Network Slicing and Emerging Technologies in 6G Networks: A Survey

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Abstract

Network slicing, a pivotal technology in the evolution of 6G networks, enables the creation of multiple virtual networks on a shared physical infrastructure, enhancing network capabilities to meet diverse application requirements. This survey explores the integration of network slicing with emerging technologies such as Multi-access Edge Computing (MEC), beamforming, millimeter wave (mmWave), Ultra-Reliable Low-Latency Communication (URLLC), and Open Radio Access Network (O-RAN), emphasizing their collective role in advancing 6G networks. MEC reduces latency by bringing computation closer to the network edge, while beamforming and mmWave technologies enhance signal quality and data transmission speed. URLLC ensures dependable, low-latency communication essential for applications like autonomous vehicles. O-RAN standardizes open network architectures to foster interoperability and innovation. Energy efficiency is addressed through dynamic resource allocation strategies, crucial for sustainable 6G networks. Terahertz communication offers potential for ultra-fast data transfer, while innovative spectrum management models optimize frequency usage. The survey underscores the importance of integrating AI/ML solutions for spectrum optimization, enhancing resource management, and addressing the challenges of spectrum access in 6G environments. Future directions include refining optimization techniques, improving real-time demand prediction, and enhancing algorithm scalability. By exploring these technologies and their integration, the survey highlights the transformative potential of network slicing in shaping the future of 6G networks, ensuring they meet the evolving demands of next-generation communication ecosystems.

1 Introduction

1.1 Significance of Network Slicing

Network slicing is a pivotal technology in the evolution of 6G networks, offering the capability to create multiple virtual networks over a shared physical infrastructure, thereby enhancing network capabilities and accommodating diverse application requirements . This approach is critical for meeting the stringent quality-of-service (QoS) demands of modern communication environments, where diverse applications must coexist efficiently, particularly in industrial settings [1]. By dynamically partitioning network resources, network slicing ensures that the varied performance requirements of different vertical industries are met in a flexible and cost-efficient manner [2].

In the context of 6G, network slicing plays a crucial role in supporting the coexistence of enhanced Mobile BroadBand (eMBB) and massive Machine-Type Communications (mMTC) services, effectively addressing resource allocation challenges amidst limited radio resources [3]. The integration of network slicing with artificial intelligence (AI) further enhances intelligent network management, which is essential for supporting emerging AI services and managing high communication uncertainty [4].

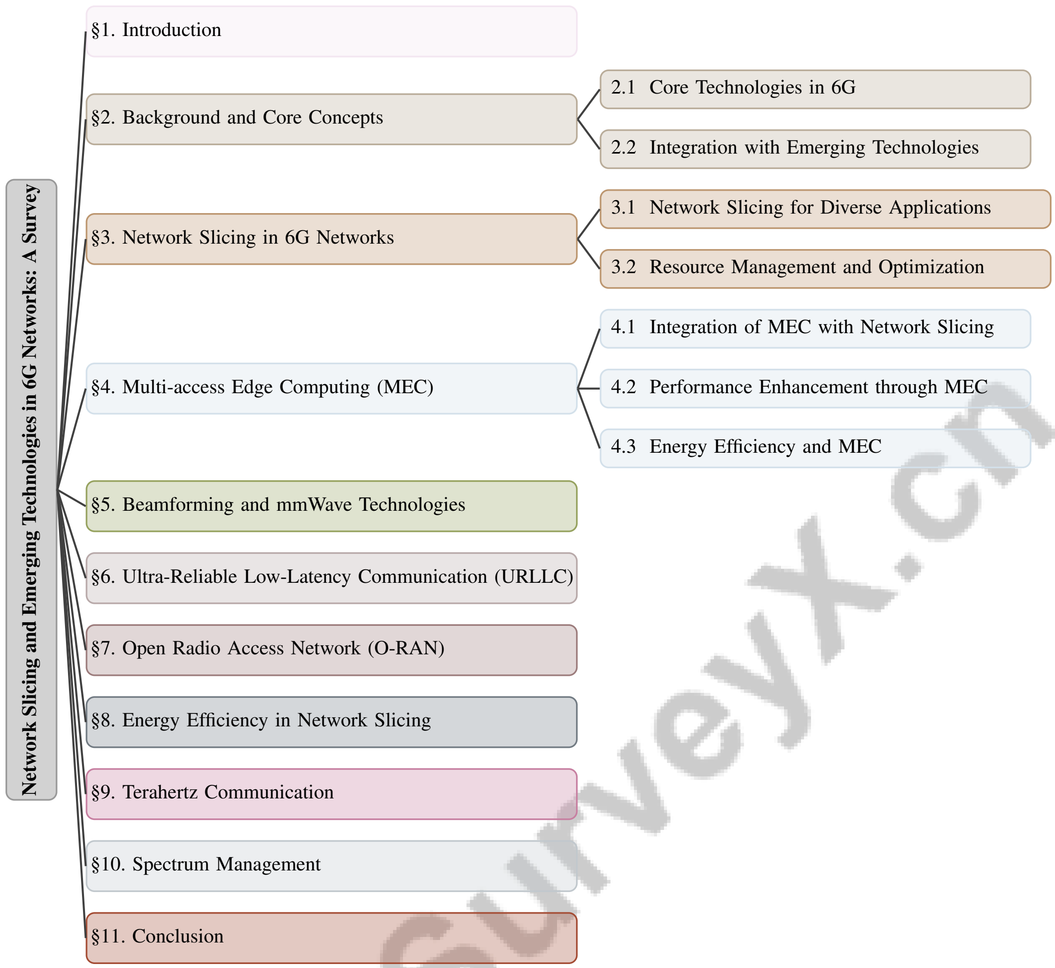

Figure 1: chapter structure

Moreover, network slicing is instrumental in enabling applications that require ultra-reliable low-latency communication, such as vehicle-to-everything (V2X) communication, which is vital for the development of intelligent transportation systems [5]. The ability to tailor network resources to specific service requirements also supports high-quality multimedia services, enhancing the user experience and fostering innovation [6]. Within the Open Radio Access Network (O-RAN) framework, network slicing addresses interoperability challenges, promoting innovation and facilitating the deployment of diverse applications.

Network virtualization, facilitated by network slicing, allows for the on-demand sharing of common infrastructure by multiple virtual networks, customized for distinct services. This flexibility is indispensable for integrating intelligent vehicular systems and smart city applications, where dynamic and efficient network management is paramount. Network slicing is a fundamental enabler of the 6G ecosystem, offering enhanced flexibility and efficiency that allows operators to create multiple isolated network instances tailored to the specific quality of service (QoS) needs of diverse applications and industries. This capability not only optimizes resource allocation and infrastructure utilization, leading to improved energy efficiency and cost-effectiveness, but also fosters innovation by addressing the evolving demands of next-generation communication networks. By facilitating on-demand service provisioning and supporting multi-tenancy through advanced architectures like SDN/NFV, network slicing significantly enhances the scalability of mobile networks, paving the way for new business models and opportunities in the telecommunications landscape. [7, 8, 9, 10, 2]

1.2 Structure of the Survey

This survey is structured to provide a comprehensive overview of network slicing and its integration with emerging technologies in the context of 6G networks. The paper begins with an **Introduction**, highlighting the significance of network slicing and introducing key technologies such as Multi-access Edge Computing (MEC), beamforming, millimeter wave (mmWave), Ultra-Reliable Low-Latency Communication (URLLC), Open Radio Access Network (O-RAN), energy efficiency, terahertz communication, and spectrum management. The introduction outlines the critical importance of network slicing as a transformative technology in future communication networks, particularly in the context of 5G and beyond, where it facilitates the creation of dedicated virtual networks tailored to the diverse and specific requirements of various tenants, such as vertical industries. By enabling flexible resource allocation and management through Software Defined Networking (SDN) and Network Function Virtualization (NFV), network slicing not only enhances operational efficiency and cost-effectiveness but also supports the delivery of customized Quality of Service (QoS) and Service Level Agreements (SLAs). This foundational understanding is essential for grasping how network slicing will drive innovation and meet the demands of emerging applications in the evolving digital landscape. [11, 12, 7, 6]

Following the introduction, the survey delves into **Background and Core Concepts**, providing detailed explanations of the core technologies related to network slicing. This section serves as a foundation for understanding how these technologies contribute to the evolution of 6G networks.

The third section, **Network Slicing in 6G Networks**, explores the application of network slicing within 6G networks, emphasizing its ability to create multiple virtual networks on a shared physical infrastructure. This section highlights the benefits of network slicing for specific applications and services.

Next, the survey examines **Multi-access Edge Computing (MEC)**, discussing its role in reducing latency by bringing computation and storage closer to the network edge. The integration of Multi-Access Edge Computing (MEC) with network slicing is critically examined, highlighting its significant role in optimizing resource allocation and enhancing performance in 6G networks. This exploration addresses the challenges of instantiating MEC slices efficiently, as traditional algorithms struggle with the tightly-coupled constraints of networking, computation, and storage resources at the edge. Innovative frameworks, such as Sl-EDGE, demonstrate how to effectively instantiate diverse slice services—ranging from video streaming to 5G access—while maintaining high efficiency and resilience against potential failures. Additionally, emerging network slicing architectures are being enhanced with machine learning and energy-efficient strategies, further contributing to the adaptability and scalability required for future applications in 6G and beyond. [13, 14, 8, 6]

In the study titled , the survey provides an in-depth analysis of beamforming as a sophisticated signal processing technique designed to enhance signal quality and mitigate the severe path loss associated with millimeter-wave (mmWave) communications, which are essential for achieving high-speed data transmission in future wireless networks, including 5G and beyond. It explores how advancements in fully digital beamforming architectures can significantly reduce energy consumption and latency during the initial access phase by allowing simultaneous sampling from multiple directions, thereby improving overall system efficiency and performance. [15, 16, 17, 18]. The integration of these technologies with network slicing and their impact on network performance and capacity are discussed.

The section on **Ultra-Reliable Low-Latency Communication (URLLC)** underscores the importance of URLLC in ensuring dependable and instantaneous data exchange. It explores its applications and challenges in the context of network slicing and 6G networks.

The **Open Radio Access Network (O-RAN)** section explains the O-RAN initiative and its role in standardizing and opening up the radio access network architecture. The impact of O-RAN on interoperability, innovation, and network slicing is also discussed.

In the survey titled , the authors examine various strategies aimed at minimizing power consumption while ensuring optimal performance in network slicing. This analysis highlights the critical role of energy efficiency in the development of sustainable 6G networks, addressing the challenges posed by increased energy demands associated with meeting the diverse requirements of multiple service slices. The survey draws on findings that indicate a potential energy efficiency improvement of 11-14

The potential of for ultra-fast wireless data transfer is thoroughly examined, highlighting its capability to operate over extreme bandwidths that exceed those of 5G millimeter wave technologies. The discussion includes the integration of Terahertz systems with advanced network slicing techniques, which are essential for optimizing resource allocation and enhancing Quality of Experience (QoE) in 6G networks. Additionally, the challenges posed by user mobility and blockage phenomena are addressed, along with the benefits of multi-connectivity strategies that improve session reliability in these high-frequency environments. This comprehensive analysis underscores the critical role of Terahertz Communication in shaping the future of wireless connectivity. [19, 20, 21, 22, 15]

The section on **Spectrum Management** addresses the challenges and strategies for spectrum management in 6G networks, focusing on optimizing radio frequency usage and preventing interference.

In the **Conclusion**, the key findings and insights from the survey are synthesized, emphasizing the critical role of network slicing in enhancing service flexibility and resource efficiency in 5G and future 6G networks. The discussion also identifies emerging challenges in network resource management, particularly in multi-tenant environments, and outlines potential research directions that focus on the integration of machine learning techniques to optimize network slicing management. Furthermore, it highlights the significance of local 5G micro-operator deployments, which can cater to diverse vertical sectors, and suggests areas for future investigation into the scalability, flexibility, and economic feasibility of network slicing solutions in next-generation networks. [23, 2, 24]The following sections are organized as shown in Figure 1.

2 Background and Core Concepts

2.1 Core Technologies in 6G

The transition to 6G networks is driven by advanced technologies that enhance network capabilities and performance. Multi-access Edge Computing (MEC) is crucial for reducing latency by placing computational and storage resources closer to the network edge, thereby supporting low-latency and computationally intensive applications such as UAVs and IoT services [25]. MEC's integration with network slicing is vital for resource management and maintaining inter-slice isolation, accommodating diverse service requirements [2].

Beamforming, a sophisticated signal processing technique, improves signal quality by directing radio waves towards specific devices, which is essential in millimeter-wave (mmWave) communications where high propagation loss and limited coverage are challenges [16]. By focusing energy in desired directions, beamforming enhances connectivity and reduces interference [26]. The challenges of severe signal attenuation at high frequencies necessitate innovative solutions to maximize network utility, especially in high-end enterprise settings [16].

Millimeter-wave (mmWave) technology, operating from approximately 24 GHz to 300 GHz, is foundational to 6G networks, enabling multi-gigabit per second data transmission. However, mmWave links are prone to blockages and rapid quality variations, requiring robust multi-connectivity solutions to ensure reliable connections [26]. Integrating sub-6 GHz and mmWave technologies is essential for next-generation wireless communications, addressing intermittent connectivity and enhancing data transfer capabilities [26]. Additionally, the sensitivity of mmWave signals to fading presents challenges in relay selection, particularly in 5G New Radio (5G-NR) communications [16].

Ultra-Reliable Low-Latency Communication (URLLC) is indispensable for applications needing high reliability and minimal delay, such as autonomous vehicles and mission-critical industrial processes. The main challenge lies in accurately modeling and predicting queuing delays, complicating the construction of network slices that meet strict latency and reliability guarantees [4]. Network slicing facilitates the creation of dedicated slices for URLLC, ensuring specific service requirements are met without compromising overall network performance [27].

The Open Radio Access Network (O-RAN) initiative aims to standardize and open up radio access network architecture, promoting interoperability and innovation. By enabling a more flexible and modular network architecture, O-RAN supports diverse application deployment across a common infrastructure [2]. The slicing-aware architecture within the O-RAN ecosystem emphasizes open interfaces and interoperability in network slicing [2].

AI-generated, for reference only.

Energy efficiency is a critical consideration in 6G networks, given the increased power demands of advanced technologies. Integrating RF and mmWave technologies addresses energy consumption and latency issues, contributing to more sustainable network operations [25]. Intelligent RAN slicing (iRAN-S) further enhances energy efficiency by dynamically allocating and managing resources while ensuring slice isolation [25].

Terahertz communication explores frequencies above 300 GHz for ultra-fast wireless data transfer, pushing the boundaries of network capacity and speed, poised to support future applications' massive data throughput requirements [2].

Spectrum management in 6G involves optimizing radio frequency usage to prevent interference and maximize efficiency. Innovative spectrum access models and AI and machine learning techniques are critical for achieving these objectives [27]. The proposed model allows Network Slice Tenants (NSTs) to select weights for resource allocation based on strategic considerations, leading to a Nash equilibrium in resource distribution [2].

Core technologies underpinning 6G networks, including Non-Terrestrial Networks (NTN), network slicing, Artificial Intelligence/Machine Learning (AI/ML), and Open Radio Access Network (ORAN), collectively enhance connectivity, speed, and flexibility, addressing traditional terrestrial infrastructures' challenges and meeting future digital ecosystems' escalating demands. These advancements enable ultra-reliable communications with high data rates and low latency across extensive regions, facilitating diverse applications and services tailored to various industries and users in the evolving 6G landscape [28, 29, 2].

2.2 Integration with Emerging Technologies

Integrating network slicing with emerging technologies is crucial for enhancing 6G networks' capabilities and performance, enabling them to meet future applications' diverse and demanding requirements. Network slicing customizes logical networks over a shared infrastructure, allowing service-oriented resource allocation by tailoring the infrastructure into multiple logical networks [30]. This capability is essential for accommodating data-intensive services such as autonomous vehicles and mobile data analytics, requiring efficient sharing of heterogeneous resources [31].

Multi-access Edge Computing (MEC) is integral to this integration, strategically positioning computational resources closer to the network edge to minimize latency and optimize processing times for latency-sensitive applications [32]. MEC's proximity to the network edge synergizes with network function virtualization (NFV) and software-defined networking (SDN) to create a flexible and efficient network architecture. SDN plays a crucial role in resource coordination among base stations during user mobility, ensuring continuous connectivity and efficient resource management [33].

Orchestrating network slices involves creating multiple isolated virtual networks on a shared physical infrastructure to meet diverse service requirements. Logical separation of network resources is fundamental for catering to different service needs, facilitated by network slicing's flexibility [34]. Innovative approaches like Joint Planning and Slicing of mobile Network and edge Computation resources (JPSNC) optimize resource allocation and minimize latency [5].

Incorporating artificial intelligence (AI) into network slice management enhances 6G networks' adaptability and efficiency. AI-driven architectures enable dynamic resource allocation and service optimization, ensuring the network can respond to changing demands and conditions in real-time [35]. This integration is particularly beneficial for vehicular communication, where a flexible communication framework is necessary to adapt to diverse requirements [36].

The integration of mmWave radio access technology (RAT) with existing 5G components enhances network performance and user experience, particularly through network slicing and multi-connectivity. The mmReliable method leverages the multipath diversity present in the environment, ensuring robust connectivity even in the presence of beam blockages [3]. This method is vital for maintaining reliable connections in high-frequency mmWave communications, susceptible to blockages and rapid quality variations.

Moreover, developing small-scale and cost-efficient testbeds is crucial for evaluating and enhancing network performance under various use cases, as highlighted in recent studies [37]. These testbeds enable practical assessments of network slicing implementations, providing valuable insights for optimizing network performance.

Integrating distributed resource allocation methods is also critical in managing bandwidth and computational resources effectively, addressing the challenges posed by the dynamic nature of 6G networks [38]. These methods ensure resource allocation aligns with different network slices' specific demands, enhancing overall network efficiency.

3 Network Slicing in 6G Networks

Network slicing is pivotal in 6G networks, enabling the division of a single physical network into multiple virtual slices, each optimized for specific Quality of Service (QoS) requirements. This technology supports diverse applications, including mobile edge computing and industrial IoT, by facilitating efficient resource allocation and enhancing infrastructure utilization. It addresses varied user demands while enabling energy-efficient operations and machine learning optimizations, playing a crucial role in the future of wireless communication [39, 9, 8, 6]. Understanding network slicing's implications is essential for realizing 6G's full potential.

3.1 Network Slicing for Diverse Applications

Network slicing in 6G facilitates the customization of network resources, supporting enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), and ultra-reliable low-latency communications (URLLC) services. This capability is crucial for applications ranging from high-bandwidth video streaming to critical IoT services [40]. Ravindran et al.'s architecture enhances service delivery and resource management for IoT and high-bandwidth applications [41], while Habibi et al.'s SLA structure defines reliability, availability, and performance metrics [42].

As illustrated in Figure 2, the hierarchical structure of network slicing in 6G highlights key application domains, vehicular network implementations, and resource management strategies. In vehicular networks, network slicing tailors solutions for Vehicle-to-Everything (V2X) applications, adapting to varying QoS requirements and enhancing communication efficiency [43, 44]. Sahoo et al.'s approach reduces handover interruption times and optimizes resource utilization in ultra-dense environments [45]. Yang et al. highlight network slicing's role in managing bursty URLLC services, ensuring reliable low-latency communication [46]. It also alleviates congestion during traffic variations managed by UAVs [47].

Integrating network slicing with mmWave networks enhances robustness and efficiency. The MilliSlice method combines slicing with carrier aggregation to improve URLLC and eMBB performance in mmWave environments [48]. This method supports high data rates and low latency, suitable for 5G use cases [22]. In vehicular networks, slicing improves packet reception ratios for V2X communications [44]. Filali et al.'s dynamic approach enables gNodeBs to borrow Resource Blocks, reducing signaling overhead [49].

Esmaeily et al.'s scheduling framework enhances eMBB data rates and reliability, even under high URLLC loads [4]. Network slicing optimizes resource allocation and infrastructure utilization, improving energy efficiency and cost-effectiveness compared to traditional architectures [4, 39, 8, 50, 2].

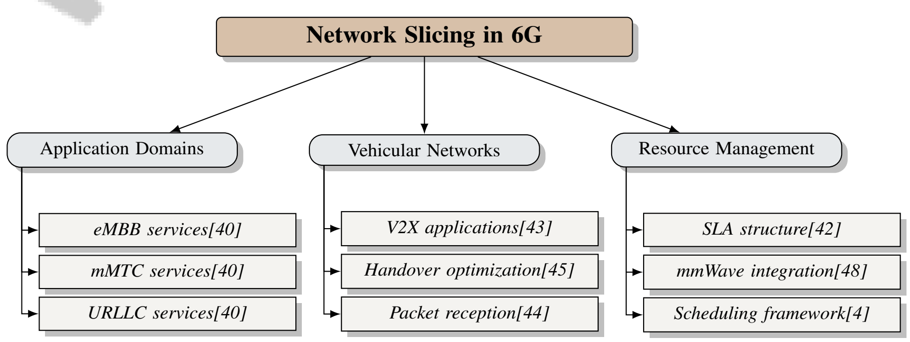

Figure 2: This figure illustrates the hierarchical structure of network slicing in 6G, highlighting key application domains, vehicular network implementations, and resource management strategies.

3.2 Resource Management and Optimization

Resource management and optimization are critical in 6G network slicing, addressing the diverse requirements of eMBB, URLLC, and mMTC. The NP-hard slicing problem challenges efficient algorithm formulation and execution, particularly as the number of Mobile Virtual Network Operators (MVNOs) and resources scale [34].

Innovative strategies like the Generalized Kelly Mechanism (GKM) allow MVNOs to bid for resources without revealing true valuations, ensuring competitive allocation [35]. The Joint Resource Allocation (JRA) method combines resource allocation with admission control to minimize costs while satisfying tenant requirements [51].

AI-based frameworks, such as the AI-Hierarchical Resource Management Framework (AI-HRMF), leverage deep reinforcement learning for dynamic resource management [30]. GREET combines reservation-based and share-based approaches for balanced resource management [52]. Huang et al.'s distributed framework improves latency and service performance by coordinating resource allocation across base stations and fog nodes [38].

Resource management in network slicing integrates advanced algorithms, AI-driven frameworks, and strategic models, employing techniques like deep reinforcement learning and knowledge transfer to enhance adaptability, service differentiation, and energy efficiency in dynamic radio access networks [30, 53, 23, 54]. These strategies ensure 6G networks efficiently support diverse applications, meeting future digital ecosystem demands.

4 Multi-access Edge Computing (MEC)

Exploring the integration of Multi-access Edge Computing (MEC) with various network architectures and technologies is crucial to understanding its transformative impact on network performance. MEC enhances network operations' efficiency and addresses emerging applications' demands within 6G networks. The following subsection examines how MEC synergizes with network slicing to optimize resource management and reduce latency across diverse scenarios.

4.1 Integration of MEC with Network Slicing

Integrating Multi-access Edge Computing (MEC) with network slicing is fundamental for boosting the performance and adaptability of 6G networks. By positioning computational resources near the network edge, MEC reduces latency and supports dynamic network slicing, enabling the creation of virtual networks for specific applications [55, 2]. This synergy is vital for low-latency, high-reliability applications like smart manufacturing and autonomous vehicles.

Advanced optimization techniques manage end-to-end resources for network slices, maximizing efficiency through optimized resource distribution, cell allocation, and user assignment [33]. Software-Defined Networking (SDN) and Network Function Virtualization (NFV) further enhance resource management and orchestration, improving overall network performance [3].

Machine Learning (ML) enhances intelligent network slicing architectures, optimizing performance and resource management [35]. The Generalized Kelly Mechanism (GKM) ensures fair and efficient bandwidth distribution between infrastructure providers and MVNOs, crucial in multi-tenant environments.

Network architectures implementing multi-connectivity solutions, such as the S3 framework using SDN and NFV, are essential for MEC and network slicing integration. This approach enhances network robustness and efficiency, ensuring reliable connectivity under challenging conditions. Automated RAN slice provisioning via a RESTful API supports seamless MEC and network slicing integration [3].

Automated admission control and resource allocation methods, leveraging real-time resource availability analysis, exemplify MEC and network slicing integration potential to enhance network performance [34]. These methods optimize resource allocation in real-time, adapting to changing demands.

Integrating MEC with network slicing enhances network performance by improving resource management and reducing latency. Incorporating Non-Terrestrial Networks (NTNs) and advanced technologies like AI/ML is essential for addressing future digital ecosystems' demands as we transition to 6G networks. This integration overcomes traditional terrestrial networks' challenges, such as coverage, reliability, and congestion, enabling ultra-reliable communications with high data rates and low latency [28, 29]. Ongoing advancements in network slicing frameworks, including improved spectral efficiency and MEC integration with machine learning, further augment this integrated framework's capabilities, ensuring robust and adaptable network operations.

4.2 Performance Enhancement through MEC

Multi-access Edge Computing (MEC) is key to enhancing 6G network performance by reducing latency and optimizing resource utilization, crucial for applications with strict performance requirements. By moving computation and storage closer to the network edge, MEC minimizes data travel distance, reducing transmission delays and enhancing real-time data processing [56]. This shift benefits latency-sensitive applications like real-time video surveillance and IoT services, enabling automated service deployment with minimal latency.

Integrating MEC with intelligent network slicing architectures amplifies performance gains. For V2X services, optimized resource allocation based on real-time data significantly reduces latency [43]. The LLM-Slice framework manages dedicated network slices for optimized service delivery based on user-specific requests, ensuring efficient resource use [57].

Advanced resource management techniques, such as the BiVNE method, enhance edge network performance by improving resource allocation and reducing fragmentation, maintaining high throughput and low latency [58]. Integrating sub-6 GHz and millimeter-wave technologies significantly reduces average delays under heavy traffic, achieving up to a 70

Dynamic resource allocation adaptation based on real-time traffic is critical for optimizing network performance. Koutlia et al.'s method dynamically adjusts allocations to ensure optimal performance amid fluctuating traffic and slice requirements [59]. Doro et al.'s structured approach allows MNOs to define resource needs for efficient allocation by infrastructure providers [60].

The SCS method offers inter-slice protection with improved job delay and throughput compared to traditional methods, highlighting tailored resource management strategies' importance in enhancing MEC performance [31]. The GREET framework balances guaranteed resource allocations with flexibility for dynamic user demands, ensuring robust performance in varying conditions [52].

As illustrated in Figure 3, the key strategies for enhancing 6G network performance through Multi-access Edge Computing (MEC) focus on latency reduction, resource optimization, and advanced resource management. Each strategy leverages specific frameworks and methods to address the challenges of efficient resource allocation and low-latency service delivery in next-generation networks.

Advancements in MEC and network slicing significantly enhance 6G networks' performance, addressing future digital ecosystems' complex demands. These technologies enable tailored virtual networks that optimize resource allocation and minimize latency for diverse applications like autonomous driving and augmented reality. MEC facilitates ultra-low latency by relocating computing resources closer to users, while NS allows dynamic virtual network function instantiation on MEC cloud servers, ensuring efficient service delivery. Innovative solutions like the Sl-EDGE framework improve MEC slicing efficiency, enhancing throughput and resilience against failures [13, 14]. These advancements improve latency and resource management and ensure reliable service delivery, crucial for 6G networks' evolving landscape.

4.3 Energy Efficiency and MEC

Incorporating energy-efficient strategies within Multi-access Edge Computing (MEC) deployments is crucial for advancing 6G networks' sustainability. As demand for high data rates rises, improving energy efficiency becomes vital. The dual sub-6 GHz and mmWave approach effectively utilizes bandwidth, ensuring low latency and high energy efficiency, addressing high energy consumption and intermittent connectivity challenges [62].

EcoSlice exemplifies balancing energy consumption and Quality of Service (QoS), allowing adaptive network resource management [63]. Its ability to assess energy use and service quality trade-offs is crucial in dynamic environments with rapidly fluctuating resource demands.

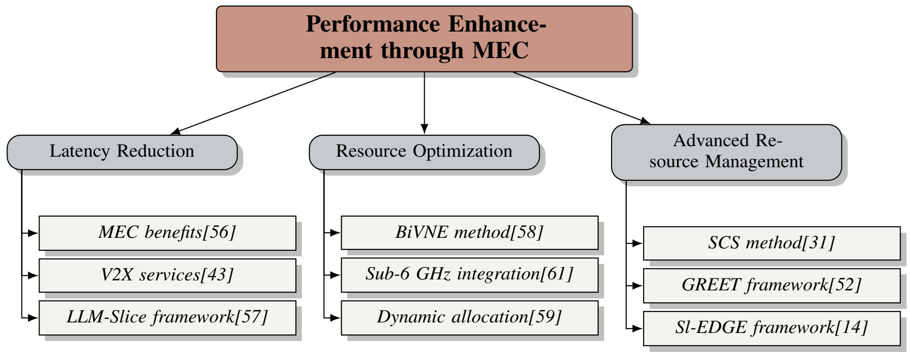

Figure 3: This figure illustrates the key strategies for enhancing 6G network performance through Multi-access Edge Computing (MEC), focusing on latency reduction, resource optimization, and advanced resource management. Each strategy leverages specific frameworks and methods to address the challenges of efficient resource allocation and low-latency service delivery in next-generation networks.

In MEC, the Predictive Dynamic Scaling method (DMUSO) dynamically adjusts resource allocation in real-time, enhancing system performance and SLA adherence [64]. This adaptability is vital for maintaining energy efficiency while meeting various applications' performance requirements.

Research into mmWave network MAC layers has yielded insights into enhancing throughput and energy efficiency [65]. These advancements optimize MEC deployments' energy consumption, especially in high-throughput, variable environments.

The Joint Planning and Slicing of mobile Network and edge Computation resources (JPSLA) method effectively reduces energy consumption while meeting user delay requirements through joint optimization [66]. This method exemplifies integrated resource management strategies' potential in achieving energy-efficient MEC operations.

The AI-assisted RAN slicing framework enhances energy efficiency by providing adaptability and flexibility in dynamic environments [53]. AI in resource management allows precise and efficient resource allocation, reducing MEC deployment energy consumption.

The OORAA algorithm balances energy efficiency and service delay in MEC-enabled IoT networks, showcasing a solution for managing performance and energy use trade-offs [25]. Addressing energy-efficient solutions in Open RAN (O-RAN) for low latency and high-throughput services remains essential [67].

Challenges persist in provisioning sufficient radio resources for each network slice, impacting energy efficiency and performance in dynamic environments [43]. Ongoing research and innovation are needed to address these challenges, particularly in standardization, deployment complexity, and emerging security threats [68].

Future research should incorporate energy efficiency into frameworks like MPMH, relevant for enhancing MEC deployments' energy efficiency [69]. These efforts are key to realizing MEC's full potential in creating sustainable and efficient 6G networks.

5 Beamforming and mmWave Technologies

Beamforming is a transformative technique in wireless communications, crucial for enhancing the performance and efficiency of millimeter-wave (mmWave) systems, particularly within 6G networks. Table 1 presents a detailed classification of beamforming techniques and innovations in mmWave communication, highlighting their significance in overcoming challenges and enhancing performance in 6G networks. Table 3 offers a comparative overview of advanced beamforming methods, hybrid beamforming architectures, and beam squinting compensation methods, elucidating their roles in enhancing signal quality, network efficiency, and reliability within 6G networks. This section explores various beamforming techniques and their roles in improving signal quality and network performance.

Category	Feature	Method
Beamforming Techniques and Their Impact	RIS and Beam Integration	IRMA[62]
	Reconfigurable and Adaptive Strategies	RR-MU-MISO-URLLC[70], BA-CoMP[71]
	Computational Complexity Management	SRT[72]
	Multi-Beam and Connectivity Enhancements	DCP[73], MR[74]
	Efficiency and Performance Optimization	LRDB[18]
Challenges and Innovations in mmWave Communication	Protocol and Performance Enhancements	mmPEP[75], BSCM[76], RL[77]
	Network Optimization Strategies	TOOF[78], RASCs[79], HMP-RP[19], ECO-TCE[80]
	Traffic and Resource Management	UAVB[47]

Table 1: This table provides a comprehensive overview of various beamforming techniques and challenges in millimeter-wave (mmWave) communication within 6G networks. It categorizes methods based on their impact on beamforming and innovations designed to address specific challenges associated with mmWave technology, including signal quality, network efficiency, and resource management.

By addressing high-frequency communication challenges, beamforming optimizes resource allocation and enhances connectivity in complex network environments.

5.1 Beamforming Techniques and Their Impact

Method Name	**Technique Categories**	**Integration Approaches**	**Performance Metrics**
RR-MU-MISO-URLLC[70]	Beamforming Methods	Refracting Ris	Sum Rate
BSCM[76]	Advanced Beamforming Methods	Hybrid Beamforming Architectures	Sinr And Throughput
MR[74]	Beamforming Methods	Intelligent Reflecting Surfaces	Throughput Reliability Product
LRDB[18]	Beamforming Architectures	Digital Front-ends	Energy Consumption
DCP[73]	Advanced Beamforming Methods	Hybrid Beamforming Architectures	Throughput Stability
mmPEP[75]	Performance Enhancement Strategies	-	Packet Delivery Ratio
BA-CoMP[71]	Beamforming Methods	Coordinated Multi-point	Power Efficiency
HMP-RP[19]	Advanced Beamforming	Hybrid Beamforming Architectures	High Throughput
RL[77]	Beamforming Methods	Hybrid Beamforming Architectures	Signal Quality

Table 2: This table provides a comprehensive overview of various beamforming methods and their associated technique categories, integration approaches, and performance metrics in 6G networks. It highlights the diverse strategies employed to enhance signal quality and network performance, including advanced beamforming methods, hybrid architectures, and performance enhancement strategies. The table also outlines the specific performance metrics used to evaluate these methods, such as sum rate, SINR, throughput, and energy consumption.

Beamforming enhances signal quality and network performance by directing radio waves to specific devices, a necessity in 6G networks where mmWave communications face blockages and signal variations. As illustrated in Figure 4, the categorization of beamforming techniques in 6G networks highlights advanced beamforming methods, hybrid beamforming architectures, and performance enhancement strategies. Table 2 presents a detailed comparison of beamforming techniques, integration approaches, and performance metrics, illustrating their significance in optimizing 6G network performance. Each category encompasses specific techniques and methods that address challenges in signal quality, network efficiency, and reliability. The integration of Reconfigurable Intelligent Surfaces (RIS) in Multi-User Multiple Input Single Output (MU-MISO) systems exemplifies the optimization of beamforming to enhance signal strength [70]. Advanced techniques like the Beam Squinting Compensation Method (BSCM) address beam squinting by applying compensation vectors to phase shifts, maintaining robust communication [76]. The mmReliable method illustrates beamforming's potential by ensuring high reliability and throughput through constructive multi-beamforming [74].

Hybrid beamforming architectures, combining analog and digital components, optimize the trade-off between complexity and efficiency. Low-resolution digital beamforming outperforms analog beamforming in discovery latency and energy consumption, enhancing signal quality and network efficiency [18]. Dual connectivity methods enable simultaneous connections to 4G and 5G cells, facilitating rapid path switching during link failures [73].

The mmWave Performance Enhancing Proxy (mmPEP) significantly improves end-to-end TCP performance over mmWave channels through early-Ack management and batch retransmission, maintaining high sending rates even in NLOS conditions [75]. Blockage-aware Coordinated Multi-Point (CoMP) transmission methods enhance power efficiency and reduce latency, ensuring reliable communication under challenging conditions [71]. The hop-by-hop multi-path routing protocol

(HMP-RP) establishes primary and backup links per destination, ensuring reliable communication under blockages [19].

Shokri-Ghadikolaei et al. highlight that fully-directional communication offers significant advantages over omnidirectional approaches in terms of throughput and interference management in mmWave networks [65]. Rapid-Link leverages sparse recovery theory for optimal beam alignment in logarithmic time, contrasting with linear or quadratic time requirements of existing methods [77].

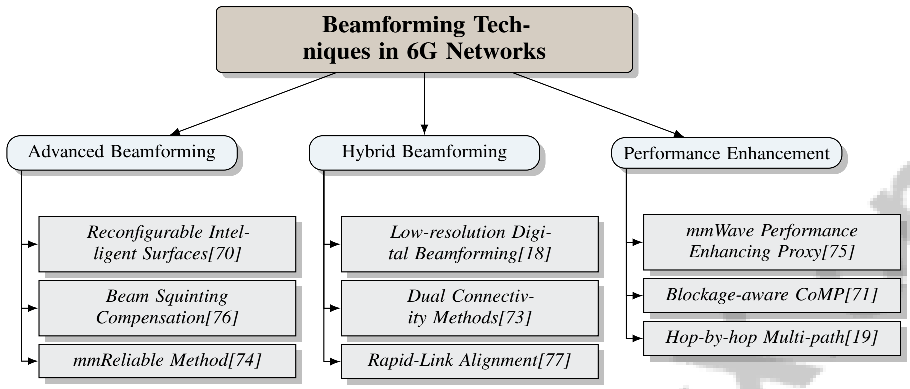

Figure 4: This figure illustrates the categorization of beamforming techniques in 6G networks, highlighting advanced beamforming methods, hybrid beamforming architectures, and performance enhancement strategies. Each category includes specific techniques and methods that address challenges in signal quality, network efficiency, and reliability.

5.2 Challenges and Innovations in mmWave Communication

Millimeter-wave (mmWave) communication is foundational to 6G networks, offering high data rates and substantial bandwidth. However, it faces challenges such as high propagation loss, blockages, and complex antenna technologies [22]. The introduction of mmWave bands in cellular systems is driven by the demand for high throughput and advanced antenna technologies [15]. Despite these benefits, mmWave signals' intermittent connectivity and blockage sensitivity hinder low-latency, ultra-reliable connectivity [22].

Innovations like the hop-by-hop multi-path routing protocol maintain high throughput and low latency amid blockages and NLOS conditions [19]. UAVs offer flexible solutions to manage traffic demand surges, leveraging their mobility to alleviate congestion [47]. Protocol improvements, such as the mmWave Performance Enhancing Proxy (mmPEP), enhance data rates and packet delivery ratios by addressing TCP limitations [75]. Rapid-Link reduces beam alignment delay significantly, enhancing mmWave network practicality [77].

Channel estimation in high-frequency THz communications involves managing vast data and complex machine learning algorithms [80]. The Beam Squinting Compensation Method (BSCM) effectively maintains beam alignment despite frequency changes, ensuring robust communication [76]. Innovative task offloading frameworks, like the two-step optimization approach by Noghani et al., utilize MILP for network topology determination and bandwidth allocation optimization [78]. Robotic Aerial Small Cells (RASCs) present an energy-efficient solution for enhancing mmWave communication through on-demand deployment [79].

6 Ultra-Reliable Low-Latency Communication (URLLC)

Ultra-Reliable Low-Latency Communication (URLLC) is a foundational element of 6G networks, essential for applications demanding high reliability and minimal latency, such as autonomous driving, remote surgery, and immersive virtual experiences. URLLC facilitates innovative solutions like machine-type communication for disaster monitoring and wireless factory automation. The integration of network slicing and artificial intelligence is critical for addressing resource allocation and service multiplexing challenges in varied industrial and emergency scenarios, ensuring resilient and efficient future communication landscapes [81, 36, 46, 82, 29]. Understanding these applications

Feature	Advanced Beamforming Methods	Hybrid Beamforming Architectures	Beam Squinting Compensation Method
Signal Quality	Enhanced Signal Quality	Enhanced Signal Quality	Maintains Robust Communication
Network Efficiency	Optimized Resource Allocation	Trade-off Optimization	Compensation Vectors Applied
Reliability	Address High-frequency Challenges	Dual Connectivity	Addresses Beam Squinting

Table 3: This table provides a comparative analysis of three significant beamforming methodologies in the context of millimeter-wave (mmWave) communications for 6G networks. It evaluates each method based on key performance indicators such as signal quality, network efficiency, and reliability, highlighting their distinct approaches to overcoming high-frequency communication challenges. The comparison underscores the advancements in beamforming techniques that are critical for optimizing resource allocation and maintaining robust communication in complex network environments.

highlights URLLC's pivotal role in shaping future connectivity, making its integration essential for next-generation communication systems.

6.1 Importance of URLLC in 6G Networks

URLLC is crucial for 6G networks, providing the framework for applications that require instantaneous and dependable data transmission. It is vital for advanced applications like autonomous driving, remote surgery, and virtual reality, where latency minimization and reliability maximization are critical [83]. As illustrated in Figure 5, the figure highlights the key aspects of URLLC in 6G networks, emphasizing its importance for these advanced applications, as well as effective resource allocation strategies and network slicing frameworks.

The JPSNC method efficiently allocates resources by considering multiple traffic types and latency needs concurrently [84]. Adaptive strategies are essential in dynamic network environments to ensure reliable data exchange in latency-sensitive applications [85]. A two-level RAN slicing approach, enhanced by deep reinforcement learning (DRL), effectively manages resource allocation in such environments [86], which is crucial for high-speed scenarios like high-speed trains [70].

Network slicing addresses Industry 4.0's diverse connectivity needs, providing reliability and low latency through efficient resource allocation [82]. The DQLD algorithm optimizes QoS for URLLC and eMBB users, ensuring reliable communication in dynamic conditions [26]. DRL-based frameworks further optimize energy efficiency and URLLC latency [36].

The coexistence of URLLC with eMBB and mMTC services presents unique challenges and opportunities. RSMA significantly outperforms NOMA and OMA in optimizing rate pairs for URLLC and eMBB, enhancing resource allocation in heterogeneous service scenarios [40, 87, 88, 46, 89].

In network slicing, the LLM-Slice framework improves response speed and resource efficiency, reducing latency by 52

The proposed method enhances delay-sensitive applications, improving data rates and packet delivery ratios [61]. Supporting multiple URLLC and eMBB users, as demonstrated by NOMA-SIC, highlights 6G networks' flexibility [87].

In autonomous vehicular networks, URLLC enhances reliability and latency, supporting critical communication needs [90]. Deploying URLLC ensures robust communication in high mobility and dynamic conditions.

URLLC is indispensable for 6G networks, supporting diverse applications requiring ultra-reliable, low-latency communication. Advanced network slicing and modular architecture integration enable digital ecosystems to meet future applications' demanding requirements. This fosters innovation and enhances user experiences across sectors like industrial IoT, mobile edge computing, and the Internet of Vehicles, allowing resource customization and optimization for specific use cases [28, 91, 6, 92].

6.2 Challenges in Implementing URLLC

Implementing URLLC in network slicing and 6G networks involves overcoming significant challenges to meet next-generation applications' stringent requirements. mmWave communication's high path loss and poor propagation complicate URLLC service delivery [55]. Dynamic network conditions, like user mobility and traffic fluctuations, further impact reliability and latency.

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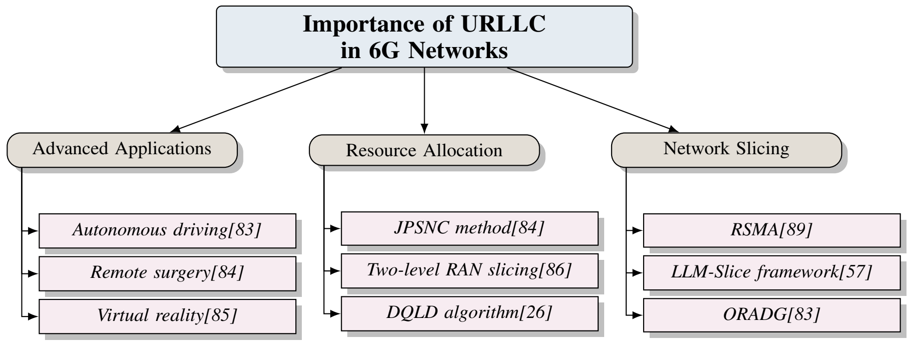

Figure 5: This figure illustrates the key aspects of URLLC in 6G networks, highlighting its importance for advanced applications, resource allocation strategies, and network slicing frameworks. It emphasizes the role of URLLC in supporting critical applications such as autonomous driving, remote surgery, and virtual reality, while also showcasing effective resource allocation methods like JPSNC and DQLD. Additionally, it presents network slicing techniques, including RSMA and LLM-Slice, that enhance URLLC performance in diverse scenarios.

Resource allocation optimization complexity complicates URLLC implementation. Relying on historical data for resource distribution may not reflect current user distribution, leading to suboptimal performance [16]. This hinders real-time demand adaptation, affecting URLLC service efficiency and reliability.

Integrating URLLC with other services, like eMBB and mMTC, introduces additional challenges. Effective network slice isolation, resource allocation, and performance monitoring remain unresolved [37]. Balancing different service demands within a single infrastructure adds complexity, especially for high reliability and low latency scenarios.

URLLC service scalability is challenging, particularly in high-density environments with high communication demand. Limited radio resources in current infrastructures hinder URLLC scaling, highlighting the need for innovative resource management strategies and advanced architectures. Studies emphasize configuring network slicing systems to meet URLLC's stringent requirements while accommodating emerging use cases like critical mMTC. Integrating communication and computation resources in O-RAN is essential for optimizing URLLC performance. Recent advancements, including DRL algorithms for resource allocation and hybrid frameworks balancing energy efficiency and latency, offer promising solutions for enhancing URLLC service scalability [86, 81, 36, 46].

Implementing URLLC in network slicing and 6G networks presents complex challenges, including balancing reliability and latency, managing resources across diverse services, and accommodating industrial applications' heterogeneous needs. Integrating communication technologies and meeting low packet blocking and error rates demands sophisticated resource orchestration. Automated QoS enforcement and tailored architectures for emerging use cases, like critical mMTC and large language models, are necessary [93, 81, 46, 82, 57]. Innovative solutions and continued advancements in network architecture and resource allocation strategies are vital to ensure URLLC meets future digital ecosystems' rigorous demands.

7 Open Radio Access Network (O-RAN)

The Open Radio Access Network (O-RAN) initiative is a transformative force in the evolution of wireless networks, emphasizing standardization and open architecture. These principles are crucial for enhancing flexibility and interoperability, enabling a modular network design that supports diverse applications and services. This section examines the significance of these foundational elements in the O-RAN framework, highlighting their role in fostering innovation and improving the performance of future 6G technologies.

7.1 Standardization and Open Architecture

O-RAN is central to the standardization of open network architectures, vital for innovation and interoperability in 6G networks. By dismantling traditional monolithic structures, O-RAN promotes a modular architecture that supports diverse applications and vendor interoperability [94]. A significant innovation is the use of a perfect graph to model user service dependencies, optimizing resource allocation and enhancing network efficiency [95]. Additionally, a joint optimization model for resource block allocation and distributed unit selection boosts energy efficiency while ensuring performance [67].

Challenges persist in scaling O-RAN, such as the SEM-O-RAN approach's complexity and limited support for direct communication between RIC apps and devices [96]. Continued refinement of O-RAN standards is necessary to fully integrate and manage network resources. Integrating advanced forecasting models, such as forecasting-aided deep reinforcement learning, further exemplifies O-RAN's innovative potential by enhancing traffic demand predictions and resource allocation [97].

7.2 Interoperability and Innovation

O-RAN is pivotal in promoting interoperability and innovation within network slicing, enhancing the adaptability and efficiency of 6G networks. Its open architecture allows seamless integration of multi-vendor solutions, fostering a competitive ecosystem that reduces costs and improves performance [94]. The flexibility of O-RAN supports dynamic resource adaptation, essential for efficient network slicing implementation. By standardizing interfaces and promoting open-source development, O-RAN ensures seamless collaboration among diverse network components, enhancing robustness and scalability [92, 98, 99, 42].

O-RAN's integration of AI and ML optimizes network slicing strategies, facilitating resource management in current and future networks. By employing AI techniques like graph learning and federated learning, O-RAN enhances system performance in RAN slicing, addressing end-to-end network slicing complexities and promoting stakeholder collaboration within a virtualized infrastructure [100, 54]. AI-driven analytics within O-RAN enable real-time decision-making and predictive resource management, crucial for agile and intelligent network management in 6G networks.

8 Energy Efficiency in Network Slicing

Achieving energy efficiency in network slicing necessitates optimizing resource utilization to respond effectively to varying demands and operational conditions. Dynamic resource allocation (DRA) is fundamental to enhancing the performance of 6G networks by efficiently managing resources while meeting Quality-of-Service (QoS) requirements. This section delves into DRA methodologies and their implications for energy efficiency in network slicing.

8.1 Dynamic Resource Allocation for Energy Efficiency

Dynamic resource allocation (DRA) is crucial for energy efficiency in 6G network slicing, adapting to real-time conditions and fluctuating demands to optimize resource use while ensuring QoS. The UAV 'bridging' method illustrates this by enhancing energy efficiency through optimized traffic management during peak loads [47]. Machine learning integration further refines DRA strategies, balancing eMBB service quality with URLLC requirements and managing service coverage and interference in Radio Access Networks (RANs) [4].

The Coverage-Aware Resource Provisioning (CARP) method ensures coverage constraints are met while optimizing resources across multiple slices, reducing costs [32]. The Joint Power Control, Server, and Link Allocation (JPSLA) algorithm minimizes energy consumption by integrating resource allocation across RAN and core networks, captured through a mixed-integer linear programming (MILP) formulation [67].

In dense networks, optimized resource allocation is vital for efficiency. Bahlke et al.'s approach optimizes resource allocation, achieving rapid convergence to the Nash equilibrium and near-optimal performance [33, 34]. The Joint Resource Allocation (JRA) method improves acceptance ratios and cost efficiency, minimizing power and bandwidth costs [51].

DRA is essential for energy efficiency in network slicing, enabling 6G networks to meet diverse application demands while minimizing energy consumption and maintaining performance. The integration of advanced algorithms and intelligent frameworks, such as AI and machine learning, is poised to enhance network adaptability and efficiency. This evolution addresses challenges in coverage, reliability, and congestion as we transition to 6G. Innovative solutions like non-terrestrial networks (NTNs), network slicing, and multi-access edge computing will enhance connectivity and data processing capabilities, promoting sustainability and efficiency across applications, including vehicle-to-everything (V2X) communications [54, 101, 29, 43].

8.2 Technological Innovations for Energy Efficiency

Technological innovations in 6G networks are crucial for enhancing energy efficiency amidst growing demand for high-performance communication services. The EcoSlice method exemplifies dynamic resource allocation by enabling operators to switch users to low-resource slices without compromising QoS, optimizing resource usage and reducing energy consumption [102]. The STEP framework improves resource efficiency by enhancing protocol interpretability, crucial for minimizing energy consumption in complex environments [103].

Machine learning integration, as suggested by Le et al., refines resource allocation, enhancing rewards and adapting to dynamic conditions [104]. The SFI2 architecture incorporates sustainability into design, focusing on energy-efficient practices for resource allocation [6]. Knowledge transfer methodologies, highlighted by Zhou et al., use AI/ML techniques to address network slicing complexities [54].

Taskou et al.'s joint approach to power control and resource allocation achieves a 30

In smart factories, continuous innovation in network slicing addresses unique challenges in dense environments, where energy efficiency and resource optimization are paramount [105]. Integrating energy-efficient practices into 6G networks is critical, as RANs significantly contribute to energy consumption. Industry standards and strategies like full stack acceleration, network functions consolidation, and shared infrastructure between communication and AI optimize energy use while enhancing throughput and reducing costs. NTNs address coverage, reliability, and congestion challenges, ensuring ultra-reliable communications with high data rates and low latency. Energy-efficient intra-domain network slicing and unsupervised reinforcement learning in 6G reduce complexity and improve scalability and efficiency, emphasizing the need for energy-conscious design in future communication infrastructures [106, 29, 107]. Advanced algorithms, machine learning techniques, and dynamic resource management strategies contribute to sustainable and efficient next-generation communication systems.

9 Terahertz Communication

The escalating demand for faster and more efficient wireless communication propels terahertz (THz) communication as a pivotal frontier for next-generation networks. This section explores the transformative potential of THz frequencies in enabling ultra-fast wireless data transfer, crucial for advancing 6G technology. As illustrated in Figure 6, the structure of Terahertz Communication is depicted, highlighting not only its potential for ultra-fast wireless data transfer but also the challenges and solutions associated with its implementation. The diagram categorizes the advantages, innovations, and challenges of Terahertz Communication, alongside strategies and solutions to overcome these challenges, thereby emphasizing its role in advancing 6G networks. By examining THz communication capabilities and applications, we gain insights into its role in meeting the burgeoning data demands of modern digital ecosystems. The following subsections will detail the specific advantages of THz communication in achieving high data rates, particularly within emerging technologies and applications.

9.1 Potential for Ultra-Fast Wireless Data Transfer

THz communication is set to revolutionize wireless data transfer, offering unparalleled data rates vital for 6G networks. Utilizing the extensive bandwidth in the THz range (0.1 to 10 THz), it enables ultra-fast data transfer capabilities surpassing current wireless technologies [76]. This technology

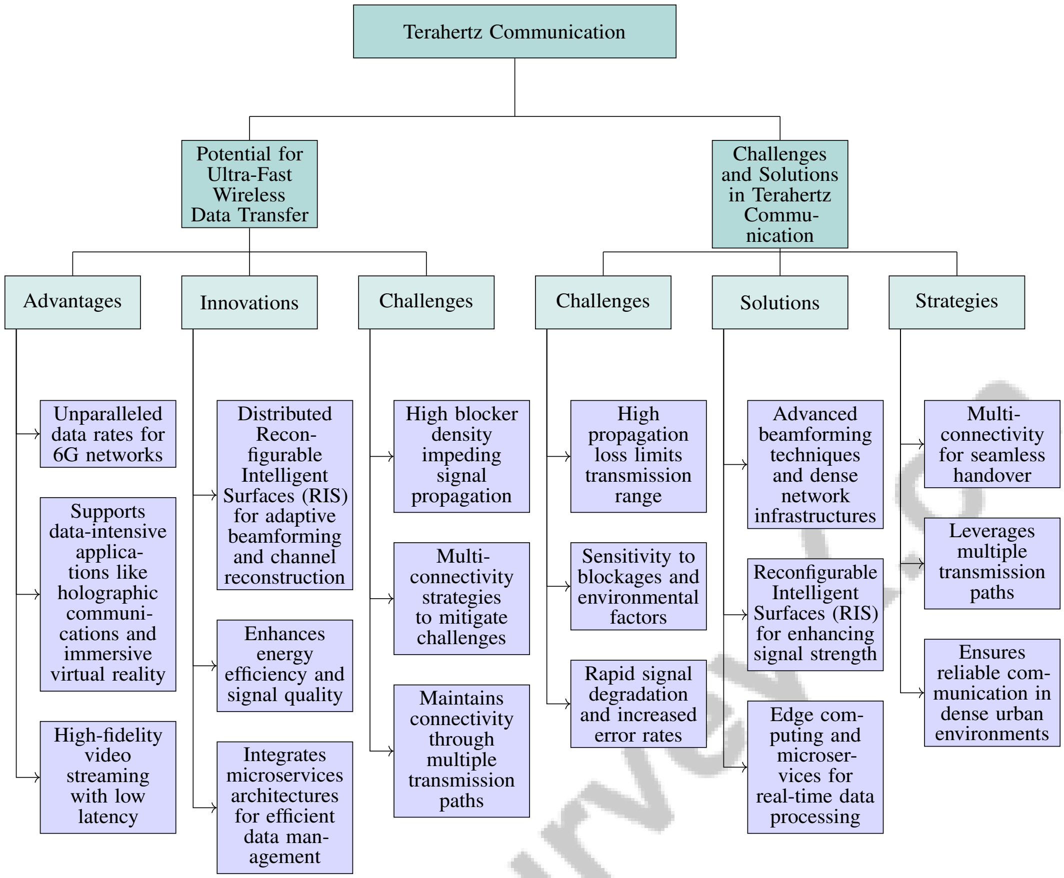

Figure 6: This figure illustrates the structure of Terahertz Communication, highlighting its potential for ultra-fast wireless data transfer and the challenges and solutions associated with its implementation. The diagram categorizes the advantages, innovations, and challenges of Terahertz Communication, alongside strategies and solutions to overcome these challenges, emphasizing its role in advancing 6G networks.

supports data-intensive applications like holographic communications, immersive virtual reality, and high-fidelity video streaming, which require high data rates and low latency.

Innovations such as distributed Reconfigurable Intelligent Surfaces (RIS) frameworks enhance adaptive beamforming and channel reconstruction, significantly improving energy efficiency and signal quality. This approach addresses inherent THz communication challenges like high propagation loss and sensitivity to blockages [20]. The distributed RIS framework dynamically adapts to environmental changes, ensuring robust and reliable communication in challenging conditions.

Sopin et al. emphasize THz communication's potential for ultra-fast data transfer while tackling high blocker density challenges that impede signal propagation and reliability [21]. Multi-connectivity strategies mitigate these challenges, enabling seamless handover and maintaining connectivity through multiple transmission paths.

Moreover, integrating microservices architectures in THz systems facilitates efficient management and processing of large datasets for channel estimation. This significantly enhances response times and improves signal quality, ensuring THz systems meet 6G network demands [80]. By leveraging advanced architectures, THz communication overcomes traditional method limitations, providing efficient, scalable solutions for ultra-fast data transfer.

9.2 Challenges and Solutions in Terahertz Communication

Implementing THz communication in 6G networks presents challenges due to THz frequencies' unique characteristics, ranging from 0.1 to 10 THz. High propagation loss, a primary issue, severely limits transmission range [20]. Addressing this requires advanced beamforming techniques and dense network infrastructures to maintain reliable communication links.

THz signals' sensitivity to blockages and environmental factors, such as atmospheric absorption and scattering, leads to rapid signal degradation and increased error rates [76]. Reconfigurable Intelligent Surfaces (RIS) offer a solution by dynamically adapting the propagation environment, enhancing signal strength and quality through intelligent reflection and refraction of THz waves [20].

High data rates achievable with THz communication necessitate efficient channel estimation and data processing techniques to manage vast transmitted information. Integrating edge computing and microservices architectures facilitates real-time data processing and reduces latency, improving THz system performance [80].

Multi-connectivity strategies provide viable solutions to THz communication challenges. By enabling seamless handover and leveraging multiple transmission paths, these strategies maintain robust connectivity amidst blockages and environmental disruptions [21]. This approach ensures reliable, uninterrupted communication, even in dense urban environments where THz signals are most susceptible to interference.

10 Spectrum Management

As communication technologies advance, effective spectrum management becomes pivotal for deploying next-generation networks. The transition to 6G necessitates addressing spectrum utilization challenges that affect both performance and efficiency. This section examines the specific obstacles in spectrum management for 6G, focusing on innovative solutions to meet the dynamic needs of modern communication environments. We explore these challenges to understand the complexities in optimizing spectrum access and resource allocation in 6G networks.

10.1 Challenges in Spectrum Management for 6G Networks

6G spectrum management faces numerous challenges requiring innovative solutions for efficient communication. A major issue is managing interference in densely populated areas, leading to suboptimal performance and energy inefficiency [108]. This is exacerbated by the need for dynamic resource allocation to satisfy Quality of Service (QoS) demands for services like enhanced Mobile Broadband (eMBB) and Ultra-Reliable Low-Latency Communication (URLLC) within the Open Radio Access Network (O-RAN) framework [109].

The integration of massive bandwidth in the millimeter-wave (mmWave) spectrum presents further challenges. Traditional cellular networks struggle with the highly directional nature of mmWave transmissions, complicating connectivity amid rapid channel condition changes [22]. The variability of mmWave links, influenced by environmental obstacles, further complicates these issues [15].

O-RAN architecture introduces challenges in designing interfaces between Radio Unit (RU) and Distributed Unit (DU), and between DU and Centralized Unit (CU), requiring high-capacity, low-latency links for flexible functional splits [110]. Ensuring O-RAN meets the demands of 6G, including integration with non-terrestrial networks, remains critical [94].

Existing mmWave spectrum access models, such as exclusive and pooled access, struggle to maximize utilization while accommodating multiple operators [111]. This is compounded by the need to manage spectrum for THz/mmWave systems, where reliable service continuity is a persistent challenge [21].

Inefficient resource allocation in network slicing, especially under stochastic loads, necessitates unique Service Level Agreements (SLAs) for each slice. Traditional static slicing methods are inefficient, requiring adaptive resource allocation approaches [35].

Strategies such as hybrid spectrum sharing models, which dynamically allocate resources based on real-time demand, are promising. Advanced technologies like AI and ML can enhance spectrum efficiency by enabling adaptive network slicing, optimizing base station coverage, and managing interference effectively [53, 54]. Multi-connectivity strategies and Reconfigurable Intelligent Surfaces

(RIS) deployment can mitigate physical obstacles and improve signal propagation, essential for overcoming 6G spectrum management complexities.

10.2 Innovative Spectrum Access Models

Innovative spectrum access models are vital for optimizing frequency usage in 6G, given the demand for high-capacity, low-latency services. Traditional exclusive access models often lead to inefficient resource use. New models promoting shared spectrum and infrastructure access allow multiple operators to utilize the same frequency bands and network assets [112].

The hybrid spectrum access scheme combines exclusive access to lower frequency mmWave bands with pooled access to higher bands, ensuring guaranteed service levels for critical applications while offering shared access flexibility [111]. This model dynamically allocates spectrum based on demand, enhancing resource allocation efficiency, reducing costs, and improving network performance.

Incorporating innovative spectrum access models into the 6G ecosystem will enhance radio frequency management by leveraging technologies like network slicing, AI/ML, and O-RAN. These models address the demand for ultra-reliable communications and high data rates, especially in Non-Terrestrial Networks (NTNs) using airborne and spaceborne vehicles to extend coverage and reduce latency. Efficient resource allocation and orchestration enable diverse applications and vertical sectors, ensuring a robust future communication infrastructure [22, 50, 29, 24]. AI/ML technologies support dynamic spectrum allocation to optimize performance and meet next-generation application needs, enhancing spectrum efficiency and supporting multiple services' coexistence.

10.3 AI/ML Solutions for Spectrum Optimization

Integrating AI and ML into spectrum management is crucial for optimizing resource allocation and enhancing 6G network performance. These technologies offer dynamic strategies for managing complex, rapidly changing environments in next-generation wireless communications. AI/ML frameworks within the O-RAN architecture provide a robust foundation for optimizing resource management and improving network performance [94].

AI/ML techniques are crucial for resource management in converged optical and mmWave networks. Current research calls for further exploration of these solutions to bridge gaps and optimize resource utilization [113]. AI/ML algorithms enable dynamic reallocation of unused bandwidth, ensuring Quality of Service (QoS) and optimizing throughput [109].

The hybrid spectrum access method, combining exclusive and pooled access in mmWave networks, benefits from AI/ML integration, enhancing throughput and resource allocation among operators [111]. AI/ML frameworks' adaptability to changing network conditions underscores their effectiveness in optimizing spectrum management [109].

Future AI/ML advancements will focus on energy efficiency and adapting methods for outdoor and high-density urban scenarios. Integrating these frameworks into distributed RIS will enhance their applicability and effectiveness in diverse environments [20]. AI/ML technologies are essential for driving energy efficiency improvements and ensuring sustainable 6G network development [106].

AI/ML solutions in spectrum management optimize resource allocation and improve 6G network performance. These technologies facilitate advanced network slicing, enable intelligent service management, and support efficient resource customization through deep reinforcement learning and knowledge transfer, enhancing next-generation wireless networks' efficiency and adaptability [30, 114, 54]. These tools address next-generation wireless communications' complexities, ensuring robust and efficient network operations amid evolving demands.

11 Conclusion

11.1 Future Directions and Innovations

The future of network slicing and 6G networks is poised to explore several pivotal areas to refine optimization techniques and ensure their applicability across diverse deployment scenarios. A promising avenue involves the development of heuristic methods for decentralized optimization in expansive networks, enhancing both scalability and adaptability. This approach will enable more

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efficient resource management within complex network environments, facilitating dynamic adaptation to evolving network conditions.

Advancements in real-time prediction techniques for user demands and enhancing the convergence speed of AI-based methods are critical for future exploration. By refining these techniques, networks can better anticipate and respond to fluctuating demands, ensuring efficient resource allocation and an improved user experience. Additionally, enhancing algorithms to further improve scalability and optimality, as well as their application in more intricate network environments, remains a priority.

The integration of planning and operation stages in slicing-based resource management will be explored to further enhance performance, leveraging AI-assisted frameworks for dynamic and efficient resource allocation. Future research should focus on implementing frameworks on real testbeds and exploring multiple use cases to validate their capabilities, providing valuable insights into the practical applications of network slicing and its potential to optimize network performance in real-world scenarios.

Moreover, future work will explore enhancements to mechanisms that handle dynamic changes in user demand and resource availability, as well as their application in more complex multi-resource scenarios. Incorporating arrival times of slice requests into models and applying frameworks in discrete event simulators is another area of interest. These advancements will ensure that network slicing solutions efficiently meet the demands of 6G networks, driving technological progress and improving user experience across various domains.

Additionally, developing adaptive mechanisms for congestion control, enhancing MAC layer designs, and exploring the implications of SDN and NFV in real-world scenarios will be crucial to fully leverage advanced capabilities. Future research could also explore further optimizations in resource allocation algorithms and the integration of advanced scheduling mechanisms. These efforts will contribute to the development of robust and efficient network management frameworks capable of supporting the diverse needs of future digital ecosystems.

Finally, enhancing the capabilities of testbeds to support advanced features like machine learning integration, improved slice isolation techniques, and effective management of cross-domain network slicing will be essential for advancing the state of the art in network slicing research. By addressing these challenges and exploring innovative solutions, future research will pave the way for the successful deployment of 6G networks, ensuring they meet the evolving demands of next-generation communication technologies.

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