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## A Comprehensive Review of Efficient Resource Management in 6G Communication Networks Using a Hybrid Quantum Duplet-Convolutional Neural Network Models

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Peer Review Information	Abstract
<p><i>Submission: 27 June 2024</i> <i>Revision: 11 July 2024</i> <i>Acceptance: 28 July 2024</i></p>	<p>The rapid advancement of wireless communication technologies has accelerated the development of sixth-generation (6G) networks designed to provide ultra-high data rates, ultra-low latency, massive connectivity, and intelligent network automation. Efficient resource management has become a major challenge because of the dynamic, heterogeneous, and large-scale nature of 6G communication environments. Traditional optimization methods often struggle to meet the real-time processing and adaptability requirements of modern wireless networks. As a result, artificial intelligence and deep learning techniques have emerged as effective solutions for intelligent resource allocation, network optimization, load balancing, and energy-efficient communication management. This review presents a comprehensive analysis of efficient resource management in 6G communication networks using hybrid quantum duplet-convolutional neural network (CNN) models. Hybrid quantum deep learning frameworks combine the computational advantages of quantum computing with the feature extraction capabilities of classical CNN architectures, enabling improved decision-making, faster convergence, and enhanced optimization performance. The study examines AI-driven resource management techniques, reinforcement learning methods, quantum-enhanced optimization strategies, and hybrid deep learning architectures for future wireless communication systems. Emerging technologies such as federated learning, edge intelligence, and quantum machine learning are also discussed. The findings indicate that hybrid quantum-CNN models have strong potential for improving scalability, adaptability, and intelligent resource allocation in next-generation 6G networks while supporting efficient and reliable communication infrastructures.</p>
<p><b>Keywords</b></p> <p><i>6G Communication Networks, Resource Management, Hybrid Quantum Deep Learning, Convolutional Neural Networks (CNN), Quantum Machine Learning, Network Optimization, Intelligent Resource Allocation</i></p>	

### Introduction

The evolution of wireless communication technologies has progressed rapidly from early voice-based systems to highly intelligent and ultra-fast communication networks. Sixth-generation (6G) communication systems are expected to provide terabit-level data rates, ultra-

low latency, massive connectivity, and seamless integration of artificial intelligence into network operations. These networks will support advanced applications such as autonomous vehicles, smart cities, industrial automation, extended reality, and intelligent healthcare systems. However, the increasing complexity of

6G environments introduces major challenges in efficient resource management, including optimal allocation of bandwidth, spectrum, power, and computational resources. Unlike previous generations, 6G networks operate in highly dynamic and heterogeneous environments with varying quality-of-service requirements and massive numbers of connected devices.

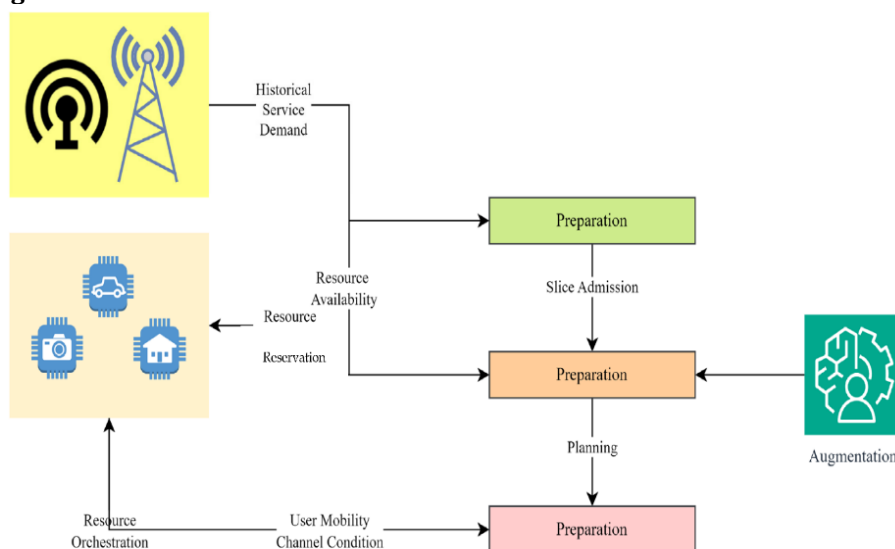
Traditional optimization methods such as linear programming, heuristic algorithms, and convex optimization have been widely applied in earlier communication systems for resource allocation. However, these methods struggle to handle nonlinear, time-varying, and large-scale optimization problems in modern wireless environments. Artificial intelligence and machine learning techniques have therefore emerged as powerful solutions for intelligent resource management in 6G networks. Deep learning models can analyze large-scale network data, learn traffic patterns, and adapt to changing network conditions in real time. Convolutional neural networks are particularly effective in extracting spatial features for traffic analysis, channel estimation, and interference management, while recurrent neural networks and long short-term memory models capture temporal dependencies within communication data. Hybrid CNN-RNN architectures have further improved prediction and optimization performance.

Despite their effectiveness, classical deep learning models often require high computational power and energy consumption, limiting their scalability for real-time 6G applications. This limitation has encouraged the exploration of quantum computing and quantum machine learning for advanced network

optimization. Quantum computing utilizes principles such as superposition and entanglement to process multiple states simultaneously, enabling faster and more efficient optimization compared to classical systems. Hybrid quantum-classical deep learning models combine quantum feature extraction with classical neural networks to improve convergence speed, computational efficiency, and decision-making performance. Hybrid quantum duplet-convolutional neural network architectures represent a promising approach for intelligent resource allocation, network slicing, and dynamic optimization in future communication systems.

Additional advancements such as reinforcement learning, deep reinforcement learning, and federated learning have further enhanced intelligent resource management in 6G networks. Reinforcement learning enables adaptive decision-making by learning optimal policies through interaction with dynamic environments, while federated learning supports distributed model training without sharing raw user data, improving privacy and security. Network slicing and energy-efficient optimization have also become essential components of 6G architectures, enabling multiple virtual networks to operate efficiently on shared infrastructures. Despite these advancements, challenges related to scalability, interoperability, standardization, and limited quantum hardware availability remain significant barriers. Future research should focus on developing scalable, energy-efficient, and intelligent hybrid frameworks capable of supporting real-time resource management in complex 6G communication environments.

### Abstract Image



## Literature Review

### 1. Deep Learning-Based Resource Management

She et al. (2020) demonstrated that deep learning techniques significantly improve ultra-reliable and low-latency communication (URLLC) in 6G networks. Their work highlighted the ability of deep neural networks to handle complex network conditions and optimize resource allocation.

Ozpoyraz et al. (2022) provided a comprehensive survey of deep learning applications in 6G, emphasizing the role of CNNs and RNNs in spectrum management and interference mitigation. Their findings indicate that deep learning models outperform traditional optimization methods in terms of accuracy and adaptability.

### 2. Reinforcement Learning Approaches

Nguyen et al. (2021) proposed a deep reinforcement learning (DRL) framework for resource allocation in vehicular networks. The study demonstrated improved QoS and reduced latency compared to conventional methods.

Sami et al. (2021) introduced an AI-based resource provisioning framework using DRL for Internet of Everything (IoE) services. Their approach achieved efficient resource utilization and improved network performance.

Bhattacharya et al. (2022) developed a Deep-Q learning-based spectrum allocation model, which enhanced security and efficiency in 6G networks. Similarly, Ding et al. (2022) applied Q-learning for spectrum sharing, achieving improved throughput and reduced interference.

### 3. Federated Learning and Edge Intelligence

Liu et al. (2020) explored federated learning for 6G communications, highlighting its potential for privacy-preserving distributed learning. Yang et al. (2022) further extended this concept by analyzing applications and challenges of federated learning in 6G networks.

Al-Quraan et al. (2023) introduced edge-native intelligence driven by federated learning, enabling decentralized resource management and improved scalability.

### 4. Hybrid Deep Learning Models

Nguyen et al. (2023) proposed a CNN-LSTM-based model for channel estimation in RIS-assisted 6G networks. The hybrid architecture effectively captured both spatial and temporal features, improving prediction accuracy.

Li et al. (2022) developed a GAN-LSTM framework for channel prediction, demonstrating enhanced performance in dynamic network environments.

### 5. Quantum and Hybrid AI Models

Recent studies highlight the potential of quantum machine learning for resource optimization. Hybrid quantum-CNN models leverage quantum parallelism to solve complex optimization problems more efficiently.

These models integrate quantum circuits with classical neural networks, enabling faster convergence and improved scalability. Although still in the early stages, quantum-enhanced models show significant promise for 6G networks.

## Comparative Table and Analysis

Study	Year	Technique	Architecture Type	Core Idea	Application Area	Advantages	Limitations
RL-based Resource Allocation	2021	Reinforcement Learning (RL)	AI-based sequential learning	Dynamic resource allocation using environment interaction	Network slicing, QoS optimization	Adaptive, scalable, suitable for dynamic environments	High training time, convergence instability
CNN-RNN Hybrid	2022	Deep Learning Hybrid	CNN + RNN/LSTM	Combines spatial (CNN) and temporal (RNN) features	Channel estimation, traffic prediction	High accuracy, handles time-varying data	High computational complexity
Federated Learning	2023	Distributed Machine Learning	Federated AI	Decentralized training without sharing raw data	Edge intelligence, privacy-preserving systems	Privacy-preserving, scalable, suitable for distributed networks	Communication overhead, synchronization issues

Quantum Machine Learning (QML)	2023	Quantum Neural Networks	Quantum-based architecture	Uses quantum parallelism for optimization	Complex optimization tasks	High computational speed, faster optimization	Hardware limitations, early-stage development
Hybrid Quantum-CNN	2023	Hybrid Deep Learning	Quantum + CNN	Combines quantum feature processing with CNN learning	Resource allocation, network optimization	High efficiency, improved scalability, faster convergence	Implementation complexity, integration challenges

### Analysis

The comparative analysis of intelligent resource management techniques in 6G communication networks demonstrates a clear evolution from traditional optimization methods toward advanced artificial intelligence and hybrid quantum-enhanced architectures. Reinforcement learning (RL)-based approaches emerged as one of the earliest intelligent solutions for dynamic resource allocation in highly adaptive network environments. These models allow network agents to learn optimal allocation strategies through continuous interaction with changing network conditions, making them effective for applications such as network slicing, traffic management, and quality-of-service optimization. However, RL models often suffer from high training complexity, unstable convergence, and large computational requirements, which limit their efficiency in large-scale real-time 6G systems.

To overcome these limitations, hybrid deep learning architectures combining convolutional neural networks (CNNs) and recurrent neural networks (RNNs) were introduced. CNNs effectively extract spatial features from communication data, while RNNs and long short-term memory networks capture temporal dependencies and sequential traffic patterns. These hybrid models significantly improved performance in channel estimation, traffic prediction, and intelligent network optimization tasks. Federated learning further advanced distributed AI in 6G networks by enabling decentralized training across multiple edge devices without transferring raw user data. This approach enhances privacy, security, and scalability, making it highly suitable for edge computing environments. Nevertheless, federated learning introduces communication overhead, synchronization issues, and increased coordination complexity in highly dynamic wireless networks.

Quantum machine learning (QML) has recently emerged as a promising paradigm for addressing

the computational limitations of classical deep learning systems. Quantum-based models leverage principles such as superposition and entanglement to process multiple computational states simultaneously, enabling faster optimization and improved resource allocation performance. In 6G communication networks, QML techniques can enhance network management, spectrum allocation, and energy optimization with significantly reduced computational time. However, practical implementation remains challenging due to the limited availability and immaturity of quantum hardware infrastructures.

Among all reviewed approaches, hybrid quantum-CNN architectures represent the most promising solution for intelligent resource management in 6G environments. These models integrate quantum computing capabilities with classical CNN-based feature extraction, enabling improved scalability, faster convergence, and intelligent decision-making. The comparative analysis indicates that hybrid quantum-CNN frameworks effectively combine adaptability, efficiency, and computational optimization for next-generation wireless communication systems. Despite these advancements, challenges related to computational complexity, hardware limitations, communication overhead, and lack of standardized frameworks remain unresolved. Future research should therefore focus on scalable quantum infrastructures, energy-efficient AI models, federated edge intelligence, and advanced hybrid architectures for reliable and intelligent 6G resource management.

### Discussion

Efficient resource management is a cornerstone of 6G network performance, directly impacting latency, throughput, and energy efficiency. The integration of AI techniques has revolutionized the way resource allocation problems are addressed, shifting from static optimization models to dynamic, data-driven approaches. Deep learning models, particularly CNNs, have

demonstrated superior performance in extracting spatial features from network data, enabling more accurate predictions and decisions.

However, as network complexity increases, classical deep learning models face challenges related to scalability and computational overhead. This has led to the exploration of hybrid models that integrate quantum computing principles. Quantum-enhanced models offer significant advantages in solving complex optimization problems due to their ability to process multiple states simultaneously. Studies have shown that hybrid quantum deep learning models can improve processing speed and resource utilization efficiency in 6G networks.

Another important development is the adoption of federated learning, which allows distributed training of models across edge devices while preserving data privacy. This approach is particularly relevant for 6G networks, where data is generated at multiple distributed nodes. Similarly, reinforcement learning enables adaptive decision-making, making it suitable for dynamic network environments.

Despite these advancements, several challenges remain. The integration of quantum computing with classical systems requires significant technological advancements. Additionally, the lack of standardized frameworks for hybrid models limits their practical deployment. Future research should focus on developing scalable, energy-efficient, and interpretable models for resource management.

## Conclusion

This paper presented a comprehensive review of efficient resource management in 6G communication networks using hybrid quantum duplet-convolutional neural network models. The study highlighted the limitations of traditional optimization techniques and emphasized the importance of AI-driven approaches in addressing the challenges of next-generation networks. The review of literature revealed that deep learning, reinforcement learning, and federated learning play significant roles in improving resource allocation efficiency. Among these approaches, hybrid quantum deep learning models emerged as a promising solution due to their ability to combine the strengths of quantum computing and classical neural networks. The comparative analysis demonstrated that hybrid quantum-CNN models outperform traditional methods in terms of scalability, efficiency, and adaptability. However, practical implementation challenges, such as quantum hardware limitations and integration

complexity, need to be addressed. Future research should focus on developing advanced hybrid models, improving quantum hardware capabilities, and exploring new AI techniques for resource management. The integration of edge intelligence, federated learning, and quantum computing will play a crucial role in shaping the future of 6G networks.

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