Guest Editorial Special Issue on Green Communication and Computing Technologies for 6G Networks

THE NEXT generation of wireless networks (i.e., 6G) is envisioned to support communication in the three-dimensional space by integrating space, aerial, terrestrial, and undersea networks. The overall goal is to provide ubiquitous and unlimited connectivity to a massive number of Internet of Things (IoT) and machine-type devices/users having diverse Quality of Service (QoS) requirements, supporting substantial and heterogeneous traffic demands, and reducing the energy consumption with the help of highly energy-efficient communication protocols, transceivers and computing technologies. Out of several innovations 6G is targeting, this special issue focuses on green communications and computing technologies, which are crucial to reduce the overall energy consumption and operational cost from both the environmental and business viewpoints. To this end, the ever-increasing demand for advanced and ubiquitous applications over the recent years has shifted the paradigm of self-organizing networks to self-sustainable networks (SSNs). One main goal of SSNs is to eliminate the need for separate charging of heterogeneous devices by combining energy-efficient communication, energy harvesting/power transfer techniques, and offloading of energy-intensive processing from the edge-devices to the edge- and cloud-servers. However, the coexistence of wireless information and power transfer systems/links should be as seamless as possible for the end-users. Furthermore, providing network sustainability, and energy-efficient, energy-aware, and environment-aware connections to the massive number of devices and users having different levels of processing capabilities is one of the key challenges.

In the above context, this special issue targets to disseminate the latest theoretical and experimental works in the domain of energy-efficient communication and computing technologies towards enabling massively connected, fully intelligent and sustainable green 6G networks. We thank all the contributors for their interest in this special issue. A large number of papers were received and following a rigorous review, eight papers were accepted, along with one invited paper. This special issue presents different contributions, ranging from reconfigurable intelligent surface-assisted ambient backscattering communication framework to UAV assisted relay transmission via cooperative computation offloading.

In [A1], the great potential to achieve spectrum and energy-efficient communications for future wireless networks using ambient backscatter communications has been shown. Mainly, the backscatter communications has been studied in combination with RF-powered cognitive networks to bring reliable and flexible communications. Using evolutionary game theory to model the competitive resource allocation and replicator dynamics to capture the dynamic change of user selections, a distributed channel selection and backscatter power allocation algorithm has been proposed.

Wang *et al.* [A2] studied a scenario of a group of cell-edge users (CEUs) with each CEU having both the task of delivering data to the cellular base station (BS) (i.e., the data-transmission task) and the task of completing a given computation workload (i.e., the computation-tasks). Also, it has been considered that the unmanned aerial vehicle (UAV) serves as a dual-role AV (DUAV), i.e., the relay for forwarding CEUs' data to the cellular BS, and the edge-server for processing the CEUs' offloaded computation workloads. Taking into account that a malicious node overhears the DUAV's relay transmission, a secrecy driven UAV assisted relay transmission via cooperative computation offloading scheme has been investigated, in which the CEUs' computation-offloading transmission has been exploited to provide cooperative jamming to the malicious node.

In [A3], Bhowal *et al.* has proposed a reconfigurable intelligent surface (RIS)-assisted ambient backscattering (ABSc) communication framework utilizing advanced spatial modulation (ASM) techniques for spectral- and energy-efficient communication. The ABSc technique has been leveraged for harnessing the power from ambient RF waves, while ASM techniques have been deployed to ensure high spectral efficiencies by activating more than one but not the full set of antennas for transmission. Extensive performance analysis of ASM techniques has been carried out, and upper-bounds on the ensuing error rates have been derived. The provided comparative results reveal the benefits of the proposed framework. In particular, it has been shown that the ASM technique of improved quadrature spatial modulation (IQSM) can achieve the highest spectral efficiency.

Another article by Lou *et al.* [A4] has proposed a network architecture that introduces tethered unmanned aerial vehicles (TUAVs) carrying green antennas to minimize the electromagnetic field (EMF) exposure while guaranteeing a high data rate for users. In particular, each TUAV can attach itself to one of the possible ground stations at the top of some buildings. The location of the TUAVs, transmit power of user equipment, and association policy are optimized to minimize the EMF exposure. An efficient low-complexity algorithm composed

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of three submodules has been proposed. Numerical results show that TUAVs with green antennas can effectively mitigate the EMF exposure compared to fixed green small cells while achieving a higher data rate.

In [A5], Gupta *et al.* has proposed an interesting decentralized blockchain scheme for UAV data dissemination security in 5G wireless communications. Since the integration of 5G with UAVs can provide real-time communication, dynamic topology, and universal coverage, UAVs are able to relay massive data between IoT sensors and data servers. This massive data communication in 5G demands for software defined network (SDN) for flexibility and maneuverability over dynamic data traffic changes and frequent device registrations. However, the SDN controller is vulnerable to outside attacks. In this regard, this paper has introduced a private blockchain for protecting the SDN controller from hijacking. It has been concluded that the proposed private blockchain does not allow any unauthenticated 5G communication access as well as untrusted data through the SDN controller.

Another article by Hu *et al.* [A6] has focused on a new energy-efficient computing model, called in-network computing. As compared to the existing in-network computing models based on the programable network device, the proposed energy-efficient in-network computing paradigm integrates network functions into a general computing platform instead of delegating computing tasks to the network devices. The proposed computing platform integrated with the network functions can provide a unified operating environment for application tasks via a hypervisor and container. The task scheduling of in-network computing has been modeled as a multi-objective optimization problem and an evolutionary algorithm based on multiple target decomposition has been formulated. The algorithm takes resource utilization, computing energy consumption and network communication overhead as the optimization targets of task scheduling, and performs task scheduling for multiple data streams. The proposed algorithm is expected to have lower computational complexity, quick convergence and better practicability.

Xu *et al.* [A7] have dealt with the energy-efficient Multi-access edge computing (MEC) optimization problem in a jamming environment, where the attack activities of the jammer are time-varying and a-priori unknown. Mainly, an energy-efficient channel access and data offloading optimization approach has been proposed while considering dynamic characteristics of jamming attacks. A joint channel access and data offloading anti-jamming game capable of modeling the interactions between the jammer and users has been formulated, and it has been proved that the proposed game resembles an Exact Potential Game (EPG), and there exists at least one pure Nash Equilibrium (NE). Besides, a Multi-pattern Best Response based Channel access and Data offloading (MBRCD) algorithm has been proposed to obtain NEs in the dynamic jamming environment. It has been concluded that with the help of the "game learning" structure, the global network energy consumption can be significantly reduced under the premise of completing computation tasks.

Zhou *et al.* has proposed an improved adaptive differential evolution (DE) algorithm in [A8] to improve the communication between the IoT and cloud infrastructure. The scaling factor, crossover probability, variation, and selection strategy of the DE algorithm has been improved for fast convergence, which could be effective in large-scale networks. The proposed algorithm has been shown to result in better mutation, crossover, and strategies selection for the standard DE algorithm. The proposed IADE algorithm and existing variants of differential evolution methods have been tested against thirty classical benchmark functions. The proposed algorithm can be applied to large-scale networks for sustainability and improving QoS of resource-constrained devices.

Routing protocols in VANET need to consider realistic road environment, optimized design, and delay. Sending frequent control messages in a routing protocol may result in network load, delay, and energy consumption. In this regard, a low-latency and energy-efficient routing protocol has been designed by Wang *et al.* in [A9] while considering the route's lifetime and network connectivity to ensure the stability and reliability of the underlying route. Fuzzy logic has been used to evaluate each path based on these parameters. Simulation results show the optimized delay and energy consumption.

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APPENDIX: RELATED ARTICLES

[A1] K. Zhu, L. Xu, and D. Niyato, "Distributed resource allocation in RF-powered cognitive ambient backscatter networks," *IEEE Trans. Green Commun. Netw.*, vol. 5, no. 4, pp. 1657–1668, Dec. 2021, doi: 10.1109/TGCN.2021.3102660.

[A2] T. Wang, Y. Li, and Y. Wu, "Energy-efficient UAV assisted secure relay transmission via cooperative computation offloading," *IEEE Trans. Green Commun. Netw.*, vol. 5, no. 4, pp. 1669–1683, Dec. 2021, doi: 10.1109/TGCN.2021.3099523.

[A3] A. Bhowal, S. Aïssa, and R. S. Kshetrimayum, "RIS-assisted advanced spatial modulation techniques for ambient backscattering communications," *IEEE Trans. Green Commun. Netw.*, vol. 5, no. 4, pp. 1684–1696, Dec. 2021, doi: 10.1109/TGCN.2021.3100009.

[A4] Z. Lou, A. Elzanaty, and M.-S. Alouini, "Green tethered UAVs for EMF-aware cellular networks," *IEEE Trans. Green Commun. Netw.*, vol. 5, no. 4, pp. 1697–1711, Dec. 2021,

[A5] R. Gupta, M. M. Patel, S. Tanwar, N. Kumar, and S. Zeadally, "Blockchain-based data dissemination scheme for 5G-enabled softwarized UAV networks," *IEEE Trans. Green Commun. Netw.*, vol. 5, no. 4, pp. 1712–1721, Dec. 2021, doi: 10.1109/TGCN.2021.3111529.

[A6] N. Hu, Z. Tian, X. Du, and M. Guizani, "An energy-efficient in-network computing paradigm for 6G," *IEEE Trans. Green Commun. Netw.*, vol. 5, no. 4, pp. 1722–1733, Dec. 2021, doi: 10.1109/TGCN.2021.3099804.

[A7] Y. Xu *et al.*, "Energy-efficient channel access and data offloading against dynamic jamming attacks," *IEEE Trans. Green Commun. Netw.*, vol. 5, no. 4, pp. 1734–1746, Dec. 2021, doi: 10.1109/TGCN.2021.3098681.

[A8] Z. Zhou, M. Shojafar, J. Abawajy, and A. K. Bashir, "IADE: An improved differential evolution algorithm to preserve sustainability in a 6G network," *IEEE Trans. Green Commun. Netw.*, vol. 5, no. 4, pp. 1747–1760, Dec. 2021, doi: 10.1109/TGCN.2021.3111909.

[A9] X. Wang, Y. Weng, and H. Gao, "A low-latency and energy-efficient multimetric routing protocol based on network connectivity in VANET communication," *IEEE Trans. Green Commun. Netw.*, vol. 5, no. 4, pp. 1761–1776, Dec. 2021, doi: 10.1109/TGCN.2021.3100526.

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