MECON

Multi-Access Edge Computing (MEC) over NTN for beyond 5G & 6G

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Executive Summary

This report provides a comprehensive overview of advancements in next-generation digital connectivity technologies, with a focus on Radio Resource Management (RRM) in Radio Access Networks and use cases as well as architectures for Non-Terrestrial Networks (NTN). The insights within this report are essential for stakeholders aiming to harness MEC (Multi-Access Edge Computing) over NTNs in 5G and 6G ecosystems, enabling ubiquitous, high-performance connectivity across rural, urban, and remote areas. MECON delivers substantial benefits by addressing key challenges in scaling connectivity for underserved regions, focusing on flexible and dynamic radio resource management through open RAN. The project also explores cutting-edge NTN and satellite implementations, presenting use cases, challenges, and opportunities for future technology integration. By examining the integration of terrestrial and non-terrestrial elements, this report highlights how enhanced RRM solutions can improve connectivity reliability, coverage, and capacity to meet the unique demands of 6G and beyond. In addition to the technical aspects, this deliverable emphasizes the importance of coordinated standardization efforts from multiple global bodies, including 3GPP, ITU, IEEE, TIP, LNF, and ESA. These efforts are vital for the successful interoperability and scalability of TN and NTN systems. This report serves as a foundational resource for policy makers, industry leaders, and researchers by offering strategic guidance and defining critical requirements for future networks in an increasingly interconnected world.

Table of Contents

List of Figures

List of Tables

Abbreviations

3GPP - 3rd Generation Partnership Project
5G NR - 5G New Radio
ACM - Adaptive Coding and Modulation
AI - Artificial Intelligence
AR - Augmented Reality
BER - Bit Error Rate
BS - Base Stations
C-RAN: Cloud RAN
CU - Centralised Unit
DU - Distributed Unit
D2D - Device-to-Device
D-RAN - Distributed RAN
DSS - Dynamic Spectrum Sharing
EO - Earth Observation
ECEF - Earth-Centered, Earth-Fixed
EIRP - Equivalent Isotropic Radiated Power
EMI - Electromagnetic Interference
eMBB - Enhanced Mobile Broadband
ETSI - European Telecommunication Standardization Institute
ESA - European Space Agency
FDMA - Frequency Division Multiple Access
FDD - Frequency division duplexing
FRF - Frequency Reuse Factor
FSO - Free Space Optics
FSS - Fixed Satellite Services
GCC - Ground Control Center
GEO - Geostationary Earth Orbit
GNB - next Generation Node B
GNSS - Global Navigation Satellite System
G/T - Gain-to-Noise Temperature
GTP - GPRS Tunneling Protocol
GW - Gateway
HAPS - High Altitude Platform Station
HEO - Highly Elliptical Orbiting
HetNet - Heterogeneous Networks
IoT - Internet of Things
IIoT - Industrial internet of things
ISL - Inter-Satellite Links
ITU - International Telecommunication Union
IEEE - Institute of Electrical and Electronics Engineers
LEO - Low Earth Orbit
LOS - Line of Sight
LTE - Long-Term Evolution
LSA - Licensed Shared Access
MAC - Medium Access Control
MIMO - Multiple input multiple output
mMIMO - massive multiple-input multiple-output
Mbps - Mega bit per second
MEO - Medium Earth Orbit
MEC - Multi-access Edge Computing
ML - Machine Learning
mMTC - Massive Machine Type Communication
MS - Mobile Services
MSS - Mobile Satellite Services
mmWave - millimeter-wave
NCC - Network Control Center
NAS-MM - Non-Access Stratum Mobility Management

NAS-SM - Non-Access Stratum Session Management
NLOS - Non-Line of Sight
NGEO - Non-Geostationary Earth Orbiting
NGSO - Non-Geostationary Satellite Orbit
NFV - Network Functions Virtualization
Non RT RIC - Non Real Time RIC
NR - New Radio
NSA - Non-Stand-alone
NTN - Non-Terrestrial Network
O-RAN - Open Radio Access Network
OFDMA - Orthogonal Frequency Division Multiple Access
QoE - Quality of Experience
QoS - Quality of Service
PHY - Physical Layer
RAN - Radio Access Network
RAT - Radio Access Technologies
RF - Radio Frequency
RFI - Radio Frequency Interference
RIC - RAN Intelligent Controllers
RL - Reinforcement learning
RRM - Radio Resource Management
RTD - Round Trip Delay
Rx - Receiver
SA - Standalone
SBA - Service-Based Architecture
SC-FDMA - Single Carrier Frequency Division Multiple Access
SDN - Software Defined Networking
SDR - Software-Defined Radio
SDO - Standards Developing Organizations
SMO - Service Management and Orchestration
SISO - Single-input single-output
SLA - Service Level Agreement
SNR - Signal-to-Noise Ratio
SRI - Satellite Radio Interface
TLE - Two-Line Element
TCP - Transmission Control Protocol
TDMA - Time Division Multiple Access
TDD - Time division duplexing
TN - Terrestrial Network
THz - Terahertz
TT&C - Telemetry, Tracking, and Command
TSN - Time-Sensitive Networking
TIP - Telecom Infra Project
UAS - Unmanned Aircraft System
UAV - Unmanned Aerial Vehicle
UE - User Equipment
URLLC - Ultra-Reliable Low-Latency Communications
V2X - Vehicle-to-everything
VLEO - Very Low Earth Orbit
VNF - Virtual Network Function
V-RAN: Virtual RAN
VSAT - Very Small Aperture Terminal
VSS - Vertical Spectrum Sharing
VR - Virtual Reality

1 Radio Access Networks

1.1 Introduction to Radio Access Networks (RAN)

A Radio Access Network (RAN) is a fundamental part of mobile telecommunications systems, connecting end-user devices (e.g., smartphones, tablets, IoT devices) to both the core network and the Internet. Serving as the interface between user devices and broader network services, RAN enables mobile communication and data transfer across various Radio Access Technologies (RAT) such as 4G LTE, 5G NR, and, in future networks, 6G. Traditionally, RAN consists of two main components: Base Stations and User Equipment (UE).

1.1.1 RAN Functionality

The RAN architecture provides several essential functions essential for maintaining and optimizing mobile communication:

- Signal Processing and Transmission: RAN handles the transmission and reception of signals, translating data between the RF domain and digital formats used by core network services. This includes modulation, coding, and transmission power adjustments.
- Dynamic Resource Allocation and Scheduling: RAN dynamically allocates radio resources to users, optimizing bandwidth and power distribution to ensure efficient use of available spectrum and a balanced load across the network.
- Mobility Management: As users move, the RAN ensures seamless connectivity by efficiently managing handovers between base stations, dynamically updating user locations, maintaining active sessions, and ensuring low latency.
- Quality of Service (QoS): To support a wide range of applications, including high-bandwidth activities such as streaming, gaming, and everyday tasks like web browsing, RAN implements QoS mechanisms that dynamically allocate and prioritize network resources. These mechanisms take into account service requirements, channel state, and traffic priorities as defined by Service Level Agreements (SLAs) in the network. This ensures an optimized and consistent user experience across various use cases, while maintaining adaptability to diverse application demands.
- Interference and Noise Management: RAN employs techniques to minimize interference between cells and users also, improving signal quality and overall network performance in high-density environments.
- Network Synchronization and Coordination: RAN maintains timing and frequency synchronization across various components and coordinates between cells to improve network coverage and performance.

1.1.2 Radio Access Technologies (RAT) in RAN

RAN is designed to support various Radio Access Technologies (RAT), allowing it to deliver different types of connectivity to user devices. RATs implemented in modern RAN include:

- LTE (Long-Term Evolution): LTE is a 4G RAT that provides high-speed data transfer, voice services, and low latency, establishing a foundation for mobile broadband.
- NR (New Radio): NR is the RAT for 5G, designed to support ultra-high-speed data, massive device connectivity, and low latency required for applications like autonomous driving and IoT.
- Multi-RAT Support: Modern RAN architectures can support multiple RATs simultaneously, enabling devices to seamlessly switch between technologies like LTE and NR as needed.

1.1.3 Key Components of RAN

- Radio Units (RU): The RU handles radio frequency (RF) processing, including signal transmission and reception to and from user devices. This unit is located close to the antennas and is responsible for converting digital signals to RF signals and vice versa.
- Distributed Units (DU): The DU performs real-time functions like encoding, modulation scheduling, and link adaptation. It manages data and signalling between the radio units and the central unit, handling lower layers of the protocol stack, such as the physical (PHY) and media access control (MAC) layers.

- Centralised Units (CU): The CU performs non-real-time functions, including control and management of sessions, user mobility, and higher protocol layers. It manages connections across the core network and interfaces with the distributed units, primarily responsible for packet processing and routing.
- Base stations, such as eNodeB (LTE) or gNodeB (5G NR), are aggregations of RUs, DUs, and CUs, with each base station serving a specific geographic area known as a cell. Base stations provide radio access and facilitate data exchange between mobile devices and the core network.
- User Equipment (UE) represents the mobile devices that connect end-users, to network services. Acting as the endpoint of the RAN, the UE uses components like RF transceivers, antennas, and baseband processors to establish and maintain wireless communication with the network. The UE's protocol stack supports functions like modulation, encoding, error correction, and secure data exchange across different layers, enabling efficient data transmission and connectivity.

1.1.4 Evolution of RAN

The evolution of Radio Access Networks (RAN) has been a cornerstone in the advancement of wireless communication technologies. The RAN has been changing from the early days of analog cellular networks to the sophisticated 5G systems of today to meet the increasing demands for higher speeds, greater capacity, and lower latency.

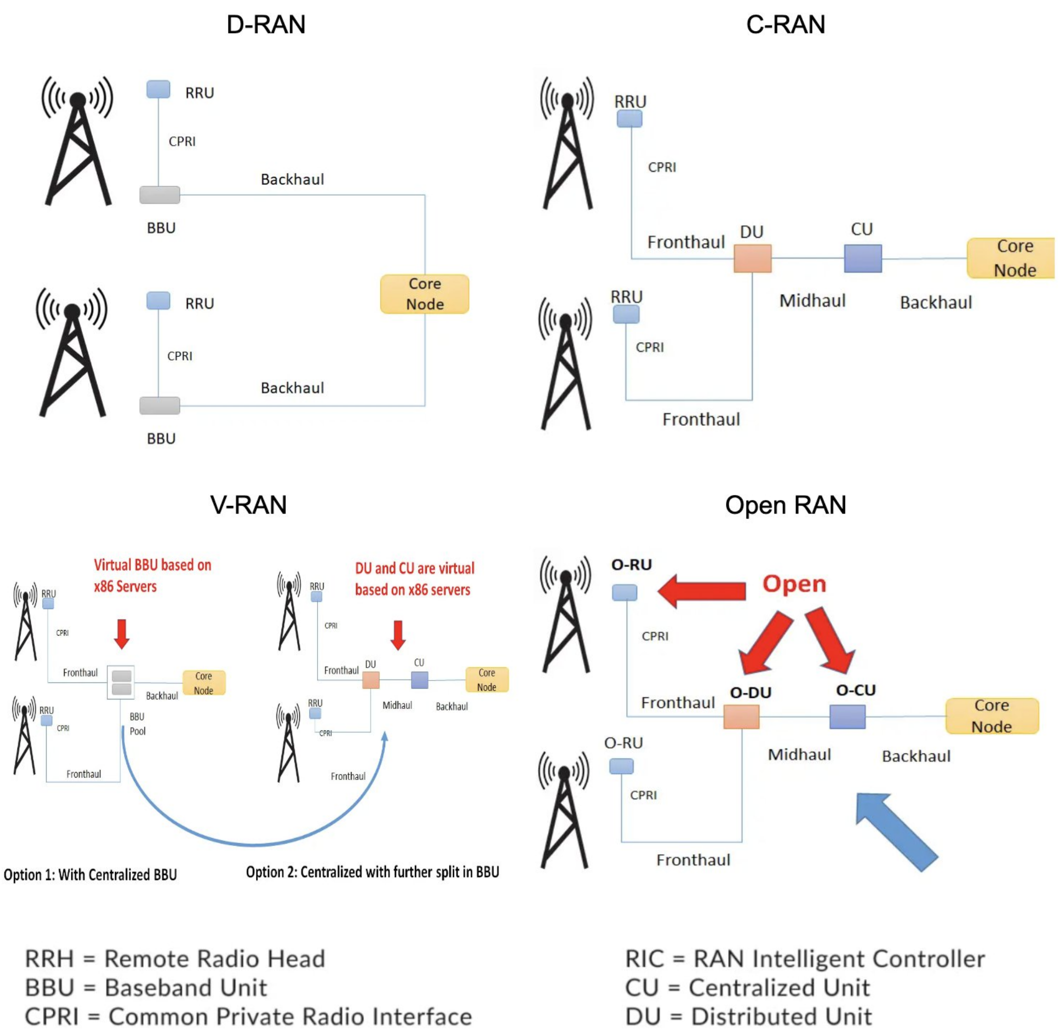

Figure 1-1:D-RAN, C-RAN, V-RAN, O-RAN[1].

[1] https://telcocloudbridge.com/blog/c-ran-vs-cloud-ran-vs-vran-vs-o-ran/

Table 1-1: Comparison Aspects among D-RAN, C-RAN, V-RAN, O-RAN.

Feature	Distributed RAN (D-RAN)	Cloud RAN (C-RAN)	Virtual RAN (V-RAN)	Open RAN (O-RAN)
Architecture	Integrated hardware & software at each site	Centralized processing in a cloud environment	Software functions on general-purpose servers	Disaggregated hardware & software with open interfaces
Hardware Dependency	Proprietary, vendor-specific	Minimizes with cloud infrastructure	Reduced, uses commercial off-the-shelf servers	Reduced; promotes multi-vendor components
Scalability	Limited; relies on vendor-specific upgrades	High; leverages centralized cloud resources	Moderate; allows flexible resource scaling	High; modular and scalable
Interoperability	Low; typically vendor-locked	Moderate; central resources manage multiple sites	Moderate; partially dependent on vendor	High; open standards support multi-vendor setups
Deployment Flexibility	Low; dedicated hardware needed at each site	High; centralized for efficient resource pooling	Moderate; partially centralized or distributed	High; supports various deployment models
Cost Efficiency	Higher CapEx and OpEx due to vendor lock-in	High savings through resource pooling	Lower hardware costs; operational savings	Reduced costs with competitive vendor options
Complexity	Simplified, but limited flexibility	Complex; requires low-latency backhaul	Moderate; virtualization adds flexibility	Moderate; requires standardization but adds flexibility
Innovation & Ecosystem	Limited, proprietary innovations	Moderate; cloud-based innovations possible	Moderate; software-driven but vendor-reliant	High; open ecosystem encourages rapid innovation
Ideal Use Cases	Legacy networks with limited upgrade paths	Dense urban deployments needing centralized resources	Urban and suburban areas with high demands	Broad range, including rural, urban, and private networks

In the Figure 1-1, different types of RANs are briefly described:

- Traditional Distributed RAN (D-RAN): In a traditional Distributed Radio Access Network (D-RAN), base stations are built with proprietary hardware and software integrated into a single unit, dedicated to a specific vendor. Each base station comprises the radio, baseband processing, and control functions within a single system.
- Cloud RAN (C-RAN): Cloud RAN takes virtualization by fully centralizing RAN functions in a cloud environment, where baseband processing is managed at a central location rather than at

individual base stations. C-RAN uses a pool of cloud resources to process data from multiple radio sites, which allows for efficient resource allocation, simplified network management, and reduced operational costs.

- Virtual RAN (vRAN): Virtualized RAN, or vRAN, decouples some of the base station functions from proprietary hardware, allowing them to run as software on general-purpose servers. This virtualization enables network operators to be more flexible and scalable in resource allocation, with RAN functions dynamically deployed as needed. vRAN reduces dependency on specialized hardware and allows RAN functionalities to be centralized or distributed depending on network demand, offering cost savings and improved efficiency.
- Open RAN: Open RAN introduces open, standardized interfaces between RAN components, enabling interoperability between equipment from multiple vendors. Unlike traditional RAN, Open RAN disaggregates hardware and software, giving operators the flexibility to select components independently.

Table 1-1 provides a comprehensive comparison of Distributed RAN (D-RAN), Cloud RAN (C-RAN), Virtual RAN (V-RAN), and Open RAN (O-RAN) across key architectural and operational features. It highlights how these architectures differ in terms of hardware dependency, scalability, interoperability, deployment flexibility, cost efficiency, complexity, and their ability to foster innovation. This comparison serves as a valuable resource for understanding the strengths and limitations of each architecture and their suitability for various network requirements.

1.1.5 Open RAN

Open RAN (Radio Access Network) represents a paradigm shift in mobile network architecture by introducing open and standardized interfaces, allowing components from multiple vendors to interoperate seamlessly. Unlike traditional RAN, which relies on proprietary systems, Open RAN enables the decoupling of hardware and software, allowing telco functions to run on vendor-agnostic hardware and cloud-based infrastructure. This open and disaggregated approach aligns well with the needs of 5G and future 6G networks, supporting the integration of intelligent functionalities and fostering a more competitive, multi-vendor ecosystem.

1.1.5.1 Architecture of Open RAN

Open RAN architecture[2] is built on three main principles: decoupling of hardware and software, disaggregation of radio and baseband components, and the use of open interfaces to introduce intelligent, automated controls. Key components include the Radio Unit (RU) for signal transmission over the air, the Distributed Unit (DU) and Central Unit (CU) for baseband processing, Near Real-Time RAN Intelligent Controller (Near RT-RIC), and Non Real-Time RIC (Non RT-RIC). Near RT-RIC enables near-real-time control and optimization of open RAN elements and resources via fine-grained data collection and actions over E2 interface. Non RT-RIC a logical function that enables non-real-time control and optimization of RAN elements and resources, AI/ML workflow including model training and updates, and policy-based guidance of applications/features in near-RT RIC[3].

1.1.5.2 Potential Benefits of Open RAN

- **Increased Competition and Vendor Diversity:** By enabling interoperability, Open RAN reduces reliance on single vendors, creating opportunities for new market entrants and fostering a more diverse ecosystem, which can lead to better cost efficiencies.
- **Enhanced Flexibility and Scalability:** The open architecture allows operators to select best-in-class components for specific network requirements, enhancing adaptability to varied deployment scenarios across urban, rural, and private networks.
- **Reduced Total Cost of Ownership (TCO):** Open RAN's software-based and virtualized approach lowers capital and operational expenditures, enabling more cost-effective network scaling and facilitating deployment in lower-density areas, which can help bridge the digital divide.
- **Support for AI-Driven Innovation:** Through the RIC, Open RAN supports AI and ML applications that can automate and optimize network operations, improving performance

[2] https://www.o-ran.org/o-ran-resources

[3] https://docs.o-ran-sc.org/en/latest/architecture/architecture.html

metrics such as latency, throughput, and energy efficiency, and reducing bit error rate, symbol error rate, and packet error rate.
- **Pathway to 6G Evolution:** The modular and flexible nature of Open RAN architecture aligns with anticipated 6G requirements, providing a foundational platform for future network innovation.

1.1.5.3 Challenges of Open RAN

- **Integration Complexity in Multi-Vendor Environments:** Managing multiple vendors in Open RAN presents operational and logistical challenges, particularly in terms of system integration, performance testing, and interoperability across diverse components.
- **Security Concerns:** The open, software-driven nature of Open RAN expands the attack surface, requiring robust security measures to protect against potential vulnerabilities, especially as interfaces become more accessible to multiple vendors.
- **Resource and Performance Optimization:** Running intensive network processes on general-purpose hardware may impact performance, necessitating the integration of specialized hardware accelerators to maintain energy efficiency and processing speed.
- **Operational Management:** The complexity of managing alarms, faults, and real-time adjustments across multi-vendor systems demands advanced orchestration and automation tools, including Service Management and Orchestration (SMO) platforms.
- **Limited Multi-Vendor Testing:** Achieving true multi-vendor interoperability requires extensive testing and certification, which can be resource-intensive. Developing certification frameworks and standardized testing regimes, especially in Europe, could help streamline this process and ensure reliable multi-vendor solutions.

1.1.5.4 Evolving Architecture with Open RAN

The trend towards network horizontalization, characterized by the separation of hardware (HW) and software (SW), management, and exposure layers, is expected to intensify as mobile networks evolve. In 6G, there is a unique opportunity to redesign and enhance the functional architecture defined by 3GPP to align better with network horizontalization principles. This approach involves harmonizing infrastructure, management tools, and orchestration processes across both RAN and Core networks, a goal closely aligned with Open RAN's development focus.

Key architectural advancements within the current open RAN design, such as cloudification, orchestration, open fronthaul interfaces for flexible RAN disaggregation, and network exposure through new interfaces, present robust options for achieving network horizontalization in the 6G era. These developments are designed to meet the increasingly diverse connectivity requirements across society and industry, supporting 6G's goal of providing ubiquitous, intelligent, and sustainable connectivity. This approach fosters openness not only for component and system interoperability but also to improve overall system efficiency and promote service innovation, both of which are crucial for 6G's continued evolution. Figure 1-2 shows the key elements of future mobile networks.

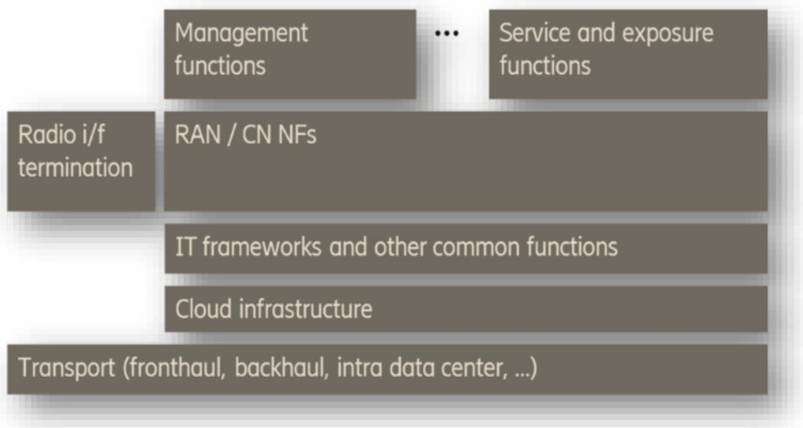

Figure 1-2:Key elements of future mobile networks[4].

[4] https://6g-ia.eu/wp-content/uploads/2024/05/6g-ia-open-sns-open-networks-status-and-future-

Integration with NTN:

One notable area within 6G that the open RAN architecture is anticipated to impact significantly is the integration of Non-Terrestrial Networks (NTN). While physical layer adaptations for NTN are being addressed by 3GPP, a native integration of NTN within the 6G framework introduces several RAN control and management challenges that can benefit from open RAN's RAN Intelligent Controllers (RICs). Figure 1-3 shows open RAN architecture extended to control TN and NTN. Key challenges in this domain include:

- UE Mobility Management: Addressing mobility procedures impacted by the movement of base stations in Non-Geostationary Satellite Orbit (NGSO) constellations.
- Regenerative Architectures: Tackling base station mobility issues in architectures where signal processing occurs directly on the satellite.
- Interference Mitigation: Managing interference between Terrestrial Network (TN) and NTN cells to maintain service quality.
- Traffic Steering: Developing flexible, per-device policies to manage traffic flow between TN and NTN cells effectively.

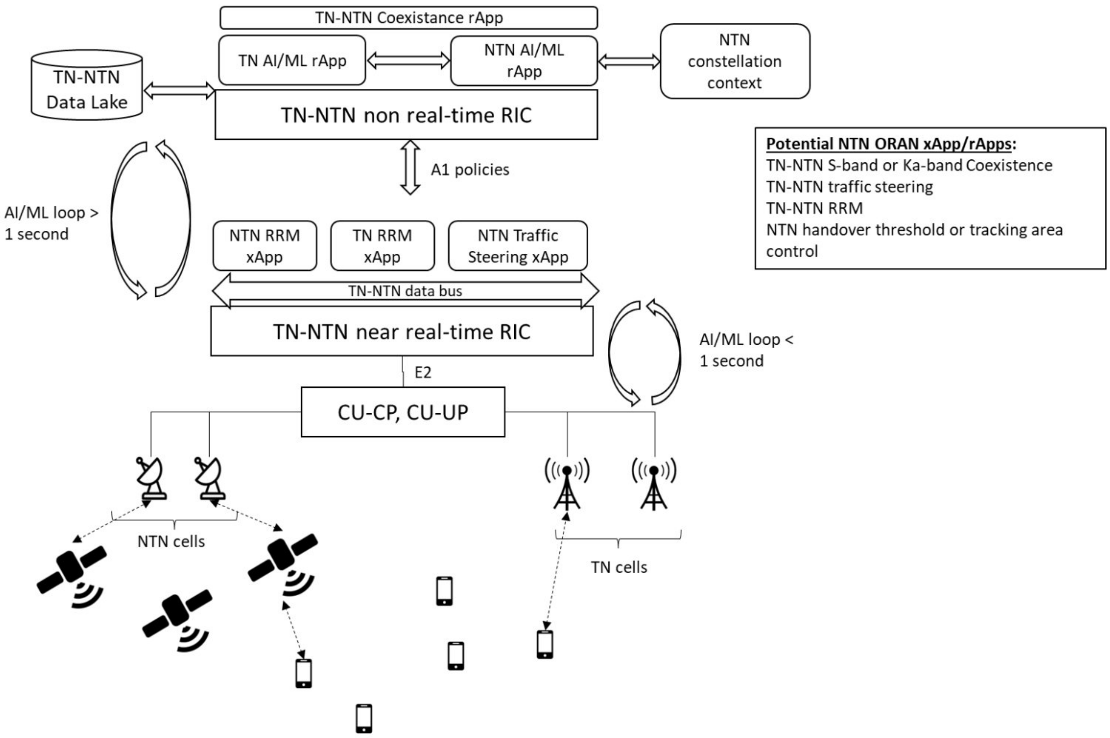

Figure 1-3: Open RAN architecture extended to control TN and NTN[5].

The open RAN architecture supports these adaptations through specialized radio applications operating across various time scales, specifically tailored to address the challenges of integrating NTN. The Near-RT RIC is a cornerstone of Open RAN, enabling real-time control and optimization of RAN functions via xApps. Within the Service Management and Orchestration (SMO) layer, the Near-RT RIC contributes significantly by providing centralized configuration and monitoring, lifecycle management, fault management, recovery processes, and integration with satellite ground systems.

development_ran-final.pdf

[5] https://6g-ia.eu/wp-content/uploads/2024/05/6g-ia-open-sns_open-networks-status-and-future-development_ran-final.pdf

To meet the unique demands of satellite networks, the F1 interface has been chosen as the functional split for the MECON project. The decision to adopt the F1 split—where the Radio Unit (RU) and Distributed Unit (DU) are deployed on satellites while the Central Unit (CU) remains on the ground—was driven by several considerations[6]. The F1 interface achieves an ideal balance by separating higher-layer processing in the CU from lower-layer processing in the DU. This minimizes the need for high-capacity backhaul, a critical limitation in satellite communications, and simplifies network architecture while ensuring compatibility with terrestrial RAN systems. By opting out of the Split 7.2 architecture, the MECON project avoids the added complexity and bandwidth demands of more granular functional splits, resulting in a more practical, robust, and efficient system for NTN applications.

Furthermore, NTN integration requires synchronizing the satellite mission's context (e.g., planned orbits, payload activity) with mobile network requirements. Open RAN provides mechanisms to incorporate external information into the RIC, enabling the RAN to account for the specific operational parameters of satellite missions. This capability enhances the RAN's ability to adapt to the unique demands of NTN while maintaining efficient, flexible, and coordinated network operations within a unified 6G framework.

1.2 Radio Resource Management

Radio resource management (RRM) encompasses the strategies and techniques employed to allocate, manage, and optimize the radio frequency (RF) spectrum and related resources in wireless communication systems[7]. Effective RRM is vital for enhancing the quality of service (QoS), maximizing the use of available spectrum, and improving overall network performance, including throughput, latency, and energy efficiency.

Existing RRM in wireless networks faces numerous challenges. These include congestion from massive channel access, requiring efficient load balancing and prioritization; power allocation and interference management in dense networks; seamless user association and hand-off management; and the coexistence of human-to-human (H2H) and IoT traffic with distinct communication requirements. Additionally, extending coverage for low-power IoT devices, ensuring energy-efficient protocols for battery-powered systems, supporting real-time applications like ultra-reliable low-latency communication (URLLC), and addressing heterogeneous QoS demands for diverse devices all contribute to the growing complexity of RRM.

To tackle these challenges, 5G+ and 6G introduce transformative technologies. Massive multiple-input multiple-output (mMIMO) systems improve spectral and energy efficiency by using spatial multiplexing and beamforming. The adoption of higher frequency bands, such as millimeter-wave (mmWave) and terahertz (THz), provides significantly increased bandwidth, enabling ultra-high data rates and reduced latency for real-time applications. Network slicing and edge computing allow tailored resources for specific use cases, ensuring efficient traffic management and QoS delivery. Moreover, advancements in artificial intelligence (AI) and machine learning (ML) optimize resource allocation and interference management dynamically. Integrated Access and Backhaul (IAB) technologies and device-to-device (D2D) communication extend coverage for IoT devices in remote and dense areas, while energy-efficient communication protocols enhance sustainability. Collectively, these innovations enable 5G+/6G to meet the stringent demands of next-generation wireless networks.

Next-generation wireless networks are expected to meet specific technical specifications set by standardization bodies such as the ITU and 3GPP, as outlined in the table below. As evident from the table, 6G will operate in higher frequency bands, including terahertz (THz), offering data rates ranging from 100 Gbps to 1 Tbps, and ultra-low latency of around 100 microseconds, significantly enhancing real-time applications. In comparison, 5G systems generate 1,000 times more data (with traffic volumes reaching tens of Tbps/km²), reduce latency by a factor of five (achieving ultra-low latency in milliseconds), increase connectivity by 100 times, deliver peak data rates of 10 Gbps, improve battery efficiency by 10 times, and enhance reliability by 100%[8].

[6] https://www.ericsson.com/en/blog/2024/10/ntn-payload-architecture

[7] Manap, S., Dimyati, K., Hindia, M. N., Talip, M. S. A., & Tafazolli, R. (2020). Survey of Radio Resource Management in 5G Heterogeneous Networks. *IEEE Access*, *8*, 131202-131223.

[8] Chowdhury, M. Z., Shahjalal, M., Ahmed, S., & Jang, Y. M. (2020). 6G Wireless Communication Systems: Applications, Requirements, Technologies, Challenges, and Research Directions. *IEEE Open Journal of the Communications Society*, *1*, 957-975.

While 5G provides broader coverage with moderate bandwidth, 6G will have smaller coverage areas due to its higher frequency but will compensate with higher bandwidth per unit area, especially in densely populated urban environments. According to Ericsson's Mobility Report from June 2024, video data traffic in mobile networks is projected to make up 80% of total mobile data traffic by 2025, marking a significant increase from 60% in 2018[9].

Next-generation networks will connect not only people but also vehicles, machines, and devices, enabling new services and user experiences, such as vehicle-to-everything (V2X) and device-to-device (D2D) communications. In other words, future wireless communication systems will need to support massive traffic volumes, a large number of connected devices, and a wide variety of use cases with specific performance requirements, including augmented reality (AR), virtual reality (VR), audio/video streaming, and vertical applications such as healthcare, autonomous vehicles, precision farming, the industrial internet of things (IIoT), and smart cities. Table 1-2 presents the technical specifications of 5G and 6G wireless systems. In the next section, we mention the key RRM techniques in brief.

Table 1-2: Technical Specifications of 5G and 6G Wireless Systems[10]

Deployment	Began in 2020	Expected around 2030
Frequency Bands	Sub-6 GHz, mmWave (24-100 GHz)	THz frequencies (above 100 GHz)
Maximum Data Rate	Up to 20 Gbps	100 Gbps to 1 Tbps
Traffic Volumes	**1000x higher than 4G**	10-100x higher than 5G
Latency	1 ms	~ 100 µs (ultra-low latency)
Network Capacity	Higher than 4G by 100x	10-100x higher than 5G
Device Density	1 million devices per km²	10 million devices per km²
Energy Efficiency	90% more efficient than 4G	Expected to be more energy-efficient
Mobility Support	500 km/h	Up to 1000 km/h
Use Cases	Enhanced Mobile Broadband (eMBB), Ultra Reliable Low Latency Communication (URLLC), Massive Machine Type Communication (mMTC)	Holographic Communications, Artificial Intelligence, Quantum Computing, Haptics Communications
Coverage	Wide coverage with lower frequencies, but limited with higher (mmWave)	Limited due to higher frequencies (THz), but can be expanded using dense micro-cell networks
Bandwidth per Unit Area	Moderate to high (limited in dense areas)	Extremely high (even in densely populated areas)

1.2.1 Spectrum Management Techniques in 5G and 6G Networks

Effective spectrum management will play an increasingly crucial role in optimizing network performance, enhancing user experience, and improving energy efficiency in both 5G and future 6G systems. Advanced spectrum management strategies will be necessary to fully leverage the high speeds and low latency offered by 5G and 6G. New technologies and approaches such as spectrum sharing, dynamic spectrum use, cognitive radio, and network slicing make spectrum management more flexible and efficient.

[9] Ericsson Mobility Report June 2024, Ericsson, Stockholm, Sweden, Jun. 2024. [Online]. Available: https://www.ericsson.com/en/reports-and-papers/mobility-report/reports/june-2024.

[10] Manap, S., Dimyati, K., Hindia, M. N., Talip, M. S. A., & Tafazolli, R. (2020). Survey of Radio Resource Management in 5G Heterogeneous Networks. *IEEE access*, *8*, 131202-131223.

1.2.1.1 Millimeter and Terahertz Waves

As cellular networks progress from 4G to 5G and eventually 6G, the use of higher frequency bands becomes increasingly necessary to meet the growing demand for data. Previously, 4G networks operated mostly below 6 GHz due to better propagation characteristics, but with the exhaustion of spectrum below 3 GHz, higher frequencies are now needed to improve data rates and capacity. This shift highlights three key frequency ranges for the future: below 6 GHz, millimeter-wave (mmWave) bands (24–100 GHz), and terahertz (THz) bands (100–3000 GHz.

The evolution from 4G to 5G and eventually 6G necessitates the use of higher frequency bands to meet growing data demands. While sub-6 GHz bands continue to provide a balance between coverage and capacity, the mmWave spectrum (24–100 GHz) supports ultra-fast data rates for high-capacity, short-range applications. However, mmWave signals face challenges like path loss and limited signal penetration, mitigated through technologies like massive MIMO and beamforming. For 6G, the THz band (100 GHz to 3 THz) is being explored for extremely high data rates and massive capacity. Advanced techniques such as reconfigurable intelligent surfaces (RIS), ultra-dense networks, and AI-driven spectrum management will address the challenges of high atmospheric absorption and short range associated with THz communications.

1.2.1.2 Spectrum Sharing

Spectrum sharing allows various users or systems to access the same frequency bands simultaneously without causing interference. Techniques include dynamic spectrum allocation, spectrum sensing to detect unused bands, and spectrum handoff for secondary users. Spectrum sharing can be horizontal, vertical, dynamic, or based on licensed shared access (LSA), each tailored to balance user priority, resource efficiency, and regulatory requirements. Despite its potential, challenges such as interference, energy consumption, and security require robust algorithms and advanced coordination mechanisms.

1.2.1.3 Spectrum Sensing and Cognitive Radio

Cognitive radio (CR) systems utilize "spectrum holes" or underutilized bands by enabling secondary users to access them without interfering with primary users[11]. CR employs spectrum sensing to detect availability, dynamic spectrum access for real-time adjustments, and mobility to switch frequencies seamlessly[12]. Architectures like centralized and distributed cooperative sensing enhance reliability and accuracy. However, CR faces challenges in sensing accuracy, real-time processing, and interference management, especially in dynamic environments.

1.2.1.4 Small Cell

Small-cell networks[13] are low-power wireless systems which were initially proposed for deployment in smaller coverage areas such as homes, offices, and shopping malls. These networks are designed to complement traditional macrocell networks and are classified into three main categories: femtocells,picocells, and relay nodes (RNs). The major benefits of small cell technology are to improve overall network capacity, coverage, and connectivity. Over time, cell sizes have progressively decreased, leading us to network densification and thereby heterogeneous networks (HetNet). The near future's HetNets are expected to be extremely dense, with femtocells potentially deployed in every room to meet the massive connectivity and data capacity demands. Moreover, these networks will integrate multiple radio access technologies (RATs), such as 2G, 3G, 4G, 5G, Wi-Fi, and device-to-device (D2D)communication. Small cell technology also improves frequency reuse, reduces resource contention, and improves data rates. On the other side, there exist arising challenges in small cell technology such as resource management (RRM), interference management, power allocation, and user association.

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[11] Sabir, B., Yang, S., Nguyen, D., Wu, N., Abuadbba, A., Suzuki, H., Lai, S., Ni, W., Ming, D., & Nepal, S. (2024). Systematic Literature Review of AI-enabled Spectrum Management in 6G and Future Networks. *arXiv preprint arXiv:2407.10981*

[12] Parvini, M., Zarif, A. H., Nouruzi, A., Mokari, N., Javan, M. R., Abbasi, B., Ghasemi, A., & Yanikomeroglu, H. (2023). Spectrum Sharing Schemes from 4G to 5G and Beyond: Protocol Flow, Regulation, Ecosystem, Economic. *IEEE Open Journal of the Communications Society*, *4*, 464-517.

[13] Manap, S., Dimyati, K., Hindia, M. N., Talip, M. S. A., & Tafazolli, R. (2020). Survey of Radio Resource Management in 5G Heterogeneous Networks. *IEEE access*, *8*, 131202-131223.

1.2.1.5 Duplexing Technologies

Duplexing[14] refers to the method of transmitting and receiving data between two communication devices, allowing bidirectional communication over a shared wireless spectrum. There are two main types of duplexing: half-duplex and full-duplex systems. In half-duplex systems, communication occurs in both directions, but not simultaneously. A common example of half-duplex communication is walkie-talkies, where one person speaks while the other listens, and they take turns. In contrast, full-duplex systems allow simultaneous transmission and reception of data in both directions. Frequency division duplexing (FDD) uses separate frequency bands for uplink and downlink, enabling simultaneous transmission and reception. However, it requires more bandwidth because each direction needs its own frequency band. FDD is widely used in 4G LTE and some 5G deployments. In contrast, time division duplexing (TDD) utilizes a single frequency band for both uplink and downlink, with transmissions divided into alternating time slots. While TDD is more spectrum-efficient, as it requires only one frequency band, it introduces a slight delay due to the time-slot switching. Typically, FDD is used in lower frequency bands, while TDD is employed in mid and high bands. In 5G, both FDD and TDD are used depending on the available spectrum and deployment scenario. In emerging 6G networks, full-duplex technology is expected to play a more prominent role.

1.2.1.6 Beamforming

Beamforming[15] directs wireless signals toward specific users rather than broadcasting uniformly in all directions. In 5G and future 6G networks, beamforming become crucial in optimizing signal quality and coverage, particularly in high-frequency millimeter-wave (mmWave) and terahertz (THz) wave bands. Although these bands offer substantial bandwidth and higher data rates, low latency, and support for advanced applications such as holographic communications and massive machine-type communications (mMTC), they are susceptible to significant signal attenuation and limited range due to factors like atmospheric absorption and foliage loss. By employing phased array antennas or digital antenna arrays and massive multiple-input multiple-output (MIMO) technologies, beamforming concentrates the signal into narrow beams directed at specific users. Therefore, modern beamforming techniques compensate for severe propagation losses and limited penetration capabilities at these higher frequencies.

1.2.1.7 Massive MIMO

Multiple-input and multiple-output (MIMO)[16] utilizes large antenna arrays to improve throughput, spectral efficiency, and network performance. While mmWave bands offer high data rates, sub-6 GHz frequencies ensure better coverage and reliability, particularly for IoT and ultra-reliable low-latency communications (URLLC). TDD mode is preferred for spectral efficiency, whereas FDD offers advantages in sub-6 GHz bands. mMIMO remains a cornerstone for advanced communication in 5G and 6G.

1.2.1.8 Network Slicing

Network slicing[17] enables the division of a physical network infrastructure into virtual segments. Each network slice is optimized for specific use cases or services. For example, one slice may be dedicated to low-latency applications, while another one is optimized for high-bandwidth video streaming. Virtualization plays a central role in network slicing through Network Function Virtualization (NFV) and Software-Defined Networking (SDN) technologies. Physical resources are abstracted into virtual instances that can be dynamically assigned to different network slices. Automation helps automate

[14] Qamar, F., Siddiqui, M. U. A., Hindia, M. N., Hassan, R., & Nguyen, Q. N. (2020). Issues, Challenges, and Research Trends in Spectrum Management: A Comprehensive Overview and New Vision for Designing 6G Networks. *Electronics*, *9*(9), 1416.

[15] H. A. Kassir, Z. D. Zaharis, P. I. Lazaridis, N. V. Kantartzis, T. V. Yioultsis and T. D. Xenos, "A Review of the State of the Art and Future Challenges of Deep Learning-Based Beamforming," in IEEE Access, vol. 10, pp. 80869-80882, 2022, doi: 10.1109/ACCESS.2022.3195299.

[16] Manap, S., Dimyati, K., Hindia, M. N., Talip, M. S. A., & Tafazolli, R. (2020). Survey of Radio Resource Management in 5G Heterogeneous Networks. *IEEE Access*, *8*, 131202-131223.

[17] "Network Slicing for 5G Networks and Services," 5G America (see https://www.5gamericas.org/wp-content/uploads/2019/07/5G_Americas_Network_Slicing_11.21_Final.pdf), 2016

resource management, optimize performance, and orchestrate network slices efficiently. Cloudification involves deploying network functions and services across cloud infrastructures, including edge and core clouds to enhance flexibility and scalability in network slicing. Challenges in managing and orchestrating network slices include handling multiple domains such as core, edge, and access networks, particularly in heterogeneous environments with multiple vendors and service providers. Ensuring seamless integration of network components across various vendors requires strict adherence to standardized interfaces and protocols to achieve interoperability. Efficiently allocating and optimizing resources across multiple slices while maintaining each slice's performance is a complex task in dynamic 6G environments. Security and privacy are also critical since maintaining isolation between slices and protecting data from unauthorized access are essential in multi-tenant setups. As 6G networks grow in complexity, managing energy consumption while optimizing network performance presents a significant challenge.

1.2.1.9 Carrier Aggregation

Carrier aggregation (CA)[18] takes combining non-adjacent bands and underutilized frequencies into account and aggregate them to maximize network capacity without additional spectrum allocation. In addition to its spectral efficiency capability, CA ensures a more seamless user experience since it allows networks to adapt dynamically to varying traffic demands. Moreover, CA helps address the growing need for bandwidth in 5G and future 6G networks by providing higher data rates and reducing latency. In spectrum-scarce environments, where contiguous large bandwidths are not always available, CA offers a practical solution for improving network performance. Additionally, some scientific studies have shown that when CA is used in conjunction with techniques like Dual Connectivity (DC) and AI-driven algorithms, it can significantly boost spectrum efficiency in future wireless networks.

1.2.2 Energy Management in 5G and 6G Networks

Energy consumption in wireless communication systems refers to the amount of energy used by base stations, antennas, user devices, and network infrastructure to support data transmission, signal processing, and computational tasks[19]. Energy consumption is a critical aspect of wireless networks due to both economic and environmental concerns. As an example, power distribution between electronic devices and cooling systems is a major concern which emphasizes the need for more innovative strategies to optimize energy usage. Recent studies continue to highlight the energy efficiency (EE) challenges of 5G and 6G networks. As of 2023, the ICT sector, including mobile networks, now consumes around 4.7% of global electricity production[20]. The ICT industry contributes to about 5% of global carbon emissions, and wireless communications account for a significant portion of that. Therefore, optimizing energy consumption not only helps reduce operational costs for network operators but also minimizes the carbon footprint of the technology. The Green Touch Consortium and similar initiatives were established to explore solutions for creating energy-efficient networks. With complex wireless technologies and data-heavy, real-time service demands, energy efficiency remains significant.

Energy efficiency is of primary importance and can be described with several metrics. It is typically measured in terms of the amount of energy required to transmit a certain amount of data. A common energy efficiency metric in bits per Joule measures how many bits of data can be transmitted per unit of energy consumed. It takes into account both the transmit power of base stations and user equipment, as well as the computational power required for signal processing and network management. Additionally, various metrics such as the energy consumption rating (ECR) and energy efficiency rate (EER) can be used to measure energy efficiency.

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[18] Sabir, B., Yang, S., Nguyen, D., Wu, N., Abuadbba, A., Suzuki, H., Lai, S., Ni, W., Ming, D., & Nepal, S. (2024). Systematic Literature Review of AI-enabled Spectrum Management in 6G and Future Networks. *arXiv preprint arXiv:2407.10981*.

[19] M. M. Mowla, I. Ahmad, D. Habibi and Q. V. Phung, "A Green Communication Model for 5G Systems," in IEEE Transactions on Green Communications and Networking, vol. 1, no. 3, pp. 264-280, Sept. 2017, doi: 10.1109/TGCN.2017.2700855.

[20] Usama M. & Erol-Kantarci M. (2019). “A Survey on Recent Trends and Open Issues in Energy Efficiency of 5G.” MDPI Sensors. 19(14):3126. https://doi.org/10.3390/s19143126

Future wireless technologies introduce new challenges in energy consumption due to its higher data rates and larger number of connected devices, but it also provides more advanced techniques for energy efficiency than earlier generations. The focus on energy efficiency in future wireless systems is essential for sustainable development in telecommunications, reducing both operational costs and environmental impact. 5G and B5G networks have brought a significant focus on energy efficiency due to their ambitious goals of supporting higher data rates, massive connectivity (e.g., IoT devices), and ultra-low latency. However, the shift towards using higher-frequency bands, such as millimeter wave (mmWave) and Tera Hertz (THz), and massive MIMO (Multiple Input Multiple Output) antennas significantly increases computational and transmission power demands. Promising technologies to optimize energy efficiency in 5G and emerging 6G networks are artificial intelligence and green energy solutions. AI-driven techniques are increasingly being used in future wireless networks to predict traffic patterns and adjust network configurations dynamically, thus improving energy efficiency. For example, machine learning algorithms can help in turning off base stations during periods of low demand or optimize power allocation for active base stations. In addition to optimizing the architecture, many novel wireless networks are exploring the use of renewable energy sources for powering base stations, such as solar and wind energy. While these technologies improve transmission energy efficiency, they also pose new challenges in managing energy consumption effectively. As an example, the increased number of base stations due to the densification of small cells raises overall energy consumption. As network demands grow, power consumption is expected to increase exponentially.

Key energy efficiency strategies at the network level include resource sharing between operators, network function virtualization (NFV), machine learning (ML), and software-defined networking (SDN). Resource sharing reduces duplication by allowing operators to share infrastructure, like base stations and spectrum, lowering energy consumption. NFV improves energy efficiency by virtualizing network functions and dynamically allocating resources, reducing the need for dedicated hardware.ML optimizes network performance by analyzing traffic patterns and adjusting resources, enabling power savings during low traffic periods. While SDN decouples the control plane, it allows centralized and flexible management of network resources and ensures efficient resource allocation. In ultra-dense networks, these strategies help mitigate energy demands by dynamically managing network components. Techniques like sharing virtualized base stations, powering down idle cells, and predicting future demand with ML ensure energy efficiency while maintaining high performance.

1.2.3 Machine Learning Techniques

Machine learning (ML) techniques significantly enhance energy efficiency in wireless networks by optimizing various aspects of network operation. ML produce promising results in modern wireless technologies.

Massive MIMO faces challenges in managing energy due to the complexity of beamforming and channel estimation. ML optimizes beamforming through deep learning, which directs transmission power precisely where needed. ML also predicts optimal power allocation across antennas, handling pilot contamination and large-scale systems to ensure efficient energy use. In ultra-dense networks (UDNs), where many small cells operate to meet high user densities, ML aids in dynamic cell on/off switching by predicting traffic patterns and deactivating unnecessary cells during off-peak times, thus saving energy. It also helps with load balancing by dynamically distributing traffic across cells based on historical data. HetNetscan benefit from ML abilities to manage user association and interference. ML models decide in real-time which users connect to which base stations, optimizing energy consumption and network load distribution. ML also dynamically adjusts power levels and resource allocation to manage interference between different cells.

mmWave Networks require many base stations which leads to increased energy use. ML optimizes hybrid precoding and beamforming, allowing energy to be directed efficiently while maintaining high data rates. Deep learning is especially useful in handling channel estimation, ensuring accurate power control and resource allocation. ML's broader applications include predicting traffic patterns to dynamically allocate resources, activating or deactivating base stations based on real-time demand, and optimizing cell switch-off strategies for energy-harvesting small cells. Reinforcement learning techniques, like Q-learning, help small cells manage power adaptively based on real-time conditions, conserving energy.

In resource allocation, ML ensures efficient spectrum and power distribution, particularly in complex heterogeneous networks and cloud-based radio access networks (RANs), where it prevents energy waste in underutilized areas while maintaining network performance. Power scaling is another area where ML dynamically adjusts power levels of base stations and small cells according to demand, ensuring energy efficiency without compromising service quality, especially in multi-operator networks. ML further enhances self-organizing networks (SONs) by allowing them to automatically adjust configurations based on real-time data, optimizing energy use by managing traffic loads, mitigating interference, and dynamically switching cells on or off. In Network Function Virtualization (NFV), ML manages virtualized network functions dynamically, enabling efficient energy use by scaling resources based on demand. It also distributes workloads across virtualized network nodes to ensure optimal energy consumption across both access and core networks.

ML techniques also tackle energy consumption of a user equipment, optimizing battery life by predicting network states and adjusting power-saving modes without affecting user experience. Additionally, ML helps balance energy efficiency and quality of service (QoS) by adjusting resource allocation and traffic management dynamically, ensuring minimal energy use while maintaining high service standards.

ML methods in energy efficiency problems can be categorized according to learning types and network types. While learning-based energy efficiency methods are divided into supervised, unsupervised and reinforcement learning methods, network-based methods consider ML solutions for core, radio access, and edge networks.

1.2.3.1 Supervised Learning

Supervised learning is highly effective particularly for tasks like channel estimation and beamforming, where the problem structure is well-defined and historical data is available. In massive MIMO systems, this learning type helps optimize power usage by predicting channel conditions and improving beamforming and pre-coding techniques, leading to more energy-efficient operations. By learning the behaviour of communication channels from historical data, supervised learning enables precise signal direction towards users and areas that need it, thus it minimizes energy waste. For instance, a deep learning model trained on past channel state information (CSI) can predict optimal power levels for future transmissions. This method enhances energy efficiency by preventing unnecessary power use.

1.2.3.2 Unsupervised Learning

Unsupervised learning is particularly useful in wireless networks for tasks such as base station clustering and spectrum sensing to discover hidden patterns in data. This approach is valuable in optimizing energy consumption by analyzing base station behaviour and traffic patterns. For base station clustering, unsupervised learning helps group BSs with similar traffic or energy consumption behaviours. This allows the system to adjust operations dynamically, i.e., turning off or putting low-traffic BSs into power-saving modes during off-peak times, thereby unsupervised learning conserves energy. In spectrum sensing, unsupervised learning identifies under-utilized frequencies or channels, enabling the network to optimize resource usage and reduce energy consumption by detecting patterns that traditional methods might miss.

1.2.3.3 Reinforcement Learning

Reinforcement learning (RL) is particularly advantageous for networks where problems arise without prior knowledge, making it ideal for resource allocation and management in dynamic environments. RL adapts its strategies based on feedback from interactions with the environment, improving decisions over time. In the context of energy efficiency, RL continuously learns and optimizes resource usage based on real-time data, making it highly relevant for 5G and 6G networks.

In RL, an agent makes decisions by receiving rewards or penalties from the environment based on its actions. This approach is especially useful for resource allocation and management, where RL allows the system to learn optimal strategies for distributing resources, such as bandwidth or power, in real time, without needing labelled data. This adaptability is crucial in current and emerging wireless networks, where traffic patterns are changeable.

For power control, RL dynamically adjusts power allocation according to network load. Therefore, it ensures the power supplied matches actual demand and minimizes energy wastage. For example, RL can be used to decide when to switch base stations on or off, learning from past traffic patterns and energy consumption to reduce unnecessary energy use. Deep reinforcement learning, which integrates deep learning with RL, further enhances this process by handling complex, large-scale environments.

1.2.3.4 Challenges and Open Issues[21]

- **Data requirements**: Machine learning models require vast amounts of high-quality data for training, particularly in real-time network environments. Collecting sufficient data in dynamic network conditions is a challenging task. While collecting data, another difficult task is data quality since the goodness of predictions is directly tied to the quality of the data used.

- **Computational complexity**: The computational demands of machine learning, particularly for deep learning and reinforcement learning models, are significant. Networks need powerful hardware, such as TPUs (Tensor Processing Units) or GPUs (Graphics Processing Units), to process these models in real-time. Moreover, integrating these solutions in energy-constrained network devices is a major hurdle.
- **Performance-Energy trade-offs**: Machine learning can optimize energy usage, but there is a risk of negatively impacting performance, especially in applications requiring low latency or high reliability. Balancing energy savings with the need for performance is a critical challenge that must be addressed.
- **Scalability**: Implementing machine learning across vast and multi-layered 5G and beyond wireless networks requires scalable solutions. As the number of users and devices increases, machine learning models need to adapt without compromising on energy efficiency or network performance.
- **Optimization of energy harvesting**: The integration of machine learning with energy harvesting, especially in applications like device-to-device (D2D) communications and massive machine-type communications (mMTC), is an active research topic. A key challenge is in optimizing the allocation of resources and scheduling of energy harvesting activities for such devices.
- **Radio access networks (RAN) intelligence**: There is a need for intelligent learning algorithms to optimize energy usage in RAN environments, especially to handle offloading and quality of service (QoS) demands in heterogeneous network scenarios. This requires further research into energy-saving strategies that reduce computational complexity while maintaining performance.

1.2.4 RRM in NTN

In Non-Terrestrial Networks (NTNs), RRM also plays a pivotal role in enabling efficient and reliable communication between terrestrial and non-terrestrial components, such as satellites, high-altitude platform stations (HAPS), and unmanned aerial vehicles (UAVs). NTNs extend connectivity to areas beyond the reach of terrestrial networks, including rural and remote locations, oceans, and skies. These networks face unique challenges, such as high propagation delays, varying link conditions, and overlapping coverage areas, making robust RRM strategies essential for optimal performance.

1.2.4.1 Key Functionalities

In 5G Non-Terrestrial Networks (NTNs), Radio Resource Management (RRM) performs several key functionalities to ensure efficient and reliable communication between terrestrial and non-terrestrial components like satellites, HAPS, and UAVs. It dynamically allocates spectrum, bandwidth, and power to optimize network performance while mitigating challenges such as interference and variable propagation delays[22]. RRM facilitates seamless mobility management[23] by ensuring smooth handovers

[21] Mughees, A., Tahir, M., Sheikh, M. A., & Ahad, A. (2020). Towards Energy Efficient 5G Networks Using Machine Learning: Taxonomy, Research Challenges, and Future Research Directions. *IEEE Access*, *8*, 187498-187522.

[22] Lu, Chen, Jianfeng Shi, Baolong Li, and Xiao Chen. "Dynamic resource allocation for low earth orbit satellite networks." *Physical Communication* 67 (2024): 102498.

[23] A. A. R. Alsaeedy and E. K. P. Chong, "A Survey of Mobility Management in Non-Terrestrial 5G Networks:

between satellite beams and terrestrial cells, while also managing interference in overlapping coverage areas. It guarantees Quality of Service (QoS)[24] by prioritizing traffic based on service type, optimizing latency, and balancing network load. Advanced link adaptation techniques adjust modulation and coding to maintain robust communication under varying channel conditions, including atmospheric attenuation and Doppler shifts. RRM also supports traffic steering, routing data through the most efficient paths, and enabling multi-connectivity to improve reliability and load sharing. Additionally, energy efficiency is prioritized through power optimization and energy-aware scheduling, while reliability and resilience are ensured via redundant resource allocation and prioritization of critical communications during emergencies. These functionalities collectively enable NTNs to deliver high-performance, sustainable, and resilient connectivity for diverse applications.

1.2.4.2 Key Challenges and Open Issues

- **High Propagation Delays and Latency:** One of the most significant challenges in NTNs is the high propagation delay caused by the vast distances between satellites, UAVs, or HAPS and terrestrial terminals. This delay impacts latency-sensitive applications, such as real-time video conferencing, online gaming, and remote surgery. Developing latency-aware scheduling, edge computing, and predictive RRM techniques is critical to mitigate these effects.
- **Doppler Shifts and Mobility:**The high relative velocities of satellites and UAVs introduce significant Doppler shifts, leading to frequency mismatches and degraded communication performance. Handling mobility and ensuring seamless handovers between satellite beams, terrestrial cells, or overlapping coverage areas are complex tasks that require advanced algorithms for link adaptation and mobility management.
- **Interference Management**: In NTNs, overlapping satellite beams, inter-satellite links, and shared spectrum usage between terrestrial and non-terrestrial components can result in severe interference. Efficient spectrum sharing, beamforming, and interference cancellation techniques are necessary to maintain communication quality in densely populated or overlapping networks.
- **Spectrum Scarcity and Utilization:**The limited availability of suitable spectrum bands, particularly in the Ka, Ku, and Q/V frequency ranges, poses a challenge to scaling NTN systems. Higher frequency bands such as THz offer new possibilities but come with challenges like increased path loss and atmospheric absorption. Sophisticated spectrum allocation and sharing mechanisms are required to address this limitation.
- **Limited Energy Resources:** Satellites, UAVs, and other non-terrestrial nodes often operate with constrained power sources, such as solar panels or batteries. Energy efficiency becomes critical for prolonging operational lifetimes. This issue necessitates energy-aware scheduling, power-efficient communication protocols, and optimization of power allocation across NTNs.
- **Atmospheric and Environmental Effects:** Atmospheric factors such as rain, fog, and ionospheric scintillation significantly affect the performance of NTN communication links, particularly at higher frequencies like mmWave and THz. Real-time channel estimation and adaptive transmission strategies are required to mitigate these environmental effects.
- **Complex Network Topology and Dynamic Environments**: NTNs have inherently dynamic topologies due to the movement of satellites, UAVs, and other non-terrestrial nodes. Managing these changing configurations, ensuring seamless connectivity, and optimizing network resources in real time require intelligent, AI-driven network orchestration and resource management systems.
- **Scalability and Network Congestion:** As NTNs expand to support massive IoT (mIoT) devices, autonomous vehicles, and high-bandwidth applications, scalability becomes a critical issue. Congestion in satellite beams or gateway nodes can degrade service quality. Load balancing and traffic steering mechanisms must evolve to handle increasing traffic volumes.
- **Seamless Integration with Terrestrial Networks:** The integration of NTNs with terrestrial 5G/6G networks introduces challenges in interoperability, resource allocation, and QoS maintenance across heterogeneous environments. Achieving seamless interworking between terrestrial and non-terrestrial components requires standardization, unified protocols, and dynamic resource coordination.

Power Constraints and Signaling Cost," in IEEE Access, vol. 12, pp. 107529-107551, 2024, doi: 10.1109/ACCESS.2024.3438613.

[24] A. F. M. S. Shah, M. A. Karabulut and K. Rabie, "Multiple Access Schemes for 6G Enabled NTN-Assisted IoT Technologies: Recent Developments, Prospects and Challenges," in IEEE Internet of Things Magazine, vol. 7, no. 1, pp. 48-54, January 2024, doi: 10.1109/IOTM.001.2300234.

2 Non-Terrestrial Networks (NTN)

2.1 Introduction to Non-Terrestrial Networks

Non-Terrestrial Networks (NTN) represent an emerging category in telecommunications, where communication networks are established through spaceborne (satellites) or airborne platforms, such as High-Altitude Platforms (HAPs) and Unmanned Aerial Vehicles (UAVs). Unlike traditional terrestrial networks that rely on ground-based infrastructure, NTNs leverage the unique capabilities of these platforms to provide connectivity in regions where terrestrial networks are either not feasible or cost-effective.

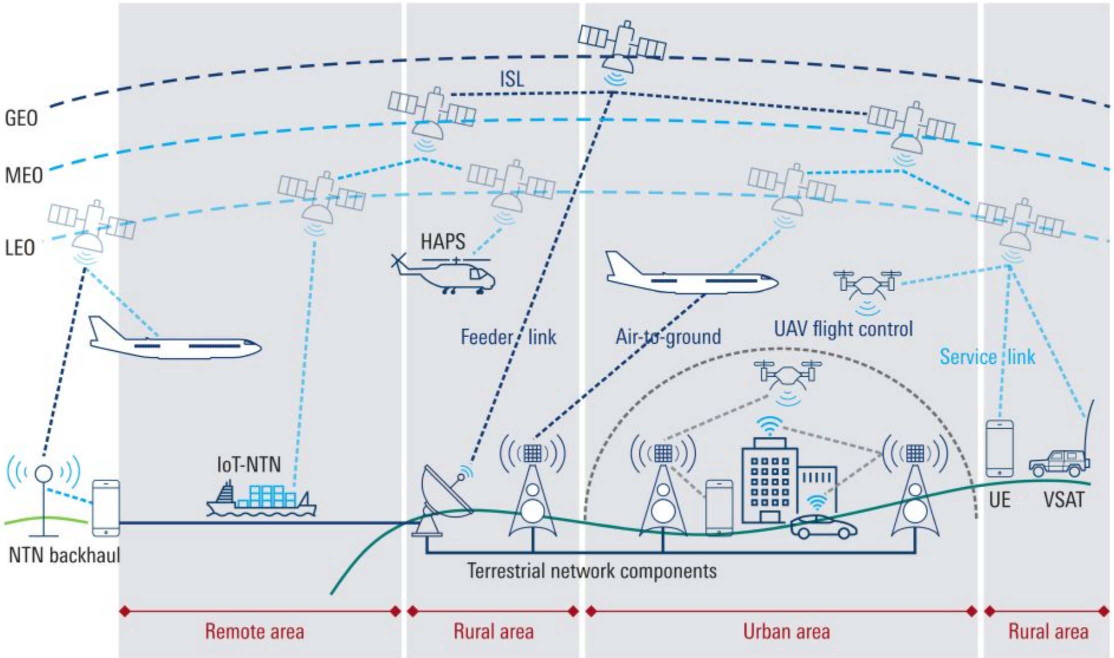

Figure 2-1: Non-Terrestrial network diversity.

The concept of NTN is particularly relevant in today's context, where global connectivity is not just a goal but a necessity. With billions of people still lacking access to reliable communication networks, NTNs offer a promising solution to bridge this digital divide. By extending network coverage beyond the reach of terrestrial infrastructures, NTNs ensure that even the most remote and under-served regions can be connected to the global network. Figure 2-1 shows the Non-terrestrial network diversity for different areas.

The increasing relevance of NTNs in modern telecommunications is driven by several factors. Firstly, the need for ubiquitous connectivity means that mobile operators must look beyond traditional methods to ensure comprehensive coverage. NTNs, especially satellite-based systems, are uniquely positioned to fill the gaps left by terrestrial networks, offering a reliable and scalable solution for extending network coverage. Secondly, the resilience of NTNs makes them an ideal choice for disaster recovery and emergency communications. Unlike terrestrial networks, which can be severely affected by natural disasters, NTNs can continue to provide vital communication links, ensuring that emergency services and humanitarian organizations can operate effectively. Finally, the integration of NTNs with emerging technologies, such as the Internet of Things (IoT), autonomous vehicles, and smart cities, highlights their critical role in the future of telecommunications. As these technologies become more widespread, the demand for robust and reliable connectivity will only increase, making NTNs an essential component of the global communication infrastructure.

2.2 Overview of Satellite in different orbits

Satellites have been a cornerstone of global communication networks for decades, providing everything from television broadcasts to internet connectivity in remote areas. In the context of NTNs, satellites offer unparalleled advantages due to their ability to cover vast geographic areas and provide connectivity in regions where terrestrial networks are either non-existent or unreliable.

Figure 2-2: LEO satellite constellations from Starlink, OneWeb, Orbcomm and Iridium.

Figure 2-2 depicts LEO satellite constellations for different companies, e.g., Starlink, OneWeb, Orbcomm, and Iridium. There are several types of satellite orbits, each with its specific characteristics. Table 2-1 provides a detailed comparison of signal parameters for various LEO constellations, including aspects like frequency bands, beacon length, active satellites, modulation techniques, channel numbers, number of beams, and altitude.

Table 2-1: Comparison of LEO constellation's signal parameters.

Parameter	Starlink	OneWeb	Orbcomm	Iridium
Bandwidth	240 MHz	230 MHz	4.8 kHz	31.5 kHz
Beacon length	4/3 ms	10 ms	1 s	90 ms
Active satellites	3,660	542	36	66
Modulation	OFDM	OFDM	SD-QPSK	DE-QPSK
Frequency band	Ku, Ka	Ku, Ka	VHF	L
Number of channels	8	8	2	240
Number of beams	≈ 48	16	N/A	48
Altitude [km]	550	1,200	750	780

2.2.1 Geostationary Earth Orbit (GEO)

Satellites in GEO orbit are positioned approximately 35,786 kilometers above the Earth's equator and rotate in sync with the Earth's rotation. This allows them to maintain a fixed position relative to the ground, making them ideal for providing continuous coverage to a specific area. However, the high altitude of GEO satellites results in higher latency, which can be a drawback for certain real-time applications. Besides, another big point which has made GEO a much easier option until recently: the user terminal. Being the satellite fixed in the sky, makes that the user terminal antenna can be a dish which is pointed once and forever to the "immobile" satellite in the sky. In the case of MEO and LEO the antenna need to either track and follow the satellite, mechanically or electronically, with impact on complexity and cost, or omnidirectional, with impact on necessary power to close the link budget.

2.2.2 Medium Earth Orbit (MEO)

MEO satellites orbit at altitudes ranging from 2,000 to 35,786 kilometers. They offer a compromise between coverage and latency, providing lower latency than GEO satellites while still covering larger areas than Low Earth Orbit (LEO) satellites.

2.2.3 Low Earth Orbit (LEO)

LEO satellites orbit at altitudes between 160 and 2,000 kilometers. Due to their proximity to Earth, LEO satellites offer the lowest latency, making them ideal for applications requiring real-time communication, such as voice and video calls. However, LEO satellites cover smaller areas and therefore require larger constellations to provide continuous coverage.

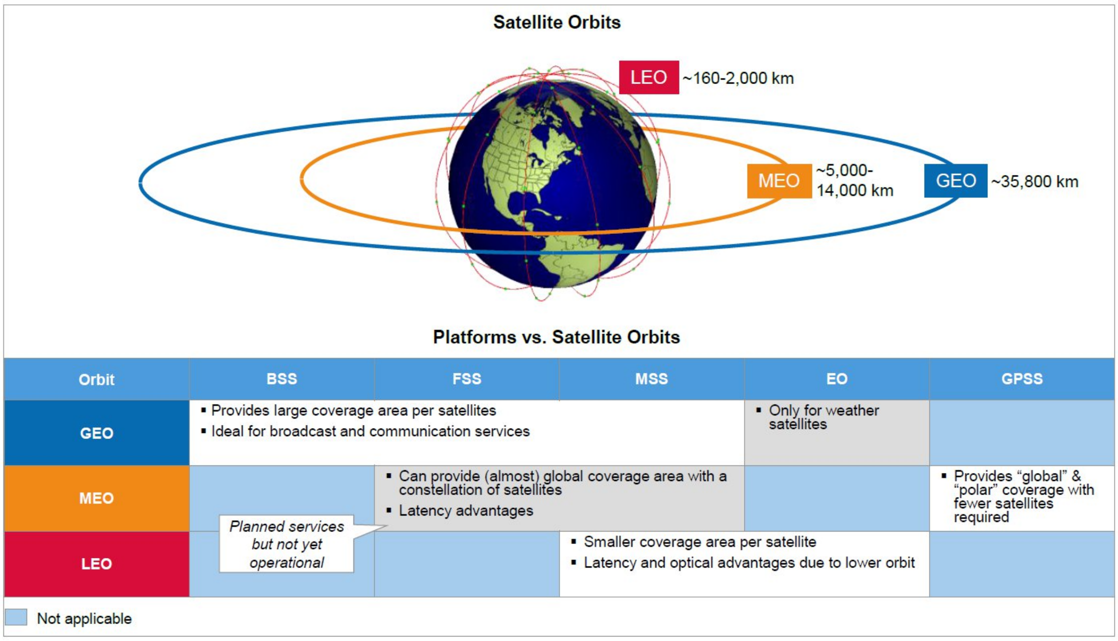

Figure 2-3: Satellite orbits and applications across different platforms.

Figure 2-3 presents the satellite orbits and their applications across different platforms. The choice of satellite orbit depends on the specific requirements, and application including coverage area, latency, and data throughput. The trend in recent years has been toward deploying large constellations of LEO and MEO satellites to provide global coverage with low latency, which is particularly important for supporting modern mobile networks.

2.3 Satellite implementation models for different use cases

Four main use cases can be identified for satellite-based solutions into NGAT (Next Generation Access Technologies): (i) Trunking and Head-end Feed, (ii) Backhauling and Multicasting Tower Feed, (iii) Communications on the Move, and (iv) Hybrid Multiplay. These use cases shown in Table 2-2 are characterised by their scale: from a few hundred or thousand sites for the Trunking and Head-end Feed use case to potentially millions in the case of Communications on the Move and Hybrid Multiplay use cases, as well as the fixed or mobility abilities of the platform connected via satellite.

Table 2-2: Satellite-based use cases.

Use case number	Example of satellite-based use cases	Use cases Examples	Number of sites
Use case 1	Trunking and head-end feed	Service to remote areas; special events	Limited to unserved areas in a carrier's network
Use case 2	Backhauling and Multicasting tower feed	Surge capacity to overloaded cells, plus content delivery (e.g. video) to local caches; efficient broadcast service	Thousands

		to end users	
Use case 3	Communications on the move	In Flight Connectivity for Aircraft; connectivity directly to land vehicles; broadband to ships and trains	Potentially millions
Use case 4	Hybrid multiplay	Video and broadband connectivity directly to home or multi-tenant building with NGAT distribution in building	Potentially millions

2.3.1 (Use case 1) Trunking and Head-end Feed

In the Trunking and Head-End Feed use case, satellites provide high speed direct connectivity option to remote and hard to reach locations.

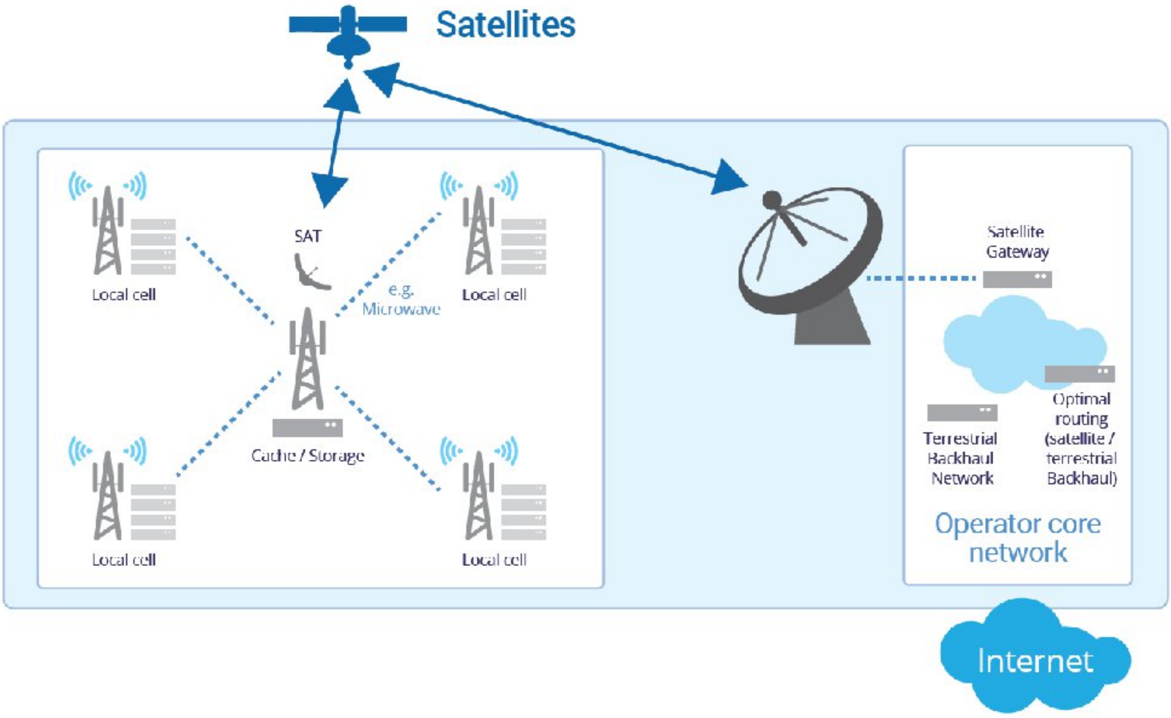

Figure 2-4: Trunking architecture.

2.3.1.1 Representative diagram of the Trunking and Head-end Feed use case

A high throughput satellite link from geostationary and/or non-geostationary satellites has the capability to complement existing terrestrial connectivity to enable high speed trunking of video, IoT and other data to a central site, with further terrestrial distribution to local cell sites (e.g. current and future cellular networks), for instance neighbouring villages, as shown in the Figure 2-4. In this category, only broadband (i.e. unicast, VSAT terminals) communications are supported and the satellite links are bidirectional. There is no use of multicasting to populate edge caches, which corresponds to a major difference with respect to the rest of the use cases presented in next use cases.

2.3.1.2 Scenarios for the Trunking and Head-end Feed Use Cases

- Broadband connectivity to remote areas: For example, coverage on lakes, islands, mountains, rural areas, isolated areas or other areas that are easily covered by satellites;
- Emergency response in wide scale natural disasters, other specific public emergency situations and other unforeseen events where satellites are the only option.
- Broadband connectivity for network Head-End;

- Secondary/backup connection (limited in capability) in the event of the primary connection failure;
- Remote cell connectivity: The following use cases can be considered as a part of the remote cell connectivity scenario:
  - Stand-alone cells;
  - Reoccurring events;
  - Rarely repeated events (concerts, sport events).

2.3.2 (Use case 2) Backhauling and Multicasting Tower Feed

In the Backhauling and Multicasting Tower Feed use case, satellites are one of the solutions for providing high speed multicast connectivity to wireless towers, access points and the cloud.

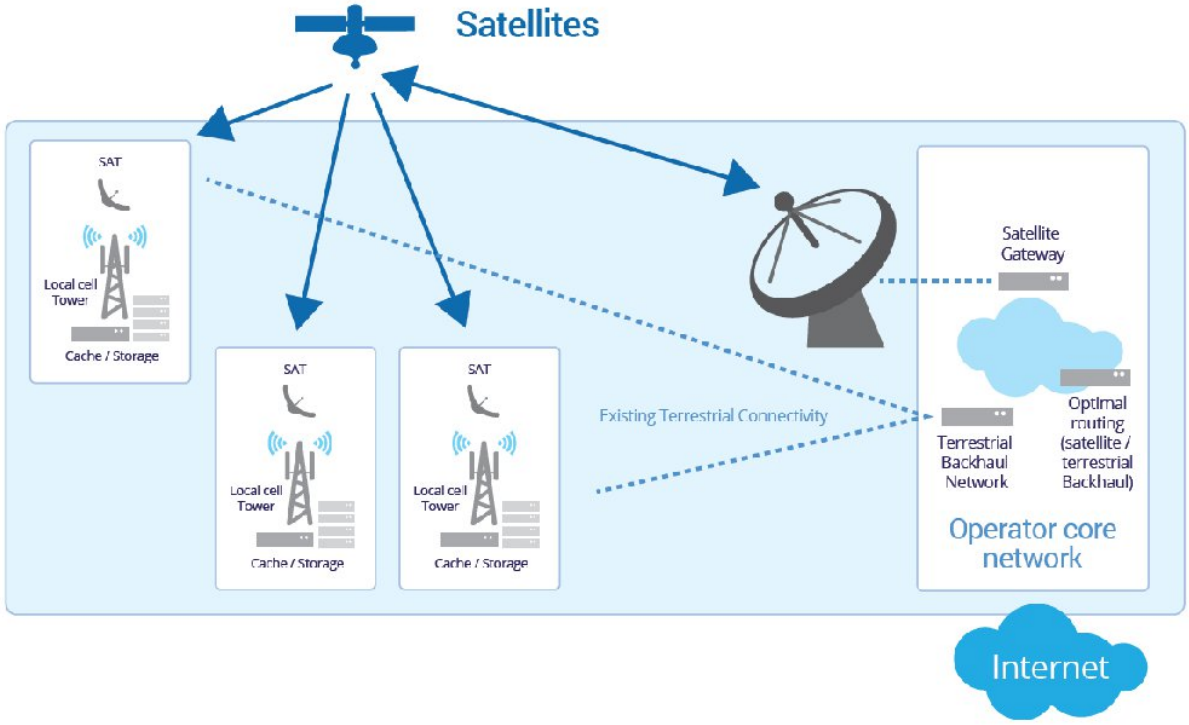

Figure 2-5: Backhauling and multicasting architecture.

A high throughput, multicast-enabled, satellite link from geostationary and/or non-geostationary satellites, direct to the cell towers complements existing terrestrial connectivity to enable backhaul **c**onnectivity to individual cells with the ability to multicast the same content (e.g. video, HD/UHD TV, as well as non-video data) across a large coverage area as well as efficient backhauling of aggregated IoT traffic from multiple sites. In cases of low latency applications where content is cached at the edge of the network, that content may be delivered by satellites in some cases. The use of multicasting to populate edge caches is a major difference of this use case with respect to the one presented in previous use case. Figure 2-5 depicts the backhauling and multicasting architecture.

2.3.2.1 Benefits of Using Satellites for Mobile Backhaul

The use of satellites in mobile network backhaul offers several key benefits that make them an attractive option for extending connectivity:

- **Wide Coverage:** One of the most significant advantages of satellite-based backhaul is its ability to provide coverage over vast areas, including remote and rural regions that are difficult to reach with terrestrial infrastructure. This makes satellites an ideal solution for bridging the digital divide and ensuring that all regions, regardless of their location, have access to reliable communication services.

- **Resilience and Redundancy:** Satellite networks are inherently resilient due to their decentralized nature. Unlike terrestrial networks, which can be severely disrupted by natural disasters or other incidents, satellite networks can continue to operate independently of ground-based infrastructure. This resilience makes satellites an essential component of disaster recovery and emergency response networks, ensuring that communication links remain operational even in the most challenging conditions.

- **Rapid Deployment:** Deploying satellite-based backhaul can be done relatively quickly compared to terrestrial infrastructure. This is particularly advantageous in situations where rapid network setup is required, such as in disaster recovery scenarios or temporary events. Satellites can provide immediate connectivity, allowing for the swift restoration of communication services.

- **Scalability:** Satellite networks can be easily scaled to accommodate growing demand. As more satellites are launched into orbit, the capacity and coverage of the network can be expanded, making satellite-based backhaul a flexible and scalable solution for mobile operators.

- **Support for Emerging Technologies**: Satellites are well-suited to support emerging technologies, such as IoT, which require wide-area coverage and reliable connectivity. By providing backhaul for IoT devices, satellites can facilitate the deployment of smart infrastructure in areas where terrestrial networks are insufficient.

2.3.2.2 Scenarios for the Backhauling and Multicasting Tower Feed use cases

- Broadcast services to end users, etc. (e.g. video, software download), support of low bit-rate broadcast service (e.g. for emergency messages and synchronization of remote sensors and actuators);
- Providing efficient multicast/broadcast delivery to network edges for content such as live broadcasts, ad-hoc broadcast/multicast streams, group communications, Mobile Edge Computing / Virtual Network Function (MEC VNF) update distribution.

Satellite can be an effective means to support edge compute functions such as caching and content processing capabilities. Depending on the deployment scenario, content is delivered to the cache either by satellite via gateway or through terrestrial connection to the Evolved Packet Core (EPC) or Content Delivery Network (CDN) edge network. An example when all the content is sent to the edge CDN by feeding only through satellite is demonstrated in the below figure.

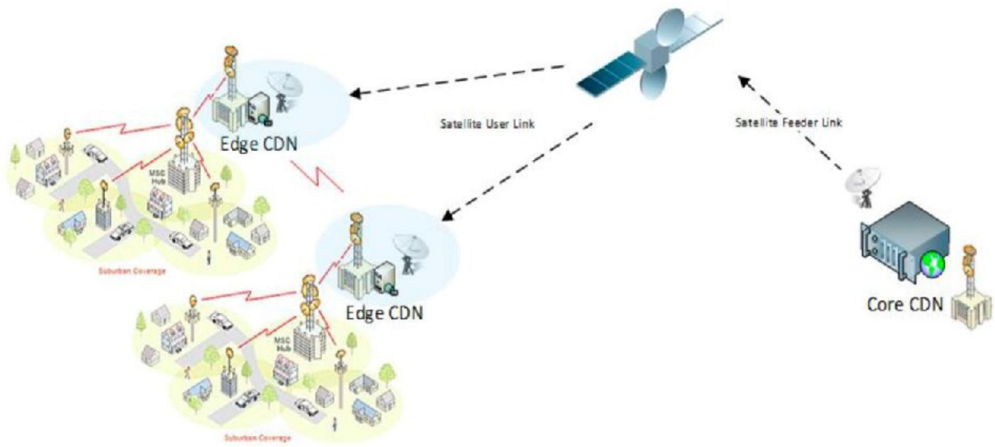

Figure 2-6: CDN based satellite backhauling architecture.

Satellite connectivity, with the help of hybrid network management, can add flexibility to backhauling networks by either providing an alternative route, through satellite, or through an alternative terrestrial link when another node is available. Future developments of smart antennas with steerable beams may further assist in this use case. Figure 2-6 depicts the CDN based satellite backhauling architecture.

Figure 2-7 illustrates a deployment scenario that demonstrates how a satellite solution can effectively address congestion issues during high-traffic events. In this scenario, the satellite network acts as a complementary backhaul, offloading excess traffic from terrestrial networks when they become overloaded. By providing an alternative communication pathway, the satellite solution ensures uninterrupted service continuity, reducing latency and avoiding data bottlenecks.

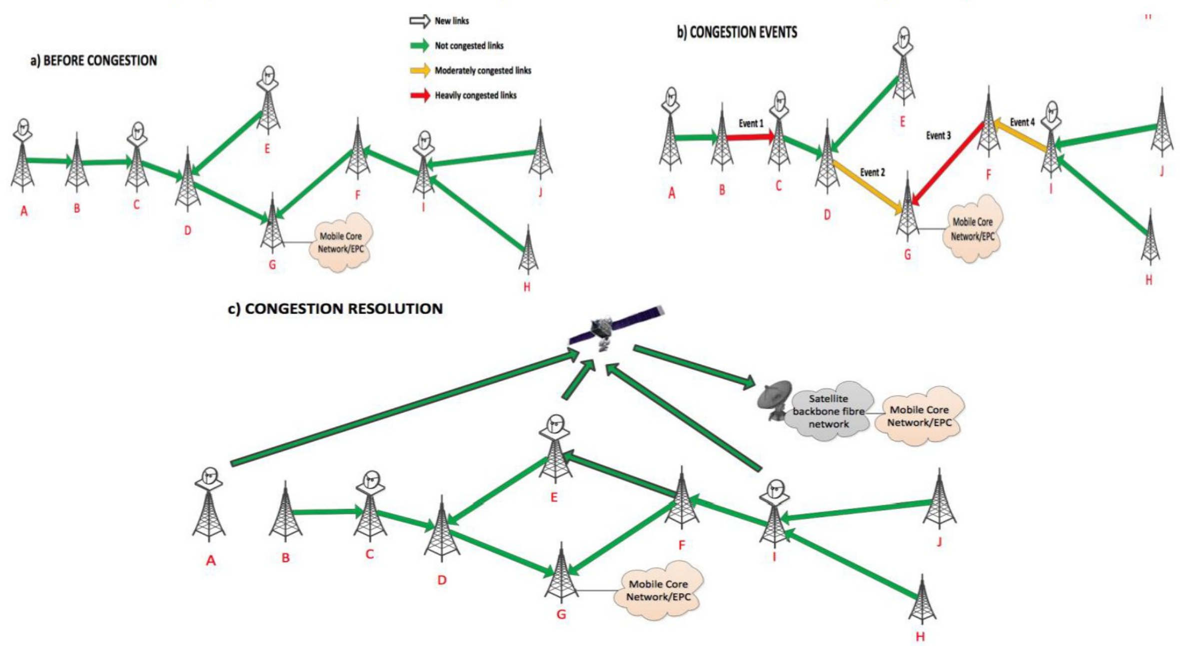

Figure 2-7: Demonstration scenario of satellite deployment for resolving congestion.

2.4.4 (Use case 3GPP) NTN for UE direct connectivity

The development of Non-Terrestrial Networks (NTN) within 3GPP began in 2017, with a Study Item introduced in Release-15 in 3GPP RAN WG1 [RP-1714501][25], focusing on deployment scenarios and channel models for NTN.

2.4.4.1 Key use cases for satellite-based NTN

- **Service Continuity**: This refers to situations where 5G services are not sufficient with terrestrial networks alone. The combination of terrestrial and non-terrestrial networks ensures uninterrupted service for mobile users, such as those on commercial or private jets, as well as maritime platforms like vessels.
- **Service Ubiquity**: Targets unserved or underserved areas where terrestrial networks are unavailable. Examples include IoT applications (e.g., in agriculture, asset tracking, and metering), public safety systems (e.g., emergency networks), and residential broadband access.
- **Service Scalability**: Satellites offer broad coverage, making them ideal for multicast or broadcast applications. A prominent use case includes the distribution of high-demand content, such as Ultra High-Definition TV, over large geographical areas.

2.4.4.2 Feature enhancements and issues to address NTN

From RAN aspect:

- Satellite's long propagation delays, large Doppler effects, and moving cells, involve enhancements on timing relationships, Hybrid Automatic Repeat Request (HARQ), and uplink synchronization.
- Adjustment of allowed values for timers to take into consideration larger latency, improvements on Random Access Channel (RACH) access procedure, and enhancement of uplink scheduling.
- In the control plane, mobility procedures are enhanced to better support satellite use cases.
- Architectural enhancements such as feed link switch over, Automatic Neighbour Relation (ANR), User Equipment (UE) registration and paging.
- UE Radio Resource Management (RRM) and RF requirement.

[25] https://www.3gpp.org/3gpp-groups/radio-access-networks-ran/ran-wg1

- Large Doppler effects, Timers and RACH, ANR and Mobility procedures have been addressed by 3GPP and will not be discussed or considered as part of the MECON project.

From SA aspect:

- Mobility Management with large coverage areas and with moving coverage areas
- E2E Delay, and delay in satellite
- QoS with satellite access and with satellite backhaul
- RAN mobility with LEO regenerative-based satellite access
- Regulatory services with supernational satellite ground station
- Regulatory services will not be discussed or considered as part of the MECON project.

2.4 System Architectures and Integration with Terrestrial Networks

The integration of NTNs with terrestrial networks is essential for providing seamless communication services. Several architectural approaches have been developed to facilitate this integration:

2.4.1.1 Hybrid Network Architectures

A hybrid network architecture combines terrestrial and satellite networks to create a comprehensive communication solution. In this architecture, satellites provide backhaul for remote and under-served areas, while terrestrial networks serve urban and densely populated regions. The integration of these two network types ensures that users experience consistent connectivity, regardless of their location. For example, a user in a remote area might connect to a satellite for backhaul, while a user in a city would connect to a terrestrial network. The hybrid approach also enhances network resilience, as it provides multiple paths for data transmission, reducing the risk of service disruption.

2.4.1.2 Interoperability with 5G Networks

NTNs are designed to be interoperable with existing and future 5G networks, ensuring that mobile devices can seamlessly switch between terrestrial and satellite backhaul as needed. This interoperability is achieved through standardized protocols and interfaces, such as those developed by the 3rd Generation Partnership Project (3GPP). For instance, the 3GPP Release 17 includes specifications for integrating NTNs with 5G networks, allowing mobile operators to leverage satellite-based backhaul as part of their overall network architecture. This integration is crucial for supporting emerging 5G use cases, such as IoT and connected vehicles, which require ubiquitous connectivity. Figure 2-8 shows the satellite payload interoperability with 5G networks.

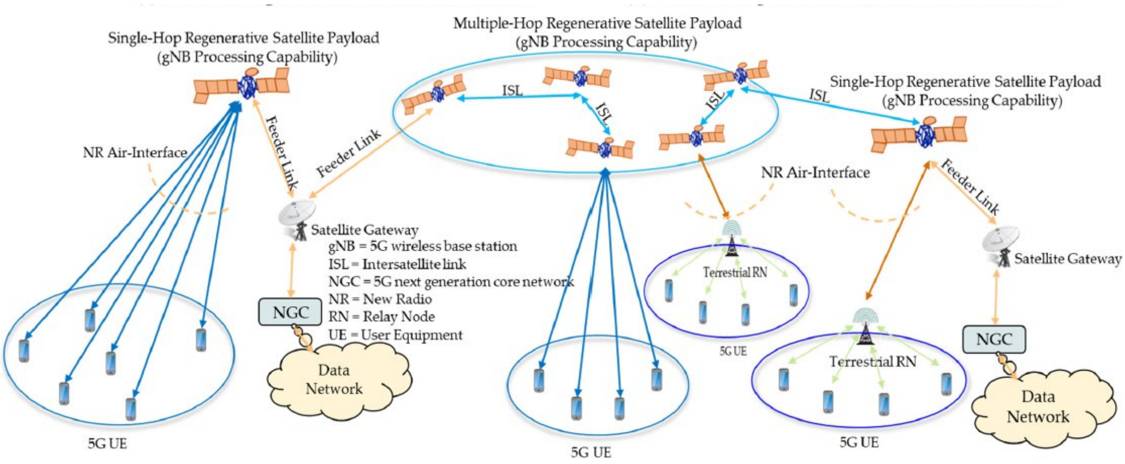

Figure 2-8: Interoperability with 5G Networks.

2.4.1.3 Edge Computing, and Network Function Virtualization (NFV)

To optimize performance and reduce latency, NTN systems can incorporate edge computing and NFV, both of which play a crucial role in enhancing backhaul efficiency. **Edge computing** brings data processing closer to the user by positioning computational resources at the network's edge, significantly reducing the time it takes for data to travel between the device and the network core. This is particularly important for applications requiring real-time communication, such as autonomous vehicles, industrial IoT, and augmented reality. By handling data locally, edge computing minimizes the amount of data that needs to be backhauled to central servers, alleviating congestion and reducing latency across the network. **Network Function Virtualization (NFV)** complements this by allowing network functions—such as routing, firewalls, and load balancing—to be virtualized and deployed on general-purpose hardware. This flexibility makes it easier to scale and manage the network, ensuring that resources are efficiently allocated based on demand. The incorporation of satellite-based backhaul into these architectures is particularly advantageous for NTN systems. Satellites provide the necessary connectivity to link edge nodes with central data centers, especially in regions where terrestrial backhaul infrastructure is either insufficient or non-existent. By combining edge computing, NFV, and satellite-based backhaul, NTN systems can offer more resilient and adaptable communication services. This integration supports the dynamic allocation of network resources, enabling faster and more efficient service delivery, particularly in remote or underserved areas where traditional backhaul options are limited.

2.4.1.4 Cloud Integration

The integration of NTN with cloud services is another critical aspect of modern network architecture, wherein backhauling plays a pivotal role. Satellite-based backhaul serves as the backbone that connects remote edge locations and mobile users directly to cloud data centers. This setup ensures that cloud-based applications and services are accessible with low latency, regardless of the user's location. The satellite backhaul facilitates the transmission of data between the edge and the cloud, enabling real-time processing and decision-making in distributed computing environments.

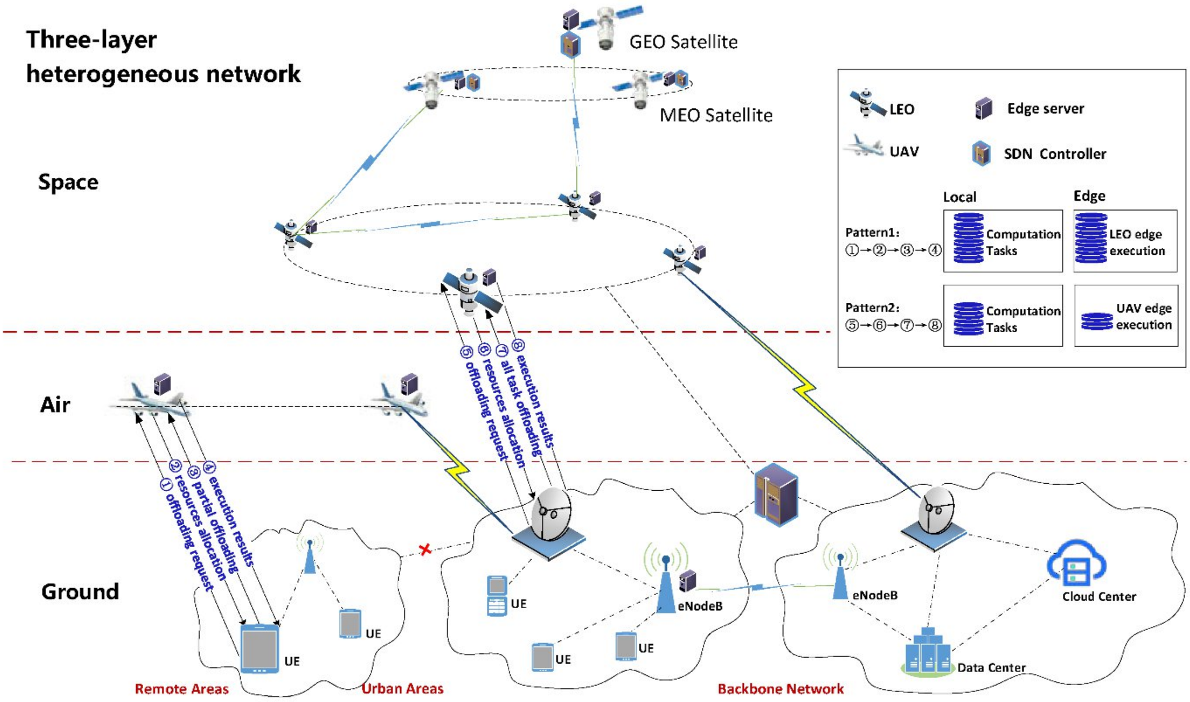

Figure 2-9: Three-layer heterogeneous network.

This architecture is particularly beneficial for enterprises, government agencies, and other organizations that require secure and reliable access to cloud resources in remote or mobile environments. By leveraging satellite-based backhaul, these entities can maintain continuous access to critical cloud services, even in challenging geographic locations. Additionally, the integration with cloud platforms allows for the deployment of **Multi-access Edge Computing (MEC)** solutions, which further reduce latency by processing data at the network edge before it reaches the cloud. MEC, combined with satellite backhaul, ensures that applications such as video streaming, online gaming, and telemedicine can operate smoothly and efficiently, even in areas with limited terrestrial infrastructure. This architecture not only enhances service quality but also enables the deployment of advanced applications that rely on fast, reliable connectivity across vast and often remote regions. Figure 2-9 depicts the three-layer heterogeneous network.

2.4.1.5 Transparent and Non-Transparent NTN

Transparent NTN - "Bent-Pipe" Architecture often referred to as a "bent-pipe" architecture, simply amplifies and retransmits the signals it receives from user devices or ground stations without any onboard data processing. The satellite functions like a relay or repeater, forwarding the signal to a terrestrial network or another satellite without altering its content. All the signal processing (e.g., modulation, encoding, etc.) occurs at the ground stations. The typical scenario of a non-terrestrial network providing access to user equipment is depicted in Fig 2-10.

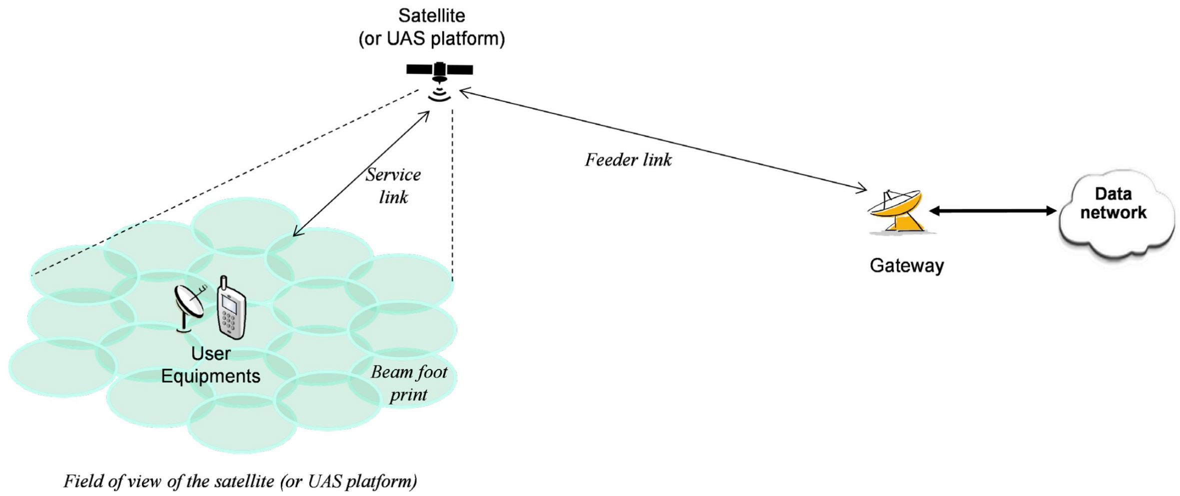

Figure 2-10: NTN Transparent payload[26].

Key Characteristics:

- **No Onboard Processing**: The satellite only amplifies and forwards signals.
- **Relay Function**: The satellite acts as a passive relay, bouncing signals between the ground station and the user terminal.
- **Lower Latency**: Since there is no onboard processing, signals can be transmitted with minimal delay.
- **Lower Cost and Complexity**: Transparent satellites are simpler to design, build, and maintain compared to more complex systems that require onboard processing.
- **Reliance on Ground Infrastructure**: Because all data processing is done on the ground, this architecture requires a robust network of ground stations to handle tasks such as error correction and signal routing.
- **Applications**: This type of NTN is typically used in scenarios where simplicity and low cost are prioritized, such as satellite TV, where the signal is broadcasted without need for processing.

The simple design of transparent satellites significantly reduces manufacturing and maintenance costs, as they only need to amplify and retransmit signals without onboard processing. This approach also leads to lower power requirements since the satellite's role is limited to signal forwarding. Additionally, due to the simpler architecture, these satellites can be brought to market faster.

However, transparent satellites have some drawbacks. They offer limited flexibility because any changes in network behaviour or functionality must be managed by ground stations, making the system less adaptable. A larger number of ground stations are required to ensure adequate coverage, which can lead to higher operational costs. Moreover, compared to non-transparent systems, transparent satellites are less capable of handling traffic in a dynamic or optimized manner.

[26] https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3525

A Non-Transparent NTN, also known as a regenerative satellite, includes onboard signal processing capabilities shown in Figure 2-11. These satellites demodulate, decode, and possibly even route the data before retransmitting it. Non-transparent NTNs perform many of the tasks typically handled by ground stations in a transparent system, thus reducing the need for extensive ground infrastructure.

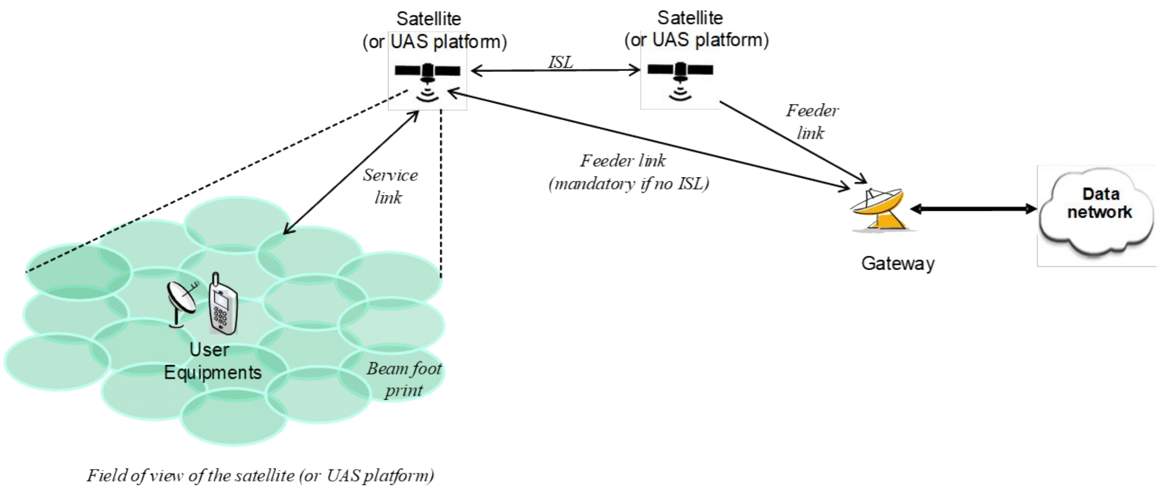

Figure 2-11: Regenerative payload.

Key Characteristics:

- **Onboard Processing**: The satellite can perform tasks such as demodulation, error correction, and even traffic management.
- **Signal Regeneration**: Non-transparent NTNs "regenerate" signals by decoding and re-encoding them, often improving the signal quality.
- **Less Ground Infrastructure Needed**: Since the satellite handles signal processing, the ground network's role is reduced, which can lower operational costs for certain regions or applications.
- **Increased Flexibility**: The onboard processing allows these satellites to dynamically manage traffic and handle more complex services, such as routing, traffic prioritization, and real-time service adjustments.
- **Applications**: This type of architecture is ideal for advanced applications like real-time communication, internet services, and data-intensive operations, especially in areas without sufficient terrestrial infrastructure.

One of the primary advantages of non-transparent satellites is their flexibility, as they can adapt to varying network conditions, enabling sophisticated services such as traffic management and dynamic bandwidth allocation. These satellites also improve signal quality by regenerating the signal, which can correct errors and enhance the quality of data transmission. Additionally, since non-transparent satellites handle some processing onboard, fewer ground stations are needed, which is particularly advantageous in remote or underserved areas.

However, non-transparent satellites come with certain disadvantages. Their higher complexity and cost are notable, as the sophisticated onboard processing systems make them more expensive to build, launch, and maintain. Moreover, they require more power for onboard processing, which can limit their operational lifespan unless larger solar arrays or battery systems are utilized.

3 Standardisation Activity

MECON will focus on compiling and analyzing the main documentations released by 3GPP standardizations and other global forums such as ITU-T, IEEE, Open radio access networks (O-RAN), Telecom infra project (TIP), European Space Agency (ESA), and Linux Networking Foundation (LNF). Our contribution will emphasize the pivotal role these standards and documents play in shaping the future of next-generation digital connectivity technologies. By providing an in-depth overview of relevant 3GPP releases, including Release 16, and 17 which cover critical advancements such as Ultra-Reliable Low Latency Communications (URLLC), Network Slicing, and Integrated Access and Backhaul (IAB), as well as future enhancements in Release 18 and beyond, we will elucidate the framework for B-5G and 6G networks. Additionally, we will review key ITU-T recommendations, such as the IMT-2020 framework and protocols for seamless communication interworking, and highlight IEEE standards that impact wireless and edge computing, particularly IEEE 802.11ax and IEEE 802.15.4. Our analysis will also cover the O-RAN Alliance's efforts to promote open and interoperable RAN interfaces, detailing the O-RAN architecture, use cases, deployment scenarios, and the near-real-time RIC and E2 interfaces. Furthermore, we will explore NTN standardization activities contributing to integrate satellite and terrestrial networks. By synthesizing this information, MECON aims to provide a comprehensive understanding of the existing standards and frameworks that will guide the development and implementation of MECON, ensuring interoperability, performance enhancement, and innovation in the project.

3.1 Standardizations for Radio Access Network

3.1.1 3GPP (3rd Generation Partnership Project)

The contributions from different releases of 3GPP have been pivotal in advancing mobile communication technologies, particularly in the context of MECON. Release 16[27] introduced significant enhancements such as Ultra-Reliable Low Latency Communications (URLLC), which is crucial for mission-critical applications requiring high reliability and low latency. This release also brought the concept of Network Slicing, enabling the creation of multiple virtual networks tailored to specific use cases, thereby enhancing flexibility and efficiency. Additionally, Integrated Access and Backhaul (IAB) was introduced to improve connectivity in rural and remote areas by using wireless links for both access and backhaul. Release 17[28] built on these foundations by refining these technologies and adding support for Non-Terrestrial Networks (NTNs), which are essential for extending coverage to under-served regions. Looking ahead, Release 18[29] and beyond are expected to further innovate with the integration of AI/ML for network optimization and automation, advanced MIMO technologies for better spectral efficiency, and enhanced non-terrestrial networks (NTN) support to ensure seamless connectivity across diverse environments. These cumulative advancements from various 3GPP releases are integral to realizing the full potential of MECON in providing next-generation digital connectivity.

The advancements in 5G New Radio (NR) systems, as detailed in 3GPP Technical Specifications (TS) and Technical Reports (TR), represent a significant leap in mobile communication technology:

- The 3GPP TS 38.300[30] outlines the overall architecture and key features of 5G NR, including support for higher frequency bands, increased bandwidth, and advanced modulation schemes. These enhancements facilitate higher data rates, improved latency, and greater capacity, enabling applications such as enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), and ultra-reliable low latency communications (URLLC).
- The 3GPP TR 38.900[31] provides comprehensive insights into the channel model for frequencies from 0.5 to 100 GHz, critical for understanding the propagation characteristics and optimizing the performance of 5G NR systems.

[27] https://www.3gpp.org/specifications-technologies/releases/release-16
[28] https://www.3gpp.org/specifications-technologies/releases/release-17
[29] https://www.3gpp.org/specifications-technologies/releases/release-18
[30] https://www.etsi.org/deliver/etsi_ts/138300_138399/138300/16.04.00_60/ts_138300v160400p.pdf
[31] https://www.etsi.org/deliver/etsi_tr/138900_138999/138900/14.02.00_60/tr_138900v140200p.pdf

- Furthermore, the 3GPP TS 38.214[32] specifies the physical layer procedures for data, which are essential for efficient spectrum utilization and robust communication. These specifications collectively ensure that 5G NR systems meet the stringent requirements of next-generation connectivity, supporting a wide array of innovative use cases and services.

The New Radio (NR) specifications for Layer 1 (Physical Layer), Layer 2 (MAC, RLC, PDCP), and Layer 3 (RRC) as defined by 3GPP, collectively enhance the efficiency and capabilities of 5G systems. The Physical Layer, described in 3GPP TS 38.211[33], encompasses key technologies such as OFDM, massive MIMO, and beamforming, which provide the foundation for high data rates, robust connectivity, and spectral efficiency. Layer 2, comprising the Medium Access Control (MAC), Radio Link Control (RLC), and Packet Data Convergence Protocol (PDCP), is detailed in 3GPP TS 38.321[34], TS 38.322[35], and TS 38.323[36] respectively. These protocols ensure efficient data transfer, error correction, and reliable delivery of packets by managing resources, retransmissions, and data segmentation. Lastly, Layer 3, focusing on the Radio Resource Control (RRC), is specified in 3GPP TS 38.331[37]. The RRC layer is responsible for connection establishment, mobility management, and the configuration of lower layers, ensuring that the network and user equipment (UE) are optimally coordinated for various operational states and mobility scenarios. Together, these layers enable the NR system to deliver high performance, low latency, and reliable communication, supporting a wide range of advanced 5G applications and services.

Network slicing, as defined by 3GPP, represents a transformative capability in 5G networks, allowing operators to create multiple virtual networks on a single physical infrastructure, each tailored to specific use cases and service requirements. According to 3GPP TS 28.530[38] and 3GPP TS 23.501[39], network slicing enables customized network configurations that can independently manage diverse applications such as enhanced mobile broadband (eMBB), ultra-reliable low latency communications (URLLC), and massive machine-type communications (mMTC). Each slice can have its own performance characteristics, security protocols, and quality of service (QoS) parameters, making it possible to meet the unique demands of various industries, from autonomous driving and smart factories to remote healthcare and immersive media. The implementation of network functions (NFs), as detailed in 3GPP TS 23.501[40] and TS 23.502[41], involves the deployment of virtualized network functions (VNFs) and physical network functions (PNFs) that operate within these slices, ensuring efficient resource utilization and flexibility. This architecture supports dynamic and on-demand allocation of resources, providing the agility required to rapidly deploy new services and respond to changing market needs. By leveraging network slicing, 5G networks can deliver tailored, high-performance connectivity solutions that drive innovation and meet the diverse requirements of modern digital ecosystems.

Figure 3-1 illustrates the placement of functions and interfaces within the RAN architecture, highlighting that O-RAN Alliance specifications are more detailed compared to the broader 3GPP standards. This level of detail is particularly valuable in a multi-vendor environment, where interfaces like X2 play a crucial role in ensuring seamless interoperability. Open RAN's vision of a multi-vendor system also helps reduce costs for mobile network operators (MNOs) by increasing software vendor options and diversifying the supply chain. However, Open RAN must still adhere to 3GPP specifications, as these form the universal standard for 5G RAN technology. While Open RAN could support other cellular generations, the current standardization efforts by the O-RAN Alliance remain focused on 5G, which is the primary focus of the telecommunication industry.

[32] https://www.etsi.org/deliver/etsi_ts/138200_138299/138214/16.02.00_60/ts_138214v160200p.pdf
[33] https://www.etsi.org/deliver/etsi_ts/138200_138299/138211/16.02.00_60/ts_138211v160200p.pdf
[34] https://www.etsi.org/deliver/etsi_ts/138300_138399/138321/16.01.00_60/ts_138321v160100p.pdf
[35] https://www.etsi.org/deliver/etsi_ts/138300_138399/138322/16.01.00_60/ts_138322v160100p.pdf
[36] https://www.etsi.org/deliver/etsi_ts/138300_138399/138323/16.02.00_60/ts_138323v160200p.pdf
[37] https://www.etsi.org/deliver/etsi_ts/138300_138399/138331/16.01.00_60/ts_138331v160100p.pdf
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[39] https://www.etsi.org/deliver/etsi_ts/123500_123599/123501/16.06.00_60/ts_123501v160600p.pdf
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[41] https://www.etsi.org/deliver/etsi_ts/123500_123599/123502/16.07.00_60/ts_123502v160700p.pdf

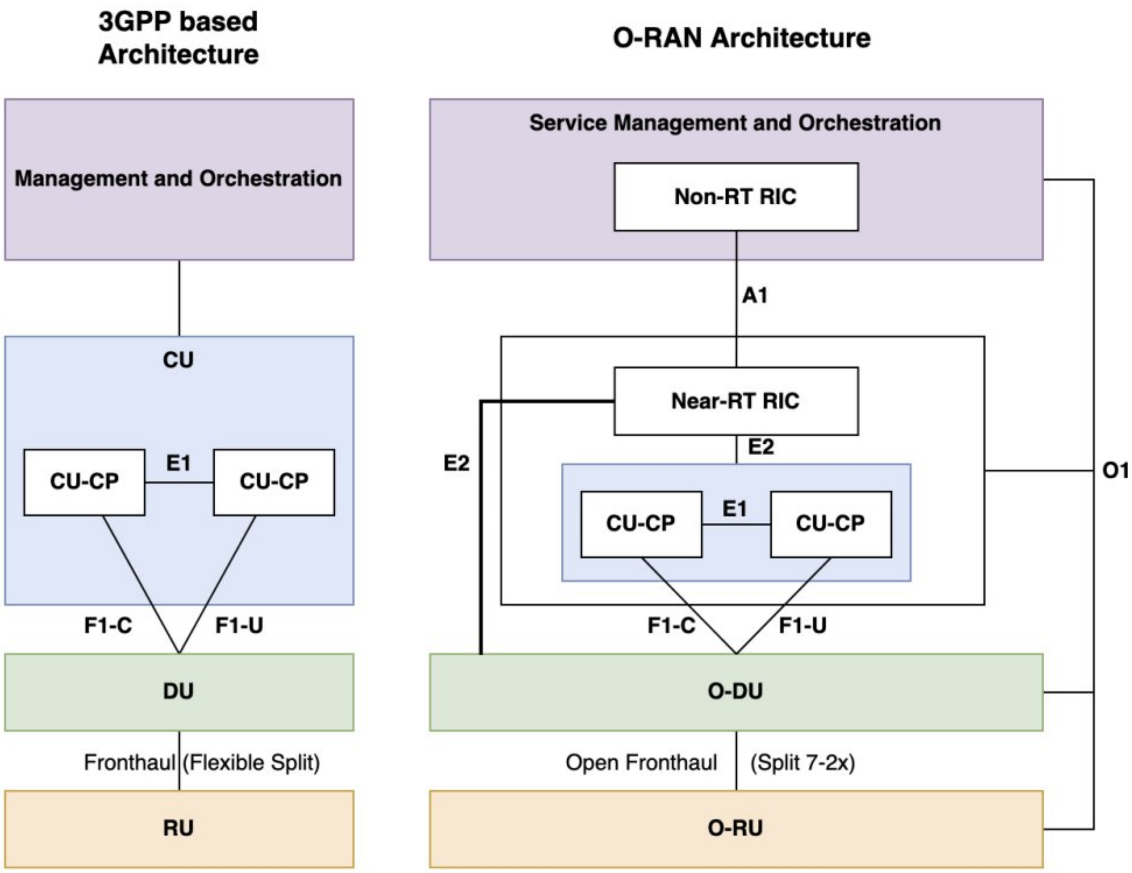

Figure 3-1: Comparison between 3GPP and O-RAN architecture.

The Next-Generation Radio Access Network (NG-RAN) systems, as defined by 3GPP, constitute a major evolution in wireless communication architecture, designed to meet the diverse demands of 5G and beyond. According to 3GPP TS 38.401[42], NG-RAN introduces a flexible and scalable architecture that separates the control and user planes, enabling more efficient handling of data traffic and better support for varied services. This architecture includes the gNB (next-generation NodeB) and the gNB-CU (central unit) and gNB-DU (distributed unit), which work together to enhance network performance and manage resources dynamically. The 3GPP TR 38.801[43] elaborates on the functional split options between these units, which allow for optimal deployment scenarios tailored to specific use cases, such as low latency applications and massive IoT deployments. Additionally, the 3GPP TS 38.470[44] specifies the interfaces between NG-RAN nodes and the 5G core network, ensuring seamless interoperability and integration. These specifications ensure that NG-RAN systems can deliver high throughput, low latency, and high reliability, making them essential for the future of mobile connectivity and enabling innovative applications across various industries.

3.1.2 ITU-T (International Telecommunication Union)

ITU-R WP 5D[45] is the group responsible for the overall radio system aspects of the terrestrial component of International Mobile Telecommunications (IMT) systems, comprising the current IMT-2000, IMT-Advanced and IMT-2020. The detailed technical specifications for ITU's IMT2020 standards (5G) are developed in close collaboration with the leading national, regional and international radio standards development organizations.

[42] https://www.etsi.org/deliver/etsi_ts/138400_138499/138401/16.03.00_60/ts_138401v160300p.pdf
[43] https://www.3gpp.org/ftp/Specs/archive/38_series/38.801/
[44] https://www.etsi.org/deliver/etsi_ts/138400_138499/138470/16.02.00_60/ts_138470v160200p.pdf
[45] https://www.itu.int/en/ITU-T/studygroups/2017-2020/13/Documents/5G/ITU-5G-Activities.pdf

The ITU-R Recommendation M.2160-0[46] outlines a detailed framework and sets comprehensive objectives for the development of International Mobile Telecommunications (IMT) for 2030 and beyond, known as IMT-2030. This initiative aims to build on the advancements of current IMT systems to better serve the global networked society's needs, emphasizing inclusivity, sustainability, and innovation. One of the primary goals of IMT-2030 is to bridge digital divides by ensuring affordable and meaningful connectivity for all, especially in remote and sparsely populated areas, thereby promoting digital inclusion and equality. The framework highlights the importance of ubiquitous connectivity, providing basic broadband services with extended coverage to underserved regions. Sustainability is a critical focus, with IMT-2030 promoting energy-efficient technologies, low power consumption, and reduced greenhouse gas emissions, aligning with the United Nations Sustainable Development Goals (SDGs). Additionally, IMT-2030 aims to foster technological innovation to enhance user experiences and enable new applications, such as immersive multimedia, digital twins, and smart industrial applications. The recommendation envisions integrating advanced technologies like artificial intelligence (AI), ubiquitous computing, and enhanced radio interfaces to create a resilient, secure, and inclusive digital future. Furthermore, IMT-2030 seeks to support the development of a wide range of use cases, from enhanced mobile broadband and ultra-reliable low-latency communications to massive machine-type communications, ensuring that the evolving needs of both urban and rural environments are met.

The ITU-R M.2410, M.2411, and M.241247 reports focus on the technical performance requirements, evaluation criteria, and guidelines for radio interface technologies for IMT-2020. These documents provide a detailed framework for ensuring that new radio networks can meet the stringent performance standards required for 5G and future technologies. This includes considerations for spectrum efficiency, latency, and peak data rates, which are critical for high-performance radio networks. The ITU-R M.2412-0 report[48], "Guidelines for evaluation of radio interface technologies for IMT-2020," provides a comprehensive framework for assessing candidate radio interface technologies (RITs) and sets of RITs (SRITs) for IMT-2020. The document outlines the scope, methodology, and evaluation criteria necessary for a fair and consistent assessment of these technologies. It emphasizes the need for simulations, analytical approaches, and inspection procedures to evaluate various technical parameters such as peak data rate, spectral efficiency, user experienced data rate, latency, reliability, mobility, and energy efficiency.

The evaluation guidelines are designed to ensure that candidate technologies meet the minimum technical performance requirements set forth by the ITU. These requirements include enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), and ultra-reliable low-latency communications (URLLC) capabilities. The report specifies different test environments and configurations to simulate real-world scenarios, ensuring the technologies can handle diverse and stringent operating conditions.

Key aspects of the evaluation include system-level simulations to assess average and 5th percentile user spectral efficiency, as well as link-level simulations for other performance metrics. The methodology allows for independent evaluation groups to use their simulation tools, ensuring flexibility and reproducibility in the evaluation process. Additionally, the report highlights the importance of consistent channel models and parameters to facilitate a unified assessment approach across different proposals.

Overall, the ITU-R M.2412-0 report provides a robust and detailed framework for evaluating IMT-2020 candidate technologies, ensuring that they can meet the future demands of mobile communication networks.

Radio Interface Enhancements: Advanced modulation methods and coding schemes like polar coding and LDPC are crucial for overcoming high-frequency RF impairments. New waveform designs and multiple access technologies, including NOMA, are considered for improved performance. Extreme MIMO (E-MIMO) with large-scale antenna arrays and AI assistance aims to enhance spectrum efficiency, coverage, and energy efficiency. Self-interference cancellation (SIC) will enable in-band full duplex (IBFD), improving spectrum efficiency and reducing interference. Technologies like reconfigurable intelligent surfaces (RIS) and holographic radio (HR) are explored for better

[46] https://www.itu.int/dms_pubrec/itu-r/rec/m/R-REC-M.2160-0-202311-I%21%21PDF-E.pdf
[47] https://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-M.2412-2017-PDF-E.pdf
[48] https://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-M.2412-2017-PDF-E.pdf

beamforming. Using appropriate frequency resources supports high data rates, low latency, and precise positioning.

Radio Network Enhancements: RAN slicing creates multiple logical networks on shared infrastructure, tailored to specific needs. Ensuring quality of service (QoS) through resilient, dynamic provisioning is essential. Future RAN architecture will be simplified, integrating AI and user-centric designs. Digital twin networks (DTNs) enable real-time mapping and intelligent management. Integrating terrestrial networks with non-terrestrial networks (NTN), including satellites, enhances connectivity. Ultra-dense networks (UDN) through dense transmission points address data rate and coverage needs. Trusted data storage and secure sharing technologies are also developed to support these advancements.

Digital Broadband Services: The ITU-T Y.3100 series, particularly ITU-T Y.3101[49], provides comprehensive requirements for the IMT-2020 network, which includes 5G and beyond. These standards outline the necessary features to ensure efficient deployment and high flexibility, such as network softwarization and network slicing, which are fundamental for supporting diverse applications and services in digital broadband environments.

The ITU-T Recommendation Y.3200[50] outlines the requirements for the convergence of fixed, mobile, and satellite networks within the IMT-2020 framework and beyond. This recommendation specifies service requirements, network capability requirements, and use cases to enable seamless service delivery regardless of access technology or user location. Key technologies such as artificial intelligence (AI), machine learning (ML), distributed ledger technology (DLT), and quantum information technology (QIT) are recommended to enhance the capabilities of converged networks. The framework supports unified user identity, seamless service continuity, and quality of service (QoS) across different access networks. The recommendation emphasizes the importance of a unified control plane, collaborative user planes, and integrated service and management planes. Use cases include enhancing connectivity in remote areas, disaster recovery, and improving service quality through network convergence. The aim is to provide users with a consistent and reliable service experience, leveraging the strengths of fixed, mobile, and satellite communications to meet future connectivity demands.

3.1.3 IEEE (Institute of Electrical and Electronics Engineers)

As we advance towards the era of beyond 5G (B5G) and 6G systems, the IEEE 802 series of standards continues to play a pivotal role in shaping the future of wireless communication. These standards are foundational for ensuring high performance, interoperability, and security across various networking environments. This analysis delves into the state-of-the-art advancements within the IEEE 802 series, focusing on their impact and contributions to beyond 5G systems.

The IEEE 802 standards play a crucial role in the evolution of broadband services, radio networks, and satellite systems for B5G networks, ensuring they meet the growing demands for higher data rates, lower latency, and increased efficiency. The IEEE 802.3 working group[51] is spearheading the development of Terabit Ethernet standards, aiming to achieve data rates beyond 400 Gbps. These advancements, which leverage new modulation techniques and high-density fiber optics, are essential for data centers, cloud computing, and backbone networks to handle the anticipated exponential growth in data traffic. Additionally, the IEEE 802.3bt standard for Enhanced Power over Ethernet (PoE) provides up to 100 watts of power over Ethernet cables, supporting a broader range of devices including 5G small cells, IoT sensors, and edge computing nodes, which are crucial for deploying dense networks in B5G environments.

In the domain of wireless LAN (Wi-Fi), the IEEE 802.11[52] standards, such as Wi-Fi 6 (802.11ax)[53] and the forthcoming Wi-Fi 7 (802.11be)[54], introduce advanced features like OFDMA, MU-MIMO, and 4096-QAM modulation to enhance throughput, efficiency, and reduce latency in dense environments. These improvements are vital for supporting applications such as augmented reality (AR), virtual reality (VR),

[49] https://www.itu.int/rec/T-REC-Y.3101-201801-I/en
[50] https://www.itu.int/rec/T-REC-Y.3200/en
[51] https://www.ieee802.org/3/
[52] https://www.ieee802.org/11/
[53] https://www.wi-fi.org/discover-wi-fi/6-ghz-wi-fi-information-center
[54] https://www.wi-fi.org/discover-wi-fi/wi-fi-certified-7

real-time gaming, and ultra-high-definition video streaming. Furthermore, these standards are designed to integrate seamlessly with 5G networks, enabling unified connectivity solutions with efficient handover mechanisms, shared spectrum usage, and coordinated resource management.

IEEE 802.15[55] standards, focusing on Wireless Personal Area Networks (WPAN), enhance Ultra-Wideband (UWB) and Low-Power Wide-Area Networks (LPWAN). The IEEE 802.15.4z standard improves UWB technology, offering precise location tracking and secure ranging capabilities essential for autonomous vehicles and smart factories. LPWAN technologies like Zigbee and Thread continue to evolve, providing low-power, long-range communication solutions suitable for massive IoT deployments. Additionally, advancements in these standards emphasize enhanced security and scalability to support the large number of connected devices anticipated in B5G systems.

Although largely superseded by LTE and 5G, the IEEE 802.16 standard (WiMAX) continues to evolve for niche applications such as rural broadband and private networks. Enhancements focus on improving spectral efficiency, reducing latency, and supporting higher data rates to meet specific needs within the B5G ecosystem.

IEEE 802.1[56] standards, particularly Time-Sensitive Networking (TSN), are critical for B5G systems, providing deterministic communication required for industrial automation, autonomous systems, and smart grids. TSN ensures low-latency, high-reliability communication over Ethernet, facilitating the convergence of IT and Operational Technology (OT) networks. Additionally, advanced security protocols like IEEE 802.1X and MACsec (IEEE 802.1AE) are continually enhanced to provide robust network access control and data encryption, ensuring secure communication in critical applications.

Finally, IEEE 802.22[57] leverages cognitive radio technology for dynamic spectrum access, allowing devices to operate in unused TV broadcast bands. This capability is crucial for extending broadband access to under-served areas and enhancing spectrum efficiency in B5G systems. Enhancements in IEEE 802.22 focus on providing reliable and high-speed internet access in rural and remote areas, supporting the goal of universal connectivity in B5G networks. These comprehensive advancements across IEEE 802 standards collectively ensure that future communication networks are robust, flexible, and capable of meeting the diverse requirements of next-generation applications.

3.1.4 Open RAN

Open RAN has sparked the emergence of many new, smaller manufacturers, often originating from universities or as offshoots of larger companies. These new players frequently specialize in a single product, offering unique implementations or architectures that set them apart from traditional vendors. Open RAN disrupts the conventional model by not only disaggregating hardware and software but also introducing new open interfaces between RAN components and adding enhanced intelligence to the network. Industry groups like 3GPP[58], the O-RAN Alliance[59], ONAP[60], ONF[61], and the Telecom Infra Project (TIP)[62] are instrumental in advancing open network and service architectures.

3.1.4.1 O-RAN Alliance (Open Radio Access Network Alliance)

The O-RAN Alliance is a pivotal force in advancing digital broadband services, radio networks, and satellite systems through its emphasis on open and intelligent RAN (Radio Access Network) standards. By promoting interoperability and open interfaces, the O-RAN standards ensure that network elements from different vendors can seamlessly work together, enhancing the flexibility and scalability of digital

55 https://www.ieee802.org/15/
56 https://1.ieee802.org/tsn/
57 https://www.ieee802.org/22/
58 https://www.3gpp.org/news-events/3gpp-news/open-ran
59 https://www.o-ran.org/
60 https://www.onap.org/
61 https://opennetworking.org/
62 https://telecominfraproject.com/openran/

broadband services. This openness facilitates innovation and reduces costs, making high-speed internet more accessible, especially in rural and under-served areas.

In radio networks, the O-RAN architecture supports the disaggregation of RAN components into the central unit (CU), distributed unit (DU), and remote radio unit (RRU), allowing for optimized resource management and deployment tailored to specific use cases. This modular approach is essential for the efficient operation of 5G networks, enabling dynamic adjustments based on traffic demands and service requirements.

An important technology related to Open RAN is Multi-access Edge Computing (MEC). MEC is a cloud-based service designed to operate at the network edge, performing tasks that would traditionally be handled by centralized core networks or cloud infrastructures. By shifting the computing processes closer to the end users, MEC facilitates the deployment of applications and services that require unique network characteristics not typically needed by standard services. MEC enables localized data processing to provide private cellular network services, supports computational offloading for IoT devices, and leverages the proximity of edge devices to enhance user experiences. Additionally, it strengthens the privacy and security of mobile applications. Ongoing research in MEC is exploring areas such as binary and partial offloading, resource management systems, the integration of MEC with Open RAN and network slicing, and the coordination between MEC and RIC (near-real-time RIC).

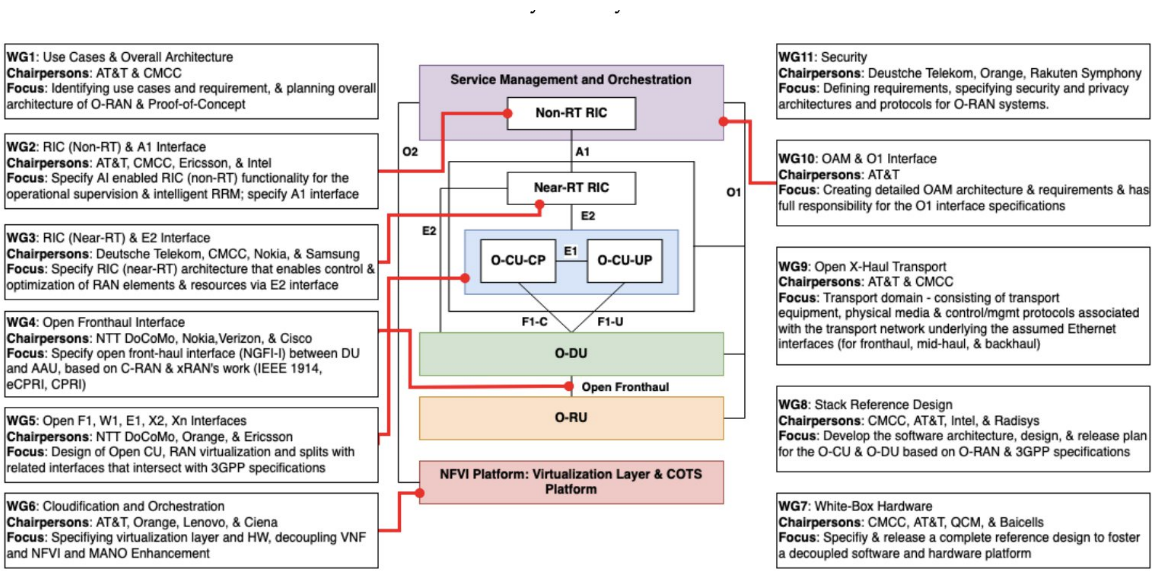

Figure 3-2 O-RAN Alliance's WGs and their objectives.

The O-RAN Alliance Working Groups (WGs)[63] each play a crucial role in advancing open and intelligent RAN technologies. WG1 is responsible for the overall O-RAN architecture and use cases, identifying and managing tasks to ensure comprehensive development. WG2 focuses on the Non-Real-Time RAN Intelligent Controller (Non-RT RIC) and A1 interface, supporting intelligent radio resource management and optimization through AI/ML models. WG3 defines the architecture for the Near-Real-Time RIC, which enables near-real-time control and optimization of RAN elements via the E2 interface. WG4 aims to deliver open fronthaul interfaces to ensure multi-vendor interoperability between distributed units (DUs) and remote radio units (RRUs). WG5 provides multi-vendor profile specifications for F1/W1/E1/X2/Xn interfaces, compliant with and enhancing 3GPP standards. WG6 focuses on cloudification and orchestration, promoting the decoupling of RAN software from hardware to leverage commodity hardware platforms. WG7 promotes open reference design hardware to reduce 5G deployment costs, fostering a decoupled software and hardware platform. WG8 develops software architecture and design for the O-RAN Central Unit (O-CU) and Distributed Unit (O-DU) based on O-RAN and 3GPP specifications. WG9 addresses the transport domain, covering transport equipment, physical media, and associated protocols. WG10 handles the OAM requirements, architecture, and O1

[63] https://public.o-ran.org/

interface. Lastly, WG11 focuses on the security aspects of the open RAN ecosystem, ensuring robust protection across the network. These WGs collectively drive the innovation and implementation of an open, flexible, and interoperable RAN environment. The overall objectives from all O-RAN WGs is shown in Figure 3-2. O-RAN specifications are being adopted by European Telecommunication Standardization Institute (ETSI) and published among ETSI standards[64]. All the O-RAN specifications from all WGs are available[65].

The O-RAN Alliance is built on two fundamental principles: openness and intelligence[66]. To fulfil these overarching goals, the alliance has developed several reference designs that outline the architecture of an Open RAN system. These designs[67], collectively known as the O-RAN vision, include standardization design, virtualization design, and white box design. These elements are critical for ensuring the architecture aligns with the principles of openness and intelligence.

In addition, the O-RAN Alliance is structured into several specialized focus groups (FGs):

- Standard Development Focus Group (SDFG): Oversees standardization within the O-RAN Alliance and liaises with other relevant Standard Development Organizations (SDOs).
- Test and Integration Focus Group (TIFG): Defines the alliance's approach to testing and integration, coordinating specifications across working groups.
- Open Source Focus Group (OSFG): Manages open-source-related matters, including overseeing the Open Source Community (OSC).
- Industry Engagement Focus Group (IEFG): Promotes the adoption and innovation of O-RAN technology within the industry and ecosystem.
- Next Generation Research Group (nGRG): Focuses on research related to open and intelligent RAN for 6G and future systems.
- Sustainability Focus Group (SuFG): Aims to develop energy-efficient and environmentally friendly mobile networks.

Several notable projects have emerged from the Open RAN movement, contributing to the development and deployment of open network technologies:

- OpenAirInterface (OAI)[68]: Launched in 2009 by Eurecom, OAI is an open-source software suite for RAN and CN, currently managed by the OAI Software Alliance. It focuses on creating a 3GPP-compliant 5G RAN stack, alongside other projects such as Mosaic5G. OAI provides software implementations for eNBs, UEs, and EPC, compatible with LTE Release 8.6, and requires specific kernel and BIOS modifications for real-time performance69.

- srsRAN[70]: Originally known as srsLTE and started in 2014, this free open-source software focuses on 4G and 5G implementations, particularly for LTE Release 10. Unlike OAI, srsRAN doesn't require kernel or BIOS modifications but does require CPU frequency scaling adjustments for real-time functionality. It is licensed under GNU Affero General Public License (AGPL) and is compatible with Ubuntu and Fedora Linux distributions71.

- TIP OpenRAN Project Group[72]: Established in 2016, this initiative seeks to develop open RAN solutions on general-purpose hardware. Focused on enabling a multi-vendor, software-based RAN ecosystem, the project aims to lower deployment and maintenance costs. The group involves major telecom companies like Vodafone, Telefonica, and Intel73.

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[64] https://www.etsi.org/standards

[65] https://specifications.o-ran.org/specifications

[66] https://www.mdpi.com/1424-8220/24/3/1038#B4-sensors-24-01038

[67] Abeta, S.; Kawahara, T.; Umesh, A.; Matsukaw, R. *O-RAN Alliance Standardization Trends*; Technical Report; NTT DOCOMO: Kyoto, Japan, 2019. doi: https://www.docomo.ne.jp/english/binary/pdf/corporate/technology/rd/technical_journal/bn/vol21_1/vol21_1_006en.pdf

[68] https://openairinterface.org/

[69] OAI 5G RAN Project Group. Available online: https://openairinterface.org/oai-5g-ran-project/ (accessed on 29 October 2023).

[70] https://docs.srsran.com/projects/project/en/latest/knowledge_base/source/oran_gnb/source/index.html

[71] The srsLTE Project Is Evolving. Available online: https://www.srslte.com/srslte-srsran

[72] https://telecominfraproject.com/openran/

[73] Brown, G. TIP openRAN: Toward Disaggregated Mobile Networking; Technical Report; Heavy Reading: New York, NY, USA,

- ONAP (Open Network Automation Platform)[74]: Launched in 2017, ONAP provides an open-source platform to design and manage network services, automating 5G deployment through SDN and NFV technologies. It includes MANO functionalities aligned with ETSI's NFV architecture and is linked to the Open RAN movement via the SMO project75.
- SD-RAN[76]: Initiated in 2020 by the Open Networking Foundation (ONF), SD-RAN focuses on building open-source RAN components, especially the near-real-time RAN Intelligent Controller (RIC) and xApps. The project collaborates closely with O-RAN Alliance, TIP, and other organizations, with its first release, SD-RAN v1.0, debuting in 2021.

Standardization plays a crucial role in the O-RAN architecture, as the O-RAN Alliance has made significant strides in developing the Open RAN framework compared to other projects. The alliance has produced detailed reference design specifications, complete with clear documentation for each design. However, despite the thorough documentation, the O-RAN Alliance's software is often not robust, deployable, or well-documented enough for real-world network implementation. This limitation arises from several factors, including incomplete open-source components that require additional integration and development, as well as some components that lack the necessary robustness for actual deployment[77].

3.1.4.2 Telecom Infra Project (TIP)

The Telecom Infra Project (TIP) is an industry-wide collaboration that brings together telecom service providers, equipment manufacturers, technology vendors, and other key stakeholders with the common goal of transforming the telecom ecosystem through openness and interoperability. TIP aims to establish an open ecosystem by defining market requirements, fostering collaboration, and conducting rigorous interoperability testing for solutions from various vendors. This open approach is designed to accelerate innovation, reduce deployment costs, and enable more flexible, scalable network infrastructures.

To achieve its objectives, TIP focuses on creating open-source hardware and software designs that facilitate seamless interoperability between different network components. This approach allows telecom operators to mix and match equipment from multiple suppliers, reducing vendor lock-in and fostering a competitive landscape.

Within TIP, there are multiple specialized project groups, each working on different facets of open network architecture. For instance, the Open RAN group is focused on developing open and interoperable interfaces for the radio access network, while the Open Core Networks group explores open solutions for the core of the telecom network. Other project groups, such as Open Optical & Packet Transport and Open Automation, are dedicated to creating open standards for transport networks and automating network management, respectively. Together, these groups contribute to a flexible, modular, and resilient telecom infrastructure that can meet the demands of modern networks.

3.1.4.3 Linux Foundation Networking (LFN)

Linux Foundation Networking (LFN)[78] is a collaborative initiative under the Linux Foundation that unites open-source communities to develop and support platforms for software-defined networking (SDN) and network functions virtualization (NFV). LFN plays a key role in advancing Open RAN solutions, particularly through the Open Network Automation Platform (ONAP) project, which provides a unified platform for managing network services and resources across multiple domains, including Radio Access Networks (RANs).

2020; Available online: https://telecominfraproject.com/tip-openran-toward-disaggregated-mobile-networking/

[74] https://www.onap.org/architecture/use-cases-blue-prints

[75] ONAP 5G Blueprint Overview. Available online: www.onap.org/wpcontent/uploads/sites/20/2018/11/ONAP_CaseSolution_5G_112118FNL.pdf

[76] https://opennetworking.org/open-ran/

[77] Bonati, L.; Polese, M.; D'Oro, S.; Basagni, S.; Melodia, T. Open, Programmable, and Virtualized 5G Networks: State-of-the-Art and the Road Ahead. Comput. Netw. 2020, 182, 107516. Doi: https://doi.org/10.1016/j.comnet.2020.107516

[78] https://lfnetworking.org/

LFN collaborates closely with the O-RAN Alliance, with the O-RAN Software Community (OSC)[79] focused on creating open-source software specifically for RAN. This community aims to develop reference software components based on specifications from both 3GPP and the O-RAN Alliance. Additionally, the OSC Community Lab serves as a testing and integration facility, designed to accelerate the development and adoption of Open RAN solutions by offering a shared platform for software validation and testing.

3.1.4.4 Collaboration with Standards Developing Organizations (SDOs)[80]

The O-RAN architecture is fundamentally built upon the foundational architecture and protocols developed by 3GPP (3rd Generation Partnership Project), ensuring compatibility and alignment with established mobile network standards. O-RAN specifications reference 3GPP protocols extensively, creating a framework where interoperability and cohesion between different RAN components are prioritized. This alignment has facilitated an exchange of liaison statements between O-RAN and 3GPP, with specific examples like collaboration between O-RAN Working Group 10 (WG10) and 3GPP SA5 focusing on management aspects. These exchanges allow both groups to keep each other updated on work progress and seek alignment in areas where specifications overlap or require synchronization, ultimately supporting the broader ecosystem's standards and adoption.

Beyond 3GPP, O-RAN maintains relationships with other standardization bodies to address specialized areas of telecom standards. For instance, ITU (International Telecommunication Union) collaborates with O-RAN on synchronization standards, crucial for ensuring timing and coordination across networks. Similarly, ETSI (European Telecommunications Standards Institute) plays a pivotal role, particularly through initiatives like Zero-touch network and Service Management (ZSM) and Network Functions Virtualization (NFV), which complement O-RAN's objectives by promoting automation, virtualization, and efficient resource management within telecom networks.

One significant aspect of the O-RAN and ETSI relationship is O-RAN's participation in the ETSI Publicly Available Specification (PAS) process. Through this process, O-RAN submits its own specifications for official recognition and adoption by ETSI. After undergoing a thorough review by ETSI, these specifications may be published as official ETSI documents, granting them an additional layer of credibility and accessibility. An example of this collaboration is the publication of the "O-RAN Fronthaul Control, User, and Synchronization Plane Specification v7.02" as ETSI TS 103 859[81]. By making these documents public through ETSI, O-RAN aims to encourage widespread adoption of Open RAN standards and increase recognition among commercial and governmental entities across various regions. This also supports Open RAN's objective of achieving broad international acceptance and fostering an open ecosystem for RAN technology.

The O-RAN Alliance's success and broader acceptance would be strengthened by fully aligning its governance with the World Trade Organization's Technical Barriers to Trade (WTO/TBT) Principles for the Development of International Standards. By adhering to these principles, O-RAN would enhance openness in its processes, making participation more accessible to a wider range of industry stakeholders beyond operators. For example, broadening voting rights to include additional stakeholders would encourage a more diverse range of perspectives and contributions. Moreover, adopting these principles would promote greater consensus and impartiality in O-RAN's decision-making, reducing the influence of its five founding members—AT&T, China Mobile, Deutsche Telekom, NTT DOCOMO, and Orange. This shift would create a more democratic and inclusive governance structure, encouraging participation from a larger set of global stakeholders and enabling O-RAN to achieve more balanced, globally accepted standards.

Current Open RAN solutions are built upon the RAN architecture defined by 3GPP, with enhancements contributed by the O-RAN Alliance. Consensus across the mobile industry suggests that 3GPP will continue to lead in defining the 6G architecture, emphasizing the importance of a unified global standard for 6G. It is anticipated that the evolution of Open RAN will closely align with, and potentially integrate into, the 3GPP standardization path. According to the 3GPP development roadmap, formal 6G (IMT-

[79] https://o-ran-sc.org/

[80] https://6g-ia.eu/wp-content/uploads/2024/05/6g-ia-open-sns_open-networks-status-and-future-development_ran-final.pdf

[81] https://www.etsi.org/deliver/etsi_ts/103800_103899/103859/12.00.01_60/ts_103859v120001p.pdf

2030) standardization efforts are expected to commence around 2025, while significant research is already underway to identify 6G use cases, requirements, and foundational architectural principles. The O-RAN Alliance has also initiated pre-6G study efforts, providing the industry with a platform to explore technical evolution paths and reach early consensus on critical 6G enablers.

3.1.4.5 Spacetime and O-RAN Interfaces for 5G/6G Non-Terrestrial Networks (NTNs)

The Spacetime[82] and O-RAN Interfaces for 5G/6G NTNs project shown in Figure 3-3, led by Aalyria in partnership with the European Space Agency (ESA), aims to create an advanced platform for managing Non-Terrestrial Networks (NTNs) in alignment with 5G and future 6G network standards. This project seeks to enhance O-RAN (Open Radio Access Network) interfaces to support NTNs, which include satellite constellations in both geostationary (GEO) and non-geostationary (NGSO) orbits, as well as High Altitude Platform Systems (HAPS). By adapting Aalyria's existing Spacetime orchestration platform, the project will develop flexible management solutions to accommodate the unique needs of NTN deployments.

The primary objective of this initiative is to extend network orchestration capabilities for NTNs by modifying O-RAN interfaces to manage and optimize satellite-based connectivity. The project will enable enhanced network planning, capacity management, and coverage expansion for both terrestrial and non-terrestrial operators. Additionally, Spacetime will support more effective spectrum sharing, enabling operators to leverage HAPS and satellite resources within the RAN (Radio Access Network) without requiring data to flow through third-party networks. This approach also aims to address key challenges such as platform mobility, steerable beam directionality, and efficient resource management.

The Spacetime platform integrates the Non-Real time RAN Intelligent Controller (Non-RT RIC) and Service Management and Orchestration (SMO) layer, core elements in the O-RAN 5G architecture. These components allow Spacetime to handle resource management tasks such as interference mitigation, traffic routing, and radio resource control through applications (xApps and rApps) that provide intelligence at various network layers. This architecture is designed to support the specific needs of NTN deployments, including adapting to satellite motion, managing directional beams, and ensuring effective signal propagation across non-terrestrial networks.

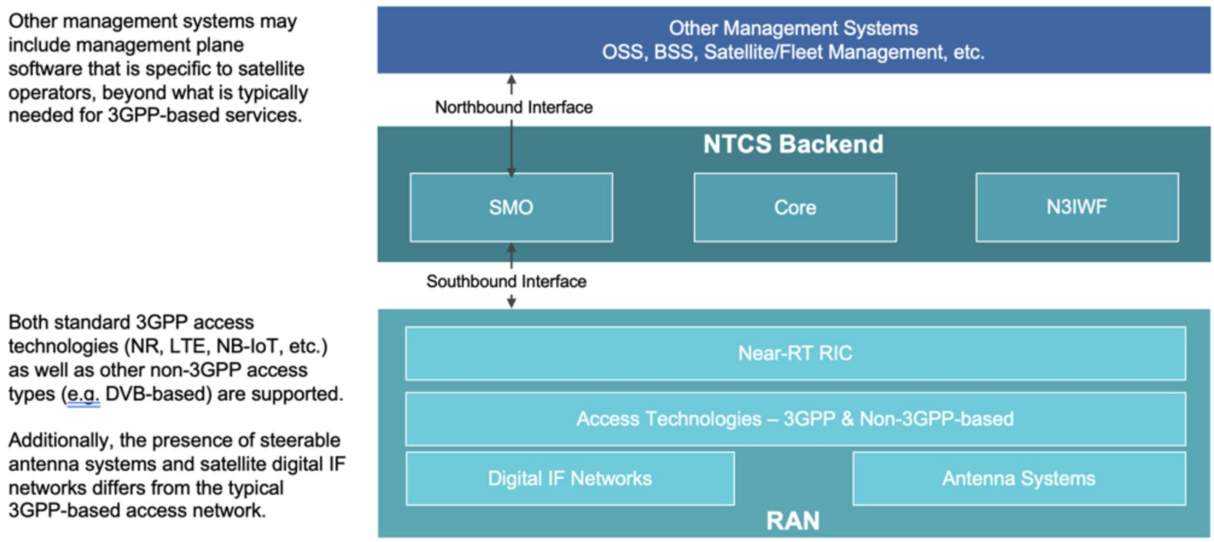

Figure 3-3 System architecture of RAN components and other management systems (ESA).

The project is scheduled to progress through key milestones in 2024:

- Early 2024: Publish proposed changes to O-RAN interfaces to meet Non-Terrestrial Connectivity Solution (NTCS) requirements.

[82] https://connectivity.esa.int/projects/spacetime-and-oran-interfaces-5g6g-ntns

- Mid-2024: Update Spacetime software to integrate with draft 5G/6G O-RAN interfaces.
- Late 2024: Finalize the integration of simulation tools and enhanced ML-based solvers to improve network orchestration for NTN environments.

The integration of NTNs within 5G and future 6G networks through open interfaces will have wide-reaching impacts, expanding connectivity options for industries and applications worldwide. This project supports use cases from global transportation and logistics to rural connectivity, environmental monitoring, and emergency response. By enabling open standards and fostering interoperability, the Spacetime platform seeks to drive broader NTN adoption and streamline the convergence of terrestrial and non-terrestrial networks. The collaboration with industry leaders, such as GSMA, TIP, and the O-RAN Alliance, is expected to influence the development of standardized frameworks for future network infrastructure, enhancing connectivity and operational resilience on a global scale.

3.2 Standardizations for NTN

Non-Terrestrial Networks (NTN) refer to communication networks that involve spaceborne or airborne platforms, as opposed to traditional terrestrial networks, which rely on land-based infrastructure like cell towers and cables. NTNs utilize satellites, drones, high-altitude platforms (HAPS), or other aerial systems to provide connectivity, especially in remote or under-served areas where traditional infrastructure may not be viable.

Key components of NTN include:

- Satellites: Often in low-earth orbit (LEO) or geostationary orbit (GEO), providing global or regional coverage for broadband, IoT, or other communication services.
- High-Altitude Platforms (HAPS): Aircraft or balloons that operate in the stratosphere to serve as communication hubs.
- Air planes, either commercial or non-commercial airplanes
- Drones: UAVs equipped with communication equipment to provide temporary or emergency coverage in specific regions.

NTNs are increasingly important for connecting hard-to-reach areas, providing communication in disaster zones, or supporting maritime and aeronautical applications. They are also part of evolving 5G standards to ensure global connectivity. There are tremendous sources for description of NTN, among others white-papers from vendors, 5G Americas, ITU-T, ETSI, IEEE and 3GPP specifications.

For the concept of MECON, we mostly consider 3GPP technical study and specifications[83], as 3GPP has been working on the standardization of NTN as part of its 5G and beyond specifications.

3.2.1 3GPP[84]

TR 38.811 - Study on Non-Terrestrial Networks (Release 15)[85]
This is a technical report that provides a feasibility study on integrating NTNs into 5G networks. It explores potential architectures, deployment scenarios, and the challenges specific to non-terrestrial platforms like satellites.

Focus Areas:
- Use of satellite or airborne platforms for providing 5G connectivity.
- Coverage considerations, delay, Doppler shifts, and radio propagation challenges.
- Potential NTN deployment scenarios such as low-earth orbit (LEO), medium-earth orbit (MEO), and geostationary orbit (GEO) satellites.

TR 38.821 - Solutions for NR to Support Non-Terrestrial Networks (Release 16)[86]

[83] https://www.3gpp.org/dynareport?code=38-series.htm
[84] https://www.3gpp.org/technologies/ntn-overview
[85] https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3234
[86] https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3525

This technical report examines solutions for New Radio (NR), which is 5G's air interface, to support NTNs. It discusses the necessary changes in physical layer design, system architecture, and protocols to adapt 5G NR for satellite and other non-terrestrial environments.

Focus Areas:
- Physical layer adaptations for NTNs.
- Protocol adjustments for handling delays and Doppler shifts.
- NTN channel modeling and beam management.

TS 38.211[87], TS 38.212[88], TS 38.213[89], TS 38.214[90], TS 38.331[91] - 5G NR Specifications for NTN (Release 17)
These are technical specifications that detail how 5G NR works, including NTN-specific adjustments introduced in Release 17. These specifications define the physical layer (radio) protocols, resource allocation, scheduling, and modulation schemes for NR with a focus on NTN use cases.

Key Standards:
- **TS 38.211**: Physical channels and modulation.
- **TS 38.212**: Channel coding and multiplexing.
- **TS 38.213**: Physical layer procedures for control.
- **TS 38.214**: Physical layer procedures for data.
- **TS 38.331**: Radio Resource Control (RRC) protocol.

TR 22.822 - Study on using Satellite Access in 5G (Release 16)
This study investigates how satellite access can be incorporated into the 5G ecosystem, addressing use cases like broadband communication in remote areas, global service continuity, and IoT.

TR 38.821 - Study on IoT over NTN (Release 17)[92]
This document addresses the use of NTNs for supporting IoT services, exploring the applicability of NTNs to massive IoT use cases. It focuses on Low Power Wide Area (LPWA) networks, latency, coverage, and other requirements specific to IoT. These documents, especially the ones in Release 15, 16, and 17, set the foundation for integrating NTNs into the 5G network framework, dealing with challenges like latency, Doppler effect, and the characteristics of space-based communication.

3.2.2 ITU

The ITU (International Telecommunication Union) plays a key role in standardizing Non-Terrestrial Networks (NTN), particularly in supporting the integration of satellite and high-altitude platforms into 5G and beyond. Some important ITU standardization documents related to NTN include: The following links are available to the ITU documents related to **Non-Terrestrial Networks (NTN)**:

- **ITU-R M.2178[93]**: Guidelines for satellite network planning, including spectrum requirements for NTNs.

- **ITU-R S.1503[94]**: Methodologies for assessing interference between NTNs and terrestrial services.

- **ITU-R M.2101[95]**: Operational characteristics and performance objectives for NTNs in mobile networks.

[87] https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3213
[88] https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3214
[89] https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3215
[90] https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3216
[91] https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3197
[92] https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3525
[93] https://www.itu.int/pub/R-REP-RS.2178
[94] https://www.itu.int/dms_pubrec/itu-r/rec/s/R-REC-S.1503-2-201312-S!!PDF-E.pdf
[95] https://www.itu.int/dms_pubrec/itu-r/rec/m/R-REC-M.2101-0-201702-I!!PDF-E.pdf

- **ITU-R M.1643**[96]: Use of satellite networks to complement terrestrial mobile systems.
- **ITU-T Y.3207**: Architectures for the integration of NTNs within the 5G ecosystem, emphasizing network control and management.

3.2.3 ESA

The European Space Agency (ESA) is positioning itself as a key leader in the development of 6G satellite technology[97], guiding its industrial partners through the transition from 5G to 6G in a seamless, secure, and sustainable manner. Through its Advanced Research in Telecommunications Systems (ARTES 4.0) program, ESA aims to collaborate with industry players dedicated to building satellite technologies and applications powered by 6G. ESA's vision includes unifying data architectures across terrestrial and non-terrestrial networks to establish versatile, resilient satellite connectivity. Figure 3-4 shows the 5G and 6G standardization roadmap.

As part of its Space for 5G/6G and Sustainable Connectivity Strategic Programme Line, ESA is preparing to launch the first 6G-enabling satellite, providing a critical space-based testbed for European industries. This testbed will allow terrestrial partners to conduct real-world experiments in a 6G laboratory environment in orbit, fostering early-stage research and development. ESA views this initiative as an open innovation platform where researchers and industry experts can collaborate to better understand 6G technology before its full roll-out. Figure 3-5 presents the 6G roadmap elements.

ESA's program promotes the creation and validation of hybrid networks that fully integrate satellites into terrestrial telecommunication infrastructures. By supporting upstream and downstream industry partners, ESA aims to strengthen the European economy through new 6G applications and solutions. Just as it guided 5G standardization, ESA will continue leading the space industry in developing satellites, networks, and applications to achieve the goals of 6G connectivity.

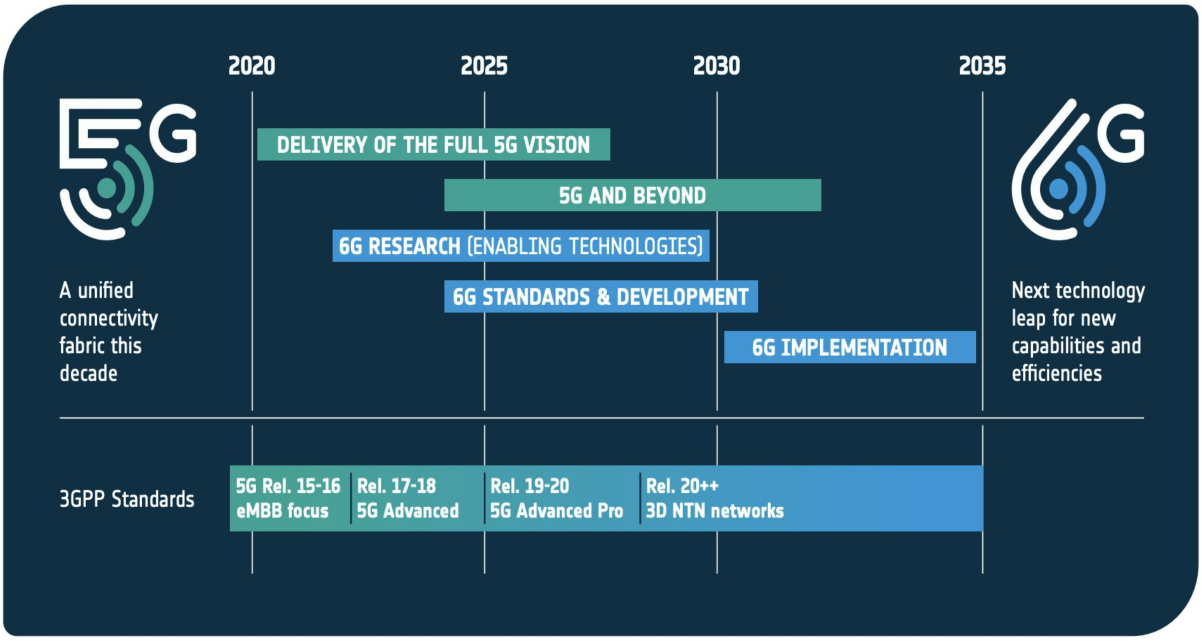

Figure 3-4: 5G and 6G standardisation roadmap.

[96] https://www.itu.int/dms_pubrec/itu-r/rec/m/R-REC-M.1643-0-200306-I!!PDF-E.pdf
[97] https://connectivity.esa.int/sites/default/files/ESA_6G_White%20Paper_Dev_Proof_V14..pdf

Figure 3-5:6G roadmap elements[98].

[98] https://connectivity.esa.int/sites/default/files/ESA_6G_White%20Paper_Dev_Proof_V14..pdf

4 Conclusion

This deliverable underscores the MECON project's role in pioneering integrated digital connectivity solutions for 5G and 6G, particularly by expanding high-speed, resilient coverage to rural and under-served regions through advanced Open RAN and NTN integration. In this deliverable we provide the state-of-the -art technologies towards next generation broadband technologies such as Open RAN, and NTN. By assessing the current technological landscape and laying the groundwork for future innovations, MECON addresses essential requirements for radio resource management, scalable backhaul, and cross-network integration.The findings highlight the potential of combining Open RAN with Non-Terrestrial Networks to support new applications across agriculture, aviation, maritime, and remote industry sectors. With contributions to standards from organizations like 3GPP, ITU, IEEE, TIP, LNF, and ESA, MECON aligns with global regulatory frameworks to create a cohesive approach to advanced connectivity.This report provides a comprehensive roadmap for future development, with a focus on AI-enabled RRM, sustainable architectures, and adaptable platform designs that ensure efficient use of NTN Open RAN payloads. By bridging digital divides, MECON's work supports the broader vision of inclusive, ubiquitous digital connectivity in the 6G era. Continued collaboration among industry stakeholders, technology developers, and policy makers will be essential to realize these goals and fully leverage the Open RAN-NTN convergence for resilient global connectivity solutions. Future deliverables will include the ICT gaps of the existing infrastructure and dynamic RAN sharing for NTN systems.