Guest Editorial Special Issue on 3GPP Technologies: 5G-Advanced and Beyond

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I. Introduction and Overview

SINCE the start of 5G New Radio (NR) work in the 3rd Generation Partnership Project (3GPP) in early 2016, tremendous progress has been made in both standardization and commercial deployments. The first 5G NR release (Release 15) laid out a solid foundation in accommodating a diverse set of services, a wide range of spectra, and a variety of deployment scenarios, while being forward compatible. Expansion to vertical domain services [e.g., vehicle to everything (V2X), non-terrestrial networks (NTN)] was introduced in Release 16. Such an expansion was further accelerated in Release 17, with the standardization work being completed despite the extreme challenges due to COVID-19.

3GPP is now entering the second phase of 5G NR standardization, known as *5G-Advanced*. The first 5G NR release for 5G-Advanced is Release 18. The package of Release 18 projects was approved in December 2021, providing a good balance in terms of:

1) Balanced mobile broadband evolution versus further vertical domain expansion.
2) Balanced immediate versus longer term commercial needs.
3) Balanced device evolution versus network evolution.

In particular, in addition to immediate commercial needs, Release 18 package also contains longer-term projects, e.g., study on artificial intelligence (AI)/machine learning (ML) for NR air interface, study on evolution of NR duplex operation. These projects would provide not only a deeper understanding of the new directions and their interaction with 5G NR, paving the way for future commercialization, but also a better foundation for future standard evolution towards 6G.

While the work for Release 18 in 3GPP is well underway, there is increased attention and effort for the next releases, particularly Release 19 and the evolution towards 6G. The first 3GPP workshop on Release 19 is scheduled to happen in June 2023, with the set of Release 19 projects targeting for approval in December 2023. It is expected that Release 19 will not only continue driving the evolution for commercial deployment needs but also further explore new areas so that Release 19 may serve as a bridge between 5G-Advanced and the upcoming 6G in 3GPP. While it is too early to predict when 6G will be initiated in 3GPP, it is envisioned that the timeline for 6G in 3GPP is to be decided through the usual contribution-driven and consensus-based process, so that 3GPP can develop an input to the International Mobile Telecommunications (IMT)—2030 process in a timely manner.

The goal of this Special Issue is to provide a comprehensive presentation of the state-of-the-art findings including technology, theory, design, optimization, and applications of 5G-Advanced, potentially shaping the future evolution of 5G NR in 3GPP and beyond. The Special Issue attracted 81 quality submissions from both academia and industry. All papers have been carefully reviewed by anonymous reviewers and guest editors, many of them with more than one round of revisions.

The tutorial paper [A1] written by the guest editorial team provides an overview of a wide range of technical enablers for 5G-Advanced, e.g., massive multiple input multiple output (MIMO), positioning, topological enhancements, extended reality (XR), sidelink, AI/ML, duplexing, and energy efficient operations. The overview for each topic covers not only the standard development in 3GPP but also the research output and directions from the academia. In addition, it presents several additional 6G aspects, including spectrum evolution, joint communication and sensing, and hyper-distributed and innovative services.

Similar to the tutorial paper, the rest of the papers included in this Special Issue are grouped into the following areas: massive MIMO evolution, positioning evolution, topological evolution, XR evolution, AI/ML evolution, energy efficiency evolution, and other aspects. Each of the papers in the respective area is summarized accordingly.

II. Massive MIMO Evolution

Massive MIMO is a crucial physical-layer technique for 5G and beyond-5G wireless communications, which can significantly enhance spectral efficiency, coverage, and localization capability, among others. Associated with massive MIMO are

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some practical deployment challenges as well as a diversity of evolution directions.

In [A2], Cao et al. focus on cell-free massive MIMO and propose a group-based fast over-the-air (OTA) reciprocity calibration scheme with a genetic algorithm-aided remote radio unit (RRU) grouping and a 5G NR compatible calibration reference signal. Furthermore, a cell-free massive MIMO prototype platform is developed based on 5G commercial off-the-shelf RRUs, which demonstrates the statistical characteristics of the calibration error and the effectiveness of the calibration algorithm.

In [A3], Jin et al. provide an overview of the evolution of standardized massive MIMO features from 3GPP Release 15 to 17 for both time and frequency-division duplex operation, analyze the progress on channel state information (CSI) frameworks and beam management frameworks, present enhancements for uplink CSI, and discuss emerging 3GPP Release 18 problems requiring imminent attention. System-level simulation results are provided for each concept to highlight their performance benefits. Moreover, field trials in an outdoor environment are also conducted to demonstrate the gains of multiple transmission/reception points (multi-TRP) coherent joint transmission relative to a single TRP at 3.7 GHz.

In [A4], Tedeschini et al. investigate non-line-of-sight (NLOS) identification from channel impulse response data collected in millimeter-wave (mmWave) massive MIMO systems and propose a deep auto-encoding kernel density model to characterize the statistics of the channel latent features. The proposed solution is validated in a 5G urban micro vehicular scenario, and the proposed model is shown to significantly outperform conventional algorithms and obtain similar performances to variational Bayes algorithms at one-tenth of the inference time.

III. Positioning Evolution

Positioning is a critical aspect of 5G networks as it enables a variety of use cases that require accurate location information, including location-based services such as navigation, asset tracking, and location-based advertising.

Uncrewed aerial vehicles (UAVs) are increasingly used in many civilian and industrial applications, from delivery services to aerial surveying. Cellular-connected UAVs can exploit the wide-area coverage and high-precision positioning capabilities of 5G networks to expand their operations. In [A5], the authors investigate cellular-connected UAV positioning in challenging urban scenarios where interference and multipath effects must be considered. The paper tackles the problem by constructing channel amplitude-phase response (CAPR) images to characterize the cellular channel and proposing a deep learning model that utilizes the multipath features learned from the CAPR images. The presented experimental results demonstrate the positioning accuracy of the proposed method.

Complex wireless environments such as indoor factories usually have severe multipath propagation and NLOS conditions, making it difficult to obtain accurate localization information. In [A6], the authors introduce the concept of blockage intelligence to provide a probabilistic description of wireless propagation conditions. The introduced blockage intelligence concept is then integrated into conventional and soft information-based localization algorithms. Several case studies are conducted in the 3GPP indoor factory scenario using various base station (BS) deployments to show the benefits of using blockage intelligence in obtaining accurate localization in 5G networks.

IV. Topological Evolution

Topological evolution is a critical component for 5G and beyond with respect to performance enhancements such as capacity, coverage, and power consumption.

In the first paper [A7] in this section, Ying et al. study the random access problem in massive MIMO-based low-earth orbit (LEO) satellite systems, considering the multi-satellite cooperative processing mechanism. A training sequence padded frame structure is first proposed to perform multi-path interference cancellation and joint activity detection and channel estimation (JADCE) in the access procedure. Different algorithms are used for JADCE at LEO satellites. Furthermore, a diversity transmission scheme is adopted to address the adverse terrestrial-satellite link circumstances. Simulation results show better performance in both perfect backhaul and quantized backhaul scenarios for quasi-synchronous random access satellite systems.

In [A8], a semi-grant-free (SGF) based transmission strategy is investigated to provide flexible connectivity for various types of users in an integrated satellite–aerial–terrestrial network (ISATN), where a high-altitude platform serves multiple mobile terminals and aims to access a satellite network with multiple earth stations simultaneously. Two SGF-based uplink transmission schemes are proposed for both perfect CSI and imperfect CSI cases. Then, closed-form throughput expressions are presented to evaluate the performance of the considered ISATN with the proposed two SGF-based schemes. Numerical evaluations are conducted to validate the theoretical performance analysis and show the superiority of the proposed schemes over the related works, demonstrating satisfactory performance of the proposed SGF-based scheme using imperfect CSI, while also revealing the impact of CSI errors on the system performance.

The last paper [A9] in this section investigates, within the time-varying space information network consisting of satellites, how to maximize the number of completed missions with the guaranteed quality of service (QoS) (e.g., an end-to-end latency) by jointly considering virtual network functions (VNFs) deployment and flow routing strategy with the service function chain constraint, i.e., the mission flow must be processed by all VNFs in a predefined order. A low-complexity algorithm is proposed in order to effectively solve the mixed integer linear programming problem. The evaluation results are provided to demonstrate that the proposed algorithm can significantly outperform the fixed VNF deployment scheme and can realize near-optimal performance.

V. XR Evolution

5G networks are designed to support a variety of services with highly demanding QoS requirements, which opens the door for novel media applications such as XR, which is a new service with different requirements from the mobile broadband traffic. The work for XR in 3GPP covers both radio as well as system level elements and reaches even to the development of suitable audio and video codecs.

In [A10], the authors look at the service requirements and analyze different improvements being considered in 3GPP, both at the radio and at the system level. The resulting performance considers both achievable capacity and user equipment (UE) power consumption (saving) when running XR service. The requirements for the use of a split-XR framework for enabling metaverse are covered, with the split-compute XR over 5G enabling sharing of the processing load between the network and the UE. The Release 18 advances to address the XR requirements are also covered, including both radio improvements as well as system-level improvements like XR service awareness.

In [A11], Bojović et al. investigate a loopback mechanism that adapts the XR traffic to the instantaneous 5G network conditions by exploiting an XR application feedback. The evaluation results of the paper show that the proposed scheme can boost XR throughout and delay performance by adapting to the instantaneous 5G network conditions while keeping the XR QoS such as packet loss under control.

VI. AI/ML Evolution

AI/ML is becoming a pervasive approach to the design of resource allocation policies in the next-generation air interfaces. Examples of AI/ML-driven radio configuration include beam management as well as resource block allocation, modulation, and coding scheme selection.

In [A12], the authors deal with time-domain beam prediction, currently under consideration within 3GPP, including reference signal received power prediction. The proposed AI/ML solution proves to significantly reduce power consumption due to beam management at the UE, when evaluated through OTA tests using BS and UE compliant with 3GPP standards.

Scheduling at the BS is instead tackled in [A13], which considers the BS functional split in a central unit (CU) and distributed units (DUs). The meta-scheduling policy presented therein can meet various QoS requirements, air interface configurations, and the number of users. The CU sets objective-specific meta-scheduling policies, which are then applied by the DUs. Importantly, the policies at the CU can be trained using the data collected from all DUs. A critical aspect in AI/ML-driven air interfaces is indeed the training and update of ML models.

In [A14], Pervej et al. address model training in the context of vehicular networks, where an edge server trains a model with the help of connected vehicles using the federated learning paradigm. Through convergence analysis, this study underlines the importance of ensuring a successful delivery of the models locally trained at the vehicles. To this end, it aims at optimizing the radio access parameters accounting for delay, energy, and cost constraints. Furthermore, the learning process is optimized by applying efficient strategies while aggregating at the edge server the models returned by the connected vehicles.

Mobility management is another area where AI/ML can help to tackle, especially in a scenario with small cells coverage, as in the case where higher frequencies are used to have sufficient bandwidth for large data rates. In [A15], Prado et al. propose and evaluate the performance of an approach for mobility management with the use of reinforcement learning-based solutions for networks of different sizes and users with different velocities. The solution is shown to outperform the classical approach considerably in fairness and results in fewer radio link failures.

In [A16], Amiri et al. introduce a new sensing solution that can be used to represent an RF-environment taking into account practical challenges such as limited time resolution while providing robustness to wireless propagation phenomena such as diffraction. The method leverages offline data collection during RF-mapping, and finds the location of virtual anchors through an iterative process. The developed models are used to improve positioning accuracy in indoor environments.

Finally, channel estimation is addressed. In [A17], the authors introduce a downlink-based channel estimation solution with a cascaded model-based and model-free deep neural network structure. The model-based module is designed by the variational Bayesian inference technique to suppress the time-varying inter-cell interference. The model-free module is designed by the denoising sparse autoencoder structure to further refine the channel estimation. The simulation results demonstrate the benefits of the introduced strategy in a large signal-to-interference-plus-noise ratio (SINR) range.

VII. Energy Efficiency Evolution

Network energy efficiency is vital with the amount of traffic carried over wireless networks increasing continuously as well as with increasing energy costs in many markets. It is also consistent with the need to contribute to the global climate goals.

In [A18], Islam et al. provide an overview of power-saving features supported in 3GPP 5G NR and discuss potential energy-saving techniques that can be considered for Release 18 and beyond, including methods in time, frequency, power, and spatial domains to adapt the power consumption depending on the traffic needs and characteristics. The paper provides energy efficiency performance for different scenarios and compares the impact on network capacity in different load conditions.

VIII. Others

Massive machine type communication (mMTC) is one of the three main use cases for 5G networks, along with enhanced mobile broadband (eMBB) and ultra-reliable low-latency communication (URLLC). mMTC enables the connectivity of a vast number of devices while maintaining low power consumption and low cost. In this context, [A19] proposes a time–frequency warped waveform for short symbols that addresses some of the challenges faced by mMTC applications. This work extends the time-frequency warping concept to discrete Fourier transform-spread orthogonal frequency-division multiplexing (DFT-s-OFDM), resulting in a waveform well-contained in time and frequency domains. The presented simulation results demonstrate the effectiveness of the proposed waveform.

Spatial division multiple access (SDMA) utilizing angular domain is essential to improve the spectrum efficiency for multi-user MIMO communications. With the dramatically increasing number of antennas, the extremely large-scale antenna array introduces an additional resolution in the distance domain in the near field. In [A20], Wu and Dai propose the concept of location division multiple access (LDMA) for near-field communications exploiting extra spatial resources in the distance domain in addition to the angle domain. It is shown that the proposed LDMA concept can enhance spectrum efficiency significantly compared to the traditional SDMA by leveraging the near-field beam focusing property.

Specialized networks are used to provide mission-critical communications, e.g., railway communications, public safety, and smart electrical power distribution grids, and can benefit from the high reliability, low latency, and high spectral efficiency of 5G NR. The specialized networks often use dedicated spectrum allocations which are narrower than 5 MHz, the minimum bandwidth required for operating 5G NR before Release 18. In [A21], as a use case study, the authors study the co-existence of the Global System for Mobile Communications - Railway (GSM-R) and Future Railway Mobile Communication System (FRMCS) based on NR. They propose the changes needed to enable NR operation in less than 5 MHz bandwidth and evaluate the impact of the proposed changes.

In [A22], Miao et al. present channel measurements and modeling for multiple frequency bands ranging from sub-6 GHz to mmWave bands. Key channel characteristics are extracted and modeled, including path loss, shadow fading, frequency dependence of cluster features, root mean square delay spread, Ricean K-factor, and correlation properties. They propose frequency-dependent models that can be used to characterize the channels and provide insights into spectrum selection and optimization.

Acknowledgment

The Guest Editors would like to express their deep gratitude to all the authors for their submissions. Sincere appreciation goes to all the reviewers for their valuable comments and suggestions, especially considering the limited amount of review time with multiple rounds for many papers, which have contributed to the high quality of this Special Issue. In addition, the Guest Editors are very thankful for the strong support and guidance provided by the Editor-in-Chief Petar Popovski and Janine Bruttin, which are critical to the success of this Special Issue.

Appendix: Related Articles

[A1] W. Chen et al., "5G-advanced towards 6G: Past, present, and future," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 6, pp. 1592–1619, Jun. 2023.

[A2] Y. Cao, "Experimental performance evaluation of cell-free massive MIMO systems using COTS RRU with OTA reciprocity calibration and phase synchronization," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 6, pp. 1620–1634, Jun. 2023.

[A3] H. Jin et al., "Massive MIMO evolution towards 3GPP release 18," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 6, pp. 1635–1654, Jun. 2023.

[A4] B. C. Tedeschini, M. Nicoli, and M. Z. Win, "On the latent space of mmWave MIMO channels for NLOS identification in 5G-advanced systems," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 6, pp. 1655–1669, Jun. 2023.

[A5] K. Gao, H. Wang, H. Lv, and P. Gao, "A DL-based high-precision positioning method in challenging urban scenarios for B5G CCUAVs," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 6, pp. 1670–1687, Jun. 2023.

[A6] G. Torsoli, M. Win, and A. Conti, "Blockage intelligence in complex environments for beyond 5G localization," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 6, pp. 1688–1701, Jun. 2023.

[A7] K. Ying et al., "Quasi-synchronous random access for massive MIMO-based LEO satellite constellations," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 6, pp. 1702–1722, Jun. 2023.

[A8] H. Kong, M. Lin, L. Han, W.-P. Zhu, Z. Ding, and M.-S. Alouini, "Uplink multiple access with semi-grant-free transmission in integrated satellite-aerial-terrestrial networks," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 6, pp. 1723–1736, Jun. 2023.

[A9] H. Yang, W. Liu, J. Li, and T. Q. S. Quek, "Space information network with joint virtual network function deployment and flow routing strategy with QoS constraints," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 6, pp. 1737–1756, Jun. 2023.

[A10] P. Hande et al., "Extended reality over 5G-standards evolution," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 6, pp. 1757–1771, Jun. 2023.

[A11] B. Bojović, S. Lagén, K. Koutlia, X. Zhang, P. Wang, and L. Yu, "Enhancing 5G QoS management for XR traffic through XR loopback mechanism," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 6, pp. 1772–1786, Jun. 2023.

[A12] Q. Li et al., "Machine learning based time domain millimeter-wave beam prediction for 5G-advanced and beyond: Design, analysis, and over-the-air experiments," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 6, pp. 1787–1809, Jun. 2023.

[A13] K. Min, Y. Kim, and H.-S. Lee, "Meta-scheduling framework with cooperative learning towards beyond 5G," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 6, pp. 1810–1824, Jun. 2023.

[A14] M. F. Pervej, R. Jin, and H. Dai, "Resource constrained vehicular edge federated learning with highly mobile connected vehicles," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 6, pp. 1825–1844, Jun. 2023.

[A15] A. Prado, F. Stöckeler, F. Mehmeti, P. Krämer, and W. Kellerer, "Enabling proportionally-fair mobility management with reinforcement learning in 5G networks," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 6, pp. 1845–1858, Jun. 2023.

[A16] R. Amiri et al., "Indoor environment learning via RF-mapping," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 6, pp. 1859–1872, Jun. 2023.

[A17] H. Guo and V. Liu, "Robust deep learning for uplink channel estimation in cellular network under inter-cell interference," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 6, pp. 1873–1887, Jun. 2023.

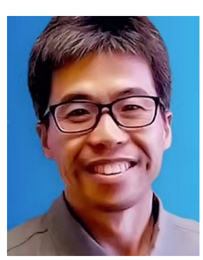
[A18] T. Islam, D. Lee, and S. S. Lim, "Enabling network power savings in 5G-advanced and beyond," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 6, pp. 1888–1899, Jun. 2023.

[A19] M. Ibrahim, H. Arslan, H. A. Cirpan, and S. Ekin, "Time-frequency warped waveforms for well-contained massive machine type communications," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 6, pp. 1900–1917, Jun. 2023.

[A20] Z. Wu and L. Dai, "Multiple access for near-field communications: SDMA or LDMA," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 6, pp. 1918–1935, Jun. 2023.

[A21] K. Hooli et al., "Extending 5G to narrow spectrum allocations," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 6, pp. 1936–1944, Jun. 2023.

[A22] H. Miao et al., "Sub-6 GHz to mmWave for 5G-advanced and beyond: Channel measurements, characteristics and impact on system performance," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 6, pp. 1945–1960, Jun. 2023.



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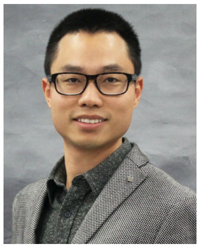

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