

Guest Editorial

Special Issue on Next Generation Multiple Access—Part II

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I. INTRODUCTION

AS the long-term evolution (LTE) system is reaching maturity and the fifth-generation (5G) systems are being commercially deployed, researchers have turned their attention to the development of next-generation wireless networks. Compared to current wireless networks, on the one hand, next-generation wireless networks are expected to achieve significantly higher capacity, extremely low latency, ultra-high reliability, as well as massive and ubiquitous connectivity for supporting diverse disruptive applications (e.g., virtual reality (VR), augmented reality (AR), and industry 4.0). On the other hand, the evolution toward next-generation wireless networks requires a paradigm shift from the communication-oriented design to a multi-functional design, including communication, sensing, imaging, computing, and localization. Looking back at the history of wireless communication systems, multiple access (MA) techniques have been key enablers. From the first generation (1G) to the fifth generation (5G), orthogonal multiple access (OMA) schemes are mainly employed, where multiple users are allotted in orthogonal frequency/time/code resources, and the uplink transmission of the code code-division multiple-access (CDMA) uses non-orthogonal code resources. However, given the enormous challenges and diverse services of next-generation wireless networks, which

significantly differ from that in current and previous wireless networks, existing MA schemes may not be applicable. As a result, a fundamental issue is the design of next-generation multiple access (NGMA) techniques. The key concept of NGMA is to enable a very large number of users/devices to be efficiently, flexibly, and intelligently connected with the network over the given wireless radio resources to not only satisfy stringent communication requirements but also realize heterogeneous functions. The investigation of NGMA is still in the infancy stage, and extensive research efforts have to be devoted to areas, including but not limited to 1) the development of new MA schemes, such as non-orthogonal multiple access (NOMA) and space division multiple access (SDMA), which are capable of achieving higher bandwidth efficiency and higher connectivity compared with conventional MA schemes; 2) the development of innovative techniques, such as reconfigurable metasurfaces, random access, advanced modulation, and channel coding, which are beneficial to the overall design of NGMA; and 3) the exploitation of advanced machine learning (ML) tools and big data techniques for providing effective solutions to address newly emerging NGMA problems.

This Special Issue (SI) aims to pave the way for the development of novel NGMA schemes for future wireless networks. We were very encouraged by the fact that this SI received a strong response from the research community and attracted 105 submissions. Most of them were of high quality, which allowed us to select an excellent set of papers. However, given the tight publication schedule and the limited space unfortunately, we had to reject many high-quality papers. After a rigorous review process, 41 papers were accepted for publication in a double-issue. In addition, a survey paper authored by the Guest Editors was reviewed and accepted by the team of Senior Editors of IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS. The first part of this double issue contains the survey paper and 20 technical papers, and the second part includes the remaining 21 technical papers. These papers cover a wide range of topics in the area of NGMA.

The 20 papers included in this issue are in the areas of 1) information-theoretic aspects of NGMA, 2) massive multiple access, 3) machine learning for NGMA, and 4) NGMA meets others. A brief account of each of these papers is given below.

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II. INFORMATION-THEORETIC STUDIES ON NGMA

In [A1], Jiang and Yu explore the interference nulling capability of reconfigurable intelligent surface (RIS) in a K -user interference channel. When the channels between the RIS and the transceivers have line-of-sight and the direct channels are blocked, it is theoretically proved that the RIS phase shifts can be adjusted to completely null out the interference and achieve the maximum K degrees-of-freedom, when the number of RIS elements is larger than a finite value that only depends on K . On the other hand, for arbitrary channel realization, an alternating projection algorithm with local convergence guarantee is developed for nulling the interference, which is numerically shown to achieve interference nulling if the number of RIS elements is slightly larger than $2K(K - 1)$. Moreover, low-complexity algorithms are proposed for the sum-rate maximization problem and the minimum rate maximization problem.

In [A2], Xu *et al.* study the secrecy achievable rate region of multiple-access wiretap (MAC-WT) channels, where users transmit both confidential messages and open messages to the legitimate user. First, an achievable rate region for the discrete memoryless (DM) MAC-WT channel is characterized based on random coding, which is then extended to the Gaussian vector (GV) MAC-WT channel. Based on these results, a sum secrecy rate maximization problem is studied, for which an iterative algorithm is proposed to find a suboptimal solution. Simulation results show that the proposed algorithm is able to achieve significantly enhanced performance compared to existing schemes while simultaneously increasing the spectral efficiency due to the transmission of open messages.

III. MASSIVE MULTIPLE ACCESS

In [A3], Wang *et al.* investigate the activity detection and channel estimation in a cell-free Internet-of-Things (IoT) network with massive random access. A two-stage approach is proposed, where the activity of each device is jointly detected by its adjacent access points (APs) based on vector approximate message passing (AMP) in the first stage, while each AP re-estimates the channels using the linear minimum mean square error (LMMSE) method in the second stage. Closed-form expressions for the activity detection error probability and mean-squared channel estimation error for a typical device are derived, followed by a coverage probability analysis of the entire network. Simulation results validate the analytical results and effectiveness of the proposed approach.

In [A4], Fang *et al.* aim to reduce the energy consumption and age-of-information (AoI) in an energy harvesting aided massive multiple access network. Two sleep-scheduling policies based on multiple vacation or start-up threshold are considered, for which the peak AoI is derived in closed form. Moreover, an average peak AoI minimization problem is studied under the energy harvesting power constraint as well as the status update rate and stability conditions. The optimal solution is found via an exact linear search-based algorithm. Simulation results show that the proposed scheme achieves a lower peak AoI with low power consumption.

In [A5], Huang *et al.* aim to jointly detect the user activity and the desired data in a noncoherent massive random

access system. First, a generalized approximate message passing (GAMP)-based algorithm is proposed, by exploiting the exact distribution information of the received signal. Then, a model-driven deep learning method is devised by utilizing deep neural networks (DNNs). Simulation results show that the GAMP-based algorithm is preferable for perfectly known channel distribution, while the deep learning method achieves better performance for imperfect channel distribution information.

In [A6], Li *et al.* aim to minimize the average queuing delay in a massive access system by applying cross-layer scheduling with joint channel and buffer awareness. An optimal cocktail filling policy and a suboptimal good-channel-first-serve (GCFS) policy are proposed, for which the performance in terms of the average delay and the queue-length-violation probability is evaluated by leveraging a mean-field approximation method. Moreover, it is shown that a complex massive user system can be decomposed into multiple single-user systems, for which the queue length distribution can be analyzed via a Markov chain model. Numerical results validate the accuracy of the mean-field approximation.

In [A7], Qiao *et al.* considered a massive IoT access system where an unmanned aerial vehicle (UAV) serves as an aerial base station (BS). A grant-free non-coherent index-modulation (NC-IM) scheme is studied, where information is modulated in the index of the transmitted signature sequence of the active devices. For the case where the UAV is equipped with a small-scale antenna array, a joint activity and blind information detection (JABID) algorithm is proposed, which is computationally efficient and achieves improved detection performance; while for the case where the UAV is equipped with a large-scale antenna array, an angular-domain based JABID algorithm is proposed. The proposed algorithms are numerically shown to outperform known state-of-the-art algorithms.

In [A8], Liu and Wang investigate the unsourced multiple access (UMA) scheme in multiple-input multiple-output (MIMO) channels. A transmission scheme based on the sparse Tanner graph is proposed, together with three iterative receiver algorithms each detecting and decoding a different number of codewords in each iteration. An asymptotic upper bound on the maximum achievable rate is derived via density evolution analysis for the Tanner graphs. Simulation results show that the proposed schemes outperform the existing compressed sensing-based UMA schemes, yet with lower receiver complexity.

In [A9], Fengler *et al.* study the unsourced random access problem over a Rayleigh block-fading additive white Gaussian noise (AWGN) channel with multiple receive antennas. An approach to split the user messages into two parts is proposed, one coded with a “pilot” codebook and the other encoded by a standard block code. The receiver applies the multiple measurement vector approximate message passing (MMV-AMP) algorithm for channel estimation from the “pilot” part, and then decodes the second part based on the estimated channels. The performance of the proposed scheme is analyzed, and the impact of power control is investigated.

In [A10], Li *et al.* studied joint device activity detection, channel estimation, and data decoding design in a MIMO massive unsourced random access (URA) system. The data

is split into two parts: one coded by compressed sensing and the rest by a low-density-parity check (LDPC) code. A low-complexity iterative message-passing algorithm is proposed for decoding the data in the compressed sensing phase and the LDPC phase separately. Moreover, a collision resolution protocol is developed to handle the codeword collision. It is shown that the proposed algorithm exhibits substantial performance improvement over the state-of-the-art algorithms.

IV. MACHINE LEARNING FOR NGMA

In [A11], Yue *et al.* developed a federated meta-learning (FML) algorithm with a non-uniform device selection scheme (called NUFM) to accelerate the convergence of conventional FML algorithms in edge learning. Specifically, NUFM maximizes the theoretical lower bound of global loss reduction in each round. Then, a device selection and resource allocation strategy is proposed to optimize the tradeoff between energy consumption and wall-clock training time. Simulation results show that the proposed algorithms outperform the baseline algorithms.

In [A12], Cao *et al.* study an over-the-air federated averaging (Air-FedAvg) system with multiple edge devices and one edge server. First, the optimality gap of the loss function over different outer iterations is analyzed to characterize the impact of the over-the-air computing error on the Air-FedAvg performance. Then, the transmission power control is optimized to minimize the optimality gap. Moreover, the training latency minimization problem is studied via joint power control and hyper-parameter optimization. Numerical results validate the learning performance gain in Air-FedAvg achieved by power control optimization.

In [A13], Guo *et al.* propose an efficient medium access control (MAC) protocol for NGMA. Specifically, a QMIX-advanced listen-before-talk (QLBT) protocol is proposed based on the multi-agent reinforcement learning (MARL) algorithm, which employs centralized training with decentralized execution to improve network throughput, delay, and jitter. Simulation results show that QLBT outperforms several competing protocols in Poisson and VoIP traffic.

V. NGMA MEETS OTHERS

In [A14], Fu *et al.* study the average latency minimization problem in a cache-assisted NOMA network, where the content cache placement, personalized recommendation, NOMA user pairing, and power control strategies are jointly optimized. A divide-and-rule method is proposed to deal with this problem, where the user pairing and power allocation are optimized in the short term, while recommendation and caching are optimized in the long term. Monte-Carlo simulations show the superiority of the proposed algorithm in terms of latency and cache hit ratio compared to various benchmark schemes.

In [A15], Xiao *et al.* propose a novel transcoding-enabled VR video caching and delivery framework for edge-enhanced next-generation wireless networks. To alleviate the viewer motion sickness and improve the quality-of-experience (QoE), an edge cooperative caching strategy and a two-tier BS-multicast group matching algorithm are proposed. It is shown via experiments that the proposed solution achieves improved cache hit rate and latency compared to other state-of-the-art alternative solutions.

In [A16], Shahsavari *et al.* considered single-cell in-band full-duplex (FD) communications. Opportunistic user scheduling and mode selection for system utility (e.g., sum-rate) maximization are studied under short-term and long-term temporal fairness constraints for both single-carrier and multi-carrier systems. Optimal temporal fair schedulers called threshold-based strategies and practical low-complexity online algorithms are proposed, whose effectiveness is validated via simulation results.

In [A17], Huang *et al.* investigated the task management among a large number of workers with scattered computing power. Specifically, it proposes a two-stage multi-task allocation method based on discrete particle swarm optimization (TMA-DPSO), which increases the workers' income and potentially improves security and fault tolerance compared to previous methods. Extensive experiments are conducted based on synthetic and real-life data sets, where the results show that TMA-DPSO can achieve higher search efficiency and stable optimization performance.

In [A18], Hashida *et al.* considered an intelligent reflecting surface (IRS)-aided multibeam transmission scenario with user mobility and proposes a user-IRS association strategy aiming to optimize the long-term performance in terms of capacity and reliability. The proposed strategy reduces the channel estimation overhead by exploiting the beam tracking technique. Simulation results show that the proposed adaptive association strategy achieves improved performance compared to a static association strategy.

In [A19], Wang *et al.* provided a practical solution to multi-frequency access for magnetic induction (MI)-based transmissions. Specifically, a multi-frequency resonating compensation (MuReC) coil-based multi-band MIMO simultaneous wireless information and power transfer (SWIPT) system is developed, which can generate multiple resonant frequencies with only one coil. Based on this, the magnetic beamforming problem for transmit power minimization is studied. Numerical results demonstrate the effectiveness of the proposed scheme in supporting multi-frequency access.

In [A20], Li *et al.* propose a novel frequency-domain multiple access scheme, termed as rainbow-link, which serves a large number of narrowband users by exploiting wideband spectrum at the millimeter-wave band. Specifically, the frequency resources are mapped to specific spatial directions such that the users can be assigned with a subset of orthogonal frequency division multiple access (OFDMA) subcarriers and enjoy the beamforming gain of the entire array. Rainbow-link supports grant-free random access without the need of explicit beam-training, which is thus a promising candidate for latency-critical applications in future massive connectivity systems. Simulation results validate the analytical findings and demonstrate the great potential of the rainbow-link technique.

In [A21], Xing *et al.* investigate visible light communication (VLC) broadcast systems, where the rate-splitting multiple access (RSMA) technique is employed to compensate for the limited modulation bandwidth of the light-emitting diodes (LEDs). The precoding and power allocation optimization problem for energy efficiency maximization is studied for both single-cell and multi-cell networks, under the dynamic operation range constraints of LEDs, quality-of-service (QoS)

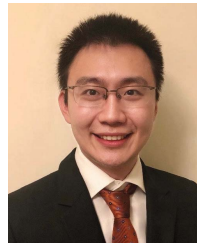
constraints, and interference elimination constraints. To handle the considered non-convex problems, successive convex approximation (SCA) based algorithms are developed. Extensive simulation results show that the proposed schemes outperform various benchmark schemes in terms of energy efficiency.

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APPENDIX: RELATED ARTICLES

- [A1] T. Jiang and W. Yu, "Interference nulling using reconfigurable intelligent surface," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 5, pp. 1392–1406, May 2022.
- [A2] H. Xu, T. Yang, K.-K. Wong, and G. Caire, "Achievable regions and precoder designs for the multiple access wiretap channels with confidential and open messages," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 5, pp. 1407–1427, May 2022.
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- [A8] J. Liu and X. Wang, "Unsourced multiple access based on sparse Tanner graph-efficient decoding, analysis, and optimization," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 5, pp. 1509–1521, May 2022.
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- [A12] X. Cao, G. Zhu, J. Xu, and S. Cui, "Transmission power control for over-the-air federated averaging at network edge," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 5, pp. 1571–1586, May 2022.
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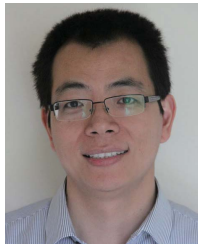
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