

Energy-Aware Task Offloading in 6G-Enabled Mobile Edge Computing Environments

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Abstract

The emergence of sixth-generation (6G) wireless communication networks is expected to revolutionize future mobile systems by enabling ultra-low latency communication, extremely high data rates, massive connectivity, and intelligent network management. In parallel, mobile edge computing (MEC) has gained significant attention as a promising paradigm that brings computational resources closer to end users, thereby alleviating network congestion and reducing end-to-end service delays. Despite these advantages, the rapid growth of computation-intensive and latency-sensitive applications, such as extended reality, autonomous systems, and intelligent healthcare, poses serious challenges in terms of energy consumption, particularly for battery-powered mobile devices. As a result, energy efficiency has become a critical performance metric in 6G-enabled MEC environments. To address this issue, energy-aware task offloading has emerged as a key research area, aiming to determine when, where, and how computational tasks should be executed to minimize energy usage while meeting strict latency requirements. This paper provides a comprehensive and descriptive analysis of existing energy-aware task offloading strategies in 6G-MEC systems. It systematically reviews optimization approaches, including heuristic methods, mathematical optimization, and emerging artificial intelligence-driven and edge intelligence techniques. Furthermore, the paper analyzes the inherent trade-offs between energy consumption, computational delay, and system scalability. Finally, it highlights open challenges, such as dynamic network conditions, heterogeneous resources, and sustainability concerns, and outlines research directions toward achieving intelligent, adaptive, and energy-efficient 6G-enabled MEC architectures.

Keywords: 6G wireless networks, artificial intelligence optimization, computation offloading, edge intelligence, energy efficiency, energy-aware task offloading, latency–energy trade-off, mobile edge computing (MEC), sustainable networking, ultra-low latency communication

INTRODUCTION

The rapid evolution of wireless communication technologies and mobile applications has significantly increased the demand for real-time data processing and intelligent services. Emerging applications, such as extended reality, autonomous driving, smart healthcare, and industrial automation, require ultra-low latency, high reliability, and massive connectivity. Traditional cloud-centric computing architecture struggles to meet these requirements because of long communication delays and bandwidth limitations. Mobile edge computing (MEC) addresses these challenges by enabling computation and storage resources at the network edge, closer to the end users [1, 2].

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The upcoming sixth-generation (6G) wireless networks are expected to further enhance MEC capabilities by offering unprecedented data rates, sub-millisecond latency, ultradense connectivity,

and native support for artificial intelligence. These features make 6G-enabled MEC a promising platform for supporting computation-intensive and delay-sensitive applications. However, despite these advancements, mobile devices remain constrained by their limited battery capacity and processing power. Inefficient computation and communication can lead to rapid energy depletion, reducing the device lifetime and degrading the user experience [3, 4].

Task offloading, which involves transferring computational tasks from mobile devices to edge servers, has emerged as an effective solution for balancing performance and energy consumption. However, offloading decisions are complex and depend on multiple factors, such as channel conditions, task size, latency constraints, device mobility, and energy availability. In 6G-enabled MEC environments, these factors become even more dynamic because of heterogeneous networks and intelligent services [5, 6].

This study focuses on energy-aware tasks offloading in 6G-enabled MEC environments. This study aims to provide a comprehensive understanding of energy consumption challenges, explore optimization strategies and AI-driven solutions, analyze performance trade-offs, and identify open research issues. By addressing these aspects, this study contributes to the development of sustainable and energy-efficient mobile computing systems for future 6G networks [1, 3, 4].

6G-ENABLED MOBILE EDGE COMPUTING ARCHITECTURE

The architecture of 6G-enabled mobile edge computing extends conventional MEC frameworks by integrating ultra-high-speed wireless communication, intelligent control mechanisms, and distributed computing resources across the network. In this architecture, mobile devices, edge servers, and cloud infrastructures collaboratively execute computational tasks based on latency, energy, and resource availability. The primary objective is to minimize the end-to-end delay while optimizing the energy consumption of mobile devices [3, 4].

6G networks introduce several key architectural features, including terahertz communication, ultradense small cell deployment, integrated terrestrial and non-terrestrial networks, and native support for artificial intelligence. These capabilities enable seamless connectivity and rapid data transmission between mobile devices and edge nodes, allowing more flexible and fine-grained task offloading decisions compared with previous generations [2, 6].

Edge servers in 6G-enabled MEC environments are equipped with enhanced processing capabilities and intelligent resource management. These servers can dynamically allocate computation and communication resources based on real-time network conditions, application requirements, and device energy states. In addition, edge intelligence enables proactive decision-making, such as predicting workload variations and user mobility patterns, which further improves system efficiency [4, 7].

The integration of cloud computing with edge nodes provides hierarchical computing support, where delay-sensitive tasks are processed at the edge, whereas computation-intensive but delay-tolerant tasks are offloaded to the cloud. This multi-tier architecture allows for the efficient utilization of network resources and supports scalable task offloading in large-scale 6G networks [1, 5].

Overall, the 6G-enabled MEC architecture provides a flexible and intelligent foundation for implementing energy-aware task offloading strategies in future mobile networks. By leveraging advanced communication technologies and distributed intelligence, adaptive and sustainable mobile computing services are to be provided for next-generation wireless systems [3, 4, 6].

ENERGY CONSUMPTION CHALLENGES IN 6G-MEC SYSTEMS

Energy consumption remains a critical challenge in 6G-enabled MEC systems owing to the increasing computational complexity of mobile applications and the limited battery capacity of mobile

devices. In such environments, energy is primarily consumed during local computation, wireless communication for task offloading, and in idle or standby states. The high data rates and ultradense connectivity envisioned in 6G networks further intensify energy usage, making efficient energy management a fundamental requirement [1, 2].

Local task execution consumes processing energy, which depends on the CPU frequency, task complexity, and execution time. Although executing tasks locally avoids communication overhead, prolonged computation can rapidly deplete the device's battery resource. Conversely, task offloading reduces local energy processing but introduces transmission energy costs, which are influenced by the channel conditions, transmission power, and data size. Poor channel quality or frequent handovers in mobile environments can significantly increase the energy consumption of communication [5, 6].

In 6G-MEC systems, user mobility and dynamic network conditions further complicate energy management. Frequent changes in network topology, varying edge server loads, and fluctuating wireless link quality render static offloading strategies ineffective. Therefore, energy-efficient decision-making must adapt to real-time conditions while considering task deadlines and quality-of-service constraints [3, 4].

Moreover, the integration of intelligent services and AI-driven applications in 6G networks increases both computational and energy demands. Although AI can assist in optimizing offloading decisions, the energy cost of model training and inference must also be considered in system design. Balancing the benefits of intelligence with energy efficiency remains a key research challenge [7, 8].

Addressing these energy consumption challenges require holistic optimization frameworks that jointly consider the computation, communication, and mobility factors. Such frameworks are essential for enabling sustainable and long-lasting mobile devices in future 6G-enabled MEC environments [1, 3, 6].

SYSTEM MODEL FOR ENERGY-AWARE TASK OFFLOADING

A typical 6G-enabled MEC environment comprises mobile user devices, edge servers deployed at or near base stations, and remote cloud data centers. Mobile devices continuously generate computation-intensive tasks that may be executed locally or offloaded to edge servers, depending on energy availability, latency constraints, and network conditions. The system model emphasizes intelligent coordination among these components to achieve efficient task execution while minimizing energy consumption.

Network Architecture

The network architecture integrates multiple interconnected components to support ultra-low latency and energy-efficient computation. User equipment (UE), such as smartphones, Internet of Things devices, and augmented or virtual reality headsets, act as task generators and service consumers. Sixth-generation base stations provide ultra-high-speed wireless connectivity with extremely low latency, thereby enabling seamless communication between mobile devices and nearby edge servers. Edge servers deployed close to end users offer real-time computational capabilities for latency-sensitive tasks, whereas cloud servers handle large-scale and delay-tolerant background computations. The 6G network enables the intelligent orchestration of these components through AI-driven resource management and context-aware decision-making, ensuring the optimal utilization of network and computational resources [2].

Task Characterization

Each computational task in the MEC system is characterized by several key parameters, including the input data size, required number of CPU cycles, maximum tolerable latency, and energy consumption threshold. These parameters directly influence offloading decisions and resource

allocation strategies. Tasks are dynamically classified as delay-sensitive or energy-sensitive, allowing the system to adaptively determine whether tasks should be processed locally, partially offloaded, or fully offloaded to edge servers. Such dynamic task classification is essential in 6G environments, where application requirements and network conditions frequently change, necessitating flexible and intelligent offloading decisions [5].

ENERGY-AWARE TASK OFFLOADING STRATEGIES

Energy-aware task offloading aims to minimize overall energy consumption while ensuring that the latency and quality-of-service (QoS) requirements are met. In 6G-enabled MEC environments, offloading strategies must intelligently decide how computational tasks are executed by considering device energy constraints, network conditions, and application requirements.

Local Computation Versus Edge Offloading

Local computation allows tasks to be processed directly on mobile devices, thereby eliminating transmission delays and reducing the dependency on network connectivity. However, this approach significantly consumes device battery power, particularly for computation-intensive applications. In contrast, edge offloading shifts computational workloads to nearby edge servers, which can substantially reduce energy consumption at the device level but introduces additional communication overhead and potential latency owing to data transmission. Achieving an optimal balance between local computation and edge offloading requires real-time decision-making algorithms that adapt to dynamic network conditions, workload characteristics, and device energy states [6].

Partial and Hybrid Offloading

Instead of fully offloading the entire task, partial offloading strategies divide applications into smaller subtasks that are executed both locally and at the edge. This approach enables more flexible resource utilization and can significantly improve energy efficiency and latency performance. Hybrid offloading strategies further enhance this concept by dynamically adjusting the degree of offloading based on factors such as network bandwidth, edge server availability, workload intensity, and remaining battery level of the device. Such adaptive strategies are particularly well suited to 6G environments, where network conditions and user mobility vary rapidly, making static offloading decisions ineffective [7].

OPTIMIZATION TECHNIQUES FOR ENERGY EFFICIENCY

Energy-efficient task offloading in 6G-enabled MEC environments relies heavily on advanced optimization techniques that balance energy consumption with latency, bandwidth, and computational constraints. These techniques can be broadly categorized into mathematical optimization models and artificial intelligence-based approaches, each offering distinct advantages and limitations.

Mathematical Optimization Models

Mathematical optimization models, including convex and non-convex optimization techniques, are widely used to minimize energy consumption while satisfying strict latency and bandwidth requirements. These models provide precise and theoretically optimal solutions by formulating tasks offloading as constrained optimization problems. However, as the network size, device heterogeneity, and task complexity increases, the computational overhead of solving such models increases significantly. This makes them less suitable for real-time decision-making in large-scale and ultradense 6G-enabled MEC systems, where rapid adaptation to dynamic conditions is essential [8].

AI and Machine Learning Approaches

Artificial intelligence and machine learning-based techniques have emerged as powerful alternatives for energy-aware task offloading because of their ability to learn optimal strategies from experience. Approaches, such as reinforcement learning, deep learning, and federated learning, enable adaptive offloading decisions without requiring complete or centralized system knowledge. These methods are particularly effective in highly dynamic 6G environments, where the network conditions, user mobility,

and workload characteristics frequently change. By continuously updating decision policies based on observed system states, AI-driven approaches improve energy efficiency while maintaining low latency and a high QoS [9].

PERFORMANCE EVALUATION METRICS

The evaluation of energy-aware task offloading mechanisms in 6G-enabled MEC environments relies on several key performance metrics. Energy consumption per task is one of the most critical indicators, as it directly reflects the efficiency of offloading decisions and their effects on device battery life. Task completion time is another essential metric that measures the end-to-end delay from task generation to execution completion, which is particularly important for latency-sensitive applications. Network throughput is used to assess a system's ability to handle high volumes of data transmission while maintaining reliable communication. System scalability evaluates the effectiveness of the offloading framework as the number of connected devices and computational tasks increases in ultradense 6G network scenarios. Additionally, user quality of experience (QoE) serves as a holistic metric that captures user satisfaction by considering factors such as response time, service reliability, and perceived performance. Simulation results reported in recent studies demonstrate that AI-driven task offloading strategies can reduce energy consumption by up to 40% compared with traditional offloading approaches, highlighting the effectiveness of intelligent optimization techniques [10].

CHALLENGES AND OPEN RESEARCH ISSUES

Despite significant progress in energy-aware task offloading techniques, several critical challenges remain unresolved in 6G-enabled MEC environments. Accurate energy consumption modeling continues to be complex because of the dynamic nature of wireless channels, heterogeneous hardware capabilities, and varying application workloads, which can lead to suboptimal offloading decisions [7]. Security and privacy concerns during task offloading also pose major challenges, as sensitive data may be exposed to attacks, such as eavesdropping, data tampering, and unauthorized access, when transmitted between mobile devices and edge servers [8]. Moreover, ensuring scalability in ultradense sixth-generation (6G) networks with massive device connectivity requires robust resource allocation and load balancing mechanisms capable of operating under extreme network conditions [9].

The integration of renewable energy sources into MEC infrastructure introduces additional complexity because of the intermittent and unpredictable nature of green energy generation [10]. Finally, achieving seamless interoperability between edge and cloud platforms remains a challenge because heterogeneous architecture, protocols, and management frameworks can hinder efficient coordination and task migration. Addressing these challenges is essential for enabling the sustainable, secure, and large-scale deployment of 6G-enabled MEC systems.

CONCLUSION

Energy-aware task offloading has emerged as a fundamental enabler for achieving efficiency and sustainability in 6G-enabled MEC environments. By intelligently deciding when and where computational tasks should be executed, such mechanisms effectively balance energy consumption, latency, and QoS requirements. The integration of artificial intelligence driven optimization techniques with the ultra-low-latency and high-bandwidth capabilities of 6G networks allows dynamic adaptation to changing network conditions, user mobility, and workload demands.

Furthermore, energy-efficient offloading strategies contribute significantly to prolonging the battery life of devices while reducing the overall energy footprint of edge infrastructure. As 6G ecosystems continue to evolve, incorporating advanced learning models, context-aware decision-making, and green networking principles are essential. Continued research in this domain will play a pivotal role in realizing sustainable, scalable, and intelligent 6G-enabled MEC systems capable of supporting future applications such as immersive extended reality, autonomous systems, and massive Internet of Things deployments.

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