Editorial
Recent Techniques of Green Information and Communications Technologies

RECENT years have witnessed the ever-increasing demand for anyone and anything (whoever, whatever) to communicate with whomever, whatever, wherever, whenever, i.e., 5Ws in wireless communications. Fifth-generation (5G) wireless networks are intended to provide mobile data connectivity to support 5W communication services (e.g., virtual reality and augmented reality) by ultra-densely deploying small base stations (BSs). It has been reported [1] that the number of 5G or multimode BSs will reach 13.1 million in 2025. When combined with massive multiple-input-multiple-output (MIMO) antennas, the deployment of numerous BSs will lead to an explosive growth in energy expenditure. Conservatively, a $1000\times$ growth in mobile data in the 5G era can increase the energy consumption by $1000\times$ [2]. It was estimated that information and communications technologies (ICTs) contribute to around 3.9% of the global electricity demand in 2007 [3], and this value was estimated to increase to 14% in 2030 [4]. Therefore, greening of ICTs becomes one of the imperative tasks for industry, government, and academia. The carbon footprint of ICTs can be broken down into three parts: 1) end devices (personal computers, mobile devices, peripherals, printers) (57%); 2) telecommunications (25%); and 3) data centers (18%) [5]. This article mainly discusses techniques that are recently under research and development for green telecommunications and data centers. Interested readers may refer to [6] for detailed discussions on greening of end devices.

Green ICT With Renewables: An intuitive technique considered by many researchers is to leverage renewable energy (e.g., solar, wind, and tide energy) to neutralize the carbon footprint of ICT. For example, Fong *et al.* [7] investigated the system capacity in a point-to-point system in which the BS is solely powered by renewable energy. The asymptotic system capacity is quantitatively characterized when the random arrivals of renewable energy are independent and identically distributed, and the coherence time is a sublinear function of total transmission duration [7]. Another research direction is to use energy harvesters (e.g., residential-level photo-voltaic panels and miniature wind turbines) to reduce the surging bills of wireless operators. For example, Huawei and Telefonica have installed solar-powered BSs in central Chile [8]. Motivated by the recent advancement of smart grid, a joint energy-sharing and resource management algorithm is proposed for a smart-grid powered multicell network to share the renewable energy in fine granularity and allocate radio resources in both fine and coarse granularity [9]. A quantitative tradeoff is established to show that the system on-grid energy expenditure linearly reduces at the expense of a sublinear growth in the end-to-end delay of users [9]. While the on-grid energy expenditure is still positive in [9], it is interesting to explore whether smart-grid powered multicell networks with energy harvesting/generation capabilities can become net producer rather than consumer of energy in the long term, and whether the tradeoff bound in [9] can be improved. Cross-fertilization of both stochastic network modeling and control theory would be required to answer these and other interesting research questions.

Green Internet and Service Provisioning: The green Internet aims at support ubiquitously data services, such as videos on Youtube, short clips on TicTok/DouYin, and short messages on Wechat and WhatsApp, over wired/wireless connections in an energy-efficient manner. The energy demand for data centers and network infrastructure is huge, and may not be satisfied solely by the application of renewable energy. Several major Internet content and computation providers are seeking ways to reduce the energy consumption of the cooling systems in their data centers. For example, Microsoft has established an experimental data center at the bottom of the Scottish sea to reduce the electricity consumption of the cooling system [10]. Besides, Apple, IBM, Huawei, and Tencent have also deployed data centers in the mountains of Guizhou Province, China, where the ambient condition provides natural air conditioning for the data centers. When combined with advanced Green ICT techniques, the energy consumption of these data centers can be further reduced. For example, when data centers are geographically distributed over different time zones with different electricity prices, recurrent neural networks can be used to predict the arrival rates of renewable energy in different data centers [11]. Based on the predicted arrival rates, load management decisions can be made to reduce the overall energy cost of these data centers. While current techniques for load management decisions are based on instantaneous arrival rates of renewable energy, the long-term effects of renewable energy are less investigated. In this regard, online learning techniques can be applied to load management to further improve the energy efficiency of geographically distributed data centers.

Interplay Between Green ICT and Machine Learning: With the advancement of computing hardware (e.g., CPUs and

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GPUs), a strong momentum has built to cross-fertilize machine learning (ML) with the design of green ICTs over the last decade. One of the directions attracting active research is applying ML to greening ICTs. For example, a green caching strategy was investigated by Tang *et al.* [12] for device-to-device (D2D) based Internet of Things (IoT). By factoring in the dynamic content request behaviors, deep Q-learning is tailored to obtain a caching policy that minimizes the system long-term energy expenditure [12]. The numerical results confirm that the caching policy realized by deep Q-learning can approach the optimal one as the training procedures continue. As research on ML matures, ML will find increasing applications in green ICTs.

Another research direction is to include green ICTs in the design of ML algorithms. While current federated ML algorithms mostly aim at improving the prediction accuracy of obtained models, a few researchers have considered the carbon footprint of the training process. For example, Zeng *et al.* [13] investigated the energy consumption minimization problem by joint management of the computation and communication resources. Their algorithm aims to achieve an equilibrium among the four dimensions of resources, i.e., bandwidth, CPU-GPU operating period, CPU-GPU frequency, and CPU-GPU workload partition. Using the additive property of wireless channels, over-the-air computing technology can combine the computing and signal processing processes at the central server such that the demand for bandwidth is reduced. Motivated by the bandwidth saving property, Amiri and Gündüz [14] proposed the digital federated stochastic gradient descent (DFSGD) algorithm and analog federated stochastic gradient descent (AFSGD). The convergence rates for DFSGD and AFSGD are faster than that of benchmarks without using over-the-air computing [14]. Besides, AFSGD outperforms DFSGD in prediction accuracy since over-the-air computing allows a more efficient usage of bandwidth. Therefore, it is envisioned that federated ML algorithms can also be designed from the green communication perspective such that the overall energy efficiency of federated (or decentralized) ML systems can be significantly optimized.

Green ICT via Quantum Computing: Quantum computing technology promises an exponential speedup to potentially solve problems that are intractable via classical computing technology. In early developments, imperfect implementation of hardware lead to noisy and intermediate-scale quantum (NISQ) limited by quantum noise [15]. Nevertheless, NISQ devices can still achieve an exponential speedup over classical computing technology, as demonstrated by the quantum topological data analysis algorithm proposed by Ubaru *et al.* [16]. It would be interesting but very challenging to leverage the computing power of NISQ devices to design green ICTs with a similar speedup property. More specifically, optimized radio resource allocation for green wireless communications often suffer from the curse of dimensionality and becomes intractable with conventional computation technology. Empowered by the quantum computing technology, Grover's algorithm can improve the allocation efficiency of radio resources. However, the searching space in classical domain needs to be encoded into quantum space, and the optimal decision of resource allocation should be decoded into classical domain via quantum measurement [17]. Since the quantum states collapse into pure state based on a predetermined distribution, it requires multiple measurements to obtain the optimal resource allocation in classical domain. The decoding procedure may dominate the time complexity when the searching space is large. In this case, novel decoding procedures are required to improve the decoding efficiency such that the "quantum supremacy" can be well utilized in the design of green ICTs.

Green ICT With Advanced Communication Technologies: The energy efficiency of wireless communications can also be improved with several advanced communication technologies, such as intelligent reflecting surfaces (IRSs). An IRS consists of a two-dimensional passive antenna array that can be individually configured to reflect an incident radio signal such that the composite reflected signal can be passively beam-formed for efficient communication with a desired receiver [18]. As IRSs can extend the coverage area of traditional wireless infrastructure at little additional energy cost, IRS communications is an emerging research area for green ICT, which deserves in-depth investigation.

The research community has contributed significant efforts to greening of ICTs by exploiting different state-of-the-art methodologies, such as advanced communication techniques, control theory, machine learning, quantum computing, and game theory. We envision that in the future powerful tools from different disciplines will be tightly coupled to maximize the efficiency of resource utilization for green ICTs. For example, powerful quantum mechanics and machine learning algorithms can be leveraged to solve energy-efficient resource allocation problems with combinatorial characteristics. Following the global requirement towards carbon neutrality, greening technologies will need to be incorporated in the design, manufacture, deployment, and maintenance of future ICT systems.

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References

[1] "Reports on the increasing energy consumption of wireless systems and digital ecosystem." [Online]. Available: https://ddl.ink/Bi79 (Accessed: Oct. 2021).

[2] D. D. Johnson. (Oct. 2018). "The 5G dilemma: More base stations, more antennas-less energy?" [Online]. Available: https://spectrum.ieee.org/energywise/telecom/wireless/will-increasedenergy-consumption-be-the-achilles-heel-of-5g-networks

[3] J. Malmodin, Å. Moberg, D. Lundén, G. Finnveden, and N. Lövehagen, "Greenhouse gas emissions and operational electricity use in the ICT and entertainment & media sectors," *J. Ind. Ecol.*, vol. 14, no. 5, pp. 770–790, 2010.

[4] S. Lange, J. Pohl, and T. Santarius, "Digitalization and energy consumption. Does ICT reduce energy demand?" *Ecol. Econ.*, vol. 176, Oct. 2020, Art. no. 106760.

[5] "SMART 2020: Enabling the low carbon economy in the information age." [Online]. Available: https://ddl.ink/hNT7 (Accessed: Oct. 2020).

[6] S. P. Raja, "Green computing and carbon footprint management in the IT sectors," *IEEE Trans. Computat. Social Syst.*, vol. 8, no. 5, pp. 1172–1177, Oct. 2021.

[7] S. L. Fong, V. Y. Tan, and A. Özgür, "On achievable rates of AWGN energy-harvesting channels with block energy arrival and non-vanishing error probabilities," *IEEE Trans. Inf. Theory*, vol. 64, no. 3, pp. 2038–2064, Mar. 2018.

[8] "Sustainability report 2017." Huawei. [Online]. Available: http://topurl.cn/8LU (Accessed: Oct. 2021).

[9] Y. Dong, M. J. Hossain, J. Cheng, and V. C. M. Leung, "Cross-layer scheduling and beamforming in smart-grid powered cellular networks with heterogeneous energy coordination," *IEEE Trans. Commun.*, vol. 68, no. 5, pp. 2711–2725, May 2020.

[10] "Microsoft plumbs ocean's depths to test underwater data center." [Online]. Available: http://topurl.cn/8NF (Accessed: Oct. 2020).

[11] M. Floridia, D. Laganà, C. Mastroianni, M. Meo, and D. Renga, "Load management with predictions of solar energy production for cloud data centers," in *Proc. IEEE ICASSP*, 2020, pp. 8986–8990.

[12] J. Tang *et al.*, "Energy minimization in D2D-assisted cache-enabled Internet of Things: A deep reinforcement learning approach," *IEEE Trans. Ind. Informat.*, vol. 16, no. 8, pp. 5412–5423, Aug. 2020.

[13] Q. Zeng, Y. Du, K. Huang, and K. K. Leung, "Energy-efficient resource management for federated edge learning with CPU-GPU heterogeneous computing," *IEEE Trans. Wireless Commun.*, early access, Jun. 21, 2021, doi: 10.1109/TWC.2021.3088910.

[14] M. M. Amiri and D. Gündüz, "Machine learning at the wireless edge: Distributed stochastic gradient descent over-the-air," *IEEE Trans Signal Process*, vol. 68, pp. 2155–2169, Mar. 2020.

[15] L. Banchi, J. Pereira, S. Lloyd, and S. Pirandola, "Convex optimization of programmable quantum computers," *NPJ Quantum Inf.*, vol. 6, no. 1, pp. 1–10, May 2020.

[16] S. Ubaru, I. Y. Akhalwaya, M. S. Squillante, K. L. Clarkson, and L. Horesh, "Quantum topological data analysis with linear depth and exponential speedup," Aug. 2021, *arXiv:2108.02811*.

[17] P. Lin, Q. Song, D. Wang, F. R. Yu, L. Guo, and V. C. M. Leung, "Resource management for pervasive-edge-computing-assisted wireless VR streaming in industrial Internet of Things," *IEEE Trans. Ind. Informat.*, vol. 17, no. 11, pp. 7607–7617, Nov. 2021.

[18] C. Huang *et al.*, "Holographic MIMO surfaces for 6G wireless networks: Opportunities, challenges, and trends," *IEEE Wireless Commun.*, vol. 27, no. 5, pp. 118–125, Oct. 2020.

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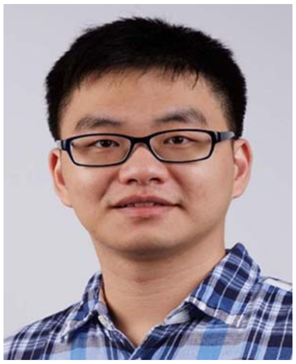

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