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**Defining 6G: Challenges and Opportunities**

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The September 2018 issue of *IEEE Vehicular Technology Magazine* represented the magazine's first publication about 6G and kick-started a discussion that continues, a year later, in this special issue. A discussion is beginning within the wireless community as to whether there is a need for 6G and whether counting should stop at five, adopting the Microsoft Windows approach or, similarly, the Internet Engineering Task Force (IETF) approach. On the one hand, there are good reasons for this change in cellular communication, such as to allow for faster adoption of innovations. However, it is important to remember that the success of cellular communications is largely based on the famous Memorandum of Understanding signed in 1987 by 13 countries for the 2G Global System for Mobile Communications.

What followed was a common and global standard that established the basis for a tremendous and coherent technology ecosystem that drove success, with interoperability and compatibility as the golden rule. Arguably, this could be achieved with an IETF approach. However, that general mantra is to make the same thing better in small steps, clearly an evolutionary approach. Such an approach generally inhibits paradigm-shifting changes, and the system might be locked in a state far from what may be achieved had fundamental technologies or architectures changed. Clearly, the shift from analog to digital in 2G was radical; optimizing analog systems endlessly would have never gotten us where we are now.

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Therefore, the key question is whether cellular communications has reached a state of optimality given the existing underlying technologies, which would support the case for never-ending, gradual improvements, or whether there is a fundamental, game-changing principle/technology, like the transition from analog to digital. Our guest editorial does not attempt to answer this question. However, this special issue offers an early platform to showcase whether such transformative technology exists. We hope that the selected articles stimulate a lively debate about whether we need 6G, what 6G is, and what the killer applications are. With this this in mind, we make the following observations.

We are witnessing an increasing role for new spectrum, which extends to the optical spectrum for free-space communications. This is not limited to backhaul use cases, i.e., free-space optical communication. It is increasingly considered for mobile access networks, specifically low-latency, machine-type communications (such as car-to-car communications) beyond gigabyte per second connectivity and up to terabyte per second for new data-demanding mobile applications including virtual reality, augmented reality, and high-definition TV. And it is considered, as well, for low-rate/low-power Internet of Things (IoT) applications and device-to-device communications.

We are also observing an increasing role for artificial intelligence (AI) and machine learning (ML) to operate wireless networks more efficiently, enhance the overall user experience, and provide new, innovative applications. This trend clearly builds on the capabilities introduced in 5G with software-defined networking. The presented software hooks provide an excellent mechanism to enhance network performance. In 6G, we might witness the union of network convergence, meaning that we may see stronger dependencies between networking infrastructures and applications, a trend that is also fueled by the need for greater security and privacy.

There also is an increasing realization that scalability in real systems and efficiency improvements will reach hard limits (i.e., Moore's law) and that the underpinning mechanisms that drive scalability for different key performance indicators (KPIs), such as densification and cost, are not always aligned. Existing wireless networks have benefited greatly from the small cell concept (or network densification), i.e., reduced cell size, often referred to as Cooper's law. However, it has been shown that further network densification will not yield substantial performance gains, as factors such as interference significantly offset area spectral efficiency (ASE) gains. In addition, cost will become prohibitively high. Similarly, with regard to the physical layer, expected improvements by moving from massive multiple-input, multiple-output (MIMO) to potentially ultramassive MIMO comes with diminishing returns due to undue increases in hardware and signal-processing complexities. Therefore, fresh, out-of-the-box thinking and new clean-slate approaches might be necessary to tackle future challenges.

Some important issues, such as security and privacy or innovative applications, and many more paradigm-shift technologies will, we hope, be presented in a future special issue of *IEEE Vehicular Technology Magazine*. For now, we thank Editor-in-Chief Prof. Javier Gozalvez for his great support, the entire publication team, and the reviewers for making this special issue a success.

Of 25 articles submitted, nine have been selected following two rounds of reviews, with typically three to four independent reviews each and some discussions among the guest editors. These nine articles can be grouped into three types: overview and requirements for 6G, AI, and other paradigm-shift technologies. Here, we provide a brief summary of these nine publications.

**Overview and Requirements for 6G**

This special issue features three articles that focus on vision, key drivers, and requirements. It is interesting to note that these have four themes in common:

1. the transition from radio to subterahertz (sub-THz) and optical spectra, i.e., visible light communication
2. the use of AI and ML to achieve intelligent network automation
3. the introduction of new network architectures
4. new applications based on new enabling technologies, such as holography.

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There is also a strong notion that the nature of mobile terminals will change, with cars and mobile robots playing a more important role.

The first article, "6G Technologies: Key Drivers, Core Requirements, System Architectures, and Enabling Technologies" by Baiqing Zong et al., proposes two candidate system architectures for 6G: 1) a multipurpose, converged, full spectral, and all photonic radio access network and 2) a laser millimeter-wave (mm-wave) converged 100-Gb/s hyperspectral space–terrestrial integrated network. The article identifies several technologies that will drive 6G, including photonics and photonic integration, holography, and AI, to achieve more network automation. It proposes a new network architecture and defines three pillars: 1) photonics-defined radio, 2) smart cars and mobile robots, and 3) distributed computing and intelligence.

Next is "6G Wireless Networks: Vision, Requirements, Architecture, and Key Technologies" by Zhengquan Zhang along with an international author team. This article aims to identify network architectures, 6G technologies, and new applications. With respect to architectures, it proposes multidimensional networks that extend terrestrial networks to include underwater, air, and space as well as nanoscale networks for the Internet of Nanothings. It proposes roughly 10× improvements in all KPIs. Further, the article proposes a mix of new technologies and advances of existing 5G technologies. Lastly, in terms of applications, it discusses interesting new ways to interact with future networks and applications, which build on the improved tactile Internet. This article also considers security-aware applications based on blockchain technologies. A general underpinning theme is the use of AI and ML to develop intelligent autonomous networks.

The third article, "6G: The Next Frontier: From Holographic Messaging to Artificial Intelligence Using Subterahertz and Visible Light Communication" by Emilio Calvanese Strinati et al., discusses technology enablers for 6G. In particular, five enablers are identified: 1) a new architecture, 2) a pervasive introduction of AI at the edge of the network, 3) 3D coverage, 4) a new physical layer incorporating sub-THz and visible light communication (VLC), and 5) distributed security mechanisms. It moves on to identify new network operation paradigms, in particular, semantic communications, ML and deep neural networks, and holistic management of C4 (communication, computation, caching, and control) resources. It makes a strong case for sub-THz and VLC to reach data rates of 1 Tb/s due to the abundance of bandwidth in these regions. It discusses technology-integration challenges and reviews enabling integrated circuit technologies beyond CMOS. The article further discusses interesting services, such as holographic communication and high-precision manufacturing.

**AI**

AI is envisioned as a key ingredient of future wireless networks to provide them smartness (network optimization) as well as autonomous functioning. The next three articles address this topic.

"Autonomous Wireless Systems With Artificial Intelligence: A Knowledge Management Perspective" by Haris Gacanin, discusses various technologies and opportunities for utilizing AI in the design of autonomous wireless systems. The author elaborates on training-based and training-free AI methods in a wireless environment. In addition, the functions of an autonomous agent with knowledge management are introduced. In summary, the article introduces the field of AI for future wireless systems.

The next AI-focused article is "Model-Aided Wireless Artificial Intelligence: Embedding Expert Knowledge in Deep Neural Networks for Wireless System Optimization" by Alessio Zappone et al. It considers deep learning based on neural networks, a technology well proven for speech recognition and image classification. Therefore, the best neural network architecture is identified for such a data-driven approach. As illustrations, numerical results to assess the performance of the proposed approaches are provided.

The final article in this section is "AI-Enabled Future Wireless Networks: Challenges, Opportunities, and Open Issues" by Medhat Elsayed and Melike Erol-Kantarci. The authors state that "when application requirements for tight quality of service (QoS) are combined with increased network complexity, legacy network-management routines will become untenable in 6G." AI is proposed to address these issues, and an overview of state-of-the-art research, challenges, and open issues is presented.

**Other Paradigm-Shift Technologies**

The seventh article, "Data-Oriented Transmission in Future Wireless Systems: Toward Trustworthy Support of Advanced Internet of Things" by Hong-Chuan Yang and Mohamed-Slim Alouin, discusses future wireless systems, which must support a very large number of IoT devices having unprecedented requirements, especially in terms of low latency and high reliability. Classical physical-layer wireless designs target average channel conditions and use metrics such as ergodic capacity and average error rate. These approaches improve average QoS, which suits large, long transmissions such as those associated with classical mobile broadband, but they ignore the specifics of individual data-transmission sessions and, therefore, fail to characterize the QoS of short transmission sessions, such as those associated with the IoT. The article introduces a data-oriented framework for wireless systems design with strategies optimally designed for individual data-transmission sessions, indicating that improvements can be achieved in terms of reliability and latency.

The eighth article is "Airplane-Aided Integrated Networking for 6G Wireless: Will It Work?" by Xiaojing Huang et al. It considers the recent growth in communications traffic and increased efforts directed toward the integration of space and terrestrial networks. This effort requires new forms of low-cost, high-capacity airborne platforms together with high-data-rate backbone links. The work reported in this article identifies two key bottlenecks that limit the capacity of these integrated terrestrial space platforms, and attention is focused on the bandwidth and ASE of the proposed systems. In addition, the authors review a range of wireless technologies that can be used to support the required backbone links. A network architecture is proposed that makes use of civil aircrafts, whose densities are high and permit the creation of such networks. The authors propose mm-wave technologies for the wireless links and discuss various supporting technologies.

The final article on this special issue's theme is "The D-OMA Method for Massive Multiple Access in 6G: Performance, Security, and Challenges" by Yasser Al-Eryani and Ekram Hossain. It introduces delta-orthogonal multiple access (D-OMA), a new multiple-access method for massive access in future 6G wireless networks. The method builds on concepts from nonorthogonal MA (NOMA) and makes use of coordinated multipoint transmissions. The performance of the proposed MA scheme is evaluated in terms of outage capacity while considering different levels of NOMA subband overlap. The favorable security implications are discussed, and attention is given to the selection and optimization of key system parameters, including cluster size, amount of spectrum overlap between clusters, number of collaborating base stations, and performance-complexity tradeoffs. Future research directions and open problems are identified.

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