Guest Editorial
Multi-Tier Computing for Next Generation Wireless Networks—Part II

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I. Introduction

MULTI-TIER computing effectively enables flexible computation and communication resource sharing by offloading computation-intensive tasks to nearby servers along the cloud-to-thing continuum. In essence, multi-tier computing networks can distribute computing, storage, and communication functions anywhere between the cloud and the endpoint to take full advantage of the resources available along this continuum, thus extending the traditional cloud computing architecture to the edge of the network. With multi-tier computing, some application component processing, such as delay-sensitive components, can take place at the edge of the network, while other components, such as time-tolerant and computation-intensive components, can be performed in the cloud. To best meet user requirements, centralized cloud computing with extensive resources, secure environments, and powerful algorithms is still needed, but also must be complemented by distributed fog and edge computing with shared resources, accessible environments, and simple algorithms for real-time decision-making. Given heterogeneous computing resources and collaborative service architectures, future multi-tier computing networks will be capable of supporting a full range of computing and networking services for different environments and applications. Multi-tier computing enables low-latency processing by allowing data to be processed at the network edge close to end devices. It also facilitates the distribution of fog/edge nodes to collect data from end devices. Therefore, multi-tier computing effectively complements the cloud computing architecture.

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This Special Issue led to a strong response and has attracted over 100 high-quality submissions from researchers around the world. This is a testament to the widespread interest in multi-tier computing research. Based on a rigorous review process, a total of 34 submissions were selected for publication in double issues. Every submission received at least three reviews, and each accepted paper went through at least one revision round.

In this guest editorial for the second part of double issues, we briefly review the research featured in the issue and highlight emerging research themes for multi-tier computing. The contributions of the papers included are categorized as follows.

II. Multi-Tier Computing for Next-Generation Wireless Networks

A. Massive Multiple Access Schemes for Multi-Tier Computing

In [A1], Wang et al. propose a non-orthogonal multiple access (NOMA)-aided joint communication, sensing, and multi-tier computing (JCSMC) framework. In this framework, a multi-functional base station (BS) carries out target sensing, while providing multi-tier computing services for nearby users.

In [A2], Shao et al. propose a Bayesian approach by letting multiple edge devices transmit two pieces of statistical information to the center device such that Bayesian estimators can be devised to tackle the misalignments of over-the-air computation, which enables efficient function computation in multi-tier computing systems.

In [A3], Zhao et al. propose a multi-tier-enabled computing framework and the associated algorithms for URLLC to support multiple end users with different QoS requirements. This technique concentrates on K-repetition Grant-Free (GF) access in light of its simplicity and well-balanced performance for practical systems.

B. Multi-Tier Computing Meets Semantic Communication

In [A4], Qin et al. derive the closed-form expressions of timeliness of information for multi-tier computing at both edge tier and fog tier, where two-stage tandem queues are exploited to abstract the task transmission and computation process. The proposed technique exploits the statistical structure of the Gauss-Markov process and derives the closed-form expression for task process-related timeliness of information

In [A5], Xiao et al. propose a novel reasoning-based implicit semantic-aware communication network, which allows multi-tier of cloud data center (CDC) and edge servers to cooperate. This technique supports efficient semantic encoding, decoding, and interpretation for end-users.

C. Multi-Tier Computing With Processing Uncertainty

In [A6], the authors formulate a Chance-Constrained Program (CCP) that guarantees the task processing delay requirement under the condition that the number of required processing cycles of a task is unknown beforehand and only known until its completion. This technique can minimize task computation energy consumption for the users while meeting the probabilistic task deadlines.

In [A7], Kim et al. propose a multi-tier computing architecture that provides a rigorous theoretical framework and studies the challenges of long-term user mobility to minimize both the service provider cost and user latency. As devices move, the proposed approach can offload the tasks to different edge servers and migrate data or state information from one edge server to another.

D. Caching for Multi-Tier Computing

In [A8], the authors investigate the issue of recommendation-enabled edge caching in multi-tier (edge-cloud) computing networks. The proposed technique integrates recommender systems and data caching to support both direct hits and soft hits. The proposed algorithm can improve the resource utilization of edge servers and alleviate the effects of soft hits.

In [A9], Tang and Lei study a multi-tier cache-aided relaying network, where the destination is randomly located in the network and it requests files from the source through the help of multi-tier cache-aided BS and relays. The proposed algorithm optimizes the caching policies among the relays and BS, to improve the network throughput.

E. Machine Learning-Aided Multi-Tier Computing

In [A10], Zeng et al. study the cost optimization for distributed Graph Neural Networks (GNNs) processing over a multi-tier heterogeneous edge network. The proposed technique theoretically reveals the structural property of quadratic submodularity implicated in GNN's unique computing pattern and serves as a foundation for future analysis and optimization on specific GNN-driven applications.

In [A11], Liu et al. propose an edge-assisted crowdsourced live video transcoding approach, where the transcoding capabilities of the edge transcoders are unknown and dynamic. Based on the derived bounds and by leveraging the contextual information of devices, two risk-aware contextual learning schemes are developed to efficiently estimate the transcoding capabilities of the edge devices.

In [A12], Deng et al. develop a joint communication and computation efficient federated learning (FL) framework for resource-limited Industrial Internet of Things (IIoT) systems. This framework integrates the deep neural networks (DNNs) partition technique into the standard FL technique, wherein IIoT devices perform local model training at the bottom layers of the objective DNN, and offload the top layers to the edge gateway side.

In [A13], the authors propose a novel technique to control the distribution of communications latency, which can support efficient multi-tier cooperative deep learning architecture in the harsh industrial environment. The proposed method is essentially an inverse process of the Gaussian Mixture Model (GMM) that controls latency distribution.

In [A14], the authors introduce the uplink and downlink fully-decoupled radio access network (FD-RAN) architecture to improve the wireless link rate via multiple BSs collaboration and power allocation solution. The proposed technique could accelerate FL-enabled multi-tier computing over wireless networks.

In [A15], the authors propose a framework to analyze the convergence behavior of multi-tier hybrid learning that leverages the server dataset and its computation capacity for collaborative model training. Different from standard FL, where stochastic gradient descent (SGD) is always computed in a parallel fashion across all clients, this proposed architecture enjoys both parallel SGD at clients and sequential SGD at the server by using the aggregated model from clients.

F. Service-Oriented Multi-Tier Computing

In [A16], the authors propose a multi-tier edge-cloud computing framework, EdgeMatrix, to maximize the throughput of the system while guaranteeing different service-level agreement (SLA) priorities. EdgeMatrix introduces the Networked Multi-agent Actor-Critic (NMAC) algorithm to redefine physical layer resources with the same quality of service. This technique can logically isolate resource units and combinations, i.e., cells and channels.

In [A7], the authors investigate the problem of service routing to achieve efficient microservice-based service provision in multi-tier computing systems. The objective is to optimize the request routing with low service delay and resource cost.

III. Conclusion

The Guest Editors hope that this Special Issue will provide valuable insights into current and future research areas on multi-tier computing technologies. They deeply appreciate the great mentoring provided by Prof. Moshe Zukerman, whose invaluable guidance was crucial to the success of the special issue. Meanwhile, the Guest Editors would like to thank both Prof. Petar Popovski and Janine Bruttin for their timely assistance in preparing the special issue. Last but not the least, they would also like to take this opportunity to thank all the authors and reviewers for their efforts in ensuring that this is a quality and relevant Special Issue.

Appendix: Related Articles

[A1] Z. Wang, X. Mu, Y. Liu, X. Xu, and P. Zhang, "NOMA-aided joint communication, sensing, and multi-tier computing systems," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 3, pp. 574–588, Mar. 2023, doi: 10.1109/JSAC.2022.3229447.

[A2] Y. Shao, D. Gunduz, and S. C. Liew, "Bayesian over-the-air computation," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 3, pp. 589–606, Mar. 2023, doi: 10.1109/JSAC.2022.3229428.

[A3] Z. Zhao, Q. Du, and G. K. Karagiannidis, "Improved grant-free access for URLLC via multi-tier-driven computing: Network-load learning, prediction, and resource allocation," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 3, pp. 607–622, Mar. 2023, doi: 10.1109/JSAC.2023.3234696.

[A4] X. Qin, Y. Li, X. Song, N. Ma, C. Huang, and P. Zhang, "Timeliness of information for computation-intensive status updates in task-oriented communications," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 3, pp. 623–638, Mar. 2023, doi: 10.1109/JSAC.2022.3229431.

[A5] Y. Xiao, Z. Sun, G. Shi, and D. Niyato, "Imitation learning-based implicit semantic-aware communication networks: Multi-layer representation and collaborative reasoning," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 3, pp. 639–658, Mar. 2023, doi: 10.1109/JSAC.2022.3229419.

[A6] S. Li, C. Li, Y. Huang, B. A. Jalaian, Y. T. Hou, and W. Lou, "Enhancing resilience in mobile edge computing under processing uncertainty," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 3, pp. 659–674, Mar. 2023, doi: 10.1109/JSAC.2023.3234706.

[A7] T. Kim et al., "MoDEMS: Optimizing edge computing migrations for user mobility," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 3, pp. 675–689, Mar. 2023, doi: 10.1109/JSAC.2022.3229425.

[A8] C. Sun, X. Li, J. Wen, X. Wang, Z. Han, and V. C. M. Leung, "Federated deep reinforcement learning for recommendation-enabled edge caching in mobile edge-cloud computing networks," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 3, pp. 690–705, Mar. 2023, doi: 10.1109/JSAC.2023.3235443.

[A9] S. Tang and X. Lei, "Collaborative cache-aided relaying networks: Performance evaluation and system optimization," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 3, pp. 706–719, Mar. 2023, doi: 10.1109/JSAC.2023.3234693.

[A10] L. Zeng, C. Yang, P. Huang, Z. Zhou, S. Yu, and X. Chen, "GNN at the Edge: Cost-efficient graph neural network processing over distributed edge servers," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 3, pp. 720–739, Mar. 2023, doi: 10.1109/JSAC.2022.3229422.

[A11] X. Liu, M. Derakhshani, L. Mihaylova, and S. Lambotharan, "Risk-aware contextual learning for edge-assisted crowdsourced live streaming," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 3, pp. 740–754, Mar. 2023, doi: 10.1109/JSAC.2022.3229423.

[A12] X. Deng, J. Li, C. Ma, K. Wei, L. Shi, M. Ding, and W. Chen, "Low-latency federated learning with DNN partition in distributed industrial IoT networks," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 3, pp. 755–775, Mar. 2023, doi: 10.1109/JSAC.2022.3229436.

[A13] F. Qin, Y. Xiao, X. Sun, X. Dai, W. Zhang, and F. Shen, "Inverse-GMM: A latency distribution shaping method for industrial cooperative deep learning systems," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 3, pp. 776–788, Mar. 2023, doi: 10.1109/JSAC.2022.3229448.

[A14] Y. Xu, B. Qian, K. Yu, T. Ma, L. Zhao, and H. Zhou, "Federated learning over fully-decoupled RAN architecture for two-tier computing acceleration," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 3, pp. 789–801, Mar. 2023, doi: 10.1109/JSAC.2023.3236003.

[A15] K. Yang, S. Chen, and C. Shen, "On the convergence of hybrid server-clients collaborative training," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 3, pp. 802–819, Mar. 2023, doi: 10.1109/JSAC.2022.3229443.

[A16] S. Shen, Y. Ren, Y. Ju, X. Wang, W. Wang, and V. C. M. Leung, "*EdgeMatrix*: A resource-redefined scheduling framework for SLA-guaranteed multi-tier edge-cloud computing systems," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 3, pp. 820–834, Mar. 2023, doi: 10.1109/JSAC.2022.3229444.

[A17] S. Wang, Y. Guo, X. Liu, and A. Zhou, "Service routing in multi-tier edge computing: A matching game approach," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 3, pp. 835–844, Mar. 2023, doi: 10.1109/JSAC.2022.3229378.

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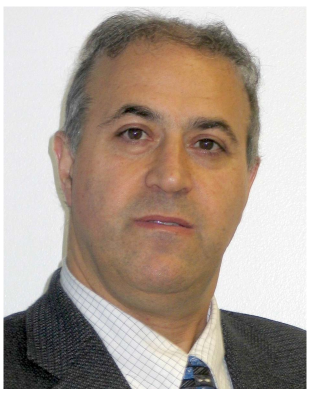

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