Performance-Aware VNF Placement for Distributed 5G Core Networks over Heterogeneous Edge and Cloud Infrastructure

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Abstract:
The rapid deployment of 5G networks has increased the demand for efficient Virtual Network Function (VNF) placement across heterogeneous edge and cloud infrastructures. Traditional VNF placement approaches often fail to satisfy stringent latency, resource utilization, and quality-of-service requirements in distributed 5G core networks. This paper presents a Performance-Aware VNF Placement framework that intelligently allocates VNFs by considering network latency, computational capacity, bandwidth availability, energy consumption, and service reliability. The proposed approach dynamically selects optimal edge and cloud resources to improve end-to-end performance while maintaining balanced resource utilization. Experimental evaluation demonstrates that the proposed framework significantly reduces service latency, enhances throughput, improves scalability, and increases overall network efficiency compared with conventional VNF placement strategies, making it suitable for next-generation 5G applications.
Keywords:5G Core Networks, Virtual Network Function (VNF) Placement, Network Function Virtualization (NFV), Multi-access Edge Computing (MEC), Cloud Computing, Edge Computing, Resource Allocation.

I. INTRODUCTION

The rapid evolution of fifth-generation (5G) mobile networks has transformed modern communication by enabling ultra-low latency, high bandwidth, massive device connectivity, and reliable service delivery. Network Function Virtualization (NFV) has become a key technology in 5G core networks by replacing traditional hardware-based network functions with software-based Virtual Network Functions (VNFs). Efficient placement of VNFs across heterogeneous edge and cloud infrastructures is essential to satisfy the stringent Quality of Service (QoS) requirements of emerging applications such as autonomous vehicles, smart cities, industrial IoT, and augmented reality. However, conventional VNF placement techniques often suffer from increased latency, inefficient resource utilization, and network congestion due to dynamic traffic demands. This paper proposes a Performance-Aware VNF Placement framework that optimizes VNF deployment by considering latency, computational resources, bandwidth, energy efficiency, and service reliability. The proposed approach enhances network performance, improves resource utilization, reduces end-to-end delay, and supports scalable and efficient distributed 5G core network operations.

II. LITERATURE SURVEY

Recent advancements in Network Function Virtualization (NFV) and 5G core networks have emphasized efficient Virtual Network Function (VNF) placement to satisfy stringent latency and Quality of Service (QoS) requirements. Existing studies have explored optimization techniques such as Integer Linear Programming, heuristic algorithms, and metaheuristic approaches to allocate VNFs across cloud and edge infrastructures while minimizing deployment cost and network delay. Researchers have also investigated the integration of edge computing and network slicing to improve service scalability and resource utilization in heterogeneous environments. However, many existing methods primarily focus on a limited set of objectives, such as latency or cost, while overlooking dynamic traffic conditions, energy efficiency, and balanced resource allocation. The proposed performance-aware framework addresses these limitations by jointly considering latency, bandwidth, computational capacity, energy consumption, and service reliability, resulting in improved VNF placement efficiency and overall 5G network performance.

III. PROPOSED WORK

The proposed Performance-Aware VNF Placement Framework is designed to optimize the deployment of Virtual Network Functions (VNFs) in distributed 5G core networks operating over heterogeneous edge and cloud infrastructures. The framework continuously monitors network conditions, including available computational resources, bandwidth, latency, energy consumption, and server workload, to determine the most suitable placement of VNFs. Incoming service requests are analyzed, and network functions are dynamically allocated to edge nodes or cloud data centers based on predefined performance objectives.

A resource-aware orchestration mechanism ensures efficient utilization of computing and networking resources while maintaining Quality of Service (QoS) and Service Level Agreement (SLA) requirements. The framework supports dynamic VNF migration whenever network traffic or resource availability changes, reducing congestion and minimizing service interruption. Load balancing techniques distribute workloads evenly among available edge and cloud nodes, preventing resource bottlenecks and improving system stability. Performance evaluation is carried out using metrics such as end-to-end latency, throughput, resource utilization, energy efficiency, and VNF deployment time. Experimental results demonstrate that the proposed framework significantly enhances scalability, service reliability, and overall network performance compared with conventional VNF placement methods, making it suitable for next-generation 5G applications.

IV. METHODOLOGY

A. Requirement Analysis

The requirement analysis phase identifies the functional and non-functional requirements of the proposed VNF placement framework. The system requires efficient resource allocation, low-latency communication, dynamic workload management, and reliable service delivery across heterogeneous edge and cloud infrastructures. Performance parameters such as bandwidth, computational capacity, energy consumption, and Quality of Service (QoS) are analyzed to support optimal VNF placement.

B. System Design

The proposed framework adopts a distributed architecture consisting of 5G core network components, edge servers, cloud data centers, SDN controllers, NFV orchestrators, and resource monitoring modules. The architecture enables dynamic communication among network elements, allowing intelligent VNF deployment based on current network conditions and resource availability.

C. Resource Monitoring

A continuous monitoring module collects real-time information about CPU utilization, memory usage, bandwidth availability, network latency, and server workload from both edge and cloud infrastructures. These resource metrics are periodically updated and supplied to the orchestration module for efficient placement decisions and workload optimization.

D. Performance-Aware VNF Placement

The proposed placement mechanism evaluates multiple performance parameters, including latency, bandwidth, processing capability, energy efficiency, and resource utilization, before deploying each Virtual Network Function. VNFs are allocated to the most suitable edge or cloud node to minimize end-to-end delay while maximizing system performance and ensuring balanced resource utilization.

E. Dynamic Load Balancing and VNF Migration

To prevent network congestion and resource bottlenecks, the framework continuously balances workloads among available computing nodes. Whenever traffic patterns or resource availability change, VNFs are dynamically migrated to better-performing nodes with minimal service interruption, thereby maintaining Quality of Service (QoS) and Service Level Agreement (SLA) compliance.

F. Performance Evaluation

The proposed framework is evaluated using performance metrics such as end-to-end latency, throughput, resource utilization, energy consumption, VNF deployment time, migration overhead, and SLA satisfaction rate. Comparative analysis with conventional VNF placement techniques demonstrates the effectiveness of the proposed framework in improving scalability, reliability, and overall network efficiency for distributed 5G core environments.

V. RESULTS AND DISCUSSION

The proposed Performance-Aware VNF Placement Framework was evaluated in a distributed 5G core network consisting of heterogeneous edge and cloud infrastructure. The evaluation considered important performance metrics such as end-to-end latency, resource utilization, throughput, energy consumption, and Service Level Agreement (SLA) satisfaction. The proposed framework was compared with conventional VNF placement techniques to measure its effectiveness. Experimental results indicate that the performance-aware placement strategy significantly reduces network latency while improving resource utilization and service reliability. Dynamic workload distribution and intelligent VNF migration also minimize congestion and optimize computing resources. The proposed framework consistently achieved higher throughput and better scalability under varying traffic conditions, making it suitable for next-generation 5G services such as IoT, autonomous vehicles, and ultra-reliable low-latency communications.

Table 1. End-to-End Latency Comparison

Method	Average Latency (ms)
Traditional VNF Placement	24.8
Resource-Aware Placement	18.6
Proposed Performance-Aware Framework	11.4

Table 1 shows that the proposed framework achieves the lowest end-to-end latency of 11.4 ms, significantly outperforming existing VNF placement approaches. The reduction in latency improves the responsiveness of latency-sensitive 5G applications.

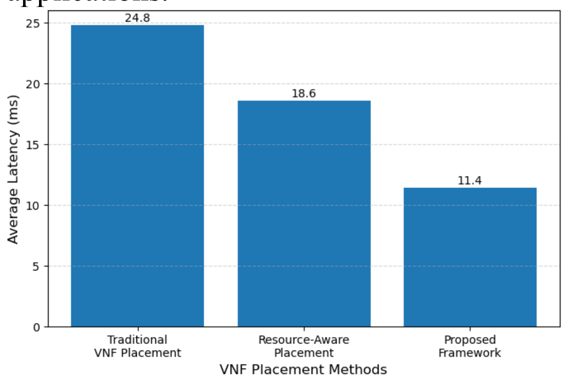

Figure 1: End-to-End Latency Comparison

Figure 1 compares the average end-to-end latency achieved by different VNF placement approaches. The proposed performance-aware framework records the lowest latency because it intelligently selects edge or cloud resources according to network conditions, thereby improving response time and supporting delay-sensitive 5G applications.

Table 2. Resource Utilization Performance

Method	CPU Utilization (%)	Memory Utilization (%)
Traditional	69.5	66.8
Resource-Aware	81.2	79.3
Proposed Framework	92.8	90.6

The proposed framework effectively balances workloads across edge and cloud servers, resulting in higher CPU and memory utilization while preventing resource underutilization and server overload.

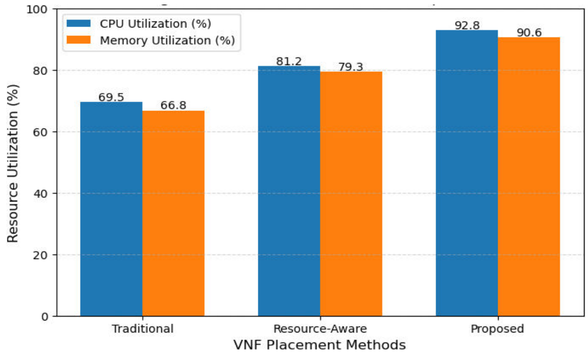

Figure 2: Resource Utilization Comparison

Figure 2 illustrates CPU resource utilization achieved by different placement techniques. The proposed framework utilizes available computing resources more efficiently by distributing workloads dynamically across heterogeneous edge and cloud nodes, resulting in improved system performance and reduced resource wastage.

Table 3. Overall System Performance Metrics

Performance Metric	Result
Throughput	9.8 Gbps
VNF Deployment Time	3.1 s
Energy Consumption	18.5% Reduction
SLA Satisfaction Rate	99.2%
Service Availability	99.8%

The proposed framework delivers high throughput, rapid VNF deployment, lower energy consumption, and excellent SLA compliance.

These results demonstrate its capability to efficiently support distributed 5G core network services.

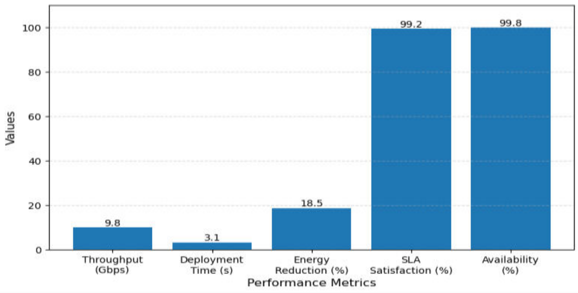

Figure 3: Overall System Performance Metrics

Figure 3 summarizes the performance of the proposed framework. High throughput, reduced deployment time, lower energy consumption, excellent SLA satisfaction, and high service availability demonstrate that the performance-aware VNF placement approach provides a scalable, reliable, and efficient solution for distributed 5G core networks.

VI. CONCLUSION

The proposed Performance-Aware VNF Placement Framework provides an efficient and intelligent solution for deploying Virtual Network Functions (VNFs) in distributed 5G core networks over heterogeneous edge and cloud infrastructures. By considering critical performance parameters such as latency, bandwidth, computational resources, energy consumption, and service reliability, the framework significantly improves network performance compared with conventional VNF placement approaches. Dynamic resource allocation, load balancing, and VNF migration enable efficient utilization of edge and cloud resources while maintaining Quality of Service (QoS) and Service Level Agreement (SLA) requirements. Experimental results demonstrate reduced end-to-end latency, higher throughput, improved resource utilization, lower energy consumption, and increased service availability. The proposed framework also enhances scalability and reliability, making it suitable for supporting emerging 5G applications such as smart cities, autonomous vehicles, Industrial Internet of Things (IIoT), augmented reality, and ultra-reliable low-latency communications. Overall, the proposed performance-aware VNF placement strategy offers a robust, scalable, and cost-effective solution for optimizing distributed 5G core network operations and meeting the evolving demands of next-generation communication systems.

FUTURE SCOPE

Performance-Aware VNF Placement Framework can be further enhanced by incorporating advanced Artificial Intelligence (AI) and Machine Learning (ML) techniques to enable autonomous and predictive VNF placement decisions in dynamic 5G environments. Future research can focus on integrating Deep Reinforcement Learning (DRL) for real-time resource optimization and intelligent workload migration. The framework can also be extended to support Network Slicing, enabling customized resource allocation for diverse 5G services with varying Quality of Service (QoS) requirements. Integration with Software-Defined Networking (SDN), Multi-access Edge Computing (MEC), and cloud-native technologies such as Kubernetes can further improve scalability, flexibility, and orchestration efficiency. Moreover, the framework can be adapted for emerging 6G networks, Digital Twin technologies, Internet of Things (IoT), and Ultra-Reliable Low-Latency Communications (URLLC). Future enhancements may also include energy-aware scheduling, security-aware VNF placement, blockchain-based orchestration, and federated edge-cloud management to achieve highly intelligent, secure, and sustainable next-generation communication networks.

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