separated in frequency and polarizations. While either approach has the capability to fulfil the requirements of ISAC in 6G networks, they also have potential drawbacks, such as mutual interference, coupling, and implementational costs. New designs are constantly emerging, aiming to address these and therefore, the development of antennas for ISAC continues to be an exciting trend in recent publications.

In addition to the need of designing novel antennas for ISAC, THz band and 6G emerging applications, the precise propagation channel measurements and modeling are also required.

In this special article collection, 31 articles [A1], [A2], [A3], [A4], [A5], [A6], [A7], [A8], [A9], [A10], [A11], [A12], [A13], [A14], [A15], [A16], [A17], [A18], [A19], [A20], [A21], [A22], [A23], [A24], [A25], [A26], [A27], [A28], [A29], [A30], [A31] are presented, dealing with: 1) antenna design; 2) propagation analysis; 3) novel devices such as metasurfaces/RIS; and 4) emerging applications and scenarios.

II. Overview of the Special Article Collection

A. Antennas (Papers [A1], [A2], [A3], [A4], [A5], [A6], [A7], [A8], [A9])

Antenna designers in the 6G era are facing an unprecedented challenge to support a continuously increasing amount of frequency bands and radio access technologies. This includes the support for ultrawide bandwidth, reconfigurability and multi-polarization on a shared antenna aperture. In [A1], wide scanning range and high polarization isolation is obtained by means of a capacitively loaded cross-shaped metallic wall configuration implemented in an 8×8 array demonstrator at the sub 3 GHz range. A linear array of modulated geodesic Luneburg lens antennas is presented in [A2] operating at the 56–62 GHz range, with 110° scanning range in the H-plane and 60° scanning range in the E-plane. Isolation values in the order of 31 dB are obtained in [A3] by proposing a novel coupled dual-mode grid structure, operating in the sub 6 GHz band. Advances in mobile terminal antenna design are described in [A4], with a low-profile wideband shared-radiator four-element MIMO antenna module, experimentally validated in an 8 × 8 configuration in the N79 frequency band at 4.4 GHz. Another mobile terminal design is proposed in [A5], based on shared aperture with mm-wave broadside beam-steering capability operating in the 3/26 GHz bands. A wideband planar antenna employing parallel folded dipole elements operating in the N257 and N258 mm-wave bands, with scanning capabilities of up to ± 50° is presented in [A6]. An 8 × 8 MIMO antenna integrated within a smartphone circuit board based on dual-antenna pair using dual-characteristic modes is described in [A7], operating in the 3.3–3.8 GHz frequency bands. An alternative design, based on magneto-electric (ME) dipole antennas is given in [A8], achieving port isolation values of up to 35 dB and stable gain values of 8.2 dBi in the sub 6-GHz frequency operating range. A substrate-integrated H-plane horn antenna with phase-corrected structures operating in the mm-wave band (24.25–29.5 GHz), achieving gains in the range of 9.3–11 dBi, is presented in [A9].

B. Propagation (Papers [A10], [A11], [A12], [A13], [A14], [A15], [A16], [A17], [A18], [A19])

Recent research on millimeter-wave (mm-wave) wireless systems has addressed various challenges, including blockage by the human body, antenna efficiency, and channel modeling. Studies reveal that hand/body blockage at 28 GHz can be mitigated with moderate array sizes and loose grips, which improve spatial area coverage due to hand reflections [A10]. In dynamic environments, human blockage losses at 27 GHz are limited by multipath components, with negligible effects in non-line-of-sight channels [A11]. High-gain multilens-horn antenna systems demonstrate effective isotropic radiated power with low transmit power, providing extensive coverage in urban settings [A12]. The low terahertz band (0.1–1 THz) shows promise for in-flight entertainment systems, with detailed propagation studies at 300 GHz informing future system designs [A13]. Path gain and azimuth models derived from extensive 28 GHz measurements in factories reveal effective coverage with a simple theoretical model, outperforming traditional models [A14]. Machine learning (ML) techniques enhance path loss prediction in urban canyons by incorporating detailed environmental features, outperforming traditional slope-intercept models [A15]. Efficient ML-based indoor radio propagation models replicate ray tracer results quickly, improving scalability and accuracy with transfer learning techniques [A16]. Innovations in static passive smart skins (SPSSs) leverage AI-based digital twins to predict electromagnetic interactions, resulting in reliable and efficient smart skin designs [A17]. AI and ML applications in channel modeling identify and predict propagation scenarios, highlighting future challenges in channel data processing [A18]. Finally, a deep-learning-based low-rank channel estimation method for high mobility V2X communications shows promise, reducing complexity and overhead while maintaining performance across varied urban scenarios [A19].

C. Novel Devices (Papers [A20], [A21], [A22], [A23], [A24], [A25], [A26])

A compact, low-cost metamaterial-based broadband and wide-angle beam-scanning array antenna with a reconfigurable monopole-like Huygens pattern for 5G base stations is introduced in [A20]. Featuring a miniaturized hybrid metasurface, it operates in the 3.30–3.80 GHz band, extending beam-scanning angles from [−35°, +35°] to [−70°, +70°]. In [A21], a low-profile, high-isolation tri-polarized metasurface antenna is presented for indoor access-point applications, utilizing characteristic mode analysis (CMA), covering 3.4–4.0 GHz with isolation better than 37 dB. The design shows excellent diversity characteristics and broadside radiation patterns. The dynamic modeling of liquid crystal (LC)-based planar multi-resonant cells, aimed at enhancing reconfigurability time, is achieved using the finite-element method to solve the dynamic LC director equation, as presented in [A22]. This approach significantly reduces transition times for both LC cells and large antennas. A 1-bit hybrid 16 × 16 transmit reconfigurable intelligent surface (TRIS) with p-i-n diodes and a rotated feed to improve gain limitations is described in [A23], achieving 0–5.6 dB gain enhancement in the −70° to 0° range and improving aperture efficiency to 24.4% using two hybrid units with a 90° phase difference. In [A24], a sustainable reconfigurable intelligent surface (RIS) for managing mmWave wireless channels by modifying the permittivity of LC molecules for beam scanning is proposed, featuring a lens-based beamforming circuit that configures a self-sustainable feedback loop, enabling channel estimation without extra hardware or signal processing costs. In [A25], the need for active and dynamic control of THz waves in wireless communication systems using a graphene-based RIS is addressed, featuring a rectangular graphene meta-atom array on a metallic grounded silicon substrate that achieves nearly 100% reflection from 0.1 to 4 THz and 100% absorption through electrical reconfiguration, showing significant improvements in signal-to-noise ratio (SNR). In [A26], a single-glass-layer optically transparent transmit array (TTA) with high aperture efficiency is presented for the mmWave 5G band. Utilizing only one glass layer enhances optical transparency while achieving high efficiency through novel analysis techniques and design methods. The fabricated TTA has a focal length-to-dimension ratio of 1.2, with simulated and measured aperture efficiencies of 51.1% and 45.3%, respectively.

D. Emerging Applications (Papers [A27], [A28], [A29], [A30], [A31])

With the growth of wireless devices and the Internet of Things (IoT), there is an urgent need for new techniques to wirelessly transfer power and communicate with these devices. A MIMO simultaneous wireless information and power transfer (SWIPT) system using inductive coupling, addressing the overlooked relationship between mathematical signal representations and real-world physical quantities is proposed in [A27]. A novel procedure for synthesizing metalens antennas in near-field complex scenarios, introducing a near-field computation model and the intersection approach (IA) algorithm is introduced in [A28]. The adaptive field-to-mask (F2M) procedure enhances local optimization algorithms by progressively defining templates, demonstrated through examples achieving uniform field distribution and phase shift synthesis for a prototype tested at 39 GHz. In [A29], instead of increasing the number of mmWave base stations, which raises costs, power consumption, and EMF levels, heterogeneous deployment of smart electromagnetic (Smart EM) entities—such as IAB nodes, smart repeaters, RISs, and passive surfaces is proposed. This approach aims to minimize installation costs and optimize network spectral efficiency, with initial network planning results demonstrating its effectiveness. In [A30], a millimeter-wave imaging system that captures spatial frequency (Fourier) domain information, improved by including more incoherent signals, is presented. This method characterizes imaging efficacy using new spatiotemporal coherence metrics and offers solutions for limited transmit resources, demonstrated by a 38 GHz imaging system capturing 5G signals from independent transmitters to image multiple objects in a scene. In [A31], an active transmitarray antenna is presented for Ka-band monopulse tracking radar in the 34–36 GHz range, utilizing commercial SiGe-based 5G beamforming chips in a large-scale naval radar array. Three arrays (0.77 m diameter) with 24 368, 19 424, and 7824 elements demonstrate sub-1° HPBW, SLL below −26 dB, and 100 dBm EIRP, with a ±60° grating-lobe-free scan range. A small-scale demonstrator with an eight-layer PCB and integrated liquid cooling achieves a peak EIRP of 56 dBm, 12° HPBW, and scanning up to ±60° in the H-plane and ±45° in the E-plane.

III. Conclusion and Acknowledgement

The steady adoption of 5G communication systems and the advent of future 6G systems exhibits multiple challenges in order to comply with current and expected device/system specifications. Different approaches are being explored in relation with the design of antennas with enhanced capabilities, full exploitation and understanding of propagation mechanisms, the proposal of novel designs based on elements such as metasurfaces/RIS and the advent of new applications and scenarios in which 5G/6G systems will operate. An exciting journey opens ahead, in which current as well as emerging research lines will appear.

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Appendix: Related Articles

[A1] D.-M. Sun, Z.-C. Hao, W.-Y. Liu, and C.-Y. Ding, "An ultrawideband dual-polarized phased array antenna for sub-3-GHz 5G applications with a high polarization isolation," *IEEE Trans. Antennas Propag.*, vol. 71, no. 5, pp. 4055–4065, May 2023.

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