Guest Editorial Special Issue on Next Generation Multiple Access—Part I

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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.

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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 articles. However, given the tight publication schedule and the limited space unfortunately, we had to reject many high-quality articles. After a rigorous review process, 41 articles were accepted for publication in a double-issue. In addition, a survey article 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 article and 20 technical articles, and the second part includes the remaining 21 technical articles. These articles cover a wide range of topics in the area of NGMA.

The first part starts with the survey article [A1] from the Guest Editors. It explores the evolution of NGMA with a particular focus on NOMA, i.e., the transition from NOMA to NGMA. In particular, this article first reviews the fundamental information-theoretic capacity limits of NOMA and discusses new requirements and possible candidates for NGMA. Then, a comprehensive overview of the state-of-the-art research contributions on NOMA is provided, including multi-antenna techniques for NOMA, promising future application scenarios for NOMA, the interplay between NOMA and other emerging physical layer techniques, and advanced mathematical optimization and machine learning tools for NOMA. Moreover, this article proposes a multi-antenna and NOMA-based unified framework for NGMA for downlink and uplink transmission with the objective to promote new research opportunities, and finally highlights several practical implementation challenges for NGMA.

The 20 articles included in this issue are in the areas of 1) coding, modulation, and detection for NGMA; 2) resource management for NGMA; 3) NGMA design with reconfigurable metasufaces; and 4) new scenarios and requirements for NGMA. A brief account of each of these articles is given below.

II. Coding, Modulation, and Detection for NGMA

In [A2], Pei *et al.* propose a spatial modulation-inspired power-domain NOMA transmission scheme, where extra information bits are encoded into the power levels, namely, power selection (PS)-NOMA. Based on a downlink two-user NOMA system, the closed-form approximate bit error ratio (BER) expressions for both users are derived and the corresponding achievable rate region is characterized. It is shown that the proposed PS-NOMA achieves lower BER and higher rate compared to the traditional NOMA.

In [A3], Wang *et al.* investigate multiuser multi-channel NOMA systems based on quadrature amplitude modulation (QAM) and imperfect successive interference cancellation (SIC). A new performance metric is considered for performance evaluation, namely, effective throughput, which is determined by the data rate and the symbol error rate. Then, a joint power allocation, channel assignment, and modulation selection problem is formulated for maximizing the effective throughput, which is efficiently solved by employing analysis, matching theory, and machine learning techniques. The simulation results verify the effectiveness of the proposed algorithm for NOMA.

In [A4], Wang *et al.* investigate the design of asynchronous NOMA detection in satellite high-mobility communications. A 3-D factor graph framework is proposed, where the high Doppler frequency offsets and Doppler rates of heterogeneous high-mobility terminals are considered in the received signal. Then, a turbo-iterative asynchronous NOMA detection algorithm is developed, which consists of the interference cancellation loop, the Doppler elimination loop, and the decoding loop. The numerical results show that the proposed algorithm can achieve better BER performance with less computational complexity compared to existing algorithms.

In [A5], Han *et al.* propose a two-stage approach for detecting sparse signals in MIMO systems with low complexity. In the first stage, the received signals are divided into different groups and the active groups are decided by employing the coordinate ascent variational inference algorithm. In the second stage, the signals associated with inactive groups are removed and sparse signal detection is carried out among the signals within the active groups. The numerical results show that the proposed two-stage approach is superior to the conventional compressive sensing-based approaches.

In [A6], Li *et al.* propose a Faster-than-Nyquist (FTN) signaling-aided asynchronous NOMA transmission scheme, where the achievable rate is quantified in the presence of random link delays of the different users. It is revealed that the link delay difference between different users can be exploited for enhancing the signal-to-interference-plus-noise ratio (SINR) and a degree-of-freedom (DoF) gain can be attained using FTN signaling. Moreover, the fundamental trade-off between the SINR gain and DoF gain is studied. The simulation results verify the correctness of the analytical results and show a significant performance gain of the asynchronous FTN-NOMA over the perfectly synchronous NOMA.

In [A7], Che *et al.* propose a novel unsourced random access (URA) scheme based on beam-space tree decoding, with the aim of supporting massive machine-type communication (mMTC) in millimeter-wave massive multiple-input multiple-output (MIMO) systems. By exploiting the beam division property, the beam-space tree decoders are developed by employing hard and soft decisions, respectively. It is shown that the hard decision-based decoder has lower complexity and the soft decision-based decoder is capable of recovering the miss-detected packets. The numerical results demonstrate that the two proposed URA schemes outperform the conventional URA schemes in terms of error probability.

III. Resource Management for NGMA

In [A8], Rezvani *et al.* study the globally optimal power allocation strategies for maximizing the sum rate (SR) and the energy efficiency (EE) in downlink single-cell multi-carrier NOMA (MC-NOMA) systems. It is first shown that the MC-NOMA system can be equivalently transformed to a virtual orthogonal multiple access (OMA) system. By exploiting this insight, a closed-form expression for the intra-cluster power allocation is obtained. Moreover, the SR and EE maximization problems can be efficiently solved using waterfilling and Dinkelbach algorithms, respectively, with low computational complexity. Extensive numerical results verify the performance gain of MC-NOMA over single-carrier NOMA (SC-NOMA) and OMA.

In [A9], Zhu *et al.* investigate distributed resource optimization strategies for NOMA-enabled multi-gateway satellite communication (SATCOM) systems. A distributed user scheduling scheme is first proposed for determining the NOMA groups. Then, a centralized beamforming design using the full channel state information (CSI) and a distributed beamforming design using local CSI are developed to maximize the worst-user signal-to-leakage-and-noise ratio (SLNR). Finally, the power allocation among users for each beamforming vector is designed with the aim of maximizing the weighted sum rate of all scheduled users. The numerical results show that the proposed algorithm can well guarantee user rate fairness and enhance spectrum efficiency.

In [A10], Zhang *et al.* investigate an uplink non-orthogonal multiple access (NOMA) terrestrial-satellite network. A utility function is first designed by jointly considering the achieved terrestrial user rate and cross-tier interference caused by terrestrial BSs to satellites. Then, a resource allocation problem is formulated for the maximization of the utility function by jointly optimizing the UE association, bandwidth assignment, and power allocation. To solve this non-convex problem, a three-stage algorithm is developed to iteratively solve the decomposed subproblems. Numerical results show the convergence and effectiveness of the proposed algorithm.

In [A11], Liu *et al.* propose a novel learning framework for multiple configured-grants grant-free NOMA systems for massive ultra-reliable and low-latency communication (mURLLC) service to users with bursty traffic under a latency constraint. A resource configuration problem is formulated for maximizing the long-term sum rate, subject to a constraint on the available resources, latency requirements, and reliability. To solve this challenging problem, a cooperative multi-agent learning technique based double deep Q-network algorithm is proposed. The numerical results show that the proposed framework can achieve lower latency and higher reliability performances than benchmark schemes.

In [A12], Mei *et al.* propose a multi-dimensional multiple access (MDMA) protocol to meet the quality-of-service (QoS) demand of users in a cost-efficient manner. The proposed MDMA protocol consists of two stages, namely, cost-aware selection of multiple access mode and situation-aware multi-dimensional radio resource allocation of users. For the first stage, a UE coalition formation algorithm is designed based on a two-sided many-to-one matching theory, which determines the multiple access mode employed at each user. For the second stage, the resulting resource allocation problem is solved by employing successive convex approximation and Lagrange dual decomposition methods. The simulation results show that the proposed MDMA scheme significantly outperforms state-of-the-art schemes in terms of both the users' QoS performance and multi-dimensional radio resource utilization cost.

IV. NGMA Meets Reconfigurable Metasurfaces

In [A13], Cao *et al.* investigate a novel multiple-RIS-aided multiple access design for simultaneously serving static and mobile users. To coordinate the communication between static and mobile users, a medium access control (MAC) protocol is designed for incorporating the RIS configuration. Based on the proposed framework and the MAC protocol, a throughput maximization problem is formulated by jointly optimizing the MAC protocol parameters and the RIS configuration parameters, which is solved by an iterative algorithm. It is shown that the proposed scheme achieves better access fairness and system throughput compared to benchmark schemes.

In [A14], Elhattab *et al.* study a multi-user two-cell joint-transmission coordinated multipoint (JT-CoMP) network, where RISs and NOMA are employed. The RISs are deployed at the edge of two cells to enhance the performance of cell-edge NOMA users. This article aims to maximize the sum rate by jointly optimizing the power allocation coefficients at the BS, the user clustering policy, and the phase shifts of RISs. An alternating optimization algorithm is proposed, where each type of optimization variable is optimized by invoking the bi-level optimization approach, the Hungarian method, and the successive convex approximation technique. The numerical results show that the proposed RIS-assisted CoMP NOMA outperforms conventional CoMP NOMA without RISs, RIS-assisted CoMP OMA, and RIS-assisted NOMA.

In [A15], Zhao *et al.* investigate air-to-ground uplink NOMA transmission assisted by RISs, where unmanned aerial vehicle (UAV) users and ground users communicate with the BS via the uplink NOMA protocol. By considering the collision avoidance mechanism, a network sum rate maximization problem is formulated by jointly optimizing the UAV trajectory design, RIS configuration, and power control. A sample-efficient deep reinforcement learning (DRL) algorithm is proposed, followed by a distributionally robust DRL algorithm to guarantee the worst-case performance when the locations of the obstacles are uncertain. The numerical results demonstrate that the proposed DRL algorithm has better learning efficiency and robustness than conventional ones, and the proposed RIS-NOMA significantly improves the network sum rate.

In [A16], Chen *et al.* propose a novel intelligent reconfigurable surface (IRS)-assisted semi-grant-free (SGF) NOMA transmission scheme. To maximize the long-term data rate, the authors investigate dynamic optimization by jointly considering the sub-carrier assignment, power allocation of users, and the amplitude control and phase shift of the IRSs. More specifically, a multi-agent Markov decision problem is first modeled and the machine learning algorithms are then employed. In particular, the deep Q-network (DQN) and the deep deterministic policy gradient (DDPG) are used for sub-carrier assignment and power allocation, respectively. In addition, two DDPGs are exploited to jointly optimize the amplitude and phase shifts of the IRSs. This article also compares the performance considering different types of IRS elements. Simulation results demonstrate that employing IRS can significantly enhance the network sum rate and the NOMA-assisted SGF transmission outperforms the OMA-assisted GF transmission.

In [A17], Deng *et al.* propose a new type of multiple access design called holographic pattern division multiple access (HDMA), which is based on space-division multiple access (SDMA) and developed with the main idea of mapping the signals intended for the receivers to a superposed holographic pattern of the reconfigurable holographic surface (RHS). Based on this, a multi-user holographic beamforming scheme is designed and theoretical analysis is carried out to demonstrate the benefits of HDMA in improving the system capacity. The simulation results verify the correctness of the theoretical analysis and show that HDMA outperforms SDMA in terms of capacity and the maximum number of served users.

V. New Scenarios and Requirements for NGMA

In [A18], Yin *et al.* propose a novel multiple access design called multi-scale NOMA (MS-NOMA) for next-generation communication-positioning integration systems. The key concept is to superimpose a low-power positioning signal on the communication signal following the NOMA principle with the aim of achieving high-range accuracy with low resource consumption. Based on this framework, the BER for communication, the ranging accuracy for positioning, and the resource consumption are analyzed, which reveals the great potential of MS-NOMA. Then, a multi-user power allocation problem for maximizing the positioning accuracy is formulated subject to communication requirements and solved by the developed algorithm. Numerical results show that MS-NOMA outperforms a conventional scheme in terms of both positioning accuracy and communication coverage.

In [A19], Khorov *et al.* investigate the application of NOMA in Wi-Fi systems considering the phase noise caused by hardware imperfections. To reduce the impact of the phase noise, the authors propose a practical, easy-to-implement, and backward-compatible method by rotating the constellation of the communication signal to enhance its robustness. Moreover, a mathematical derivation is provided to find the optimized rotation which minimizes the BER. A prototype testbed is developed to validate the performance of the proposed NOMA Wi-Fi scheme. The experimental results are provided to verify the effectiveness of the proposed method and show that the proposed constellation rotation approach can reduce the BER in high signal-to-noise scenarios.

In [A20], Xu *et al.* investigate a device-to-multi-device (D2MD)-assisted cooperative NOMA system, where cell-edge users (CEUs) and cell-center users are paired into a D2MD cluster. To enhance the spectral efficiency and the reliability of the CEU, an adaptive aggregate transmission scheme is proposed using dynamic superposition coding, pre-designing the decoding orders, and prior information cancellation. Employing the proposed scheme, the closed-form expressions for diverse performance metrics are derived over Nakagami-m fading channels with imperfect SIC. The simulation results verify the correctness of the analytical results and show the significant performance gain of the proposed scheme over the conventional D2D scheme.

In [A21], Xie *et al.* propose two privacy-preserving physical-layer authentication (PLA) schemes for improving the authentication and privacy in NOMA systems. The authors provide a theoretical analysis of the proposed schemes in terms of robustness, compatibility, privacy, and security and derive corresponding closed-form expressions. A theoretical comparison between the proposed schemes and the existing schemes is also presented. The correctness of the theoretical results is validated via simulations. It is also shown that a significant performance gain can be achieved by the proposed schemes in terms of different performance metrics.

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Appendix: Related Articles

[A1] Y. Liu *et al.*, "Evolution of NOMA toward next generation multiple access (NGMA) for 6G," *IEEE J. Sel. Areas Commun.*, early access, Jan. 25, 2022, doi: 10.1109/JSAC.2022.3145234.

[A2] X. Pei, Y. Chen, M. Wen, H. Yu, E. Panayirci, and H. V. Poor, "Next-generation multiple access based on NOMA with power level modulation," *IEEE J. Sel. Areas Commun.*, early access, Jan. 14, 2022, doi: 10.1109/JSAC.2022.3143240.

[A3] Y. Wang, J. Wang, V. W. S. Wong, and X. You, "Effective throughput maximization of NOMA with practical modulations," *IEEE J. Sel. Areas Commun.*, early access, Jan. 14, 2022, doi: 10.1109/JSAC.2022.3143244.

[A4] J. Wang, C. Jiang, and L. Kuang, "Iterative NOMA detection for multiple access in satellite high-mobility communications," *IEEE J. Sel. Areas Commun.*, early access, Jan. 14, 2022, doi: 10.1109/JSAC.2022.3143254.

[A5] R. Han, L. Bai, W. Zhang, J. Liu, J. Choi, and W. Zhang, "Variational inference based sparse signal detection for next generation multiple access," *IEEE J. Sel. Areas Commun.*, early access, Jan. 14, 2022, doi: 10.1109/JSAC.2022.3143234.

[A6] S. Li *et al.*, "Faster-than-Nyquist asynchronous NOMA outperforms synchronous NOMA," *IEEE J. Sel. Areas Commun.*, early access, Jan. 14, 2022, doi: 10.1109/JSAC.2022.3143245.

[A7] J. Che, Z. Zhang, Z. Yang, X. Chen, C. Zhong, and D. W. K. Ng, "Unsourced random massive access with beam-space tree decoding," *IEEE J. Sel. Areas Commun.*, early access, Jan. 21, 2022, doi: 10.1109/JSAC.2022.3143241.

[A8] S. Rezvani, E. A. Jorswieck, R. Joda, and H. Yanikomeroglu, "Optimal power allocation in downlink multicarrier NOMA systems: Theory and fast algorithms," *IEEE J. Sel. Areas Commun.*, early access, Jan. 14, 2022, doi: 10.1109/JSAC.2022.3143237.

[A9] Y. Zhu, C. A. Hofmann, and A. Knopp, "Distributed resource optimization for NOMA transmission in beamforming SATCOM," *IEEE J. Sel. Areas Commun.*, early access, Jan. 14, 2022, doi: 10.1109/JSAC.2022.3143215.

[A10] Y. Zhang, H. Zhang, H. Zhou, K. Long, and G. K. Karagiannidis, "Resource allocation in terrestrial-satellite based next generation multiple access networks with interference cooperation," *IEEE J. Sel. Areas Commun.*, early access, Jan. 26, 2022, doi: 10.1109/JSAC.2022.3145810.

[A11] Y. Liu, Y. Deng, M. Elkashlan, A. Nallanathan, and G. K. Karagiannidis, "Optimization of grant-free NOMA with multiple configured-grants for mURLLC," *IEEE J. Sel. Areas Commun.*, early access, Jan. 21, 2022, doi: 10.1109/JSAC.2022.3143264.

[A12] J. Mei, W. Han, X. Wang, and H. V. Poor, "Multi-dimensional multiple access with resource utilization cost awareness for individualized service provisioning in 6G," *IEEE J. Sel. Areas Commun.*, early access, Jan. 26, 2022, doi: 10.1109/JSAC.2022.3145909.

[A13] X. Cao *et al.*, "Massive access of static and mobile users via reconfigurable intelligent surfaces: Protocol design and performance analysis," *IEEE J. Sel. Areas Commun.*, early access, Jan. 26, 2022, doi: 10.1109/JSAC.2022.3145908.

[A14] M. Elhattab, M. A. Arfaoui, C. Assi, and A. Ghrayeb, "RIS-assisted joint transmission in a two-cell downlink NOMA cellular system," *IEEE J. Sel. Areas Commun.*, early access, Jan. 24, 2022, doi: 10.1109/JSAC.2022.3143211.

[A15] J. Zhao, L. Yu, K. Cai, Y. Zhu, and Z. Han, "RIS-aided ground-aerial NOMA communications: A distributionally robust DRL approach," *IEEE J. Sel. Areas Commun.*, early access, Jan. 14, 2022, doi: 10.1109/JSAC.2022.3143230.

[A16] J. Chen, L. Guo, J. Jia, J. Shang, and X. Wang, "Resource allocation for IRS assisted SGF NOMA transmission: A MADRL approach," *IEEE J. Sel. Areas Commun.*, early access, Jan. 20, 2022, doi: 10.1109/JSAC.2022.3144726.

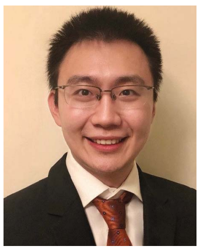
[A17] R. Deng, B. Di, H. Zhang, H. Zhang, and L. Song, "HDMA: holographic-pattern division multiple access," *IEEE J. Sel. Areas Commun.*, early access, Jan. 14, 2022, doi: 10.1109/JSAC.2022.3143221.

[A18] L. Yin, J. Cao, Q. Ni, Y. Ma, and S. Li, "Design and performance analysis of multiscale NOMA for future communication-positioning integration," *IEEE J. Sel. Areas Commun.*, early access, Jan. 14, 2022, doi: 10.1109/JSAC.2022.3143223.

[A19] E. Khorov, A. Kureev, I. Levitsky, and I. F. Akyildiz, "A phase noise resistant constellation rotation method and its experimental validation for NOMA Wi-Fi," *IEEE J. Sel. Areas Commun.*, early access, Jan. 17, 2022, doi: 10.1109/JSAC.2022.3143236.

[A20] Y. Xu, J. Tang, B. Li, N. Zhao, D. Niyato, and K.-K. Wong, "Adaptive aggregate transmission for device-to-multi-device aided cooperative NOMA networks," *IEEE J. Sel. Areas Commun.*, early access, Jan. 25, 2022, doi: 10.1109/JSAC.2022.3143267.

[A21] N. Xie, Q. Zhang, J. Chen, and H. Tan, "Privacy-preserving physical-layer authentication for non-orthogonal multiple access systems," *IEEE J. Sel. Areas Commun.*, early access, Jan. 14, 2022, doi: 10.1109/JSAC.2022.3143222.



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