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

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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. This Special Issue aims to provide a forum for the latest advances in multi-tier computing for next-generation wireless network research, innovations, 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 first part of double issues, we briefly review the research featured in the issue and focus on the research development of task offloading. It opens with a paper by the guest editors that highlights the major challenges of multi-tier computing in next-generation wireless networks and surveys an important research topic of task offloading. The contributions of the other papers are categorized as follows.

II. Task Offloading in Multi-Tier Computing-Based Next-Generation Wireless Networks

In [A1], Wang et al. investigate key techniques and directions for wireless communications and resource allocation approaches to enable task offloading in multi-tier computing systems. This paper presents a multi-tier computing model in detail, including its main functionality and optimization methods.

A. Task Offloading With Intelligent Reflecting Surface (IRS)

In [A2], Xu et al. propose a novel framework of intelligent reflecting surface (IRS) backscatter-aided multi-tier computing system. This paper leverages IRS backscatter at the user devices to offload tasks to the edge servers, aiming at maximizing the sum of computational bits during the considered time block. The proposed algorithm jointly optimizes the active beamforming at the power beacon, the passive beamforming at the user devices, the active beamforming at the access points (APs), the bandwidth and power allocation among all the user devices, as well as the computational time of local computing.

In [A3], Li et al. propose a novel transmissive reconfigurable meta-surface (RMS) transceiver-enabled multi-tier computing networks, which can improve computing capability, decrease computing latency and reduce base station (BS) deployment cost. The proposed system can be regarded as a new type of multi-antenna system by equipping it with a feed antenna for transmissive RMS.

In [A4], Chen and Wu develop a unified dynamic IRS beamforming framework in an IRS-aided mobile edge computing (MEC) system to improve the sum task computational rate. The results illustrate the significance of deploying the IRS in MEC systems for achieving coverage extension and task offloading for multiple energy-limited devices.

B. Task Offloading in Satellite-Terrestrial Integrated Network (SAGIN)

In [A5], the authors investigate cooperative multi-tier computing in the integrated satellite-terrestrial network, where the computational tasks of users are processed by leveraging the collaboration of devices, edge nodes, and cloud servers. With the optimal task splitting strategy obtained, the original task offloading optimization problem is reformulated as the problem of the offloading time allocation strategy and the computation resource allocation strategy.

In [A6], Cao et al. investigate a low earth orbit satellite (LEOS) edge-assisted multi-layer multi-access edge computing system. In this system, the MEC framework is extended to LEOS by deploying the LEOS edge, to enhance the coverage of the multi-layer MEC system and address the tasks' computational problems both in congested and isolated areas.

In [A7], Chen et al. propose an innovative multi-tier hybrid parallel computation architecture in CA-augmented space-air-ground integrated networks (CAA-SAGIN). In this work, devices perform local computing, CAs and satellites act as edge servers, and ground stations of satellite networks operate cloud computing. The optimal tradeoff between end-to-end (E2E) delay and energy consumption can be achieved by the proposed task offloading algorithm.

In [A8], the authors propose a multi-functional time expanded graph (MF-TEG) to jointly model the communication, storage and computation capability of nodes for SAGIN-aided multi-tier computing networks over time. The proposed technique adopts the virtual network graph (VNG) to virtually decompose multi-tier computing networks into three virtual components: sub-virtual nodes, virtual computing nodes, and virtual transmission links, where the virtual computing node provides the task computation function.

C. Task Offloading With Internet of Vehicles and Autonomous Unmanned Vehicles

In [A9], Feng et al. investigate the task offloading and resource allocation strategy in Cellular Vehicle-to-Everything (C-V2X) enabled multi-tier vehicular edge computing (VEC) system. The successful transmission probability of task offloading is characterized to obtain the normalized transmission rate. This work minimizes the system latency of task execution while satisfying the resource requirements of the vehicle-to-everything interfaces.

In [A10], the authors consider a multi-tier computation offloading system for 6G applications, where the cloud computing server and the nearby vehicle edge server (VES) can partially compute the tasks offloaded from the user equipment (UE), while the remaining task is processed locally in the UE.

In [A11], Xiao et al. propose a perception task offloading framework with a collaborative computing approach, where an Autonomous Vehicle (AV) can achieve a comprehensive perception of the surrounding environment by leveraging collaborative computation with the aid of nearby AVs and roadside-units (RSUs). Besides, collaborative computation provides offloading service for computation-intensive tasks to reduce processing delay.

In [A12], Hou et al. conceive a multi-tier underwater computing framework by carefully harnessing the computation, communications, and storage resources at the surface-station, autonomous underwater vehicles (AUVs), and the Internet of underwater things (IoUT) devices. The task offloading technique meets the stringent energy constraints of the IoUT devices and reduces the total cost of the multi-tier computing framework.

In [A13], the authors propose the paradigm of AUV flock-based networking system and Software-Defined Networking (SDN)-enabled AUV flock Networking System (SDN-AUVNS). It utilizes the multi-tier computing mechanism to improve the scalability of the AUV flock and revises the control input for the SDN-AUVNS. This multi-tier computing technique can intelligently schedule the SDN-AUVNS to track underwater pollution equipotential lines.

In [A14], the authors propose a deep reinforcement learning (DRL) based task offloading technique to jointly make optimal task scheduling decisions and UAV flying orientation choices, which solves the problem of multi-UAV cooperative target search.

D. Ultra-Reliable Low-Latency Task Offloading

In [A15], Huynh et al. study joint communication and computation offloading (JCCO) for multi-tier computing systems with ultra-reliable and low latency communications (URLLC). This technique can minimize the end-to-end (E2E) task offloading latency among multiple industrial Internet of Things (IIoT) devices by jointly optimizing offloading decisions, task processing rates, user association policies, and power control.

In [A16], the authors consider task offloading for mobile applications with task-dependency requirements in multi-tier computing systems. Based on the online arrival patterns and various delay constraints of practical tasks, the proposed technique focuses on minimizing the system deadline violation ratio (DVR) to improve the overall task processing reliability performance.

In [A17], Zhang et al. propose a novel task offloading method named OSTTD, to offload the splittable tasks with topological dependence in multi-tier computing systems. The proposed technique formulates task offloading as a sequential decision-making problem and learns the task offloading policy by DRL, which can significantly reduce the task processing time.

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 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] K. Wang et al., "Task offloading with multi-tier computing resources in next generation wireless networks," vol. 41, no. 2, Feb. 2023, doi: 10.1109/JSAC.2022.3227102.

[A2] S. Xu, J. Liu, N. Kato, and Y. Du, "Intelligent reflecting surface backscatter enabled multi-tier computing for 6G Internet of Things," vol. 41, no. 2, Feb. 2023, doi: 10.1109/JSAC.2022.3231861.

[A3] Z. Li, W. Chen, Z. Liu, H. Tang, and J. Lu, "Joint communication and computation design in transmissive RMS transceiver enabled multi-tier computing networks," vol. 41, no. 2, Feb. 2023, doi: 10.1109/JSAC.2022.3228553.

[A4] G. Chen and Q. Wu, "IRS aided MEC systems with binary offloading: A unified framework for dynamic IRS beamforming," vol. 41, no. 2, Feb. 2023, doi: 10.1109/JSAC.2022.3228605.

[A5] X. Zhu and C. Jiang, "Delay optimization for cooperative multi-tier computing in integrated satellite-terrestrial networks," vol. 41, no. 2, Feb. 2023, doi: 10.1109/JSAC.2022.3227083.

[A6] X. Cao et al., "Edge-assisted multi-layer offloading optimization of LEO satellite-terrestrial integrated networks," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 2, Feb. 2023, doi: 10.1109/JSAC.2022.3227032.

[A7] Q. Chen, W. Meng, T. Q. S. Quek, and S. Chen, "Multi-tier hybrid offloading for computation-aware IoT applications in civil aircraft-augmented SAGIN," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 2, Feb. 2023, doi: 10.1109/JSAC.2022.3227031.

[A8] W. Liu, H. Yang, and J. Li, "Multi-functional time expanded graph: A unified graph model for communication, storage and computation for dynamic networks over time," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 2, Feb. 2023, doi: 10.1109/JSAC.2022.3233533.

[A9] W. Feng, S. Lin, N. Zhang, G. Wang, B. Ai, and L. Cai, "Joint C-V2X based offloading and resource allocation in multi-tier vehicular edge computing system," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 2, Feb. 2023, doi: 10.1109/JSAC.2022.3227081.

[A10] H. Zhang, L. Feng, X. Liu, K. Long, and G. K. Karagiannidis, "User scheduling and task offloading in multitier computing 6G vehicular network," vol. 41, no. 2, Feb. 2023, doi: 10.1109/JSAC.2022.3227097.

[A11] Z. Xiao, J. Shu, H. Jiang, G. Min, H. Chen, and Z. Han, "Perception task offloading with collaborative computation for autonomous driving," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 2, Feb. 2023, doi: 10.1109/JSAC.2022.3227027.

[A12] X. Hou, J. Wang, T. Bai, Y. Deng, Y. Ren, and L. Hanzo, "Environment-aware AUV trajectory design and resource management for multi-tier underwater computing," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 2, Feb. 2023, doi: 10.1109/JSAC.2022.3227103.

[A13] C. Lin, G. Han, J. Jiang, C. Li, S. B. Hussain Shah, and Q. Liu, "Underwater pollution tracking based on software-defined multi-tier edge computing in 6G-based underwater wireless networks," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 2, Feb. 2023, doi: 10.1109/JSAC.2022.3233625.

[A14] Q. Luo, T. H. Luan, W. Shi, and P. Fan, "Deep reinforcement learning based computation offloading and trajectory planning for multi-UAV cooperative target search," vol. 41, no. 2, Feb. 2023.

[A15] D. V. Huynh, V.-D. Nguyen, S. Chatzinotas, S. R. Khosravirad, H. V. Poor, and T. Q. Duong, "Joint communication and computation offloading for ultra-reliable and low-latency with multi-tier computing," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 2, Feb. 2023, doi: 10.1109/JSAC.2022.3227088.

[A16] "Dependent task scheduling and offloading for minimizing deadline violation ratio in mobile edge computing networks," Tech. Rep.

[A17] R. Zhang et al., "OSTTD: Offloading of splittable tasks with topological dependence in multi-tier computing networks," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 2, Feb. 2023, doi: 10.1109/JSAC.2022.3227023.

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