Decomposing Complexity: Strategies for Problem Decomposition in 5G Networks and Beyond

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***Abstract*—Ultra-dense networks (UDNs) play a pivotal role in 5G and beyond systems, crucial for facilitating the seamless communication of users. However, the dense deployment of numerous small base stations (SBSs) within UDN introduces significant heterogeneity, particularly in tasks such as user allocation for offloading and migration. Traditional centralized strategies become infeasible due to the vast state-action space inherent in UDN. This paper offers a comprehensive overview of various approaches proposed in the literature to address this challenge. It explores horizontal decomposition, utilizing multiple decision makers, vertical decomposition into manageable subproblems, and hybrid strategies combining both approaches. By doing so, this work aims to provide a pragmatic framework for tackling the mathematically intractable problems inherent in future communication networks.**

Keywords: Ultra-dense networks (UDNs), 5G, Multi-agent systems, Hierarchical framework.

I. Introduction

As a key enabler for the deployment of 5G and the anticipated 6G wireless communications, the ultra-dense network (UDN) has received significant attention recently. UDN entails the dense deployment of numerous small base stations (SBSs) atop macro base stations (MBS), serving users through mmWave and THz band transmission. User association, a fundamental concept within UDN, pertains to the allocation of users to specific base stations based on various factors such as signal strength, available bandwidth, and traffic load. Given the vast heterogeneity of devices and the multitude of network parameters, optimizing these offloading decisions poses a multifaceted challenge. In practice, centralized user association strategies proves arduous due to the sheer volume of SBSs and users in UDN. To tackle this challenge, multiple approaches have been explored. Some research endeavors have pursued a horizontal decomposition strategy, dividing the problem into distinct decision-making units, often referred to as multi-agent systems. Alternatively, other studies have adopted a vertical decomposition approach, breaking down the original resource allocation problem into a series of subproblems. Moreover, certain works have opted for a hybrid approach.

This paper offers a preview into the efforts aimed at pragmatically addressing the intricacies associated with navigating the vast solution space inherent in resource allocation for 5G networks and beyond.

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II. Problem Decomposition

In UDN deployments for 5G and beyond, the abundance of SBS leads to a multitude of communication channels, power levels, and computational states. This, coupled with the heterogeneous nature of user devices, poses a formidable challenge in navigating the solution space for optimal resource allocations to fulfill user needs. To address these complexities, this section delves into the various efforts been initiated to decompose the overarching problem into more manageable subproblems.

A. Horizontal Decomposition

Multiple studies consider the resource allocation and user association problems as compositions of multiple decision-making entities. This decomposition approach can be considered as a horizontal breakdown of the original problem into distinct agents, each accountable for contributing to the overall solution. This strategy offers a practical framework tailored for addressing challenges stemming from a vast number of decision-makers. Within this decomposition, these agents are often designated as either representing the users or the base stations.

Liu et al. explore in [1] the problem of unmanned aerial vehicle (UAV)-assisted mobile edge computing (MEC). Each MU and UAV is treated as an independent agent, leading to a Markov decision process (MDP) with multiple agent types. To optimize computation offloading policies, they propose a deep reinforcement learning approach based on multi-agent proximal policy optimization (MAPPO). This decomposition framework enables a nuanced customization of observations, actions, and rewards for each decision-maker. Their work stands as an exemplar of efficiently navigating a vast solution space populated by diverse entities.

In another notable study, Park et al. [2] consider the problem of the joint trajectory and spectrum, computation optimization for MEC-powered UAVs utilized in sub-THz communication within remote areas. Given the multitude of control aspects involved, they adopt a novel approach: treating each control aspect as its own agent. Rather than assigning agent status to individual system entities (MEC, UAVs, or MUs), they designate the actions taken by these entities as the agents themselves. This horizontal decomposition strategy facilitates a more streamlined navigation of the heterogeneous state-action space.

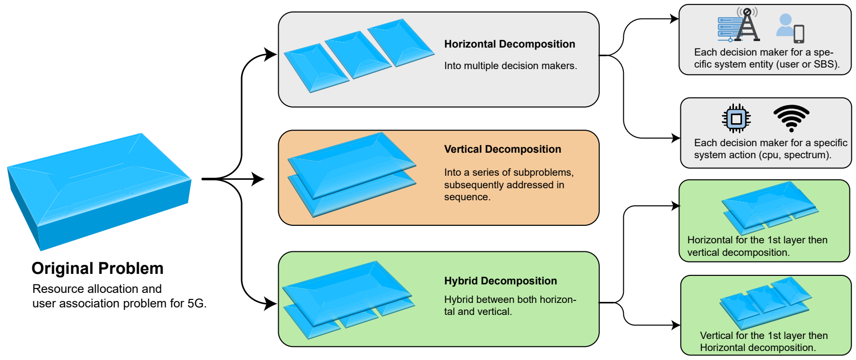

Fig. 1: Decomposition Approaches for Resource Allocation and User Association in 5G

B. Vertical Decomposition

To efficiently tackle problems with multiple interdependent objectives, a strategy of subdividing the intricate resource allocation problem into manageable subproblems has emerged. Some studies advocate for a vertical or hierarchical decomposition of the original problem into sequential subproblems.

In their investigation [3], Zhang et al. delve into resource allocation challenges within MEC systems and the need for load balancing among collaborating MEC servers. They propose a hierarchical reinforcement learning (HRL) approach, where the lower layer employs a deep Q network (DQN) to determine service caching and workload offloading decisions. Subsequently, the upper layer employs DQN to optimize load balancing among cooperative MEC servers.

In a related study, Peng et al. [4] explore the joint allocation of spectrum, computing, and storage resources in a MEC-based vehicular network. They adopt a hierarchical solving approach using Deep Deterministic Policy Gradient (DDPG), with the first layer focusing on spectrum allocation optimization, while the second layer prioritizes computation and storage resource allocation.

C. Hybrid Decomposition

In the ever-evolving landscape of 5G networks and beyond, systems grapple with a multitude of decision-making entities, encompassing users and SBSs, alongside an array of overarching objectives. These objectives span spectrum allocation, computation management, caching strategies, and offloading decisions. To facilitate a more pragmatic navigation through the expansive state-action space, some studies have embraced a hybrid approach, amalgamating elements of both horizontal and vertical decomposition.

Liu et al. delve into the intricacies of multidimensional resource management within multi-access MEC networks amidst external dynamic jamming [5]. Their approach involves employing a distributed multi-agent hierarchical deep reinforcement learning (MAHDRL) framework. Initially, they centrally optimize discrete channel access strategies at the low level, before horizontally decomposing the problem of data offloading strategies into a distributed multi-agent scenario at the upper level.

Similarly, Jiang et al. [6] address the challenge of computation offloading for device-to-device communications in MEC environments. Their solution utilizes a hierarchical framework that combines DQN and Deep Deterministic Policy Gradient (DDPG) to handle continuous-discrete mixed action spaces. In contrast to [145], their approach incorporates a multi-agent actor-critic setup at the first lower layer for each user to compute its own continuous offloading ratio. At the upper layer, a centralized DQN is then employed to determine the global discrete offloading destination and spectrum allocation.

III. Conclusion

Decomposing complex problems into more manageable subproblems presents a pragmatic approach to addressing the diverse array of decision-makers and overarching system objectives. In the 5G networks and beyond, systems are expected to accommodate a myriad of users and SBSs, while simultaneously adhering to multiple system objectives. Hence, frameworks adept at managing the complex solution space hold significant value. This study serves as an initial exploration into the diverse approaches for problem decomposition within the evolving landscape of 5G networks and beyond.

References

[1] Wenshuai Liu, Bin Li, Wancheng Xie, Yueyue Dai, and Zesong Fei. Energy efficient computation offloading in aerial edge networks with multi-agent cooperation. *IEEE Transactions on Wireless Communications*, 22(9):5725–5739, 2023.

[2] Yu Min Park, Sheikh Salman Hassan, Yan Kyaw Tun, Zhu Han, and Choong Seon Hong. Joint trajectory and resource optimization of mec-assisted uavs in sub-thz networks: A resources-based multi-agent proximal policy optimization drl with attention mechanism. *IEEE Transactions on Vehicular Technology*, 73(2):2003–2016, 2024.

[3] Wenqian Zhang, Guanglin Zhang, and Shiwen Mao. Deep-reinforcement-learning-based joint caching and resources allocation for cooperative mec. *IEEE Internet of Things Journal*, 11(7):12203–12215, 2024.

[4] Haixia Peng and Xuemin Shen. Deep reinforcement learning based resource management for multi-access edge computing in vehicular networks. *IEEE Transactions on Network Science and Engineering*, 7(4):2416–2428, 2020.

[5] Songyi Liu, Yuhua Xu, Guoxin Li, Yifan Xu, Xiaokai Zhang, Fanglin Gu, WenFeng Ma, and Taoyi Chen. Multi-dimensional resource management for distributed mec networks in jamming environment: A hierarchical drl approach. *IEEE Internet of Things Journal*, pages 1–1, 2024.

[6] Wei Jiang, Daquan Feng, Yao Sun, Gang Feng, Zhenzhong Wang, and Xiang-Gen Xia. Joint computation offloading and resource allocation for d2d-assisted mobile edge computing. *IEEE Transactions on Services Computing*, 16(3):1949–1963, 2023.