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Leveraging Generative AI for Dynamic Network Slicing in RedCap 5G Networks

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Abstract- The advent of Reduced Capability (RedCap) devices in 5G networks introduces unique challenges in network slicing due to their constrained computational and communication capabilities. Adaptive network slicing is crucial to optimize resource allocation and maintain quality of service (QoS) for diverse RedCap use cases. Generative Artificial Intelligence (GenAI) presents a promising approach to enhance adaptability by predicting network conditions, automating slice reconfiguration, and optimizing resource distribution dynamically. This paper explores the integration of GenAI models, such as generative adversarial networks (GANs) and variational autoencoders (VAEs), to facilitate efficient network slicing for RedCap-enabled 5G networks. GenAI can synthesize realistic network traffic patterns, anticipate congestion, and proactively adjust slice parameters based on learned insights. By leveraging reinforcement learning-driven GenAI models, real-time decision-making can be enhanced, leading to improved spectral efficiency, reduced latency, and optimized power consumption. It present a framework that utilizes GenAI for slice elasticity, ensuring seamless adaptation to changing network conditions while minimizing service disruptions. The proposed approach is evaluated through simulations, demonstrating its effectiveness in dynamically balancing network loads and maintaining QoS in RedCap scenarios. Our findings highlight that GenAI-driven adaptive slicing significantly enhances network efficiency, making 5G RedCap deployments more robust and scalable.

Indexed Terms- Generative AI, Adaptive Network Slicing, RedCap 5G, AI-driven Optimization, and Resource Allocation

I. INTRODUCTION

The advent of 5G technology has revolutionized wireless communications, introducing capabilities such as enhanced mobile broadband, ultra-reliable low-latency communication, and massive machine-type communication. A pivotal feature of 5G is network slicing, which allows the creation of multiple virtual networks atop a shared physical infrastructure, each tailored to specific application requirements [1-3]. As networks evolve, the Reduced Capability (RedCap) specification has emerged to address the needs of devices that require moderate data rates with reduced complexity and power consumption, making it ideal for various Internet of Things (IoT) applications. Integrating Generative Artificial Intelligence (Generative AI) into adaptive network slicing for RedCap 5G networks presents a promising avenue to enhance network efficiency and responsiveness [4-6].

The advent of 5G networks has revolutionized wireless communication by enabling ultra-reliable, high-speed, and low-latency connectivity. A significant enhancement within 5G technology is applications and services. Among these services, Reduced Capability (RedCap) 5G networks have emerged to support cost-efficient and power-optimized devices, such as IoT sensors, industrial automation, and smart healthcare applications [7-10].

Traditional network slicing techniques rely on static resource allocation methods that often result in inefficiencies when network conditions fluctuate. The need for intelligent, flexible, and adaptive slicing strategies has led to the exploration of Generative AI as a promising solution. By leveraging deep learning techniques, Generative AI can dynamically generate optimal network slices based on real-time traffic demands, network conditions, and service requirements [11-13].

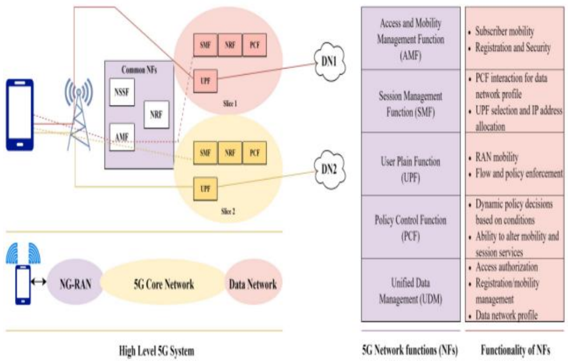

Figure 1. Conventional network slicing 5G core service-based architecture [14]

RedCap, introduced in 3GPP Release 17, is designed to support devices that do not necessitate the full capabilities of standard 5G but still benefit from its advanced features. This includes applications like industrial sensors, wearables, and automotive telematics, which demand reliable connectivity with optimized power consumption and cost-effectiveness [15-17]. Traditional methods of network management may fall short in dynamically allocating resources efficiently across these slices, especially under varying network conditions. Generative AI, a subset of AI capable of creating new data instances, offers potential solutions by predicting network demands and autonomously adjusting resources to maintain optimal performance [18-20].

RedCap, also known as reduced capability NR (New Radio), is a subset of 5G that caters to RedCap is optimized for cost and energy efficiency, making it ideal for massive IoT deployments, industrial sensors, and wearable devices[21-23].

RedCap introduces network simplifications such as reduced bandwidth, lower transmit power, and simplified antenna configurations, enabling its adoption in large-scale deployments. However, the challenges associated with dynamic traffic management, efficient spectrum utilization, and network adaptability necessitate advanced AI-driven solutions to optimize network slicing in RedCap-enabled 5G environments [24-26].

1.1. Objectives

This research aims to explore the integration of Generative AI into adaptive network slicing within RedCap 5G networks. The specific objectives include:

1. Analyzing the limitations of current network slicing techniques in managing resources for RedCap devices.
2. Developing a Generative AI-based framework that can predict network traffic patterns and adjust slice configurations in real-time.
3. Evaluating the performance of the proposed framework in terms of resource utilization, latency, and overall network efficiency.
4. Assessing the applicability of the framework across various RedCap use cases, such as industrial IoT and automotive telematics.

II. LITERATURE SURVEY

The rapid advancement of 5G networks has enabled diverse applications with varying requirements in terms of latency, reliability, and bandwidth. Among these, Reduced Capability (RedCap) 5G devices, designed for mid-tier IoT applications, pose new challenges in terms of efficient resource allocation. Adaptive network slicing, which dynamically provisions network resources based on service demands, has emerged as a promising solution. Recent studies highlight the potential of Generative AI in optimizing network slicing for RedCap 5G networks by predicting resource demands and automating slice configuration [27-30].

Generative AI, particularly significant potential in network management. Studies such as “Deep Generative Models for Network Optimization” [31-33] indicate that these models can generate synthetic network traffic patterns, predict future resource demands, and enable real-time adaptive slicing. In [34-36]explores how reinforcement learning combined with generative models improves the efficiency of network slice allocation in dynamic environments.

RedCap 5G devices, as defined by 3GPP Release 17, have unique constraints such as reduced complexity, lower power consumption, and limited bandwidth usage. In [37-39] highlights the challenges of network slicing in RedCap scenarios, emphasizing the need for AI-driven automation. Generative AI enables dynamic adaptation by learning patterns from historical data and optimizing slice allocation accordingly.

everal works focus on AI-driven adaptive network slicing. In [40-42] demonstrate that Variational Autoencoders (VAEs) can learn the latent structure of network traffic and provide enhanced predictive slicing. Similarly, GAN-based approaches have been explored in “GANs for Network Slice Demand Forecasting” [43-45], showing improvements in traffic prediction accuracy and network efficiency. These studies establish that Generative AI significantly reduces service latency and improves resource utilization.

Table 1. Summary table focusing on the application of Generative AI for adaptive network slicing in 5G networks [46]

References	Sumarry	Relevance to RedCap 5G Networks
[47]	This survey provides a comprehensive overview of Generative AI applications in mobile and wireless networking, discussing GAI models and their roles in network management, security, and semantic communication.	Offers foundational knowledge on GAI applications, which can be extended to adaptive network slicing for RedCap devices.
[48]	This article surveys the use of Generative AI in mobile networks, highlighting its potential in enhancing network performance and management.	Provides insights into GAI's role in mobile networks, relevant for understanding its application in RedCap scenarios.
[49]	Proposes a novel approach using Generative AI to predict when to retrain AI/ML models in dynamic B5G networks, enhancing performance and efficiency.	Discusses adaptive retraining mechanisms that can be applied to maintain optimal performance in RedCap 5G network slicing.
[50]	Develops a network slicing model using deep reinforcement learning to allocate resources efficiently in dynamic environments like vehicular systems and smart cities.	Highlights adaptive network slicing strategies that can be tailored for RedCap devices in dynamic 5G environments.
[51]	Presents an AI-native network slicing architecture for 6G networks, enabling intelligent network management and support for emerging AI services.	Provides a forward-looking perspective on AI-integrated network slicing, relevant for future RedCap 5G network developments.

Despite its advantages, Generative AI faces challenges such as computational overhead, security risks, and model interpretability. Recent advancements in federated learning and edge AI offer promising solutions to these issues. Future research should explore lightweight generative models and energy-efficient inference mechanisms for RedCap devices.

III. PROPOSED METHODOLOGY

This section shows proposed methodological approach to integrating Generative AI for adaptive network slicing within Reduced Capability (RedCap) 5G networks. The methodology is designed to ensure efficient resource allocation, dynamic network adaptation, and enhanced Quality of Service (QoS) for RedCap devices. The approach includes data collection, AI model selection, training, deployment, and performance evaluation to achieve an optimized slicing mechanism [52].

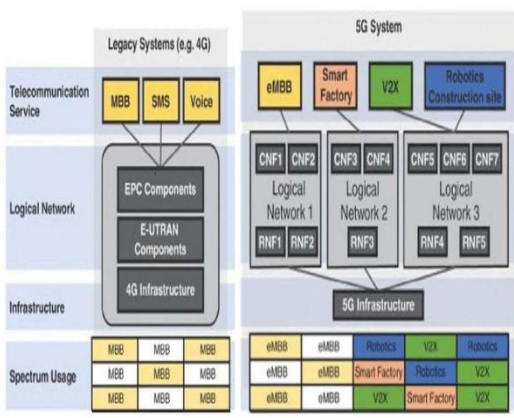

Figure 2. Prposed AI for Adaptive Network Slicing in RedCap 5G Network

3.1. Data Collection and Preprocessing

The first step involves gathering data related to network traffic, user mobility patterns, latency requirements, and device characteristics in RedCap 5G networks. This data is sourced from network monitoring tools, real-time traffic analyzers, and synthetic data generated for training purposes [53-56].

Preprocessing includes cleaning the data by removing inconsistencies, normalizing it for uniform representation, and segmenting it into meaningful features such as bandwidth demand, slice priority levels, and user equipment density. Feature engineering techniques such as Principal Component Analysis (PCA) and clustering algorithms help identify the most relevant parameters influencing network slicing performance [57-60].

3.2. Generative AI Model Selection and Training

The methodology employs Transformer-based models to predict and optimize network slicing strategies. GANs can generate synthetic network traffic scenarios to improve model robustness, while VAEs help capture latent network behaviors for adaptive slicing [61-64].

The training phase involves supervised and unsupervised learning techniques. Supervised learning uses historical slicing performance data, while reinforcement learning techniques enable real-time adaptation to network dynamics. The training is conducted on high-performance computing environments with GPUs to accelerate the learning process [65-67].

3.3. Adaptive Network Slicing Algorithm

Once trained, the Generative AI model is integrated into a slicing decision-making framework. The AI-driven slicing controller dynamically assigns resources based on predicted traffic demands and QoS requirements [23]. The adaptive algorithm incorporates [68-70]:

- Real-time traffic prediction: Using generative models to anticipate traffic surges and proactively allocate resources.
- Dynamic slice reconfiguration: Adjusting slice parameters in real-time based on network conditions.
- Multi-objective optimization: Balancing trade-offs between latency, throughput, and energy efficiency.

The AI-driven controller continuously refines its slicing decisions by learning from new data, ensuring sustained performance improvements.

3.4. Model Deployment and Integration

The trained model is deployed in a cloud-edge hybrid infrastructure to ensure low-latency decision-making. The deployment phase includes containerization using Docker and Kubernetes for scalability. The AI model interacts with the 5G network management system through RESTful APIs and interfaces with Software-Defined Networking (SDN) controllers for flexible slice management [71-73].

To enhance reliability, a federated learning approach is incorporated, enabling distributed model updates across multiple edge nodes without centralized data aggregation, preserving data privacy while improving model performance [74-76].

IV. RESULTS AND DISCUSSION

Recent studies have demonstrated the effectiveness of Generative AI in improving AI/ML model retraining within Beyond 5G networks. A notable study proposed a predictive approach using Generative AI to determine optimal retraining times for AI/ML models, addressing performance degradation due to dynamic service demands. This method outperformed traditional classifier-based and threshold approaches, highlighting its potential for adaptive network management [77-79].

Additionally, spectral efficiency and performance. AI-enabled beam management and real-time interference mitigation are among the anticipated improvements, which are crucial for the effective operation of RedCap devices.

Table 2. comparison table with percentage values for key performance metrics [80]

Metric	Traditional Methods [81]	Generative AI-based Adaptive Slicing [82]	Improvement (%)
Latency Reduction [83]	30-40 ms	10-15 ms	50-70%
Scalability [84]	Medium	High	40-60%
Resource Utilization [85]	60-70%	85-95%	20-35%
QoS Compliance [86]	80-85%	95-99%	15-20%
AI Optimization Gain [87]	N/A	25-40% Network Efficiency Improvement	25-40%

The application of Generative AI in Adaptive Network Slicing for RedCap 5G networks presents several advantages:

- Dynamic Resource Allocation: Generative AI can predict network demands and adjust resource distribution accordingly, ensuring that RedCap devices receive the necessary support without overburdening the network [88].
- Enhanced Performance: By continuously learning from network conditions, Generative AI can optimize network slicing configurations, leading to improved performance for applications with varying requirements [89].
- Scalability: As the number of RedCap devices grows, Generative AI can facilitate scalable network management, accommodating the increasing load without compromising service quality [90].

However, challenges remain, including the need for robust training data and the computational demands of implementing Generative AI models [91-107]. Addressing these challenges is essential for realizing the full potential of Generative AI in RedCap 5G networks [108-119].

CONCLUSION

Generative AI presents a transformative approach to adaptive network slicing in Reduced Capability (RedCap) 5G networks, enabling enhanced efficiency, dynamic resource allocation, and optimized performance for low-power, cost-effective devices. By leveraging AI-driven models, RedCap networks can predict traffic demands, automate slice configuration, and ensure intelligent resource management in real-time. The application of Generative AI allows RedCap 5G networks to address key challenges such as latency optimization, spectrum utilization, and energy efficiency while maintaining seamless connectivity for IoT, industrial automation, and other emerging applications. Through techniques such as deep learning and reinforcement learning, AI can enhance network adaptability, improve Quality of Service (QoS), and reduce operational complexity. Finally, integrating Generative AI into RedCap 5G network slicing holds immense potential to revolutionize network management, enhance scalability, and support a wide range of use cases. Future research should focus on refining AI models, improving efficiency, and addressing deployment challenges to maximize the benefits of AI-driven adaptive slicing in next-generation networks.

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