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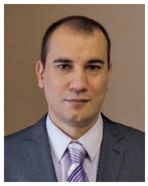

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Laying the Milestones for 6G Networks

The continuous evolution of network technology and the digitization of the economy are key drivers for defining the expected 6G networks. Academia and industry have made tremendous strides during the past few years to shift the networking paradigm from human-centric communication to machine-type communication, and those gains will eventually lead to everything-type communication. Such developments have already enabled 5G systems to support massive connectivity, multigigabit data rates, massive multiple-input/multiple-output (MIMO), millimeter-wave (mm-wave) communication, nonorthogonal multiple access, multiuser access, edge computing, dense wavelength division multiplexing for transport networks, service-based architectures, network slicing, network function virtualization, network automation, and core network encryption. Moreover, service requests are now processed using various sets of performance metrics in intelligent and self-healing fashions.

Scaling these types of automated networks requires paradigm changes in communication network management, where communication and computation must ultimately fuse. Overall, this will lead to orders of magnitude of improved user satisfaction, and it eventually will spin out new, smaller domains for local and efficient service provisioning (e.g., private networks). The tremendous efforts dedicated to the development of 5G concepts, standards, technologies, and products have transformed the fabric of cellular networks once and for all. Also, 5G offers opportunities for the development of more advanced technologies in the future. On the other hand, 6G will adopt new paradigms, one of which may be networked visible light communication (VLC)—also referred to as *light fidelity*—which, for the first time, extends the electromagnetic spectrum from radio frequency (RF) to the optical domain for wireless networking.

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The new technology domains in 6G may extend to enhanced mobile access and wireless backhauling; smart and reconfigurable metasurfaces, where the wireless channel is "engineered" to improve system performance; and molecular communications, a process that could be achieved using a tactile Internet for pairing network components, deploying artificial intelligence (AI) for communications/networking and to administer network functionalities, and employing advanced security techniques against cyberattacks. From a verticals perspective, urban air mobility, energy, transportation, health, and manufacturing are examples of new slices that future networks will need to facilitate and support. Those techniques and verticals span beyond 5G visions and will certainly influence the way we think about communication. Although 5G is still undergoing deployment and may not have reached its full functionality as defined by standards, we believe now is the time to outline the milestones for basic 6G concepts and what could be the main verticals and empowering technologies.

6G might become the first network of its kind that supports humanity in dealing with disastrous situations. For example, delivery robots are the latest wave of technology evolution to help serve communities during ongoing social distancing mandates. 6G could provide more sophisticated management of supply chains that autonomously produce, package, and deliver services at large. Decisions about providing those services will be intelligently made using various technical and data enablers, such as AI, smart transportation,

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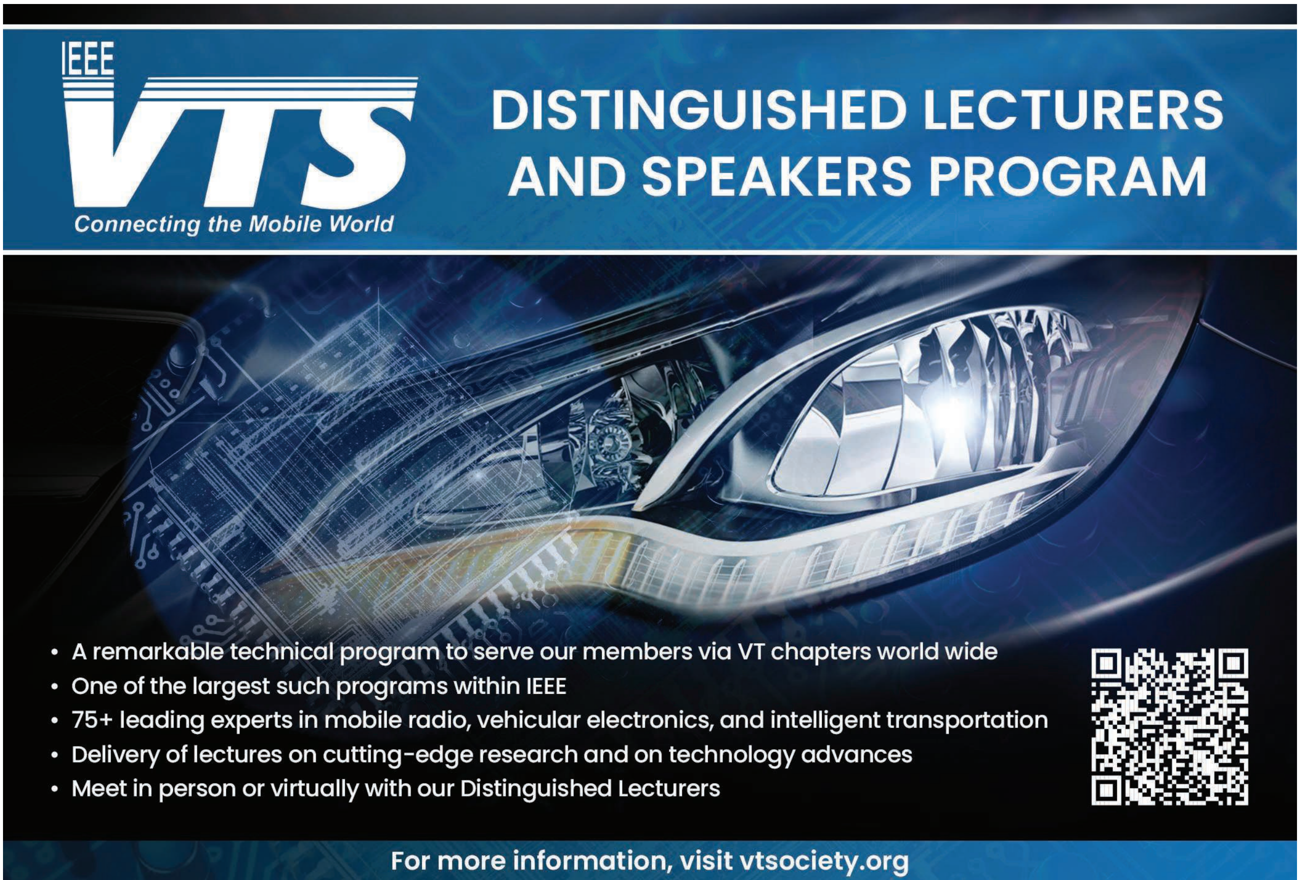
network-managed unmanned aerial vehicle (UAV) taxis, behavioral analysis stored in big data, and the monitoring of connected users' health.

The emergence of blockchain-based networks will redefine the known architectures for network segments through the adoption of shared, immutable records of data transactions between various parties. Blockchains will improve the efficiency of, and people's trust in, the communication ecostream through a more resilient system of authentication and confidentiality, yielding advantages by removing the risks of cyberattacks and data altering that originate from breaches in network entities and cloud platforms. Moreover, the adoption of AI to manage the network lifecycle will result in a significant reduction in power consumption across network segments. This will lessen the impact of mobile networking on the environment and cut emissions, leading to greener technologies and demonstrating that communication engineering is not just about improving the quality of human life but about helping to protect the planet.

This is the second special issue of *IEEE Vehicular Technology Magazine* focused on 6G technologies, and it is the inaugural installment of the "IEEE Future Networks Series on 6G Technologies and Applications," which succeeds the "IEEE Future Networks Series" that examined 5G. The special issues will cover different technical areas to help the research and industrial communities achieve a better understanding of the state of art for 6G communications. Toward that end, this special issue presents 11 articles that address various 6G wireless segments and technologies.

The articles accepted for this special issue cover different research topics, starting with physical layer-related subjects, such as wireless mobile radio channels, multiple antennas, metasurfaces, and VLCs. There is one article about tethered drones, followed by two articles covering various aspects of using AI, which also plays an important part in several of the other articles. All in all, this issue provides an interesting mix of subjects that address how 6G could look in future. We are confident that readers will enjoy studying this issue and find it helpful for their future research into 6G.

The first article, "6G Wireless Channel Measurements and Models: Trends and Challenges" by Cheng-Xiang Wang et al., provides new visions for global coverage, all spectrums, full applications, and strong and endogenous security within the scope of 6G wireless communication networks. The authors survey 6G channel measurements, characteristics, and modeling,



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COMMUNICATION ENGINEERING IS NOT JUST ABOUT IMPROVING THE QUALITY OF HUMAN LIFE BUT ABOUT HELPING TO PROTECT THE PLANET.

considering mm-wave, terahertz, and optical wireless communication channels.

The next article, "Ultramassive MIMO Systems at Terahertz Bands: Prospects and Challenges" by Alice Faisal et al., studies holistic ultramassive MIMO system design in terahertz bands and shows that, with proper configurations, ultramassive MIMO antenna arrays can overcome propagation losses and power limitations and realize the terahertz band capacity gain. The authors highlight several research advances that could enhance resource allocation in these high-frequency bands, and they examine use cases that are likely to yield terahertz ultramassive MIMO.

Third, "Massively Distributed Antenna Systems With Nonideal Optical Fiber Fronthauls: A Promising Technology for 6G Wireless Communication Systems," by Lisu Yu et al., provides an overview of, and outlook for, the architecture, modeling, design, and performance of massively distributed antenna systems that have nonideal optical fronthauls. Simulation results show that systems with analog-RF-over-fiber links outperform their baseband-over-fiber and intermediate-frequency-over-fiber counterparts for systems that have shorter fiber lengths and more radio access points, which are desired properties for future wireless communication systems.

The fourth article is "Radio Localization and Mapping With Reconfigurable Intelligent Surfaces: Challenges, Opportunities, and Research Directions," by Henk Wymeersch et al. It provides an overview of reconfigurable intelligent surfaces (RISs), summarizing open technical challenges and highlighting opportunities for RISs. While previous generations of cellular communication systems have always been designed "around" the channel, RISs represent a method to actively engineer the propagation channel to aid AI and other emerging technologies. Therefore, RISs constitute a strong candidate technology for 6G.

The next article is by Lina Mohjazi et al. "An Outlook on the Interplay of Artificial Intelligence and Software-Defined Metasurfaces: An Overview of Opportunities and Limitations" reviews recent advances in the architecture and electromagnetic wave manipulation functionalities of software-defined metasurfaces (SDMs), which offer a paradigm shift from uncontrollable to fully tunable and customizable wireless propagation environments. The authors elaborate on how AI can address various constraints introduced by the real-time deployment of SDM-enabled wireless networks to improve latency, storage, energy efficiency, and computation.

"Wireless 2.0: Toward an Intelligent Radio Environment Empowered by Reconfigurable Metasurfaces and Artificial Intelligence," by Haris Gacanin and Marco Di Renzo, introduces AI-based computational methods and gives an overview of intelligent radio environments based on reconfigurable metasurfaces. It elaborates on management aspects, the requirements of supervised learning by examples, and the paradigm of reinforcement learning. Numerous open challenges and research directions are highlighted.

The seventh article, "Topology Optimization for 6G Networks: A Network Information-Theoretic Approach" by Abdulkadir Celik et al., provides a new way to cope with interference by utilizing it for the topology optimization of 6G networks. To accomplish this, the authors present their vision for diversifying and hybridizing potential network subtopologies for a more efficient utilization of cellular network resources. They propose interference management schemes that enable interference rather than ignoring and avoiding it.

Next, in "Visible Light Communication in 6G: Advances, Challenges, and Prospects," Nan Chi et al. introduce VLCs as a 6G technology. They summarize achievable data rates using current transmitter and receiver device technology and highlight research areas that require future attention to fully exploit the potential of VLC technology. The article shows that VLC can extend wireless networks into areas that cannot be covered with radio technology, such as subsea environments. The authors also discuss the benefits of hybrid RF and VLC networks and demonstrate how AI can be used to enhance VLC toward fully fledged wireless networks.

The ninth article is "Aerial Base Station Deployment in 6G Cellular Networks Using Tethered Drones: The Mobility and Endurance Tradeoff," by Mustafa Kishk et al. In the authors' proposed setup, a tethered UAV (tUAV) is connected to a ground station, which provides the tUAV with energy and data. The performance of such an approach is explored for applications such as such as capacity enhancement in urban areas and coverage improvements in rural areas.

In "Trustworthy Deep Learning in 6G-Enabled Mass Autonomy: From Concept to Quality-of-Trust Key Performance Indicators," Chen Li et al. address the coordination of complex communication between hyperdense autonomous agents by using automated AI networks. The article's models and algorithms add trust brokerage alongside current and new wireless technologies.

Finally, "Machine Learning for 6G Wireless Networks: Carrying Forward Enhanced Bandwidth, Massive

Access, and Ultrareliable/Low-Latency Service" by Jun Du et al., introduces and surveys state-of-the-art techniques based on AI/machine learning (ML) and their applications in 6G. Such AI/ML approaches include supervised learning, unsupervised learning, deep learning, and reinforcement learning. Applications include energy management, especially for large-scale energy harvesting networks, and security enhancement mechanisms, including authentication, access control, and attack detection. Also, efficient mobility and handover management are introduced.

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