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 crucial technology in the advancement of 6G networks, enabling the creation of multiple virtual networks over a shared physical infrastructure. This capability enhances network performance and accommodates diverse application requirements, essential for meeting the stringent quality-of-service (QoS) demands of modern communication environments, particularly in industrial contexts [1]. By dynamically partitioning network resources, network slicing addresses the varying performance requirements of different vertical industries in a flexible and cost-effective manner [2].

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

Moreover, network slicing facilitates applications requiring ultra-reliable low-latency communication, such as vehicle-to-everything (V2X) communication, which is essential for intelligent transportation

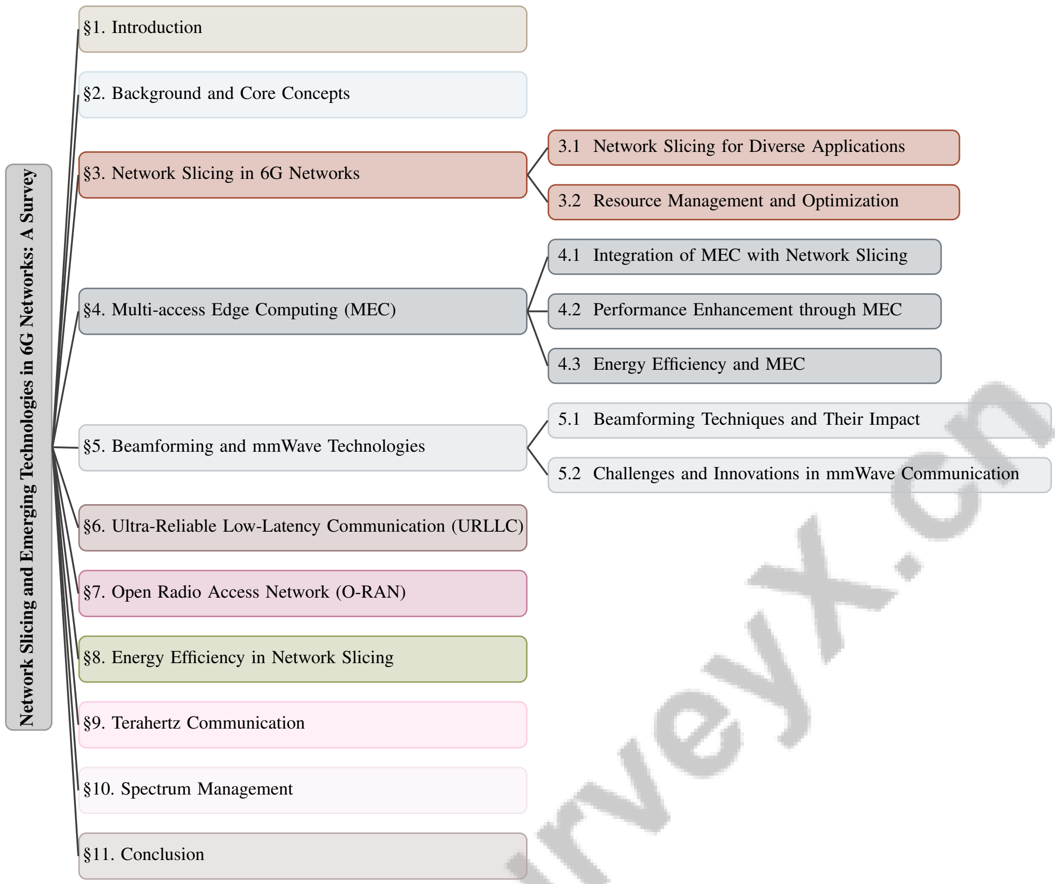

Figure 1: chapter structure

systems [5]. The ability to customize network resources for specific service requirements enhances multimedia service quality, fostering innovation and improving user experiences [6]. Within the Open Radio Access Network (O-RAN) framework, network slicing addresses interoperability challenges, promoting innovation and supporting diverse application deployments.

Network virtualization, enabled by network slicing, allows on-demand sharing of common infrastructure among multiple virtual networks tailored for distinct services. This flexibility is critical for integrating intelligent vehicular systems and smart city applications, facilitating dynamic and efficient network management through advanced techniques like network slicing and machine learning. These technologies enable the creation of multiple logical networks on shared physical infrastructure, supporting various use cases such as autonomous driving and infotainment services that demand ultra-reliable V2X communication. By optimizing resource allocation and ensuring low latency and high reliability, this approach significantly enhances service quality for connected vehicles and smart city infrastructures [7, 8, 9]. Network slicing thus emerges as a key enabler of the 6G ecosystem, providing the necessary flexibility and efficiency to support a wide range of services and applications, driving innovation and addressing the evolving needs of next-generation communication networks.

1.2 Structure of the Survey

This survey presents a comprehensive overview of network slicing and its integration with emerging technologies in 6G networks. The paper commences with an **Introduction** that underscores the significance of network slicing while 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. This section establishes a foundational understanding of network slicing's critical role in the evolution of future communication networks, particularly in enabling flexible, cost-effective service delivery to various vertical industries in 5G and beyond. By allowing multiple

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tenants to utilize isolated and dedicated virtual networks tailored to their specific QoS requirements, network slicing enhances resource allocation and overall network performance, essential for addressing the increasing demand for customized services amidst diverse and dynamic application requirements [10, 11, 6, 12, 13].

Following the introduction, the survey delves into **Background and Core Concepts**, providing detailed explanations of the core technologies related to network slicing, laying the groundwork for understanding their contributions to 6G networks.

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

The survey further examines , emphasizing its crucial role in minimizing latency by strategically positioning computational and storage resources at the network edge. This proximity enables real-time, high-bandwidth access to radio network resources, essential for advanced applications with stringent QoS requirements, particularly in 5G and future 6G networks. MEC enhances IoT service performance and fosters a new ecosystem that improves overall network efficiency and reliability through effective resource allocation and network slicing [14, 15, 16, 17, 18]. The integration of MEC with network slicing and its performance impact in 6G networks are thoroughly explored.

In **Beamforming and mmWave Technologies**, the survey investigates beamforming as a signal processing technique to enhance signal quality and mmWave for rapid data transmission. The discussion focuses on integrating advanced technologies, including Machine Learning (ML), Software Defined Networking (SDN), and Network Function Virtualization (NFV), with network slicing, highlighting their significant influence on enhancing network performance and capacity. This integration is vital for optimizing resource allocation across various applications and services in 5G and future 6G networks, where tailored network slice instances are essential for meeting the diverse QoS requirements of different vertical industries. Additionally, the exploration of frameworks for managing and orchestrating these slices emphasizes the complexity and necessity of efficient end-to-end orchestration for effective service delivery [19, 20, 11, 6, 13].

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

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

In the survey titled , the authors explore various strategies aimed at reducing power consumption while ensuring optimal performance in network slicing. They emphasize the critical role of energy efficiency in achieving sustainable 6G networks, as network slicing inherently increases energy demands compared to traditional non-sliced networks. Innovative approaches such as slice activation/deactivation strategies and multi-objective optimization techniques are highlighted to balance energy consumption with user QoS, addressing the dual challenges of enhancing operational efficiency and minimizing environmental impact in future telecommunications infrastructure [21, 22, 23, 12, 24].

The potential of for ultra-fast wireless data transfer is examined, showcasing its ability to utilize higher frequency bands than current 5G technologies for unprecedented data rates. This exploration includes its integration with network slicing to facilitate resource management and enhance user experience, addressing challenges such as user mobility and blockage phenomena through advanced strategies like multi-connectivity and reconfigurable intelligent surfaces (RIS). The research underscores the importance of precise modeling for effective THz propagation and energy efficiency, paving the way for robust and efficient communication systems in future wireless networks [25, 26, 27, 28].

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

The **Conclusion** synthesizes key findings and insights derived from the survey, emphasizing the implications of network slicing and its associated technologies in the context of 6G networks. It outlines critical challenges and opportunities identified in managing network resources, particularly through machine learning and artificial intelligence applications. Furthermore, the conclusion highlights potential future research directions, including exploring scalable and flexible architectures for local 5G micro-operator deployments and the economic viability of serving multiple vertical sectors through efficient network slicing strategies [29, 2, 30].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 underpinned by advanced technologies that enhance performance and broaden functionality. Multi-access Edge Computing (MEC) reduces latency by situating computational resources at the network's edge, crucial for low-latency services and resource-intensive applications like UAVs and IoT [31]. Its integration with network slicing ensures effective resource management and inter-slice isolation, accommodating diverse service requirements [2].

Beamforming, a sophisticated signal processing technique, enhances signal quality by directing radio waves towards specific devices, addressing the high propagation loss and limited coverage challenges in millimeter-wave (mmWave) communications [32, 33]. Operating in frequency bands from 24 GHz to 300 GHz, mmWave technology enables multi-gigabit per second data transmission. However, its susceptibility to blockages and rapid quality variations necessitates robust multi-connectivity solutions [33]. The combination of sub-6 GHz and mmWave is vital for next-generation wireless communications, improving connectivity and data transfer capabilities [32].

Ultra-Reliable Low-Latency Communication (URLLC) is crucial for applications requiring high reliability and minimal delay, such as autonomous vehicles and critical industrial processes. Accurate modeling and prediction of queuing delays remain challenging, complicating network slice construction that meets stringent latency and reliability guarantees [4, 34].

The Open Radio Access Network (O-RAN) initiative standardizes and opens the radio access network architecture, promoting interoperability and innovation. Its slicing-aware architecture emphasizes open interfaces and interoperability in network slicing [2].

Energy efficiency is paramount in 6G networks due to increased power demands from advanced technologies. Integrating RF and mmWave technologies addresses energy consumption and latency issues, contributing to sustainable operations [31]. Intelligent RAN slicing (iRAN-S) enhances energy efficiency by dynamically managing resources while ensuring slice isolation [31].

Terahertz communication, utilizing frequencies above 300 GHz, offers ultra-fast wireless data transfer, pushing network capacity and speed limits to meet future applications' massive data throughput requirements [2].

Spectrum management in 6G networks focuses on optimizing radio frequency usage to minimize interference and maximize efficiency. Innovative spectrum access models, along with AI and machine learning techniques, are crucial for achieving these goals [34, 2].

The integration of technologies such as Non-Terrestrial Networks (NTNs), network slicing, Artificial Intelligence/Machine Learning (AI/ML), and O-RAN forms a robust foundation for 6G networks, facilitating exceptional connectivity, speed, and flexibility. These advancements are crucial in addressing the escalating demands of future digital ecosystems, enhancing coverage, reliability, and efficiency while overcoming challenges such as interference and congestion faced by current terrestrial networks [35, 36].

2.2 Integration with Emerging Technologies

Integrating network slicing with emerging technologies is critical for enhancing 6G networks' capabilities and performance to meet future applications' diverse requirements. Network slicing allows for the customization of logical networks over shared infrastructure, enabling service-oriented resource allocation tailored to multiple logical networks [37]. This capability supports data-intensive services like autonomous vehicles and mobile data analytics, requiring efficient sharing of heterogeneous resources [38].

MEC is integral to this integration, positioning computational resources closer to the network edge to minimize latency and optimize processing times for latency-sensitive applications [39]. MEC's proximity synergizes with network function virtualization (NFV) and software-defined networking

(SDN) to create a flexible network architecture. SDN plays a crucial role in coordinating resources among base stations during user mobility, ensuring continuous connectivity and efficient resource management [40].

Orchestrating network slices involves creating multiple isolated virtual networks on shared physical infrastructure to meet varying service requirements. The logical separation of network resources is fundamental for catering to different service needs, facilitated by network slicing's flexibility [41]. Approaches like Joint Planning and Slicing of mobile Network and edge Computation resources (JPSNC) optimize resource allocation and minimize latency [5].

Incorporating AI into network slice management enhances adaptability and efficiency in 6G networks. AI-driven architectures enable dynamic resource allocation and service optimization, allowing the network to respond to changing demands in real-time [42]. This integration is particularly beneficial for vehicular communication, requiring a flexible framework to adapt to diverse requirements [43].

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 utilizes multipath diversity to ensure robust connectivity, even amid beam blockages [3].

Developing small-scale, cost-efficient testbeds is essential for evaluating and enhancing network performance across various use cases [44]. These testbeds enable practical assessments of network slicing implementations, providing insights for optimizing performance.

Integrating distributed resource allocation methods is vital for effectively managing bandwidth and computational resources, addressing 6G networks' dynamic challenges [45]. These methods ensure resource allocation aligns with specific network slices' demands, enhancing overall network efficiency.

3 Network Slicing in 6G Networks

Network slicing is integral to 6G networks, addressing the diverse demands of modern applications. By employing software-defined networking and network function virtualization, this approach allows for efficient resource allocation, accommodating varied service needs through a dynamic admission control mechanism that adapts to slice requests and resource uncertainties [46, 47, 48]. Figure 2 illustrates the hierarchical structure of network slicing in 6G networks, highlighting its applications and resource management strategies. This figure categorizes the primary applications of network slicing, such as enhanced Mobile Broadband (eMBB), massive Machine Type Communications (mMTC), and Ultra-Reliable Low Latency Communications (URLLC), while also detailing its specific use in vehicular networks and integration with mmWave technology. Additionally, it outlines innovative strategies and frameworks for resource management and optimization, emphasizing the role of artificial intelligence (AI) and advanced algorithms in enhancing service quality and efficiency. Understanding these applications is crucial to harnessing 6G's full potential.

3.1 Network Slicing for Diverse Applications

Network slicing in 6G networks customizes resources to meet specific application needs, supporting enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), and ultra-reliable low-latency communications (URLLC), which enhances network efficiency [49]. This capability supports a range of applications, from high-bandwidth streaming to critical IoT services requiring low latency and high reliability [50]. Ravindran et al. proposed an architecture improving service delivery through network slicing [50], while Habibi et al. introduced an SLA structure for effective service delivery [51].

In vehicular networks, network slicing tailors solutions for V2X applications, dynamically adapting to QoS demands [9]. This adaptability is crucial for handling heterogeneous traffic, enhancing communication efficiency [7]. Sahoo et al. proposed an approach reducing handover times and improving reliability in ultra-dense environments [52].

Network slicing also manages bursty URLLC services, as Yang et al. discuss resource orchestration for reliable, low-latency communication [53]. In scenarios with spontaneous traffic variations, such as those managed by UAVs, network slicing alleviates congestion [54].

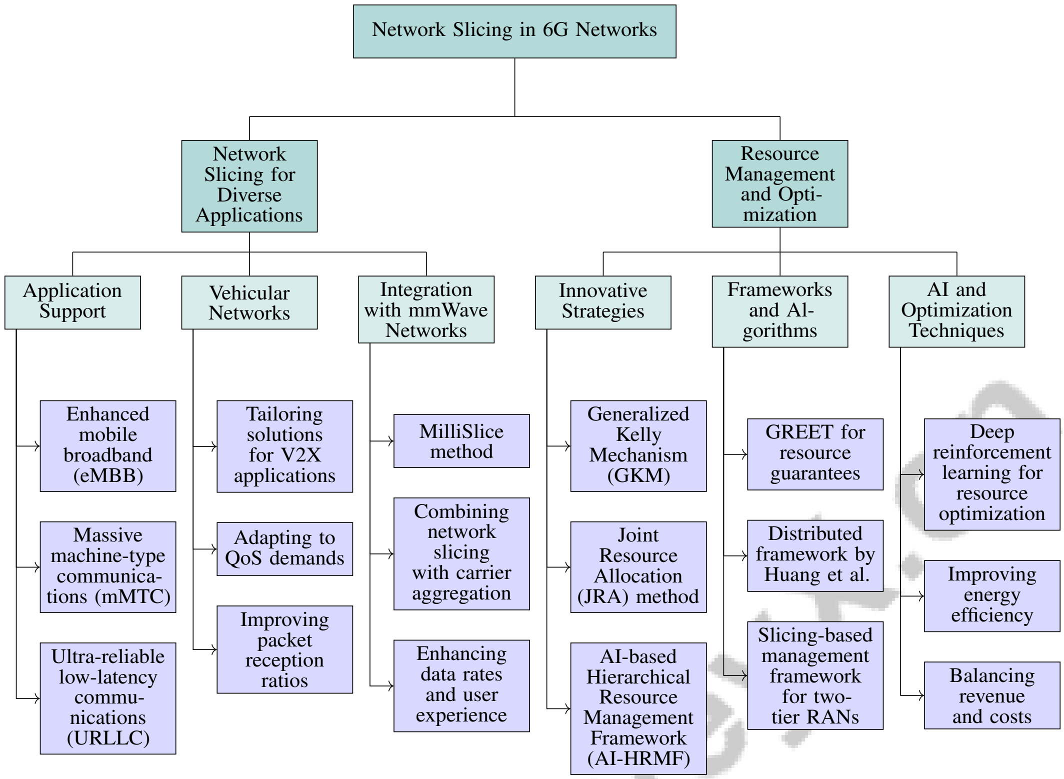

Figure 2: This figure illustrates the hierarchical structure of network slicing in 6G networks, highlighting its applications and resource management strategies. It categorizes the primary applications of network slicing, such as eMBB, mMTC, and URLLC, and its specific use in vehicular networks and integration with mmWave technology. Additionally, the figure outlines innovative strategies and frameworks for resource management and optimization, emphasizing the role of AI and advanced algorithms in enhancing service quality and efficiency.

Integrating network slicing with mmWave networks enhances robustness and efficiency. The MilliSlice method combines network slicing with carrier aggregation to improve URLLC and eMBB performance in mmWave environments [55]. This approach offers enhanced data rates and improved user experience through low latency [26].

In vehicular networks, slicing improves packet reception ratios, ensuring reliable V2X communications [7]. Filali et al. proposed a dynamic approach allowing gNodeBs to borrow Resource Blocks, facilitating rapid responses to user demands [56].

Esmaeily et al. developed a scheduling framework enhancing eMBB data rates under high URLLC loads, improving transmission reliability [4]. Network slicing enables operators to create virtual networks tailored to specific applications, each with distinct QoS requirements, enhancing flexibility and scalability compared to traditional models. By partitioning the network into dedicated slices, operators better meet the demands of next-generation technologies, support critical low-latency services, and drive innovation, presenting significant revenue opportunities for operators [4, 12, 2].

As shown in Figure 3, network slicing is crucial for accommodating diverse applications with varying requirements. The "Traffic Mask Evolution over Time" image illustrates how traffic mask values fluctuate across slices, highlighting the dynamic nature of network demands and the need for adaptable strategies. The "Slicenet Architecture" image provides insight into a sophisticated framework for managing and orchestrating network services, emphasizing the complexity and versatility of network slicing in efficiently managing resources for 6G applications [57, 10].

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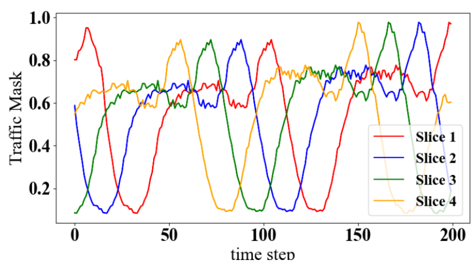
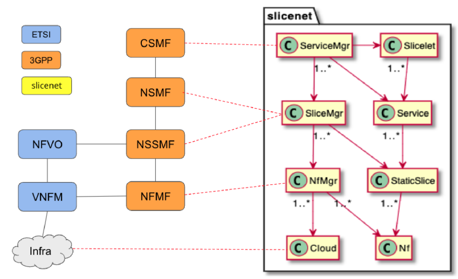


(a) Traffic Mask Evolution over Time[57]



(b) Slicenet Architecture[10]

Figure 3: Examples of Network Slicing for Diverse Applications

3.2 Resource Management and Optimization

Effective resource management and optimization are critical in 6G network slicing, addressing the dynamic requirements of eMBB, URLLC, and mMTC. The complexity of the slicing problem, being NP-hard, poses challenges in developing scalable algorithms [41]. Innovative strategies like the Generalized Kelly Mechanism (GKM) allow MVNOs to bid for resources without revealing true valuations, facilitating efficient allocation based on demand [42].

The Joint Resource Allocation (JRA) method optimizes resource allocation and admission control for slice requests, minimizing costs while satisfying tenant needs [46]. The AI-based Hierarchical Resource Management Framework (AI-HRMF) employs deep reinforcement learning to enhance admission control and resource adjustments, adapting to network conditions in real-time [37].

GREET combines reservation-based and share-based approaches, ensuring resource guarantees without compromising efficiency [48]. The distributed framework by Huang et al. uses a regional orchestrator to coordinate resource allocation, improving latency and service performance [45].

Resource management in network slicing involves advanced algorithms, AI frameworks, and strategic models, particularly in radio access networks (RANs) and next-gen wireless systems. This includes a slicing-based management framework for two-tier RANs to enhance service differentiation and manage interference. Hierarchical frameworks leverage deep reinforcement learning for resource optimization, ensuring quality of service while balancing revenue and costs. These strategies improve energy efficiency and service quality through AI techniques, supporting diverse applications in future digital ecosystems [37, 58].

4 Multi-access Edge Computing (MEC)

4.1 Integration of MEC with Network Slicing

Integrating Multi-access Edge Computing (MEC) with network slicing is pivotal for optimizing 6G network performance and adaptability. MEC's proximity to the network edge minimizes latency, enhancing the dynamic capabilities of network slicing to form virtual networks tailored for specific applications [59, 2]. This integration benefits low-latency, high-reliability services such as smart manufacturing and autonomous vehicles.

Resource orchestration within network slices employs advanced optimization techniques like 'Optimized Cell Planning for Network Slicing,' which enhances resource efficiency by optimizing resource distribution and cell allocation [40]. Software-Defined Networking (SDN) and Network Function Virtualization (NFV) further streamline resource management, boosting network performance [3].

Intelligent network slicing architectures augmented with Machine Learning (ML) enhance performance and resource management. Mechanisms like the Generalized Kelly Mechanism (GKM) ensure fair and efficient bandwidth distribution among infrastructure providers and MVNOs [42]. This approach is critical for maintaining efficient resource management and service continuity in multi-tenant environments.

Multi-connectivity solutions, exemplified by the S3 framework utilizing SDN and NFV technologies, bolster network robustness and efficiency [3]. Automated RAN slice provisioning via RESTful APIs ensures seamless MEC and network slicing integration, facilitating effective radio resource management.

In scenarios of network component failures, automated admission control and real-time resource allocation methods exemplify MEC and network slicing integration's potential to enhance performance [41]. These methods dynamically optimize resource allocation to adapt to changing demands.

MEC integration with network slicing enhances network performance by enabling efficient resource management and reducing latency, essential for future digital ecosystems. This framework is particularly relevant for 6G networks, expected to leverage Non-Terrestrial Networks (NTNs), network slicing, and artificial intelligence to address challenges in coverage, reliability, and resource optimization across diverse applications [36, 6, 35, 29, 60]. Advancements in network slicing frameworks, including improved spectral efficiency and MEC integration with machine learning techniques, further enhance this integrated framework's capabilities, ensuring robust and adaptable network operations.

4.2 Performance Enhancement through MEC

Multi-access Edge Computing (MEC) significantly boosts 6G network performance by minimizing latency and optimizing resource utilization, crucial for applications with stringent performance requirements. By relocating computation and storage resources closer to the network edge, MEC reduces transmission delays and enhances real-time data processing [61]. This is particularly advantageous for latency-sensitive applications like real-time video surveillance and IoT services [61].

Integrating MEC with intelligent network slicing architectures amplifies performance gains. Architectures for V2X services reduce latency by optimizing resource allocation based on real-time data, proving effective in dynamic environments [9]. The LLM-Slice framework creates dedicated slices tailored to user-specific requests, ensuring efficient resource utilization [62].

Advanced resource management techniques, such as the BiVNE method, enhance edge network performance by improving resource allocation and reducing fragmentation, crucial for maintaining high throughput and low latency [63]. Integrating sub-6 GHz and millimeter-wave technologies significantly reduces average delays under heavy traffic, achieving up to 70

Dynamic resource allocation adaptation based on real-time traffic demands is critical for optimizing network performance. Koutlia et al.'s method dynamically adjusts resource allocations to ensure optimal performance in response to fluctuating traffic conditions and slice requirements [64]. Doro et al.'s structured approach enables MNOs to define resource needs, allowing efficient resource allocation by infrastructure providers [65].

The SCS method provides inter-slice protection while improving job delay and throughput compared to traditional allocation methods, highlighting tailored resource management strategies' importance in enhancing MEC performance [38]. The GREET framework balances guaranteed resource allocations with the flexibility needed to adapt to dynamic user demands, ensuring robust performance in varying network conditions [48].

Advancements in MEC and network slicing enhance 6G network performance, enabling them to meet future digital ecosystems' rigorous demands with improved latency, resource management, and service delivery. Ongoing MEC framework development, coupled with innovative resource management strategies like Network Slicing and multi-connectivity, ensures 6G networks remain resilient and flexible, supporting diverse applications, including latency-sensitive services for industries like autonomous driving and augmented reality, while addressing challenges related to network failures and resource optimization through innovative orchestration techniques [66, 17].

4.3 Energy Efficiency and MEC

Incorporating energy-efficient strategies in Multi-access Edge Computing (MEC) is crucial for advancing 6G network sustainability. As high data rate demands rise, significant energy efficiency improvements are essential. 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 [67].

The EcoSlice method exemplifies balancing energy consumption and Quality of Service (QoS), enabling adaptive network resource management [22]. Its ability to assess energy use and service quality trade-offs is vital in dynamic environments with rapidly fluctuating resource demands.

In MEC contexts, the Predictive Dynamic Scaling method (DMUSO) dynamically adjusts resource allocation in real-time, enhancing system performance and adherence to Service Level Agreements (SLAs) [68]. This adaptability is crucial for maintaining energy efficiency while meeting diverse application performance requirements.

Research on MAC layer designs in mmWave networks has provided significant insights, particularly in enhancing throughput and energy efficiency [69]. Such advancements are instrumental in optimizing energy consumption in MEC deployments, especially in high data throughput and variability environments.

The Joint Planning and Slicing of mobile Network and edge Computation resources (JPSLA) method stands out for its joint optimization approach, effectively reducing energy consumption while meeting user delay requirements [21]. This method highlights integrated resource management strategies' potential for achieving energy-efficient MEC operations.

Additionally, the AI-assisted RAN slicing framework enhances energy efficiency by providing substantial adaptivity and flexibility in dynamic network environments [58]. AI in resource management processes allows more precise and efficient resource allocation, reducing energy consumption across MEC deployments.

The OORAA algorithm effectively balances energy efficiency and service delay in MEC-enabled IoT networks, showcasing a promising solution for managing trade-offs between performance and energy use [31]. Addressing energy-efficient solutions in Open RAN (O-RAN) to satisfy low latency and high-throughput services remains essential, as highlighted by recent research [70].

Despite advancements, challenges in provisioning sufficient radio resources to each network slice persist, potentially impacting energy efficiency and overall performance in dynamic environments [9]. Ongoing research and innovation are required to address these challenges, particularly in standardization, deployment complexity, and emerging security threats [17].

Future research directions include incorporating energy efficiency considerations into frameworks like the MPMH, relevant for enhancing energy efficiency in MEC deployments [71]. These efforts are crucial for realizing MEC's full potential in creating sustainable and efficient 6G networks.

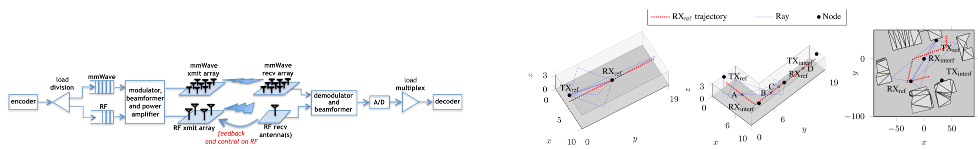
5 Beamforming and mmWave Technologies

5.1 Beamforming Techniques and Their Impact

Beamforming is a pivotal signal processing technique in 6G networks, enhancing signal quality and network performance by directing radio waves toward specific devices, particularly in high-frequency mmWave communications. It addresses challenges like blockages and signal fluctuations, with Reconfigurable Intelligent Surfaces (RIS) in MU-MISO systems optimizing signal strength [72]. Advanced methods, such as the Beam Squinting Compensation Method (BSCM), correct beam squinting through phase shift adjustments, maintaining robust communication across frequencies [73]. The mmReliable method further demonstrates beamforming's potential for reliability and throughput enhancement through constructive multi-beamforming [74].

Hybrid beamforming architectures, blending analog and digital elements, balance complexity and efficiency, with low-resolution digital beamforming surpassing analog in latency and energy efficiency [75]. Dual connectivity methods enhance user experience by enabling rapid path switching between 4G and 5G cells during link failures [76]. The mmWave Performance Enhancing Proxy (mmPEP) improves TCP performance over mmWave channels by managing early acknowledgments and batch retransmissions, reducing loss recovery times even in NLOS conditions [77].

Blockage-aware Coordinated Multi-Point (CoMP) transmission methods improve power efficiency and reduce latency, addressing traditional beamforming limitations [78]. The hop-by-hop multi-path routing protocol (HMP-RP) establishes reliable communication under blockages by providing primary and backup links [79]. Shokri-Ghadikolaei et al. highlight the advantages of fully-directional communication over omnidirectional approaches in throughput and interference management [69]. The Rapid-Link innovation uses sparse recovery theory for optimal beam alignment in logarithmic time, contrasting with linear or quadratic time methods [80].



(a) A Block Diagram of a mmWave Communication System[67]

(b) Interference-free trajectory planning for a mobile robot in a complex environment[81]

Figure 4: Examples of Beamforming Techniques and Their Impact

As shown in Figure 4, beamforming and mmWave technologies significantly advance communication systems and robotics. The mmWave communication system diagram highlights its complex architecture, enhancing data transmission through efficient components like encoders and beamformers. The second scenario illustrates beamforming's role in enabling precise robotic navigation in complex 3D environments, underscoring its transformative impact on communication and robotics [67, 81].

5.2 Challenges and Innovations in mmWave Communication

Millimeter-wave (mmWave) communication is crucial for 6G networks, offering high data rates and bandwidth, yet it faces challenges like high propagation loss, blockage susceptibility, and antenna complexity [26]. The adoption of mmWave bands is driven by the demand for high throughput, enabled by advanced antenna technologies [27]. However, mmWave signals' intermittent connectivity and blockage sensitivity impede low-latency, ultra-reliable connectivity [26].

Innovations like the hop-by-hop multi-path routing protocol maintain high throughput and low latency despite blockages and NLOS conditions [79]. UAVs offer flexible solutions for traffic management, leveraging mobility to alleviate congestion [54]. Protocol enhancements, such as the mmWave Performance Enhancing Proxy (mmPEP), improve TCP performance by managing early acknowledgments and batch retransmissions [77]. Rapid-Link reduces beam alignment delay significantly, enhancing mmWave network practicality [80].

Channel estimation complexity in high-frequency THz communications involves managing large data volumes and computationally intensive algorithms [82]. The Beam Squinting Compensation Method (BSCM) uses a compensation vector to adjust phase shifts, ensuring effective beam alignment despite frequency variations [73]. Frameworks like the two-step optimization approach by Noghani et al. employ MILP for network topology and bandwidth allocation optimization [83]. Robotic Aerial Small Cells (RASCs) provide an energy-efficient, on-demand solution for enhancing mmWave communication without hovering [84].

6 Ultra-Reliable Low-Latency Communication (URLLC)

6.1 Importance of URLLC in 6G Networks

Ultra-Reliable Low-Latency Communication (URLLC) is fundamental to 6G networks, supporting applications that require immediate and reliable data transfer, such as autonomous vehicles, remote surgeries, and virtual reality [85]. The Joint Planning and Network Slicing (JPSNC) method enhances resource allocation by concurrently addressing multiple traffic types and their latency needs [14]. Adaptive strategies are essential for ensuring reliable data exchange in dynamic environments, particularly for latency-sensitive applications [86]. A two-level RAN slicing approach employs deep reinforcement learning to manage resources effectively under rapidly changing conditions, crucial for high-speed scenarios like train communications [87, 72].

Network slicing addresses the diverse connectivity needs of Industry 4.0, ensuring low latency and reliability through strategic resource allocation [88]. The Deep Q-Learning with Delay (DQLD) algorithm optimizes Quality of Service (QoS) for URLLC and enhanced Mobile Broadband (eMBB) users, maintaining low latency and reliability in dynamic settings [33]. A DRL-based resource allocation framework further enhances energy efficiency and reduces URLLC latency across varied environments [43].

The coexistence of URLLC with eMBB and massive Machine-Type Communications (mMTC) presents unique challenges and opportunities. Rate-Splitting Multiple Access (RSMA) techniques significantly improve network performance over Non-Orthogonal Multiple Access (NOMA) and Orthogonal Multiple Access (OMA) by optimizing rate pairs for diverse services, enhancing resource allocation and connectivity [49, 89, 90, 91]. The LLM-Slice framework enhances response speed and resource efficiency, cutting average latency by 52% and boosting resource utilization by 30.8%, crucial for URLLC applications [62]. An optimization model ensures maximum delay thresholds for URLLC, highlighting its significance in 6G networks [85].

Proposed methods benefit delay-sensitive applications in mobile networks, improving end-to-end data rates and packet delivery ratios [92]. Supporting multiple URLLC users alongside eMBB users, as demonstrated by the NOMA-SIC method, underscores 6G networks' flexibility in meeting diverse service demands [90]. In autonomous vehicular networks, URLLC is crucial for enhancing reliability and reducing latency, supporting critical communication needs under high mobility and dynamic conditions [93].

URLLC is indispensable for 6G networks, providing the necessary framework for a wide range of applications requiring ultra-reliable, low-latency communication. Integrating advanced network slicing and modular architecture is key to developing future digital ecosystems that address the diverse and demanding requirements of next-generation applications. This integration fosters innovation and enhances user experiences across sectors like industrial IoT, mobile edge computing, and smart transportation, enabling tailored resource allocation and optimized service delivery [6, 94, 35, 20].

6.2 Challenges in Implementing URLLC

Implementing Ultra-Reliable Low-Latency Communication (URLLC) in network slicing and 6G networks presents significant challenges. Key issues include the vulnerabilities of mmWave communication, such as high path loss and poor propagation, which complicate reliable URLLC service delivery [59]. Dynamic network environments, with rapid changes in user mobility and traffic patterns, further impact service reliability and latency.

Optimizing resource allocation for URLLC services is complex. Current methods often rely on historical data, which may not reflect real-time user distribution, leading to suboptimal performance [32]. This outdated data reliance hinders the network's adaptability to real-time demands, affecting URLLC service efficiency and reliability.

Integrating URLLC with other service types, like eMBB and mMTC, presents additional challenges. Effective network slice isolation, efficient resource allocation, and dynamic network performance monitoring remain unresolved issues [44]. Balancing different service demands within a single network infrastructure complicates URLLC implementation, especially in scenarios requiring high reliability and low latency.

Scaling URLLC services in high-density environments is challenging due to stringent requirements for low packet blocking and error decoding probabilities. Conventional network slicing techniques struggle to meet the simultaneous demands of URLLC and mMTC, particularly in applications like factory automation that require latencies under 4 ms and support for up to 1,000,000 devices per square kilometer. Advanced resource orchestration strategies, such as optimizing physical resource blocks and leveraging coordinated multipoint beamforming, are needed to ensure reliable service delivery while maximizing shared network infrastructure utility [53, 95]. Limited radio resources in existing networks further hinder effective URLLC service scaling, necessitating ongoing research into innovative resource management strategies and network architectures.

The implementation of URLLC in network slicing and 6G networks involves complex challenges, including balancing reliability and latency, managing diverse resource demands, and integrating various service types. Orchestrating resources for bursty URLLC services requires addressing stringent performance metrics, such as low packet blocking and error decoding probabilities, while ensuring compliance with service level agreements (SLAs) through automated enforcement mechanisms. These challenges necessitate innovative approaches, such as advanced resource optimization algorithms and network slicing techniques, to effectively support the diverse requirements of future wireless networks [88, 53, 96]. Addressing these challenges requires innovative solutions and continued advancements in network architecture and resource allocation strategies to ensure that URLLC meets the rigorous demands of future digital ecosystems.

7 Open Radio Access Network (O-RAN)

7.1 Standardization and Open Architecture

The Open Radio Access Network (O-RAN) initiative is pivotal in establishing open network architectures that promote innovation and interoperability within the framework of future wireless networks, particularly 6G. By endorsing openness and modularity, O-RAN dismantles conventional monolithic structures, fostering a collaborative ecosystem where multiple vendors can contribute to and benefit from network infrastructure [97]. This modular architecture is crucial for ensuring vendor interoperability and creating a competitive environment.

A notable advancement in O-RAN is the use of a perfect graph to model user service dependencies, which enhances resource allocation efficiency compared to traditional methods [98]. Additionally, a joint optimization model for resource block allocation and distributed unit selection improves energy efficiency while maintaining performance in O-RAN deployments [70].

Despite these innovations, scaling O-RAN presents challenges. The SEM-O-RAN approach, which utilizes semantic-based methods for increased flexibility, encounters implementation complexities and limited support for direct communication between RIC applications and device applications within current O-RAN specifications [99]. This highlights the ongoing need to refine O-RAN standards for seamless integration and resource management.

Integrating advanced forecasting models into O-RAN architectures demonstrates potential for further innovation. Forecasting-aided deep reinforcement learning (DRL) approaches can enhance the performance of DRL-based slicing agents, allowing for more precise traffic demand predictions that optimize resource allocation and improve network efficiency [100].

7.2 Interoperability and Innovation

O-RAN plays a crucial role in enhancing interoperability and driving innovation in network slicing, thereby increasing the adaptability and efficiency of 6G networks. Its open architecture facilitates seamless integration of diverse network components, encouraging multi-vendor collaboration and fostering a competitive ecosystem that spurs technological advancements. This openness is key to reducing costs and improving performance, as demonstrated by O-RAN's support for flexible and cost-effective deployments [97].

The flexibility inherent in O-RAN's design allows for dynamic adaptation of network resources to meet varying service demands, which is essential for effective network slicing. By standardizing interfaces and encouraging open-source development, O-RAN ensures interoperability among network elements from different vendors, enhancing the robustness and scalability of network slicing solutions. This interoperability optimizes network management, reduces reliance on single-vendor solutions, and provides end-users with higher quality and reliability. Network slicing enables service providers to create customized slices for various industries, such as automotive and manufacturing, ensuring efficient resource allocation and performance that meets specific Quality of Service (QoS) and Service Level Agreement (SLA) requirements [20, 51].

O-RAN's commitment to innovation is also evident in its support for advanced technologies like artificial intelligence and machine learning, which are crucial for optimizing network slicing strategies. AI-driven analytics within the O-RAN framework facilitate real-time decision-making and predictive resource management, ensuring efficient allocation and adjustment of network slices to meet dynamic user demands. This capability is particularly relevant for 6G networks, which are anticipated to support a wide range of complex applications requiring high data rates, low latency, and reliable connectivity. As traditional terrestrial networks face challenges such as coverage limitations and congestion, integrating Non-Terrestrial Networks (NTNs) using airborne and spaceborne technologies becomes essential. These advancements necessitate agile and intelligent network management solutions, particularly through AI and Machine Learning techniques, optimizing resource allocation and enhancing network slicing capabilities to effectively address the diverse requirements of various vertical sectors [29, 60, 36, 101].

8 Energy Efficiency in Network Slicing

8.1 Dynamic Resource Allocation for Energy Efficiency

Dynamic resource allocation (DRA) plays a crucial role in enhancing energy efficiency in 6G network slicing by adapting to fluctuating network conditions and demands, ensuring optimal resource utilization while meeting Quality-of-Service (QoS) requirements. The UAV 'bridging' method exemplifies this by optimizing traffic management during peak loads, enhancing energy efficiency [54]. Integrating machine learning into DRA further bolsters adaptability and efficiency, as demonstrated by a method that maintains eMBB service quality while satisfying URLLC requirements, effectively managing service coverage and interference in Radio Access Networks (RANs) [4]. The Coverage-Aware Resource Provisioning (CARP) method also exemplifies optimized resource utilization across multiple slices, leading to cost reductions while meeting coverage constraints [39].

The Joint Power Control, Server, and Link Allocation (JPSLA) algorithm provides a comprehensive approach to resource allocation across RAN and core networks, minimizing energy consumption through a holistic resource management view [70]. Its mixed-integer linear programming (MILP) formulation captures the interactions between resource block allocation and distributed unit selection, enhancing resource efficiency [70]. In dense network environments, optimized resource allocation is vital, as demonstrated by Bahlke et al.'s approach, which significantly improves resource efficiency [40]. Algorithms that achieve rapid convergence to Nash equilibrium and near-optimal performance further enhance resource allocation efficiency [41].

The Joint Resource Allocation (JRA) method significantly improves acceptance ratios and cost efficiency compared to disjoint methods, facilitating better resource utilization [46]. Simulation results show JRA's effectiveness in minimizing power and bandwidth costs, contributing to energy efficiency in network slicing [46]. DRA is pivotal for achieving energy efficiency in network slicing, enabling 6G networks to meet diverse application demands while minimizing energy consumption and maintaining high performance. The integration of advanced algorithms, such as machine learning, alongside frameworks like network slicing and Open Radio Access Networks (ORAN), enhances the adaptability and efficiency of Non-Terrestrial Networks (NTNs). These innovations address challenges faced by traditional terrestrial communication systems, such as coverage and congestion, while facilitating ultra-reliable communications with low latency and high data rates. As the 6G era approaches, these developments will be critical for creating sustainable and efficient next-generation communication systems [15, 36].

8.2 Technological Innovations for Energy Efficiency

Technological innovations are essential for enhancing energy efficiency in 6G networks, especially given the rising demand for high-performance communication services. The EcoSlice method allows operators to transition users to low-resource slices without significantly affecting QoS, optimizing resource usage and reducing energy consumption [23]. This underscores the potential of dynamic resource allocation strategies in achieving energy efficiency while maintaining service quality.

The STEP framework advances energy-efficient operations in network slicing by improving protocol interpretability and resource efficiency, optimizing resource management processes essential for minimizing energy consumption in complex network environments [102]. Machine learning techniques further refine the resource allocation process, enhancing the reward function and adaptability to dynamic network conditions [103]. The SFI2 architecture emphasizes energy-efficient slicing by incorporating sustainability into its design, focusing on improved resource allocation through energy-efficient practices [6]. Knowledge transfer methodologies, as highlighted by Zhou et al., further improve resource management efficiency, showcasing AI/ML techniques' potential to address network slicing complexities [101].

Taskou et al. propose a joint approach to power control and resource allocation, achieving a 30

In smart factories, ongoing research in network slicing is necessary to fully leverage emerging technologies like 6G. Continuous innovation is crucial for addressing the unique challenges posed by dense industrial environments, where energy efficiency and resource optimization are paramount [104]. Integrating energy-efficient practices into the design and operation of 6G networks is increasingly vital, as recent advancements in technologies such as Non-Terrestrial Networks (NTNs), network slicing, and Machine Learning (ML) optimizations demonstrate. These innovations aim to enhance the energy efficiency of RANs and address complex challenges posed by anticipated 6G demands, including coverage, reliability, and resource allocation among diverse applications. By adopting energy-efficient slicing strategies and leveraging AI/ML for network management, the telecommunications industry can significantly reduce energy consumption while improving throughput and operational costs, ensuring a sustainable and robust communication infrastructure for the future [105, 36, 6, 106, 29]. Through advanced algorithms, machine learning techniques, and dynamic resource management strategies, these innovations contribute to developing sustainable and efficient next-generation communication systems.

9 Terahertz Communication

9.1 Potential for Ultra-Fast Wireless Data Transfer

Terahertz (THz) communication promises to revolutionize wireless data transfer with its capability to support ultra-high data rates, essential for 6G networks. Operating within the 0.1 to 10 THz frequency range, THz communication offers bandwidths that far exceed those of current wireless technologies [73]. This makes it ideal for data-intensive applications such as holographic communications, immersive virtual reality, and high-definition video streaming, which demand both high throughput and low latency.

The use of distributed Reconfigurable Intelligent Surfaces (RIS) marks a significant advancement in this domain, enhancing adaptive beamforming and channel reconstruction. This innovation addresses issues like high propagation loss and obstruction sensitivity by improving energy efficiency and signal quality [25]. The versatility of the distributed RIS framework ensures reliable communication even in challenging environments.

Research by Sopin et al. highlights the potential of THz communication for rapid data transfer, noting challenges such as high blocker density that can impede signal propagation and reliability [28]. Multi-connectivity strategies are employed to mitigate these challenges, enabling seamless handovers and maintaining connectivity through multiple pathways.

Moreover, integrating microservices architectures within THz systems enhances the management and processing of large datasets necessary for channel estimation, significantly improving response times and signal quality [82]. These advanced architectures allow THz communication to transcend the limitations of traditional systems, offering a scalable solution for ultra-fast data transfer.

9.2 Challenges and Solutions in Terahertz Communication

Deploying terahertz (THz) communication in 6G networks involves overcoming several challenges inherent to THz frequencies (0.1 to 10 THz). A major issue is the pronounced propagation loss, which limits transmission range [25]. This necessitates sophisticated beamforming techniques and dense network infrastructures to maintain reliable communication links.

THz signals are particularly susceptible to blockages and environmental factors such as atmospheric absorption and scattering, leading to rapid signal degradation and higher error rates [73]. Reconfigurable Intelligent Surfaces (RIS) are proposed to dynamically modify the propagation environment, enhancing signal strength and quality through intelligent reflection and refraction of THz waves [25].

The high data rates of THz communication require efficient channel estimation and data processing techniques to handle the vast amounts of transmitted data. The integration of edge computing and microservices architectures facilitates real-time data processing and reduces latency, thereby improving the overall performance of THz systems [82].

Multi-connectivity strategies offer a robust solution to the challenges in THz communication, enabling seamless handovers and utilizing multiple transmission paths to maintain strong connectivity despite blockages and environmental disruptions [28]. This approach ensures reliable communication, especially in densely populated urban areas where THz signals are prone to interference.

10 Spectrum Management

10.1 Challenges in Spectrum Management for 6G Networks

Spectrum management in 6G networks presents complex challenges requiring innovative solutions to ensure efficient and reliable communication. Current methods inadequately handle interference in densely populated areas, leading to suboptimal performance and energy inefficiency [107]. This is compounded by the necessity for dynamic resource allocation to meet diverse Quality of Service (QoS) requirements, such as enhanced Mobile Broadband (eMBB) and Ultra-Reliable Low-Latency Communication (URLLC) within the Open Radio Access Network (O-RAN) framework [108].

The integration of vast bandwidth and spatial degrees of freedom in the millimeter-wave (mmWave) spectrum further complicates spectrum management. Traditional cellular networks struggle to efficiently utilize these resources due to the highly directional nature of mmWave transmissions, which challenges robust connectivity amid rapid channel condition changes due to obstacles [26, 27]. The O-RAN architecture also imposes specific challenges in designing interfaces between the Radio Unit (RU), Distributed Unit (DU), and Centralized Unit (CU), necessitating high-capacity, low-latency links for flexible functional splits [109]. Ensuring that O-RAN meets 6G's stringent requirements, including integration with non-terrestrial networks, remains critical [97].

Existing spectrum access models in mmWave networks, such as exclusive and pooled spectrum access, are insufficient for maximizing spectrum utilization while accommodating multiple operators [110]. This is further complicated by managing spectrum for THz/mmWave systems, where maintaining reliable service continuity is a persistent challenge [28]. Inefficient resource allocation in network slicing, especially under stochastic loads, necessitates unique Service Level Agreements (SLAs) for each slice, reflecting distinct metrics and requirements. Traditional static slicing methods yield poor efficiency, highlighting the need for more adaptive resource allocation approaches [42].

Hybrid spectrum sharing models can dynamically allocate spectrum resources based on real-time demand and usage patterns. Leveraging advanced technologies such as artificial intelligence (AI) and machine learning (ML) for predictive resource management and dynamic spectrum allocation significantly enhances spectrum efficiency by enabling adaptive management of network resources. These technologies facilitate improved performance in complex environments, such as 5G and future 6G networks, through innovative approaches like transfer learning and AI-assisted frameworks, optimizing resource allocation and interference management across multiple service slices. Integrating techniques such as multi-access edge computing and semantic communications addresses the growing demand for data processing at the network edge while promoting efficient communication focused on meaningful information exchange, ultimately leading to better spectrum utilization [15, 58, 101]. Additionally, employing multi-connectivity strategies and deploying Reconfigurable Intelligent Surfaces (RIS) can mitigate the effects of physical obstacles and enhance signal propagation in challenging environments, thus addressing the complexities of spectrum management in 6G networks.

10.2 Innovative Spectrum Access Models

Optimizing frequency usage in 6G networks necessitates innovative spectrum access models, especially given the increasing demand for high-capacity, low-latency communication services. Traditional management approaches, reliant on exclusive access models, often result in inefficient resource utilization. New models promoting shared access to spectrum and infrastructure enable multiple operators to leverage the same frequency bands and network assets [111].

The hybrid spectrum access scheme effectively combines exclusive access to lower frequency mmWave bands with pooled access to higher mmWave bands. This strategy allows operators to maintain guaranteed service levels for critical applications while benefiting from the flexibility and efficiency of shared access in higher frequency bands [110]. By dynamically allocating spectrum based on real-time demand and usage patterns, this hybrid model enhances resource allocation efficiency, reduces operational costs, and improves overall network performance.

Integrating these innovative spectrum access models into the 6G ecosystem is expected to facilitate more effective management of radio frequency resources. Utilizing advanced technologies such as AI and ML for predictive resource management enables dynamic spectrum allocation that enhances performance and addresses the varied requirements of next-generation applications. This approach is particularly relevant in the context of 5G and anticipated 6G networks, where AI techniques—like transfer learning, deep reinforcement learning, and other emerging ML methods—facilitate efficient resource management and network slicing. These technologies support service-oriented resource allocation, allowing networks to adapt to the dynamic demands of diverse vertical industries while maintaining service quality and optimizing resource efficiency [37, 30, 101]. Such models not only enhance spectrum efficiency but also ensure the seamless coexistence of multiple services, maintaining the robustness and adaptability of 6G networks in response to evolving demands.

10.3 AI/ML Solutions for Spectrum Optimization

Integrating Artificial Intelligence (AI) and Machine Learning (ML) solutions into spectrum management is crucial for optimizing resource allocation and enhancing 6G network performance. These technologies provide dynamic and adaptive strategies for managing the complex and rapidly changing environments characteristic of next-generation wireless communications. Implementing AI/ML frameworks within the O-RAN architecture offers a robust foundation for optimizing resource management and improving network performance [97].

AI/ML techniques are vital in addressing resource management challenges in converged optical and mmWave networks. Current research emphasizes the need for further exploration of these solutions to effectively optimize resource utilization [112]. By leveraging AI/ML algorithms, networks can dynamically reallocate unused bandwidth from less active slices, ensuring QoS and optimizing throughput [108].

The hybrid spectrum access method, which combines exclusive and pooled spectrum access in mmWave networks, significantly benefits from AI/ML integration. This approach enhances throughput and resource allocation among multiple operators, as demonstrated in experimental setups simulating scenarios with varying user and base station densities [110]. The adaptability of AI/ML frameworks to changing network conditions further underscores their effectiveness in optimizing spectrum management [108].

Future advancements in AI/ML solutions for spectrum optimization will focus on enhancing energy efficiency and adapting methods for outdoor and high-density urban scenarios. Integrating these frameworks into distributed Reconfigurable Intelligent Surfaces (RIS) will further improve their applicability and effectiveness across diverse environments [25]. The continuous evolution of AI/ML technologies is essential for driving energy efficiency improvements and ensuring the sustainable development of 6G networks [106].

Applying AI and ML solutions in spectrum management is crucial for optimizing resource allocation and enhancing network performance in 6G networks. Integrating advanced technologies such as Non-Terrestrial Networks (NTNs), network slicing, and AI/ML is essential for effectively navigating the complexities of next-generation wireless communications. These innovations enhance coverage and reliability while addressing issues like interference and congestion, increasingly critical as the demands of the 6G era escalate. By leveraging airborne and spaceborne communication systems, these technologies facilitate ultra-reliable connectivity with high data rates and low latency across vast regions, ensuring robust and efficient network operations that can adapt to evolving challenges and user needs [113, 15, 36].

11 Conclusion

11.1 Future Directions and Innovations

The evolution of network slicing within 6G networks is poised to advance significantly through targeted research in several critical areas. A primary focus will be developing heuristic methods for decentralized optimization, enhancing scalability and adaptability in large network environments. These methods aim to streamline resource management, enabling dynamic adjustments to meet changing network conditions effectively. Additionally, refining real-time prediction techniques for user demands and accelerating the convergence speed of AI-based methods are vital for anticipating fluctuating demands, thereby optimizing resource allocation and enhancing user experience.

Future research will also prioritize integrating planning and operational stages in slicing-based resource management, leveraging AI-assisted frameworks to achieve dynamic and efficient resource allocation. Implementing these frameworks on real testbeds and exploring diverse use cases will provide valuable insights into the practical applications of network slicing, demonstrating its potential to optimize real-world network performance. Enhancements to the Generalized Kelly Mechanism (GKM) will focus on addressing dynamic changes in user demand and resource availability, particularly in complex multi-resource scenarios, further enabling effective management of 6G network demands.

Moreover, the development of adaptive mechanisms for congestion control, improvements in MAC layer designs, and exploration of SDN and NFV implications in real-world settings are essential to fully harness mmWave capabilities. Continued optimization of resource allocation algorithms and integration with lower-level scheduling mechanisms will contribute to robust network management frameworks, supporting the diverse needs of future digital ecosystems.

Finally, advancing testbed capabilities to support machine learning integration, improved slice isolation, and effective cross-domain network slicing management will be crucial. By addressing these challenges and pursuing 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.

AI-generated, for reference only.

References

[1] Jaya Thota and Adnan Aijaz. Demo: Slicing-enabled private 4g/5g network for industrial wireless applications, 2020.

[2] P. Rost, C. Mannweiler, D. S. Michalopoulos, C. Sartori, V. Sciancalepore, N. Sastry, O. Holland, S. Tayade, B. Han, D. Bega, D. Aziz, and H. Bakker. Network slicing to enable scalability and flexibility in 5g mobile networks, 2017.

[3] Youssouf Drif, Emmanuel Chaput, Emmanuel Lavinal, Pascal Berthou, Boris Tiomela Jou, Olivier Gremillet, and Fabrice Arnal. An extensible network slicing framework for satellite integration into 5g, 2020.

[4] Ali Esmaeily, Katina Kralevska, and Toktam Mahmoodi. Slicing scheduling for supporting critical traffic in beyond 5g, 2021.

[5] Wei-Kun Chen, Ya-Feng Liu, Antonio De Domenico, Zhi-Quan Luo, and Yu-Hong Dai. Optimal network slicing for service-oriented networks with flexible routing and guaranteed e2e latency, 2021.

[6] Joberto S. B. Martins, Tereza C. Carvalho, Rodrigo Moreira, Cristiano Both, Adnei Donatti, João H. Corrêa, José A. Suruagy, Sand L. Corrêa, Antonio J. G. Abelem, Moisés R. N. Ribeiro, Jose-Marcos Nogueira, Luiz C. S. Magalhães, Juliano Wickboldt, Tiago Ferreto, Ricardo Mello, Rafael Pasquini, Marcos Schwarz, Leobino N. Sampaio, Daniel F. Macedo, José F. de Rezende, Kleber V. Cardoso, and Flávio O. Silva. Enhancing network slicing architectures with machine learning, security, sustainability and experimental networks integration, 2023.

[7] Hamza Khan, Petri Luoto, Sumudu Samarakoon, Mehdi Bennis, and Matti Latva-Aho. Network slicing for vehicular communication, 2019.

[8] Hamza Khan, Petri Luoto, Mehdi Bennis, and Matti Latva-aho. On the application of network slicing for 5g-v2x, 2018.

[9] Jie Mei, Xianbin Wang, and Kan Zheng. Intelligent network slicing for v2x services towards 5g, 2019.

[10] Viswanath KumarSkandPriya, Abdulhalim Dandoush, and Gladys Diaz. Slicenet: a simple and scalable flow-level simulator for network slice provisioning and management, 2023.

[11] Panagiotis Promponas and Leandros Tassiulas. Network slicing: Market mechanism and competitive equilibria, 2023.

[12] Mohammad Asif Habibi, Bin Han, and Hans D. Schotten. Network slicing in 5g mobile communication architecture, profit modeling, and challenges, 2017.

[13] Jose Ordonez-Lucena, Oscar Adamuz-Hinojosa, Pablo Ameigeiras, Pablo Muñoz, Juan J. Ramos-Muñoz, Jesús Folgueira Chavarria, and Diego Lopez. The creation phase in network slicing: From a service order to an operative network slice, 2018.

[14] Bin Xiang, Jocelyne Elias, Fabio Martignon, and Elisabetta Di Nitto. Joint planning of network slicing and mobile edge computing: Models and algorithms, 2021.

[15] Nikos G. Evgenidis, Nikos A. Mitsiou, Vasiliki I. Koutsioumpa, Sotiris A. Tegos, Panagiotis D. Diamantoulakis, and George K. Karagiannidis. Multiple access in the era of distributed computing and edge intelligence, 2024.

[16] Salvatore D'Oro, Leonardo Bonati, Francesco Restuccia, Michele Polese, Michele Zorzi, and Tommaso Melodia. Sl-edge: Network slicing at the edge, 2020.

[17] Madhusanka Liyanage, Pawani Porambage, and Aaron Yi Ding. Five driving forces of multi-access edge computing, 2018.

[18] JaeYoung Hwang, Lionel Nkenyereye, NakMyoung Sung, JaeHo Kim, and JaeSeung Song. Iot service slicing and task offloading for edge computing, 2020.

[19] Adel Nadjaran Toosi, Redowan Mahmud, Qinghua Chi, and Rajkumar Buyya. Management and orchestration of network slices in 5g, fog, edge and clouds, 2018.

[20] Mohammad Asif Habibi, Bin Han, Faqir Zarrar Yousaf, and Hans D. Schotten. How should network slice instances be provided to multiple use cases of a single vertical industry?, 2021.

[21] Shiva Kazemi Taskou, Mehdi Rasti, and Pedro H. J. Nardelli. Minimizing energy consumption for end-to-end slicing in 5g wireless networks and beyond, 2022.

[22] Hnin Pann Phyu, Razvan Stanica, Diala Naboulsi, and Gwenael Poitau. Going green in ran slicing, 2023.

[23] Hnin Pann Phyu, Diala Naboulsi, Razvan Stanica, and Gwenael Poitau. Towards energy efficiency in ran network slicing, 2023.

[24] Bho Matthiesen, Osman Aydin, and Eduard A. Jorswieck. Throughput and energy-efficient network slicing, 2018.

[25] Yiming Huo, Xiaodai Dong, and Nuwan Ferdinand. Distributed reconfigurable intelligent surfaces for energy efficient indoor terahertz wireless communications, 2022.

[26] Mehrdad Shariat, David M. Gutierrez-Estevez, Arnesh Vijay, Krystian Safjan, Patrik Rugeland, Icaro da Silva, Javier Lorca, Joerg Widmer, Maria Fresia, Yilin Li, and Isabelle Siaud. 5g radio access above 6 ghz, 2017.

[27] Menglei Zhang, Marco Mezzavilla, Russell Ford, Sundeep Rangan, Shivendra Panwar, Evangelos Mellios, Di Kong, Andrew Nix, and Michele Zorzi. Transport layer performance in 5g mmwave cellular, 2016.

[28] Eduard Sopin, Dmitri Moltchanov, Anastasia Daraseliya, Yevgeni Koucheryavy, and Yuliya Gaidamaka. User association and multi-connectivity strategies in joint terahertz and millimeter wave 6g systems, 2022.

[29] Idris Badmus, Marja Matinmikko-Blue, and Jaspreet Singh Walia. Network slicing management technique for local 5g micro-operator deployments, 2019.

[30] Bin Han and Hans D. Schotten. Machine learning for network slicing resource management: A comprehensive survey, 2020.

[31] Han Hu, Weiwei Song, Qun Wang, Rose Qingyang Hu, and Hongbo Zhu. Energy efficiency and delay tradeoff in an mec-enabled mobile iot network, 2022.

[32] Asim Mazin, Mohamed Elkourdi, and Richard D. Gitlin. Accelerating beam sweeping in mmwave standalone 5g new radios using recurrent neural networks, 2018.

[33] Medhat Elsayed and Melike Erol-Kantarci. Radio resource and beam management in 5g mmwave using clustering and deep reinforcement learning, 2021.

[34] Binquan Guo, Hongyan Li, Zhou Zhang, and Ye Yan. Online network slicing for real time applications in large-scale satellite networks, 2023.

[35] Xueli An, Riccardo Trivisonno, Hans Einsiedler, Dirk von Hugo, Kay Haensge, Xiaofeng Huang, Qing Shen, Daniel Corujo, Kashif Mahmood, Dirk Trossen, Marco Liebsch, Filipe Leitao, Cao-Thanh Phan, and Frederic Klamm. End-to-end architecture modularisation and slicing for next generation networks, 2016.

[36] Cong T. Nguyen, Yuris Mulya Saputra, Nguyen Van Huynh, Tan N. Nguyen, Dinh Thai Hoang, Diep N Nguyen, Van-Quan Pham, Miroslav Voznak, Symeon Chatzinotas, and Dinh-Hieu Tran. Emerging technologies for 6g non-terrestrial-networks: From academia to industrial applications, 2024.

[37] Wanqing Guan, Haijun Zhang, and Victor C. M. Leung. Customized slicing for 6g: Enforcing artificial intelligence on resource management, 2021.

[38] Jiaxiao Zheng and Gustavo de Veciana. Elastic multi-resource network slicing: Can protection lead to improved performance?, 2019.

[39] Quang-Trung Luu, Sylvaine Kerboeuf, Alexandre Mouradian, and Michel Kieffer. A coverage-aware resource provisioning method for network slicing, 2020.

[40] Florian Bahlke, Oscar D. Ramos-Cantor, Steffen Henneberger, and Marius Pesavento. Optimized cell planning for network slicing in heterogeneous wireless communication networks, 2018.

[41] Salvatore D'Oro, Francesco Restuccia, Tommaso Melodia, and Sergio Palazzo. Low-complexity distributed radio access network slicing: Algorithms and experimental results, 2018.

[42] Yan Kyaw Tun, Nguyen H. Tran, Duy Trong Ngo, Shashi Raj Pandey, Zhu Han, and Choong Seon Hong. Wireless network slicing: Generalized kelly mechanism based resource allocation, 2019.

[43] Rana M. Sohaib, Syed Tariq Shah, and Poonam Yadav. Towards resilient 6g o-ran: An energy-efficient urllc resource allocation framework, 2024.

[44] Ali Esmaeily and Katina Kralevska. Small-scale 5g testbeds for network slicing deployment: A systematic review, 2021.

[45] Anqi Huang, Yingyu Li, Yong Xiao, Xiaohu Ge, Sumei Sun, and Han-Chieh Chao. Distributed resource allocation for network slicing of bandwidth and computational resource, 2020.

[46] Sina Ebrahimi, Abulfazl Zakeri, Behzad Akbari, and Nader Mokari. Joint resource and admission management for slice-enabled networks, 2019.

[47] Quang-Trung Luu, Sylvaine Kerboeuf, and Michel Kieffer. Admission control and resource reservation for prioritized slice requests with guaranteed sla under uncertainties, 2022.

[48] Jiaxiao Zheng, Gustavo de Veciana, and Albert Banchs. Constrained network slicing games: Achieving service guarantees and network efficiency, 2020.

[49] Petar Popovski, Kasper F. Trillingsgaard, Osvaldo Simeone, and Giuseppe Durisi. 5g wireless network slicing for embb, urllc, and mmtc: A communication-theoretic view, 2018.

[50] Ravishankar Ravindran, Asit Chakraborti, Syed Obaid Amin, Aytac Azgin, and Guoqiang Wang. 5g-icn : Delivering icn services over 5g using network slicing, 2016.

[51] Mohammad Asif Habibi, Bin Han, Meysam Nasimi, and Hans D. Schotten. The structure of service level agreement of slice-based 5g network, 2018.

[52] Biswa P. S. Sahoo, Chung-Wei Weng, and Hung-Yu Wei. Sdn - architectural enabler for reliable communication over millimeter-wave 5g networks, 2018.

[53] Peng Yang, Xing Xi, Tony Q. S. Quek, Jingxuan Chen, Xianbin Cao, and Dapeng Wu. How should i orchestrate resources of my slices for bursty urllc service provision?, 2020.

[54] Nikita Tafintsev, Dmitri Moltchanov, Sergey Andreev, Shu ping Yeh, Nageen Himayat, Yevgeni Koucheryavy, and Mikko Valkama. Handling spontaneous traffic variations in 5g+ via offloading onto mmwave-capable uav 'bridges', 2020.

[55] Matteo Pagin, Francesco Agostini, Tommaso Zugno, Michele Polese, and Michele Zorzi. Enabling ran slicing through carrier aggregation in mmwave cellular networks, 2020.

[56] Abderrahime Filali, Zoubeir Mlika, Soumaya Cherkaoui, and Abdellatif Kobbane. Dynamic sdn-based radio access network slicing with deep reinforcement learning for urllc and embb services, 2022.

[57] Tianlun Hu, Qi Liao, Qiang Liu, Antonio Massaro, and Georg Carle. Fast and scalable network slicing by integrating deep learning with lagrangian methods, 2024.

[58] Conghao Zhou, Jie Gao, Mushu Li, Xuemin Shen, Weihua Zhuang, Xu Li, and Weisen Shi. Ai-assisted slicing-based resource management for two-tier radio access networks, 2023.

[59] Russell Ford, Menglei Zhang, Marco Mezzavilla, Sourjya Dutta, Sundeep Rangan, and Michele Zorzi. Achieving ultra-low latency in 5g millimeter wave cellular networks, 2016.

[60] Wen Wu, Conghao Zhou, Mushu Li, Huaqing Wu, Haibo Zhou, Ning Zhang, Xuemin, Shen, and Weihua Zhuang. Ai-native network slicing for 6g networks, 2021.

[61] B. Shariati, J. J. Pedreno-Manresa, A. Dochhan, A. S. Muqaddas, R. Casellas, O. González de Dios, L. L. Canto, B. Lent, J. E. López de Vergara, S. López-Buedo, F. J. Moreno, P. Pavón, L. Velasco, S. Patri, A. Giorgetti, F. Cugini, A. Sgambelluri, R. Nejabati, D. Simeonidou, R, P, Braun, A. Autenrieth, J. P. Elbers, J. K. Fischer, and R. Freund. A latency-aware real-time video surveillance demo: Network slicing for improving public safety, 2021.

[62] Boyi Liu, Jingwen Tong, and Jun Zhang. Llm-slice: Dedicated wireless network slicing for large language models, 2024.

[63] Yingying Guan, Qingyang Song, Weijing Qi, Ke Li, Lei Guo, and Abbas Jamalipour. Multidimensional resource fragmentation-aware virtual network embedding in mec systems interconnected by metro optical networks, 2023.

[64] K. Koutlia, R. Ferrus, E. Coronado, R. Riggio, F. Casadevall, A. Umbert, and J. Perez-Romero. Design and experimental validation of a software-defined radio access network testbed with slicing support, 2019.

[65] Salvatore D'Oro, Francesco Restuccia, and Tommaso Melodia. Toward operator-to-waveform 5g radio access network slicing, 2019.

[66] Prabhu Kaliyammal Thiruvasagam, Abhishek Chakraborty, and C Siva Ram Murthy. Resilient and latency-aware orchestration of network slices using multi-connectivity in mec-enabled 5g networks, 2021.

[67] Morteza Hashemi, C. Emre Koksal, and Ness B. Shroff. Dual sub-6 ghz – millimeter wave beamforming and communications to achieve low latency and high energy efficiency in 5g systems, 2017.

[68] Sharvari Ravindran, Saptarshi Chaudhuri, Jyotsna Bapat, and Debabrata Das. Predictive dynamic scaling multi-slice-in-slice-connected users for 5g system resource scheduling, 2021.

[69] Hossein Shokri-Ghadikolaei, Carlo Fischione, Gabor Fodor, Petar Popovski, and Michele Zorzi. Millimeter wave cellular networks: A mac layer perspective, 2015.

[70] Turgay Pamuklu, Shahram Mollahasani, and Melike Erol-Kantarci. Energy-efficient and delay-guaranteed joint resource allocation and du selection in o-ran, 2022.

[71] Yong Niu, Chuhan Gao, Yong Li, Depeng Jin, Li Su, Dapeng, and Wu. Boosting spatial reuse via multiple paths multi-hop scheduling for directional mmwave wpans, 2015.

[72] Changzhu Liu, Ruisi He, Yong Niu, Shiwen Mao, Bo Ai, and Ruifeng Chen. Refracting reconfigurable intelligent surface assisted urllc for millimeter wave high-speed train communication coverage enhancement, 2024.

[73] Diego A. Sousa, Fco. Rafael M. Lima, Victor F. Monteiro, Tarcisio F. Maciel, and Behrooz Makki. Beam squinting compensation: An ncr-assisted scenario, 2024.

[74] Ish Kumar Jain, Raghav Subbaraman, and Dinesh Bharadia. Two beams are better than one: Enabling reliable and high throughput mmwave links, 2022.

[75] C. Nicolas Barati, Sourjya Dutta, Sundeep Rangan, and Ashutosh Sabharwal. Energy and latency of beamforming architectures for initial access in mmwave wireless networks, 2020.

[76] Michele Polese, Marco Giordani, Marco Mezzavilla, Sundeep Rangan, and Michele Zorzi. Improved handover through dual connectivity in 5g mmwave mobile networks, 2017.

[77] Minho Kim, Seung-Woo Ko, and Seong-Lyun Kim. Enhancing tcp end-to-end performance in millimeter-wave communications, 2017.

[78] Dileep Kumar, Satya Joshi, and Antti Tölli. Latency-constrained highly-reliable mmwave communication via multi-point connectivity, 2021.

[79] Chanaka Samarathunga, Mohamed Abouelseoud, Kazuyuki Sakoda, and Morteza Hashemi. On the benefits of multi-hop communication for indoor 60 ghz wireless networks, 2020.

[80] Haitham Hassanieh, Omid Abari, Michael Rodreguez, Mohammed Abdelghany, Dina Katabi, and Piotr Indyk. Agile millimeter wave networks with provable guarantees, 2017.

[81] Mattia Lecci, Paolo Testolina, Michele Polese, Marco Giordani, and Michele Zorzi. Accuracy vs. complexity for mmwave ray-tracing: A full stack perspective, 2020.

[82] Zied Ennaceur, Anna Engelmann, and Admela Jukan. Engineering edge-cloud offloading of big data for channel modelling in thz-range communications, 2021.

[83] Kyoomars Alizadeh Noghani, Hakim Ghazzai, and Andreas Kassler. A generic framework for task offloading in mmwave mec backhaul networks, 2018.

[84] Jongyul Lee and Vasilis Friderikos. Robotic aerial 6g small cells with grasping end effectors for mmwave relay backhauling, 2022.

[85] Flávio G. C. Rocha, Gabriel M. F. de Almeida, Kleber V. Cardoso, Cristiano B. Both, and José F. de Rezende. Optimal resource allocation with delay guarantees for network slicing in disaggregated ran, 2023.

[86] Sergio Martiradonna, Andrea Abrardo, Marco Moretti, Giuseppe Piro, and Gennaro Boggia. Deep reinforcement learning-aided ran slicing enforcement for b5g latency sensitive services, 2021.

[87] Abderrahime Filali, Boubakr Nour, Soumaya Cherkaoui, and Abdellatif Kobbane. Communication and computation o-ran resource slicing for urllc services using deep reinforcement learning, 2022.

[88] Anders Ellersgaard Kalør, René Guillaume, Jimmy Jessen Nielsen, Andreas Mueller, and Petar Popovski. Network slicing for ultra-reliable low latency communication in industry 4.0 scenarios, 2017.

[89] Yuanwen Liu, Bruno Clerckx, and Petar Popovski. Network slicing for embb, urllc, and mmtc: An uplink rate-splitting multiple access approach, 2023.

[90] Eduardo Noboro Tominaga, Hirley Alves, Richard Demo Souza, João Luiz Rebelatto, and Matti Latva-Aho. Non-orthogonal multiple access and network slicing: Scalable coexistence of embb and urllc, 2021.

[91] Eduardo Noboro Tominaga, Hirley Alves, Onel Luiz Alcaraz López, Richard Demo Souza, João Luiz Rebelatto, and Matti Latva-Aho. Network slicing for embb and mmtc with noma and space diversity reception, 2021.

[92] Guidan Yao, Morteza Hashemi, and Ness B. Shroff. Integrating sub-6 ghz and millimeter wave to combat blockage: Delay-optimal scheduling, 2019.

[93] Xiaohu Ge. Ultra-reliable low-latency communications in autonomous vehicular networks, 2019.

[94] Rodrigo Moreira, Flavio de Oliveira Silva, Tereza Cristina Melo de Brito Carvalho, and Joberto S. B. Martins. Intelligent data-driven architectural features orchestration for network slicing, 2024.

[95] Shiva Raj Pokhrel, Jie Ding, Jihong Park, Ok-Sun Park, and Jinho Choi. Towards enabling critical mmtc: A review of urllc within mmtc, 2020.

[96] Sebastian Gallenmüller, Johannes Naab, Iris Adam, and Georg Carle. 5g qos: Impact of security functions on latency, 2019.

[97] Sneihil Gopal, Aziz Kord, and Richard A. Rouil. O-ran and 6g: The future of wireless innovation?, 2024.

[98] Sharvari Ravindran, Saptarshi Chaudhuri, Jyotsna Bapat, and Debabrata Das. Optimization results for 5g slice-in-slice scheduling, 2021.

[99] Corrado Puligheddu, Jonathan Ashdown, Carla Fabiana Chiasserini, and Francesco Restuccia. Sem-o-ran: Semantic and flexible o-ran slicing for nextg edge-assisted mobile systems, 2022.

[100] Ahmad M. Nagib, Hatem Abou-Zeid, and Hossam S. Hassanein. How does forecasting affect the convergence of drl techniques in o-ran slicing?, 2023.

[101] Hao Zhou, Melike Erol-Kantarci, and Vincent Poor. Knowledge transfer and reuse: A case study of ai-enabled resource management in ran slicing, 2022.

[102] Farhad Rezazadeh, Hatim Chergui, Shuaib Siddiqui, Josep Mangues, Houbing Song, Walid Saad, and Mehdi Bennis. Intelligible protocol learning for resource allocation in 6g o-ran slicing, 2024.

[103] Linh Le, Tu N. Nguyen, Kun Suo, and Jing He. Efficient embedding vnfs in 5g network slicing: A deep reinforcement learning approach, 2022.

[104] Regina Ochonu and Josep Vidal. Slicing for dense smart factory network: Current state, scenarios, challenges and expectations, 2024.

[105] Navideh Ghafouri, John S. Vardakas, Kostas Ramantas, and Christos Verikoukis. Energy-efficient intra-domain network slicing for multi-layer orchestration in intelligent-driven distributed 6g networks: Learning generic assignment skills with unsupervised reinforcement learning, 2024.

[106] Lopamudra Kundu, Xingqin Lin, and Rajesh Gadiyar. Towards energy efficient ran: From industry standards to trending practice, 2024.

[107] Junyuan Wang, Lin Dai, Lu Yang, and Bo Bai. Clustered cell-free networking: A graph partitioning approach, 2022.

[108] Nien Fang Cheng, Turgay Pamuklu, and Melike Erol-Kantarci. Reinforcement learning based resource allocation for network slices in o-ran midhaul, 2022.

[109] Sourav Mondal and Marco Ruffini. Optical front/mid-haul with open access-edge server deployment framework for sliced o-ran, 2022.

[110] Mattia Rebato, Federico Boccardi, Marco Mezzavilla, Sundeep Rangan, and Michele Zorzi. Hybrid spectrum sharing in mmwave cellular networks, 2017.

[111] Mattia Rebato, Marco Mezzavilla, Sundeep Rangan, and Michele Zorzi. The potential of resource sharing in 5g millimeter-wave bands, 2016.

[112] Doruk Sahinel, Simon Rommel, and Idelfonso Tafur Monroy. Resource management in converged optical and millimeter wave radio networks: a review. *Applied Sciences*, 12(1):221, 2021.

[113] Hang Zhang. Future wireless network: Mynet platform and end-to-end network slicing, 2016.

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