New and Emerging Directions in the Fields of Antennas and Propagation

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(Invited Paper)

***Abstract*— In this invited paper, the New Technology Directions Committee (NTDC) of the IEEE Antennas and Propagation Society (AP-S) presents new and emerging research directions to commemorate the 70th anniversary of *the* IEEE Transactions on Antennas and Propagation. The NTDC consists of three working groups (WGs); the members and collaborators of these groups provide their perspectives on topics related to WG themes in this article. WG-1 focuses on the advancement of materials and manufacturing processes for future antenna applications. WG-2 focuses on advances in communications, sensing, and imaging. WG-3 focuses on maximizing the societal impact of wireless connectivity. The discussion in this article ranges from additive manufacturing (AM) techniques and system integration to advanced communications and quantum-based sensing technologies. Numerous applications are explored and a perspective on the digital divide is offered.**

***Index Terms*— Additive manufacturing (AM), circuits/antennas integration, digital divide, heterogeneous integration, intelligent surfaces, microwave medical imaging, mobile communications, quantum sensing, sub-terahertz (THz) antennas, wearable/implanted antennas, wireless connectivity, wireless network security.**

I. Introduction

In celebration of the 70th anniversary of the IEEE Transactions on Antennas and Propagation (T-AP), the Editor-in-Chief invited the New Technology Directions Committee (NTDC) of AP-S to contribute this article highlighting potential future directions and emerging technologies. In 2022, the NTDC Chair, Koichi Ito, established three working groups (WGs) within the committee related to new and upcoming areas/fields within AP-S.

The advancement of materials and manufacturing processes for future antenna applications is the focus of WG-1 (Lead: Katherine Duncan). This area can be broadly categorized into six themes, namely: 1) additive manufacturing (AM) for radio frequency (RF) and microwave applications; 2) antenna and microwave circuit design/integration; 3) intelligent surfaces; 4) nano-optical antennas; 5) new materials for antennas; and 6) wearable/implantable devices, as discussed in the following.

1) AM technologies have attracted a surge of interest for their potential to achieve antenna devices with performance beyond what is possible with conventional processes, along with reduced cost and time required for fabrication.
2) Increased degrees of integration have been required of wireless systems to address both growing demands on system functionality and required reductions in form factor. Example techniques include combining RF/microwave devices and the reduction or elimination of standalone interconnects by the use of fabrication or packaging processes that enable the co-location of sensors and processing components.
3) Reconfigurable intelligent surfaces (RISs), also known as intelligent reflecting surfaces, can enable improved control of RF signals between a transmitter and a receiver. RISs have been proposed for dynamic operation while meeting specified goals and maintaining this performance in complex and varying wireless channels.
4) Wearable/implanted devices are an enabling technology that can provide better health care, seamless communication, enhanced performance in sports, and new and improved products in defense and consumer electronics.

Advances in communications, sensing, and imaging are the focus of WG-2 (Lead: Christian Pichot). WG-2 focuses on five themes: 1) mobile communications systems; 2) subterahertz (THz) and millimeter-wave (mm-wave) technologies; 3) microwave systems and technologies for medical applications; 4) application of machine learning (ML) to inverse problems; and 5) quantum-based electromagnetic (EM) sensing technologies, as discussed in the following.

1) The evolution of mobile communications has been tremendous since the first-generation (1G) mobile network was introduced. Communications systems con-

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tinue rapid advancement with the development of the sixth-generation (6G) and beyond. Recent trends, such as joint communication and sensing, demand innovation in antenna designs.
2) mm-wave and THz technologies are expected to play a role in the development of high-bit-rate wireless communication systems and high-resolution sensing systems. Challenges extend from antenna design to material selection and implementation.
3) Microwaves for medical diagnostic radiology have been the subject of numerous research and development efforts for many years, including the advancements exploiting magnetic nanoparticles and magnetic fluids. After three decades of promising proofs-of-concept supported by numerical simulations and laboratory experiments on phantoms, microwave diagnostics for medical applications have finally entered a translational era, due to a handful of spin-off companies from academia that have succeeded in developing advanced prototypes.
4) ML and artificial intelligence (AI) are expected to continue to advance techniques for addressing inverse problems.
5) The area of quantum antennas (q-antennas) is actively researched for possible implementation in quantum communications, quantum imaging, and sensing, which could revolutionize communications and sensing.

Maximizing the societal impact of wireless connectivity is the focus of WG-3 (Lead: Gregory Huff). Guided by the notion that new antenna technologies and systems are critical for maximizing the societal impact of wireless connectivity, the goals of WG-3 are to: 1) investigate strategies and collaborative opportunities that enable insight into current and emerging societal needs for wireless connectivity; (2) identify both technical and societal challenges that may impact the development, deployment, and adoption of new technologies for wireless connectivity; and 3) enhance the current landscape of outreach opportunities (e.g., conferences, workshops, etc.) with new activities that seek to operationalize societal-driven initiatives that promote the advancement, socialization, and dissemination of new technologies for wireless connectivity.

These goals bring stakeholders from public policy and social science together with communities pioneering new antenna technologies for the Internet of Space (IoS), energy-efficient antenna systems, Next-G Technologies, spectrum access and utilization techniques, and wireless power transfer and energy harvesting systems.

In this article, Section II highlights new technologies related to WG-1, Section III presents WG-2's views on emerging directions related to communications, sensing, and imaging, and Section IV summarizes the important aspects of the impact of wireless connectivity on our community at large. Finally, Section V summarizes the discussion.

II. Advancement of Materials and Manufacturing Processes for Future Antenna Applications

A. Additive Manufacturing for Antennas

AM antennas can be categorized into three groups in terms of fabrication materials: metal-only, [1], [2], dielectric-only [3], and conductive and dielectric multimaterial antennas [4].

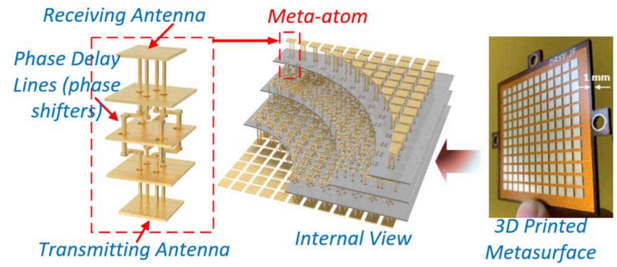

Fig. 1. Additively manufactured metasurfaces with seven metal layers in a single substrate. Blind vias are 3-D printed for interconnecting phase delay lines among the transmitting/receiving antennas at the top/bottom surfaces [10].

1) Additively Manufactured Metal-Only Antennas: The popular metal printing techniques used for antenna prototyping include direct metal laser sintering (DMLS) and selective laser melting (SLM), which can prototype complex antenna structures using metal powders melted by lasers. Metal printers can be used to prototype entire microwave devices without the need to assemble components, thus potentially avoiding interconnection loss. Metal printing also enables the prototyping of increasingly complex 3-D structures that were previously unrealizable, such as metamaterials [5], power combiners [1], and antennas [2].

2) Additively Manufactured Dielectric-Only Antennas: Dielectric-only 3-D printing plays a dominant role in consumer electronics, where the state-of-the-art techniques include fused deposition modeling (FDM), continuous liquid interface production (CLIP), aerosol jet printing, and piezoelectric inkjet. Each of these techniques has their specific advantages. As a cost-effective solution, FDM has been widely adopted for prototyping low-cost, high-performance reflectarrays, polarizers, lens antennas, and transmitarrays. Dielectric-only printing techniques have also been applied to design metallic waveguides/antennas with the addition of postmetalizing operations [6].

3) Additively Manufactured Multimaterial Antennas: The conductive and dielectric multimaterial 3-D printing is an emerging process and presents vast potential for innovative new antenna designs. Multimaterial AM techniques use more than one printing head for conductive and dielectric inks. Multimaterial printers can seamlessly sinter conductive and dielectric inks for prototyping PCB-like circuit boards. This process enables multiple metallic layers to be printed in a single substrate while offering unique design capabilities, such as flexible/dynamic spacing between metal layers, printable vias and through holes, conformal/nonplanar surfaces, and vertically designed circuit/antenna elements. This approach is ideal for antenna-in-package (AiP) manufacture, as well as large and complex antenna arrays/metasurfaces that can offer exceptional beam-shaping performance [7]. Demonstrated designs include circuit components [8], patch arrays [9], a dual-band Fresnel zone plate lens antenna [4], and the metasurfaces [10], which are highlighted in Fig. 1.

B. Integration of Microwave Circuits and Antennas

Wireless systems for beyond fifth-generation (B5G) and 6G communications require considerable increases in levels of integration. Some of the B5G operation will occur at much shorter wavelengths than the sub-6-GHz predecessors, so conventional connection solutions between antennas and front-end circuits are no longer suitable. The border between the antennas and circuit topologies is increasingly blurred as the entire front-end subsystem must be considered to improve the impedance matching, minimize the footprint, and enhance the overall performance [11]. This presents a major shift for microwave researchers who have traditionally been committed to designing single-packaged devices, e.g., AiP, filter-in-package, and so on. A growing number of researchers in the community have been devoted to the integration and co-design of multiple components as a single module. For example, filters and antennas [12], as well as filters and amplifiers [13], can be seamlessly combined to realize performance improvements compared to direct cascading of these components. Increasing levels of co-design will become necessary for B5G systems.

One primary area of interest is the integration of antennas and passive circuits located at the system's front end. A common example is the filtenna [14], formed by merging a radiator and frequency-selective circuit into a single component. This not only eliminates the mismatch between the radiator and filter but also improves the frequency selectivity and reduces the overall footprint. More recently, new methods for realizing filtennas have been proposed, including exploiting reverse-phase currents on the radiator [15] and engineering transmission zeros of the antenna from the equivalent circuit perspective [16], which facilitates further miniaturization. The co-design of antennas and other types of circuits, such as diplexers [17], have also been carried out for satellite and space applications.

Another emerging technology trend with increased focus is the co-design and integration of antennas with silicon-based transceiver/beamforming chips. This is largely in response to enabling beam scanning functionalities required in B5G applications with a technology that is consistent with mass product electronics development [18]. Integrated phased array modules are evolving toward low-cost and high performance at a faster pace than ever, with characteristics adapted to platforms ranging from base stations [19], small satellites [20], and mobile terminals [21]. Moreover, highly integrated systems have also been developed for radars [21] and biomedical sensing [22]. These innovations suggest a major shift in antenna research toward systems-centric, multidisciplinary exploration of antenna-integrated components and systems.

C. Intelligent Surfaces

RIS can be broadly categorized as engineered materials with configurable EM properties due to the inclusion of integrated electronic circuits and/or software that enables control of the wireless environment, where the latter aspect is known as software-controlled metasurfaces [23]. The principle of operation is based on the generalization of Snell's law. Specifically, energy from a plane wave incident onto the RIS is scattered with spatially inhomogeneous phase shifts that are tailored to produce the desired reflection characteristics. RIS presents the potential to manipulate the EM properties of a wireless propagation environment. This may enable wireless channels to be optimized to maximize the overall system performance, including channel capacity, coverage, positioning, security, and sustainability.

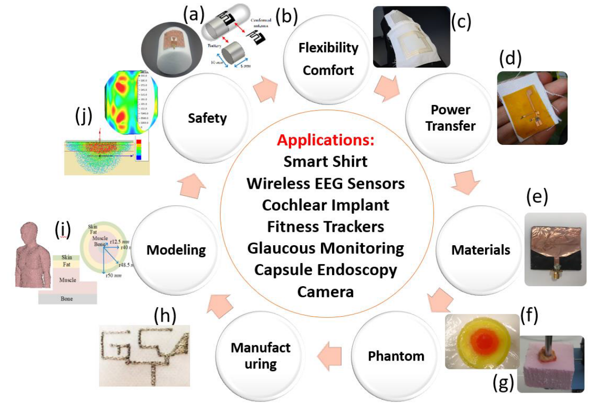

Fig. 2. Wearable and implanted antenna research topics. (a) and (b) Flexible conformal antennas [36], [71], (c) and (d) all-textile wireless power transfer [37], (e) bio-based substrate material [38], (f) breast phantom [39], (g) breast tissue measurement [69], (h) embroidery of E-threads [40], (i) human body electromagnetic modeling [36], and (j) specific absorption rate analysis [36], [41].

A summary of concepts and realizations for a smart radio environment has been presented in [24]. This includes diverse application scenarios from media-sharing Wi-Fi systems to mm-wave, THz, and even optical communications. Recent examples of RIS prototypes have been presented covering a wide range of frequencies [24], [25]. Several papers have discussed the challenges and relevant research opportunities, as well as future perspectives for RIS [24], [26], [27], [28], [29], [30], [31], [32].

D. Wearable and Implanted Antennas and Sensors

Wearable and implanted antennas/sensors have experienced a revolution in applications, fabrication techniques, and design methodologies (see Fig. 2). In general, implanted antennas and sensors refer to a system that is located inside the human body. The system may be injected [33], placed via surgery [34], or swallowed as an ingestible system [35].

1) Applications: New and emerging applications for wearable antennas and sensors include biomedical sensing and monitoring [42], human-centric Internet of Things and Wi-Fi devices [43], wearable connectivity [44], environmental monitoring and tracking [45], and wireless power transmission (WPT) [38]. Implantable antennas have found widespread applications in biomedical sensing and monitoring [46], WPT [47], body-centric communications [48], pacemakers [49], RF identification (RFID) [50], wireless capsule endoscopy [51], drug delivery [52], and biotelemetry [53].

2) Wireless Power Harvesting and Transfer: Flexible, conformable, and textile-based wearables cannot rely on rigid batteries. RF wireless power has an inherent advantage over other energy harvesting technologies, as exotic materials are not required. Instead, conductors are used to realize the rectennas or coils [54]. Wearable rectennas closely followed the development of textile antennas, with rectifiers first implemented on flexible textile substrates in [55]. It has been demonstrated that textiles, despite being lossy ($\tan\delta > 0.01$), can still achieve best-in-class RF to dc conversion efficiencies, outperforming or matching those provided by rigid systems [54]. As materials for RF power transfer and harvesting continue to develop, ecological sustainability needs to be considered from a life cycle assessment perspective [56].

Implants need to be maintenance-free or remain reliable via a wireless approach in circumstances where intermittent energy harvesting sources are not available [57]. Wirelessly powered implants enable minimally invasive optogenetics [34] and closed-loop stimulation [58]. In systems using radiative sources, body-matched antennas are key components for both implantable power transfer and communication [59].

3) Materials and Fabrication Technologies: Emerging materials are crucial for retaining the flexibility, reliability, stretchability, mechanical stability, and energy efficiency of wearable antennas. Examples include smart textile [60], flexible [61], biodegradable [62], [63], and polymer-based materials [64]. Fabrication technologies are key drivers impacting the manufacturability and achievable performance of low-cost wearable antenna prototypes. Several fabrication techniques have been reported for the realization of wearable antennas, including substrate integrated waveguide (SIW)-based technology [65], embroidery [66], inkjet printing [67], screen printing [68], and adhesive [36] methods.

Implanted antennas face additional stringent requirements, such as biocompatibility, patient safety, and miniaturization, posing challenges for practical antenna fabrication and implementation [70]. Several techniques have been explored for this application, including using biocompatible materials for antenna fabrication, such as Kapton [71], coating the antenna with a thin layer of a biocompatible material, such as silicon [72], and encapsulating the antenna with a layer of a biocompatible material, such as ceramic alumina [73].

In addition, agile-tunable materials, such as ferrites, ferroelectrics, and multiferroics, hold great potential for future intelligent antenna and medical applications. Their unique properties and dynamic tunability make them ideal for smart antennas used in biomedical and sensing applications. Ongoing research and innovation in this field is expected to lead to the development of new, high-performance antennas that will significantly impact future intelligent wireless devices.

E. Future Perspectives and Challenges

Future directions for additively manufactured antenna applications involve designing antennas using multimaterial 3-D printing processes. Currently, commercially available 3-D printing systems are restricted to specific materials and face significant challenges, such as multimaterial adhesion and heteromaterial integration. Despite these obstacles, integrating the printing of both conductive and dielectric materials within the same processing system offers a promising solution for microwave circuits and antenna integration.

Future technological advancements in RIS include sustainable and low-cost hardware implementation, compensating for possible performance degradation due to limited-precision RIS elements, integrating renewable energy sources to reduce power consumption, developing low-complexity RIS architectures for practical deployment, AI-based designs, and hybrid transceivers for RIS-assisted systems.

For wearable antennas, future challenges in integrating antennas within clothing include identifying cost-effective manufacturing techniques and materials suitable for both antennas and everyday objects. Other considerations include

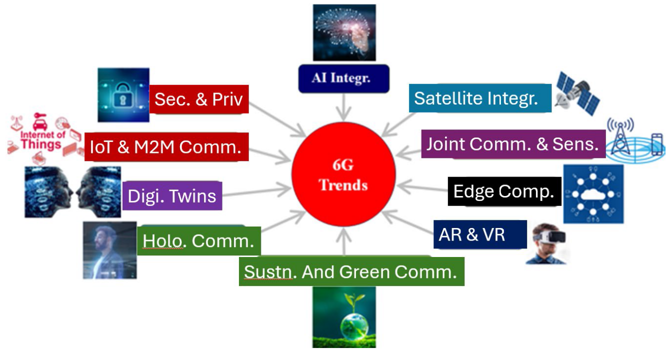

Fig. 3. Trends in the next-generation mobile systems.

durability and ease of integration with other electronic systems. Future directions encompass the development of multifunctional and reconfigurable antennas [74], fabrication reliability [68], washability [75], testing standards, safety and regulations, security, and ML approaches to design antennas that interact with the body. Future research and development directions for implantable antenna systems include miniaturization [72], the use of metasurfaces/metamaterials [76], biocompatible/biodegradable materials [63], integration [52], and establishing safety and standards [77].

III. Advances in Communications, Microwave Systems for Medical Applications, and Quantum Sensing Technologies

A. Mobile Communications

Mobile communications have undergone rapid development over the past 30 years. Cellular radio systems have evolved from 2G to 5G, and smartphones have become an essential part of our daily lives. This is partially due to the significant progress in antennas: here are now at least ten antennas inside a standard smartphone. This is still a very exciting and energetic area, with new functions and applications are emerging more rapidly than expected. For example, the latest Huawei Mate-60-pro smartphone can directly communicate with the geostationary satellite Tiantong 1 which is 36 000 km above the Earth [78], representing a significant development in mobile antennas. In addition, Starlink has been working with mobile service providers (such as T-Mobile) to provide mobile satellite service directly to smartphone users from 2024 [79]. The era of developing 6G could provide even more advanced capabilities, such as terabit-per-second data speeds, ubiquitous connectivity, and reduced energy consumption. While the details are yet to be defined, emerging trends and possibilities are summarized in the following and highlighted in Fig. 3 [80], [81], [82], [83].

1) *AI Integration:* To optimize network performance, personalize services, and improve security.
2) *Satellite Integration:* To extend to remote areas (including oceans) and enhance global coverage through low Earth orbit (LEO) satellites, high altitude platforms (HAPs), and geostationary satellites; also known as nonterrestrial networks.
3) *Joint Communication and Sensing:* To enable simultaneous data sensing and transmission at a relatively low

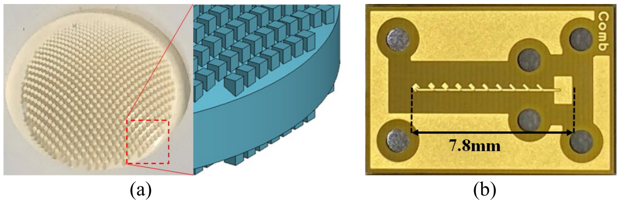

Fig. 4. Sub-THz antennas. (a) 10-mm lens with matching corrugation. (b) Planar comb-line antenna.

cost, which has significant potential for applications, including healthcare, environmental monitoring, and transportation.

4) *Edge Computing:* To enable faster data processing and reduce latency. This is crucial for applications, such as autonomous vehicles, augmented reality, and virtual reality.
5) *Augmented and Virtual Reality (AR/VR):* May lead to new applications in gaming, education, healthcare, and more. Cellular phones are the gateway for AR/VR systems.
6) *Sustainable and Green Communications:* To reduce the environmental impact of communication networks, more energy-efficient networks are required, including incorporation of renewable energy sources and reduction of electronic waste.
7) *Holographic Communication:* To provide 3-D holographic calls and interactions via mobile devices.
8) *Digital Twins:* To enable real-time monitoring, analysis, and simulation.
9) *IoT and M2M Communications:* To lead to more seamless machine-to-machine (M2M) communications, enabling smart cities, and industrial automation.
10) *Security and Privacy:* Will be required to improve authentication methods, encryption, and privacy-preserving technologies.

These new technology areas will bring new challenges to antenna designs, which include the following.

1) Compact/broadband, high-gain circularly polarized antennas.
2) Efficient higher frequency antennas (THz antennas and mm-waves).
3) Reconfigurable antennas.
4) Integration of antennas with RF front ends.
5) Antenna measurements, especially over the air (OTA).

B. Sub-THz Antennas and Channel Characterizations

In the development of sub-THz antennas, not only the antenna design techniques but also the material technologies for lens antennas and substrates and manufacturing techniques are important. High-gain, beam-scanning, and low-loss feeding are key features of the development of sub-THz antennas. Lens antennas shown in Fig. 4(a) are advantageous in a sub-THz band. Beam scanning is achieved by shifting the primary radiator from the focal point. When the focal length is short for low profile configurations, the lens thickness is large for large refraction. To reduce the thickness, high-permittivity material is desired. However, high-permittivity material has a high loss tangent. Uniformity of the permittivity distribution is also important in lens production.

Planar arrays on substrates shown in Fig. 4(b) are popular. However, the transmission loss of planar transmission lines is significant in the sub-THz band. Dielectric loss increases as a function of frequency, as does conductor loss due to the surface roughness of the copper foil adhered to the dielectric sheet. New dielectric materials to adhere to the copper without surface roughness are expected for high-gain planar antennas. As fine pitch patterns are necessary, the modified semi-additive process (MSAP) is becoming popular [84].

As is well known, phased arrays are comprised of antenna elements fed independently of RF circuits [85]. To reduce the feeding loss, the on-chip antennas and AiP techniques have been developed for the integration of these modules [86].

Operating emerging wireless technologies at a higher RF, such as mm-wave and quasi-THz, is a route to achieve higher data bandwidths and support the growth at the network edge for terabit transmission. In particular, a single-input single-output (SISO) system at 237.5 GHz for transmitting data over 20 m at a rate of 100 Gbit/s illustrates the promise that the sub-THz band offers in the delivery of 6G [87]. However, there is currently a lack of real-world empirical measurement data to support the research and development advances toward 6G definitions and new product development. As sub-THz wide bandwidth propagation channel characterizations have not been extensively studied, nor experimentally verified in the open literature, this frequency band has not been incorporated in the standardization efforts that are led globally by ITU-R, 3GPP, ETSI, and IEEE. Furthermore, practical and traceable sub-THz propagation channel characterization presents new measurement challenges in a real-world environment. These challenges arise from the high signal transmission loss, limited equipment dynamic range, limited availability of commercial RF components, the need for high-gain and beam steerable antennas, and the requirement for extreme data rates [88].

Propagation channel models for sub-THz in city deployment are an active research topic and work has been reported at 90 and 200 GHz [89], [90]. However, this work is only from a numerical and analytical modeling perspective with limited variables in both environmental settings and parametric studies. In [91], two vector network analyzer (VNA)-based frequency-domain sub-THz channel sounder systems were developed for operating at the frequency ranges of 75–110 and 220–330 GHz. In [92], an instrument-based time-domain sub-THz channel sounder was developed for the frequency range between 280 and 330 GHz. The overall propagation path of these sounding systems between transmitter and receiver is limited to about 10 m for [91] and 3.85 m for [92]. In practice, coaxial cable losses restrict the practical measurement range, and therefore, the use of an optical-fiber based phase-compensated sounder to mitigate the coaxial cable loss issue and extend the measurement range has been investigated [93]. This addresses the issue relevant to optical fiber cables being inherently sensitive to phase changes due to bending and temperature and extends the measurement range from meters to tens of meters for mm-wave and sub-THz bands. Furthermore, there is currently on-going work developing long-range phase-compensated VNA-based frequency-domain sub-THz channel sounder systems for operating at frequency ranges of 330–500 and 500–750 GHz [94].

C. Microwave Systems and Technologies for Medical Applications

Medical technologies using microwaves are established for treatment and have been proposed for a variety of imaging and sensing applications. To support patient care and home-based safety, radar-based approaches for monitoring vital signs and detecting falls have been introduced [95]. RF and microwave ablation have been developed to treat liver, lung, and kidney cancers, as well as cardiac arrhythmias, maturing into clinical product offerings [96], [97], [98]. Key imaging and sensing applications that involve bulk tissues at microwave frequencies are the detection of breast cancer [99], differentiation of ischemic and hemorrhagic stroke [100], [101], and assessment of lung water content [102], [103], [104]. Moreover, microwave tumor detection and imaging can be enhanced by exploiting magnetic nanoparticles as modulated contrast agents selectively delivered to the tumor [105], [106]. Solutions for these applications have advanced beyond initial feasibility studies into physical systems capable of scanning human subjects. Recently, testing with human subjects has commenced and several start-up companies are pursuing commercialization of these technologies [99]. Emerging applications include colon health using microwave sensors incorporated into endoscopes for [107], as well as hydration monitoring [108]. For smaller samples and single cells, microwave biosensors have been developed for applications, such as monitoring blood glucose levels, and gaining insight into the effects of chemo-electrotherapy on single cells [109], [110]. Interest in utilizing mm-waves is growing. However, the limited penetration of these signals suggests that the analysis of small samples and assessment of skin cancers will only be the potential applications [111].

Several important general technology improvements may enable advances in medical applications. First, enhanced computational power and speed have enabled the development of detailed models to support the design of complex components and systems, feasibility analysis, and performance assessment. For imaging applications, this also accelerates iterative reconstruction algorithms that require multiple forward solutions. Second, the reduction in the cost of hardware has enabled prototypes to be developed and tested. This testing is key for unraveling assumptions that reduce efficacy in real-world scenarios. Rapid manufacturing, such as 3-D printing, also allows for the development of prototypes with less overhead, as well as phantoms to support this testing.

Recently, testing in realistic scenarios has increased, corresponding to the availability of prototype systems capable of scanning human subjects or samples. For example, a microwave stethoscope for monitoring heart and respiration rates has been tested in small-scale studies [104]. Differentiation of ischemic and hemorrhagic stroke has been tested with groups of 20 patients, as well as a second group of 25 patients and 65 volunteers [100]. As recently reviewed in [99], the growing number of studies with human subjects is pointing toward breast imaging as the first clinical application of this technology.

As microwave technologies become increasingly established for medical applications, several key trends are anticipated. First, improvements in imaging technologies are expected with the incorporation of multimodality information. This may be in the form of prior information available from other clinical methods or through the collection of information with a co-located system (e.g., ultrasound). The growth in commercialization activity is also expected to increase the availability of devices and help establish collaborations with clinicians. This is also expected to refine clinical use cases for microwave imaging (MI) technologies. Utilization of machine and deep learning (DL) methods to elucidate trends data will improve images or enable detection of anomalies with the expansion of datasets [112]. Microwave technologies are also anticipated to be incorporated into wearables used for monitoring via IoT technologies [52].

D. Application of Machine Learning to Inverse Problems

MI is a nondestructive testing (NDT) technique employing EM waves with a frequency range of 300 MHz–300 GHz. The main goal of MI is to reconstruct the permittivity of unknown scatterers by measuring the scattered data, which is often described as an EM inverse scattering problem (ISP). Although rigorous and demanding in terms of mathematical skill, solving inverse problems is a significant technological achievement in the field of satellite-based remote sensing, biomedical imaging, geophysics exploration, and several defense applications.

ISPs are typically nonlinear and ill-posed in nature. Thus, the legacy practice was to deal with them either with noniterative methods (Born or Rytov approximations) or with iterative methods, e.g., Born and distorted Born iterative methods, constant source inversion, and subspace-based optimization methods. The limited accuracy of noniterative methods restricts their wide acceptance, whereas more accurate iterative methods come with a huge computational load.

Recently, ML, a widely accepted tool for signal and image processing, has demonstrated potential to transform the solution of ISPs. More specifically, DL techniques that mimic the learning process of the human brain using a convolution neural network (CNN) can offer unprecedented improvement in speed and accuracy of solving ISPs. The general framework for these recipes is to use a forward solver to generate a training dataset, which then can be used to train the CNN. Legacy techniques like support vector machine (SVM) were initially adapted to solve ISPs [113], followed by CNN-based approaches. In the literature, deep neural networks were combined with traditional iterative methods [114] to improve the computational load. It is quite straightforward to predict that the choice and efficacy of the neural network (NN) plays a crucial role in improving the accuracy, and thus, a three-layer CNN [115] following the U-net [116] architecture was also explored. However, one drawback of this approach is that a custom built and dedicated NN is necessary for solving each ISP; thus, the versatility of such a method remains restricted. This challenge motivated the application of DL into well-described existing techniques. An excellent solution is using such a CNN, which is trained to learn the underlying signal patterns. Chang et al. [117] proposed an NN that can solve any arbitrary linear ISP. Improved magnetic resonance image reconstruction was achieved using the alternating direction method of multipliers (ADMM) [118].

The future research scope for embedding AI/ML techniques into ISPs is exciting. Various research groups around the globe are striving to improve the speed and accuracy of ISPs and new advancements are frequently being reported. To name a few, Li et al. [114] proposed a more realistic model of DNN termed DeepNIS. Sanghvi et al. [119] developed an excellent CNN network that can learn the noise space components of the radiation operator. To consider the effect of system noise, a physics-assisted ML approach has also been examined [120]. A more advanced approach of using the physics-informed supervised residual learning (PhiSRL) method following the traditional Born iterative method has very recently come into the picture [121]. Incorporation of AI/ML is important when developing algorithms for larger size electrical objects. Large electrical objects typically possess intricate geometries and diverse material composition, necessitating computationally intensive simulations. Thus, the use of AI/ML is necessary to tackle these problems. Future research directions and the interests of the AP-S community are expected not only to focus on the popular, such as medical imaging and NDT, but expand to geophysical exploration, extraction of cosmological parameters, and space weather prediction.

E. Quantum-Based Electromagnetic Sensing Technologies

The traditional metallic antenna can cause invasive perturbation to the original EM field generated by an antenna under test (AUT) due to the presence of conductive surfaces, which may possess surface charges [122]. Photonic electro-optical methods for electric field (E-field) sensing have redefined in situ noninvasive near-field characterization in harsh thermal environments, exhibiting wide frequency bandwidths spanning from near direct current to the edge of the THz regime [123]. These sensors operate on the principle of optical intensity varying bulk parameters, including the electroabsorption effect [124], the electrochromatic effect [125], the linear Pockel's effect [126], and the nonlinear Kerr effect [127]. Two mature Pockel's-based designs, namely, the Mach–Zehnder interferometer and whispering gallery mode sensor, have dominated the field, due to their simplicity and superior figures of merit. The first is the standard Mach–Zehnder interferometer, where the optical length inside the measurement arm varies with respect to the applied EM field. The other is a whispering gallery mode sensor, which possesses a resonant cavity whose frequency may be modulated by the changing refractive index induced by the E-field. However, these sensors have fundamental operational limitations, such as bandwidth-sensitivity tradeoffs, the requirement of complex calibrated digital signal postprocessing, and expensive costs.

Atom-based noninvasive measurements of EM fields are receiving increasing attention due to the advantage of a predictable response directly tied to fundamental concepts (resulting in traceable self-calibrated measurement [128]). The operation is based on quantum interference by means of a coupling/probe laser [129] incident on a vapor cell containing alkali atoms (potassium, rubidium, and cesium). The enclosed atoms could be excited to high-energy Rydberg states (where the principal quantum number n typically takes values between 10 and 100) [130]. These Rydberg atoms are identical quantum particles exhibiting large polarizability and sensitivity [131] ($<1\ \mu$V cm^{-1} Hz$^{-1/2}$ [132]) in the presence of the EM field generated by the AUT; change in probe transmission through the vapor cell is detected with a photodetector. The atom in this atomic state acts as a dipole due to the separation of charge between the valence electron and remaining positively charged ion. A variety of laser configurations/techniques have been used to induce this excitation, including electromagnetically induced transparency (EIT) and Autler–Townes splitting, allowing Rydberg atoms to be used as high-sensitivity noninvasive tunable sensors/antennas [127] within electrometry up to the THz regime [132], [133], [134]. Such atomic E-field sensors have predicted applications in RF telecommunications, EM sensing, imaging, and metrology [135]. However, at present, this technology is still in the very early stages of development. Various research challenges, such as equipment miniaturization, finding the optimum RF modulation, and signal processing, will need to be addressed to enable its wider uptakes [136].

IV. Maximizing the Societal Impact of Wireless Connectivity

Wireless connectivity is set to play a key role in addressing a growing number of societal challenges related to digital equity, climate change, and public health. New antenna technologies will serve at the forefront of these efforts by enabling persistent and ubiquitous access to the EM spectrum and the Internet. Their role will be largely unseen, when successful, as they facilitate the exchange of information and energy amongst people, machines, and infrastructure. Fig. 5 summarizes expected growth in this area. It will be critical for new antenna technologies to enhance access to this connectivity and lower or even remove many of the barriers to information, tools, and opportunities on the Internet. These are essential to the empowerment of digitally underserved communities and to link all people to the advanced distributed data storage and computing resources at the network edge and its backend linkage of high-speed fiber, satellites, and other networks.

A. Digital Divide

It is constructive to first examine a global view of digital equity to gain a better understanding of the importance of new antenna technologies. For this, we look to September of 2015 when more than 190 members of the United Nations (UN) committed to 17 Sustainable Development Goals (SDGs) [138] for bringing equality across the world, both in the present and for generations to come. These goals represent a call to action for every nation, irrespective of its development status, to engage in a unified global partnership. These goals also underscore the critical need to simultaneously address poverty and various forms of deprivation alongside endeavors to enhance healthcare and education, diminish inequality, stimulate economic advancement, and confront the challenges of climate change.

The UN has recognized Internet access as a basic human right, emphasizing the need for social workers to advocate for policies that address this digital divide [139], [140]. The critical role of high-speed broadband access was especially evident during the COVID-19 pandemic for social, educational, financial, health, and other needs. Even in the USA, a significant portion of the population, particularly low-income individuals, people of color, older adults, Native Americans, and rural residents, lack home access to high-speed Internet, exacerbating social, economic, and political disparities.

Wireless systems have the potential to help bridge the digital divide and promote digital equity by providing reliable Internet access to underserved and remote areas. The discussion in [141] and [142] outlines key challenges and solutions to

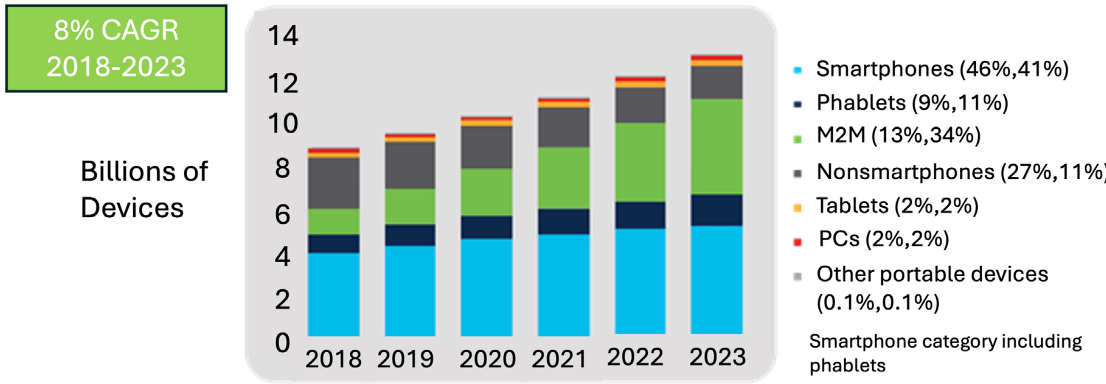

Fig. 5. Example of growth in the number of devices using telecommunication services (from [137]).

provide Internet and wireless systems worldwide. However, access to wireless systems alone is not enough. People also need digital literacy skills to effectively use online resources. Lack of digital literacy can perpetuate the digital divide, and initiatives to address the digital divide in the U.S. frame it as a social justice and human rights issue, where advocacy tools can be aimed at reducing the digital divide at the state and local levels.

B. Connecting Policy to Practice

The societal impact of major advancements in new antenna technologies is contingent on the allowances made for the actual use of allocated bands. Substantial new investments in digital infrastructure are necessary, but public policy also substantially lags technological realities that span from increasingly "smart" transceivers to distributed networking. Innovations in antenna design are often ignored in current decision-making, with many of the shared spectrum proceedings lagging decades behind the state of the art. In turn, bringing high-speed connectivity to underserved communities is often hampered by the limited spectrum assets allocated for the implementation of innovative solutions, including the next-generation antenna deployment.

Recent initiatives in the USA may be examined as a bellwether for global efforts. The many federal broadband grant and loan programs to increase connectivity across the USA are predicated on the creation of a meaningful impact from public investment in critical infrastructure, including \$42.45 billion for NTIA's BEAD initiative, \$10 billion from the U.S. Treasury's Capital Project Fund, roughly \$14 billion from the FCC's RDOF Phase II, and billions from additional USDA, DOE, and other agencies' programs.

Unfortunately, the accurate baseline measures of connectivity across the USA still do not exist. The FCC's Broadband Fabric and National Broadband Map advertise availability [143], but these self-reported measures by Internet service providers often substantially overstate speed and coverage (especially regarding wireless connectivity). To date, no scientifically rigorous analysis of actual broadband speeds has documented household-level realities. Poor, rural, and communities of color often show the greatest discrepancies between "advertised" availability and "on-the-ground reality." When metrics contain measurement artifacts, it then becomes all-the-more difficult to target federal funding to the communities most in need. Limitations in network architecture have compounded these problems. One example is hub-and-spoke wireless implementations in areas with substantial topology and/or trees. Meanwhile, distributed and software defined networking (and the concomitant internetworking of antennas across arrays of transceivers) remains almost entirely unexplored, given current spectrum allocations.

Digital equity efforts face a major hurdle. Areas may be declared "served" when they are, in reality, un-or under-served (e.g., receive broadband speeds of less than 25/3 or 100/20 Mb/s, respectively, as of Fall 2023). These same areas may then be declared ineligible for funding that aims to address the digital divide. Furthermore, key metrics like overall network and link reliability over time and pricing (as well as latency, bufferbloat, etc.) are all currently missing from national data collection efforts. A real-world example is the rural Alaskan Tribes, experiencing challenges, such as satellite broadband that regularly experiences 2000–3000-ms latency, and often goes entirely offline 4–6 times/day during longitudinal data collection efforts. This connectivity is too often unusable for any real-time application (e.g., telehealth and other video conferencing needs), as well as for any critical communications. Thus, a substantial and immediate documentation effort is both timely and essential to bridge the digital divide more efficaciously, spanning both innovative network implementations (especially distributed and shared spectrum implementations) and far more nuanced data collection that captures the quality of service faced within marginal connectivity areas and among underserved constituencies.

Opportunistic spectrum access (e.g., FCC Docket 04-186) has also long languished; while enabling technologies for opportunistic and shared spectrum access has radically improved, no new spectrum licensure has been introduced in over 20 years. This does not leverage the possibilities from advancements in software defined radio (SDR) and software defined networking (SDN) technologies. A potential starting point for approaching this oversight would be to conduct audits of actual spectrum utilization to determine the magnitude of the discrepancy between spectrum allocation and assignment, as well as the actual utilization of those same bands. Prior analyses conducted by McHenry et al. in the 2004–2007 timeframe as a part of the NSF Spectrum Occupancy Measurements Project documented widespread underutilization of the public airwaves, often with less than 10% utilization. In the 20 years since these studies, many spectrum license holders have shifted from analog to digital, which may lead to even lower spectrum utilization in many areas of the country. An updated analysis would prove incredibly enlightening, helping to spur a new generation of more efficient spectrum allocation, assignment, and overall utilization, and simultaneously alleviating the "spectrum crunch" lamented by many contemporary spectrum users and license holders.

In the USA, this issue is particularly important to Tribal authorities who, under their current treaty rights, retain control over any natural resources not explicitly given away during their treaty-signing. As such, EM spectrum should be available for use by Tribes, yet is currently often assigned to non-Tribal license-holders. License-holders may not be using the licensed spectrum in Tribal areas, yet Tribes are forbidden to utilize this spectrum because it is officially in use by non-Tribal entities. Tribal areas are often "spectrum green fields" with close to zero actual spectrum use across wide spectral bands; they are the natural location for prototyping next-generation wireless technologies and cost-effective broadband implementations. Tribes should be the vanguard for pushing the research and development envelope and, with the $3 billion in Tribal Broadband funding being made available over the next two years, are perfectly situated to partner on everything from basic research and development to real-world proof-of-concept implementation of solutions to bridge the digital divide.

C. Extending Socioeconomic Benefits of Cellular

In addition to investments in infrastructure and the impact of public policy, it is instructive to highlight the impact of wireless connectivity in society and examine the challenges faced when socializing and adopting new technologies. This can be observed by first examining the well-known generational (e.g., "Next G") upgrades in telecommunication technology. While performance metrics representing improvements in system performance can be identified, deployment is complicated by a combination of regulatory bodies, private companies, and end-user device makers. Under this scheme, digital equity is sometimes undermined despite a technological upgrade.

One example is the technology standard for cellular networks. Wireless companies and technology news media often depict Next G upgrades in bandwidth and transmission speed [144], [145]. While upgrades from 3G to 5G have increased the number of frequency bands, their availability still depends on a nation's radio spectrum allocation and compatibility of a mobile device's radios and antennas. Even in the same country, such as the USA, device makers often manufacture carrier-specific phones that support only a subset of available frequency bands. While 3G has a clear divide between UMTS and CDMA2000, a phone's compatibility with a specific mobile network operator (MNO) has become less straightforward and lacked transparency in later generations [146]. This leads to premature obsolescence of an older mobile device, which creates e-waste and an additional economic burden on many underserved communities. There is also the problem of spectrum fragmentation; in each frequency band, contiguous spectrum blocks theoretically available for more efficient usage are divided by several MNOs, each of which may in the end utilize a collection of scattered spectrums based on their acquired licenses [147].

At the current state of 5G deployment, the GSM Association (GSMA) maintains its position that without sufficient low-band (<1 GHz) spectrum, "the digital divide is likely to widen, and those living in rural areas will be excluded from the latest digital technologies." The same report, however, discovers that low-band spectrum has not been used at all for 5G in more than a half of the surveyed countries [148]. Considering that there are usually several MNOs in a country and that MNOs may prioritize the provision of midband (1–7 GHz) and high-band (or mmWave) spectrum, even if low spectrum is deployed, it remains uncertain whether 5G will fulfill its potential to deliver what the report considers needed to achieve "digital equality."

A lesson learned for the engineering communities is that, while there is never a shortage of new technological ways to solve a challenge, there are always several larger sociotechnical systems that surround a technology. As a society, it is necessary to approach these entanglements with both engineering and nonengineering perspectives. To illustrate this, in communication system engineering, "spectrum allocation" represents innovative ways to dynamically allocate scarce spectrum resources based on temporal usage, price, and other factors [149], [150]. However, in the context of technology policy and management, the same term means an international or national spectrum planning process to optimize overall system efficiency and to maintain fairness and equity for all stakeholders [151], [152]. Accommodating different perspectives and drawing from cross-disciplinary approaches (e.g., [153]) is key to extend our technology's socioeconomic benefits to a broader (often socially disadvantaged) population.

D. WiFi and Bridging the Gap in the Digital Divide

Given the challenges surrounding the deployment of new and existing antenna technologies for wireless connectivity, it is crucial to grasp society's reliance on Internet access. The absence of such access can deprive nearly 34% of the world's population of services, such as ride-sharing, map navigation, and accessing restaurant menus. According to [154], as of 2022, there were 5.3 billion Internet users worldwide, representing 66% of the global population. As Internet usage grows, the digital divide widens, posing a gap between those with access and those without.

While alternatives like device-to-device (D2D) communication offer solutions, challenges persist. Antennas must ensure sufficient coverage without causing interference, necessitating strong beamforming capabilities. This, in turn, requires miniaturization and coupling reduction within limited volumes. Careful planning for power consumption and spectrum management is imperative.

Bridging the digital divide is about more than Internet availability; it is also about equipping individuals with the skills and resources to use it effectively. WiFi plays a pivotal role in developing digital literacy and is affordable, showcasing the impact of standardized services. Efforts to expand outdoor and free WiFi access, particularly to underserved communities, are underway globally, leveraging cost-effective hotspot setups. Initiatives like New York's LinkNYC repurpose payphone kiosks into multifunctional WiFi hotspots, offering free Internet access, calls, and device charging.

The study in [155] examined the effects of providing wireless connectivity, such as free WiFi, to digitally underserved communities through municipal-university partnerships. Three services, namely, work opportunities, education via massive open online courses, and communication, were found to significantly impact economic metrics. This highlights the importance of comprehensive research on the economic, societal, and educational implications of accessible and affordable wireless connectivity. Bridging the digital gap goes beyond providing free Internet; it involves empowerment, education, and economic advancement, fostering a more connected and inclusive global community.

As technology advances to offer wider bandwidth and access, device costs are likely to rise. The challenge that the Antennas and Propagation Society faces lies in developing low-cost solutions, such as higher efficiency antennas, ensuring affordability, and accessibility for all.

E. Drones/Unmanned Aerial Vehicles

LEO satellite networks have recently been used to develop the IoS and even space-based WiFi-like services for wireless connectivity. The role of these space-based systems will continue to play an increasingly important role in maximizing the societal impact of wireless connectivity. In a synergistic effort, drones, unmanned aerial vehicles (UAVs), and other autonomous vehicles and systems are also being used to reshape the landscape of wireless communications. Several industries, such as agriculture, real estate, infrastructure inspections, and package delivery, are already employing drones to enable quick, affordable, and safe operations. In the antennas and propagation realm, drones have garnered interest in characterizing large antennas, where size precludes the use of conventional anechoic chambers [156], [157], [158], [159].

A major limitation of the current use of drones for wireless communication is the line of sight (LOS) requirements between the operator and the drone. This severely limits the scale at which drones can be deployed and the ability to bring wireless connectivity and/or services. Investments in beyond visual LOS (BVLOS) operations with drones, where cellular base stations can be used for control via cellular networks [160], may help alleviate the challenges. This allows drones to fly unseen by operators but results in unique challenges for engineers as the existing base station antenna technologies are typically oriented to serve users on the ground. In contrast, drones fly at an altitude above the base station and thus communicate to the base stations exclusively through sidelobes of the base station antenna [161]. Assuming that the drone antenna patterns are quasi-omnidirectional implies that they can transition rapidly from a zone of good signal to a zone of no signal without excessive base station handovers.

On the other hand, the communication link between drones and base stations is relatively free of multipath and obstructions. This can cause increased interference levels at base stations that the drone does not intend to communicate with, thus impacting the network performance. These issues can be alleviated by a directional antenna onboard the drone. This ensures that the main beam of the drone antenna stays aligned with the sidelobe of the base station antenna if the drone enters regions where the signal levels are changing rapidly. The directional antenna also minimizes radiation toward the base stations with which the drone does not intend to communicate. The key challenge for antennas onboard aerial vehicles, thus, is the necessity of a reconfigurable directional antenna that can adhere to the SWAP-C constraints posed by the drone, especially in the sub-6-GHz spectrum. For higher frequencies (mm-wave and beyond), such antennas might be more feasible.

F. Heterogeneous Integration and Packaging

The transition to SDR and SDN, key enabling technologies for wireless communication networks, has been driven in part by advancements in high-speed digitizers, field-programmable gate arrays (FPGAs), and ultimately RF system-on-chip (RFSoC). The at-scale development and transition of mmWave systems is also growing, with fieldable links now being deployed beyond 100 GHz. This consolidation of the RF front end for wireless communication has created a unique relationship between semiconductor, packaging, antenna, and networking communities, as all are now interlinked in their societal impact. The deployment of low-cost wireless communication technologies resides at the forefront of this discussion, but costs of semiconductor device fabrication are increasing due to rising capital costs.

Heterogeneous integration and higher level assembly (e.g., system-in-package) are emerging as a key mechanism to mitigate rising costs and address the inequitable economic impact this creates among users. The disaggregation and reaggregation of large dies from advanced technology nodes into smaller dies connected in a package shorten design times. Savings can also be gained using smaller dies from legacy and advanced technology nodes that are combined on high-density packages. This can also lead to enhanced functionality with improved electrical, thermal, and mechanical performance [162], [163], where the systems range from a microelectromechanical system to an assembled package for high-bandwidth memory or active and passive components interconnected as part of a logic-memory-RF block. A more-than-Moore system can thus help integrate logic, memory, sensors, and antennas from various front-end manufacturing nodes into a single package. The main challenges for the advanced packaging industry relate to the required process, tooling, and metrological improvements [164]. These challenges include developing technologies for power delivery, thermal management, and selection of appropriate materials for densely integrated systems.

Heterogeneously integrated advanced packages are also seen as the performance drivers for several wireless communication technologies, including Next-G, autonomous vehicles and IoTs, and AR/VR with the design of these packages primarily driven by end-user applications [165]. However, given the complex and capital-intensive nature of running semiconductor fabs, there are several challenges that need to be addressed [166]. These include workforce development, reduced emissions along supply chains, and, critically, effective material sourcing with minimal environmental impact to ensure a vibrant semiconductor ecosystem that can support the deployment of low-cost wireless communication.

G. Physical Layer and Wireless Network Security

Expanding access and coverage is a key aspect of tackling the digital divide, but these are complicated by challenges in network security from physically complex, infrastructure-poor, and contested or unregulated environments. This challenge is further exacerbated by the fact that nearly 70% of the world's population is expected to live in dense urban environments by

2050 [167] and that there is a growing presence of sophisticated bad actors that may exploit networking technologies to cause significant damages and loss (e.g., ransomware attacks).

This poses major threats to user privacy and security in addition to the direct impact such actions may cause on private and public entities (e.g., ransomware attacks, spoofing, wireless sniffing, and attacks on public infrastructure). It may also lead users to lose trust and may delay the adoption of networking technologies globally, especially in developing countries where a significant portion of the population has very limited digital literacy [168]. The lack of infrastructure makes this even more challenging as it limits the deployment of network security technologies that rely on extensive and reliable infrastructure. As part of the overarching efforts to close the gap due to the digital divide, novel physical layer technologies will play a significant role in helping expand access while providing robust wireless network security features.

Emerging networking technologies that could help to deliver robust wireless network security while expanding access and coverage include intelligent and opportunistic heterogeneous networks. These can enhance security by adaptively exploiting multiple communications technologies operating at different parts of the EM spectrum [169], [170]. The expanded utilization of spectrum comes with additional security requirements. Another future direction is the development of novel antenna technologies that enable a new layer of wireless security capability at the physical layer. For example, compact antenna diversity systems, in addition to enabling MIMO-based wireless networking technologies, can be used to create protection against signal energy and feature detection schemes especially when combined with advanced coding and signal processing techniques [171], [172]. Such techniques provide novel protection schemes against eavesdroppers that attempt to detect and intercept communications signals among legitimate users.

Additionally, RIS (described in Section II-C) can enable novel security features by reducing the probability of detection (LPD) by adversaries [173]. Directional networking enabled by antennas with directional modulation capabilities, as well as phased arrays and adaptive beamforming approaches, also shows promise for more resilient and secure communications among legitimate users [174].

V. Conclusion

In this invited paper, members from the three WGs in the IEEE AP-S NTDC have presented recent and emerging research directions in the fields of antennas and propagation. WG-1 focused on materials and manufacturing processes for novel antenna applications, covering several emerging areas of research that could fundamentally shape the future of antenna and sensor system technologies. WG-2 focused on advances in communications, sensing, and imaging. For mobile communications, recent research focuses on the development of 6G, sub-THz antennas, and propagation. For microwave medical imaging systems, advances in computational power and speed combined with ML techniques will provide more accurate results and offer more potential benefits. The advent of quantum technologies for sensing systems could revolutionize the domain. The primary goal of WG-3 is to examine the new technology directions that intersect with the overarching goal of maximizing the social impact of wireless connectivity. This WG brings attention to the considerations that social science, economics, and public policy have. To this end, the challenge of new technologies does not just reside within the technical community but rather the entirety of the problem space.

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