# Guest Editorial: Special Cluster on Antenna Considerations for Future Millimeter-Wave and Terahertz Wireless Systems

## I. Introduction

RECENT developments in data-intensive applications and emergence of Internet-of-Things (IoT) have exponentially increased the wireless data traffic. IoT also requires fusion of multiple sensors and wireless devices operating in real time. The global IoT market, which was US$ 212 billion in size in 2019, is expected to surpass the 1.6 trillion mark by 2025.[1] This mammoth growth is driven by factors, such as increasing population, sharply growing use of mobile devices, upsurge in the integration of virtual reality, augmented reality and artificial intelligence, expanding subscriptions of over-the-top platforms, intensive penetration of Internet users, and rising audience of e-sports.

5G/6G and beyond are expected to be the strongest enabler in the expansion of the IoT due to unparalleled speed, large bandwidth, massive capacity, ultra-low latency, towering scalability, and high reliability. High-transmission data rates, low latency, enhanced reliability, and interference-free operation are, therefore, most sought-after features today for applications ranging from communications to infotainment and positioning to healthcare. Supporting these demands within the framework of existing wireless networks was a challenging task. It has driven the wireless industry to investigate new paradigms resulting in the exploitation of new frequency ranges. Consequently, the millimeter-wave (30–300 GHz) and terahertz (0.1–10 THz) bands have surfaced to become the key candidates for future wireless networks.

Successful deployment of wireless technologies relies heavily on the performance of antenna design and future wireless networks are no exception. Since a new generation of wireless networks is on the horizon that will deliver multigigabit-per-second data speeds, a thorough understanding of the antenna design is eminent for full exploitation of the potentials of the millimeter-wave and terahertz spectrum. These frequencies offer great opportunities for device miniaturization, thanks to short wavelength fostering compact and high-gain antennas. Though research in this field was going on for some time, it has now seen a wider adoptability at academic, industrial, and regulatory levels. Engineers are facing immense challenges in the antenna design as low-cost and intelligent antennas for future wireless networks must be materialized to support these frequency bands. Nevertheless, preserving good performance with ever-decreasing form factor and under ever-increasing interference scenarios is making the complicated task of antenna design more complex.

This special cluster was motivated by the need to compile the recent research trends on the design and analysis of millimeter-wave and terahertz antennas providing a comprehensive understanding of the stimulating novel methods for the development of efficient, reliable, robust, and cost-effective antenna solutions for future wireless networks.

TABLE I
Overview of the Letters in the Special Cluster

| No. | Authors | Emphasis |
|---|---|---|
| 1 | Chattha *et al.* | MIMO Systems |
| 2 | Muhammad *et al.* | Array Antennas |
| 3 | Wang *et al.* | Array Antennas |
| 4 | Ziane *et al.* | Array Antennas |
| 5 | Abohmra *et al.* | Array Antennas |
| 6 | Zhang *et al.* | Array Antennas |
| 7 | Giddens *et al.* | Lens Antennas |
| 8 | Poyanco et al. | Lens Antennas |
| 9 | Abbasi *et al.* | Lens Antennas |
| 10 | Liang *et al.* | Lens Antennas |
| 11 | Ahmed *et al.* | Polarizers |
| 12 | Lundgren *et al.* | Polarizers |
| 13 | Umar *et al.* | Bondwires |

## II. Contributions

This special cluster consists of 13 peer-reviewed letters from 57 authors of various academic institutions, government entities, and industries worldwide. The contributing authors present state-of-the-art research on a wide range of antenna technologies, analysis techniques, and application scenarios in millimeter-wave and terahertz regimes. The 13 letters of this cluster are categorized in five groups based on the type of the antenna/broader focus. Table I provides a list of these letters, along with the authorship and emphasis of discussion. The five groups of the cluster and associated letters are briefly described as follows.

### A. MIMO Systems

Multiple-input–multiple-output (MIMO) antenna systems are lately being popular to support high-gain and high-data-rate 5G

[1] https://www.statista.com/statistics/976313/global-iot-market-size

applications [1]. These systems effectively handle the multipath fading non-line-of-sight situations by employing space, pattern, and polarization diversity schemes [2]. Chattha *et al.* have presented some of the latest developments in this area in “Compact multiport MIMO antenna system for 5G IoT and cellular handheld applications” discussing a fairly less found 3-D MIMO antenna system. The MIMO system exploits a four-element geometry with eight ports and exhibits space as well as polarization diversity by having each element fed by two orthogonal ports for a sub-6 GHz 5G operation between 2.4 and 3.8 GHz frequencies.

### *B. Array Antennas*

Array antennas have found increasing use in high-performing and reliable compact devices in a widespread range of applications including 5G, radars, wearables, and autonomous systems [3]–[5], [9]. Vehicle-to-everything (V2X) communications is a key element of IoT enabling autonomous systems. V2X communications typically utilizes dedicated short-range communication at 5.9 GHz band and require compact arrays for interference-free operation [6]. Ishfaq *et al.* in “Compact wide-angle scanning multibeam antenna array for V2X communications” have taken up on the challenges of mutual coupling, cross polarization, and limited scanning angle through their multibeam planar inverted-E antenna array. The array is fed through a $4 \times 4$ Butler matrix designed without the use of phase shifters and crossover and is able to achieve a wide-angle scanning of $\pm 87°$.

Unmanned aerial vehicles (UAVs) have found their applications in assisting the traditional cellular networks by sharing the communication load as airborne base stations, radars, and air taxis. Associated with multirotor UAV radars for imaging is the challenge of an antenna having small form factor and low side lobe level (SLL). Wang *et al.* have shown in “*W*-band low-SLL size-reduction microwaveguide array antenna using $TE_{120}$-mode-cavity dual-layer power divider” that a 25% size reduction with an SLL of $<-18$ dB at 96 GHz can be attained by their $6 \times 16$ microwaveguide slot array antenna fed by a multistage T-junctions and $TE_{120}$-mode-cavity dual-layer power dividers.

Body-centric wireless networks (BCWNs) relying mostly on wearable devices stand at the brink of massive diversification with an explosive popularity and applicability. The 60 GHz band offering higher data rates, larger bandwidth, secure communications, and compact device size has been identified as a potential candidate for next-generation BCWNs [7]. Power density (PD) is a figure of merit used to quantify the electromagnetic exposure of human tissues to wireless devices operating in the vicinity of the human user at millimeter-wave frequencies [8]. In “High-resolution technique for near-field power density measurement accounting for antenna/body coupling at millimeter waves,” Ziane *et al.* have utilized a purposely built skin-equivalent structure for the measurement of heating pattern by remote infrared (IR) imaging. PD distributions for a four-element patch antenna array and a conical horn antenna at 60 GHz are measured to experimentally validate the technique.

Terahertz systems can potentially reach a capacity of several terabits per second with applications ranging from space instrumentation to environmental monitoring and biomedical engineering to imaging systems [10], [11]. Despite having huge potential, terahertz is rather a terra-incognita due to limitations of sources and detectors, size and complicated structure of the antenna, and limitations of material and fabrication capability. “An ultrawideband microfabricated gold-based antenna array for terahertz communication” by Abohmra *et al.* discusses performance of an experimentally fabricated and tested $1 \times 4$ planar inverted cone antenna array for ultrawideband terahertz operation in 0.75–1.10 THz.

Phased arrays are another popular research area with wide range of applications particularly due to their capability of beamforming and beam switching. Optimal radiation performance of practical phased arrays necessitates array calibration to counteract the inhomogeneities in the associated radio frequency chain [12]. Zhang *et al.* review the calibration methods for phased arrays highlighting their limitations and describe a multiprobe scheme to overcome the beam-steering range reduction problem at millimeter-wave frequencies in “An improved complex signal-based calibration method for beam-steering phased array.”

### *C. Lens Antennas*

Dielectric lenses having a specific permittivity profile offer a cost-effective alternative to phased arrays for conformal beam steerable operation in data-intensive applications, such as 5G [13]. Lenses can modify the amplitude or phase or both of a signal to generate a set output radiation pattern through the refraction of electromagnetic waves within the lens dielectric material [14]. They are gaining significant interest at the millimeter-wave and terahertz frequencies due to possibility of size miniaturization.

In “Multimaterial 3-D printed compressed Luneburg lens for mm-wave beam steering,” Giddens *et al.* investigate the performance of a compressed Luneburg lens prototyped via 3-D printing of five different dielectric filaments using multimaterial fused deposition modeling. The antenna offers a 3.8-times width reduction while having a 25° beam steerability at 84 GHz with a peak gain of 22 dBi.

Periodic structures that remain invariant after translation and mirroring operations are characterized as glide-symmetric. They are known to broaden the bandwidth, reduce the reflections in the transitions between dielectric materials, and increase the equivalent refractive index [15]. Poyanco *et al.* in “Two-dimensional glide-symmetric dielectric structures for planar graded-index lens antennas” have demonstrated that a 2-D fully dielectric glide-symmetric periodic structure can potentially be used as a low-cost and low-profile Luneberg lens with broader bandwidth and reduced refractive index in 24–33 GHz frequencies.

Direction-of-arrival (DoA) is an essential information for channel sounding. In “Lens-loaded cavity antenna with detector diode as a direction-of-arrival estimator,” Abbasi *et al.* have discussed a bandwidth-efficient DoA technique at millimeter-wave frequencies employing quasi-random radiation modes of a lens-loaded cavity antenna along with the frequency-diverse impulse response of the metallic cavity connected to a sensitive detector diode.

Though highly efficient, complexities involved in the integration of horn antennas limit their usability. A 2-D horn antenna operating at terahertz frequencies of 220–330 GHz integrated with a dielectric lens on the same platform is proposed by Liang *et al.* in "All-silicon terahertz planar horn antenna." The antenna exhibits a broad fractional impedance bandwidth of 40% and orthogonal polarizations.

### *D. Polarizers*

Satellite communications and point-to-point communications make use of the circular polarized electromagnetic signals to eliminate the need of polarization matching at the receiving end. This, along with insensitivity to Faraday effect, reduces polarization mismatch losses in these systems [3]. A polarizer converting linear polarization (LP) to circular polarization (CP) enables the use of linear polarized antennas in systems requiring CP resulting in multipolarized cost-effective solutions.

Ahmed *et al.* have designed and reviewed the performance of a 2-D C-shaped unit cell metasurface polarizer in "A multifunctional polarization transforming metasurface for *C*-, *X*- and *K*-, band applications." The proposed structure acts as an LP cross polarizer as well as LP-to-CP polarizer in multiple frequency bands with a stable operation up to 75° incidences.

"Fully metallic dual-band linear-to-circular polarizer for K/$K_a$-band" by Lundgren *et al.* presents the design of a three-screen slot-based metallic millimeter-wave polarizer. The proposed polarizer effectively transforms LP into right-hand CP at 19.7–20.2 GHz band and LP into left-hand CP at 29.5–30 GHz band.

### *E. Bondwires*

With recent technological advancements, a wide variety of commercial off-the-shelf RF components are readily available including switches and amplifiers. Bondwires are commonly being used to interconnect RF chips to PCB and off-chip antennas to feed-lines. Umar *et al*. in "Bondwire model and compensation network for 60 GHz chip-to-PCB interconnects" have come up with a lumped-element model for bondwires synthesized and evaluated for RF chips to PCB interconnections operating at 50–70 GHz. The matching network for the bondwires based on the proposed approach is observed to reduce the insertion loss and improve the bandwidth significantly.

## III. Conclusion

Millimeter-wave and terahertz antenna design is a trending topic for researchers around the globe carrying great potential of cutting-edge innovations, scientific advancements, and future developments. We hope that this cluster will give the readers a good overview and descriptive account of these progresses and will enrich and inspire new ideas, applications, and research directions in this interesting field.

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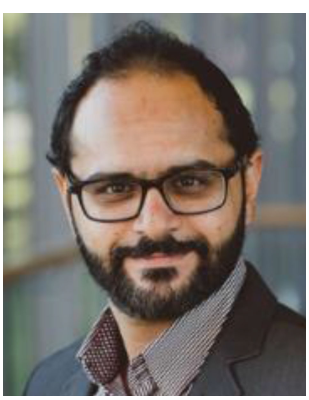

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