

A 5G AMERICAS WHITE PAPER

3GPP TECHNOLOGY TRENDS

JAN 2024



Contents

1. Introduction	3
2. Release-17 and the Journey Toward 5G-Advanced	5
2.1 Progress and Roadmap of 5G and 5G-Advanced: Advancing Connectivity and Standardization	5
2.2 Summary of Rel-17 Network and Device Enhancements	5
2.3 New Network and Device Features in 3GPP Rel-17	6
2.4 Security Enhancements and Features in Release 17	7
3. Key Technology Use Cases in 5G-Advanced	9
3.1 Metaverse Evolution	9
3.2 RedCap	12
3.3 Integrated Communication and Sensing (ICAS)	13
3.4 Ambient IoT	15
4. Artificial Intelligence (AI) and Machine Learning (ML) for 3GPP-Based Wireless Networks	17
4.1 Overview of AI/ML in 3GPP	17
4.2 Life-cycle Management of an AI/ML Functionality	19
4.3 Trustworthy AI.....	20
5. Spectrum and Air Interface in 3GPP.....	21
5.1 FR3 Spectrum Deployment for 5G-Advanced: Challenges and Solutions	21
5.2 Carrier Aggregation and Air Interface.....	22
6. Sustainable Development	26
6.1 Enhancing Energy Efficiency in the RAN	26
6.2 Energy Consumption as Performance Criterion for Best-Effort Communication and Support of Energy Related SLAs.....	27
6.3 Exposure of Energy Consumption and Efficiency Information	27
Conclusion	29
Appendix	30
Acknowledgements.....	32
References.....	33

1. Introduction

In the ever-evolving realm of telecommunications, the 3rd Generation Partnership Project (3GPP) plays an important role in the innovation and progress of connectivity and communication in an interconnected world. While 5G networks have already started a transformative journey for many people worldwide, members within 3GPP tirelessly dedicate themselves to elevating these networks to even greater heights with the development of 5G-Advanced. 5G-Advanced, the natural successor to 5G, heralds an extraordinary evolution in our connectivity experience. With faster data speeds, reduced latency, and ultra-reliability, 5G-Advanced promises to unlock a vast array of opportunities for industries, consumers, and the broader ecosystem. This white paper ventures deep into the core of 5G-Advanced, shedding light on the pivotal technologies, features, and use cases that will define the forthcoming era of wireless communication.

In June 2022, 3GPP Release (Rel)-17 was introduced, heralding significant enhancements to existing applications, complementing the advancements in data speeds, reduced latency, and ultra-reliability. These encompass Multiple In Multiple Out (MIMO) for 5G New Radio (NR), Improved Uplink Coverage, Enhanced Sidelink Communications, Positioning Enhancement, UE Power Saving, Ultra-Reliable Low Latency Communications (URLLC)/Industrial Internet of Things (IIoT) Enhancements, Integrated Access and Backhaul (IAB), and Non-Terrestrial Networks (NTN). These enhancements collectively propel the comprehensive development of 5G networks, driving progress in areas like MIMO technology, power efficiency, communication reliability, positioning capabilities, and support for non-terrestrial networks. Moreover, the expansion of spectrum utilization designed to enhance coverage has contributed to the emergence of a more versatile and efficient 5G ecosystem with 3GPP Rel-17. 5G NR introduces key features that enhance the network's capabilities and functionalities, making 3GPP Rel-17 a pivotal milestone in the evolution of cellular networks. Throughout the paper, we will use the term NR Rel-17, 3GPP Rel-17, and Rel-17 interchangeably.

The evolution of 3GPP technology trends continues with Rel-18, exploring cutting-edge topics such as the metaverse. The metaverse is a dynamic concept in the realm of digital technology, offering immersive digital experiences that seamlessly interconnect people, places, objects, and information in real time, transcending the constraints of the physical world. In addition to the metaverse, RedCap (Reduced Capability) devices were also initially introduced in 3GPP Rel-17, which supports diverse use cases and lays the foundation for additional specification work on NR RedCap. This work includes applications like wearables (e.g., smartwatches, wearable medical devices, augmented reality (AR)/VR goggles, industrial wireless sensors, and video surveillance). Planned enhancements for RedCap devices in 3GPP Rel-18 aim to improve these features and expand into new realms, including smart grid technology. 3GPP Rel-18 also delves into features like joint communication and sensing (JCAS), integrating communication and sensing functionalities within the same system or network.

Where ML (machine learning) coverage was expanded to provide descriptions of principles for Radio Access Network (RAN) intelligence enabled by ML in Rel-17, Rel-18 extends specifications for AI/ML into the new radio air interface. The focus on this area of the air interface, specifically addresses ML solutions that require interactions between network infrastructure and user equipment. Future AI/ML use cases will be addressed in the air interface, RAN, and system architecture in Rel-19. As we approach Rel-20, 6G will be studied with AI/ML as an integral component of the system. Advanced technologies such as distributed learning, in conjunction with deeply embedded AI, will significantly boost performance and usability, marking 6G as the first generation of data-driven mobile networks.

As 3GPP technology trends continue to evolve, spectrum and sustainability also take center stage. Spectrum remains a critical necessity, with new spectrum bands holding the promise of not only enabling innovative applications but also enhancing the capabilities of existing ones within the realm of 5G-Advanced. The spectrum allocated for 5G-Advanced cellular deployments, often occupying the upper midbands from 7.125 GHz to 24.25 GHz, possesses key advantages such as substantial bandwidth and suitability for extensive geographical coverage. This designated “FR3” spectrum, highlighted in this whitepaper, shows promise for enhancing positioning and sensing capabilities.

Finally, 3GPP recognizes the importance of addressing climate change by paying careful attention to the United Nations Sustainable Development Goals. 3GPP diligently works on standards related to energy efficiency, resource efficiency, circularity, and social responsibility. This comprehensive approach underscores the commitment of 3GPP to lead global technology trends while innovating on connectivity, systems, and various modes of communication. Their approach has broad impacts on minimizing resource usage, limiting the environmental effects of network operations, and increasing global resource efficiency.

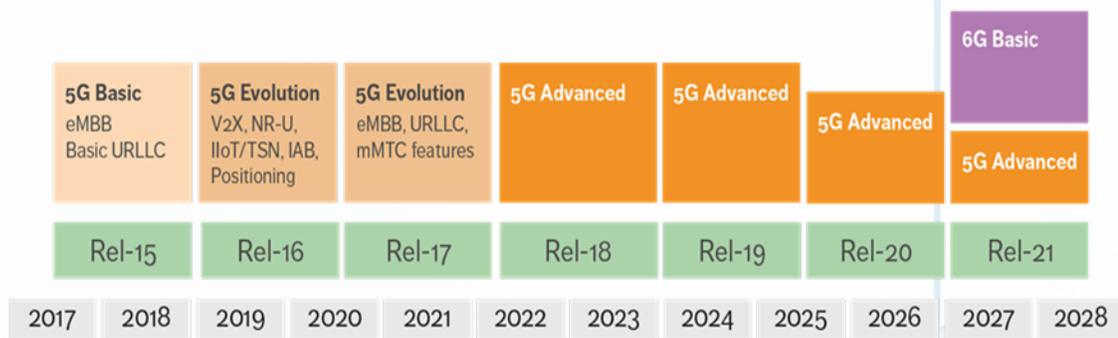
2. Release-17 and the Journey Toward 5G-Advanced

2.1 Progress and Roadmap of 5G and 5G-Advanced: Advancing Connectivity and Standardization

5G has emerged as a transformative technology, revolutionizing connectivity, and enabling a wide range of innovative services. To further advance the capabilities of 5G, 3GPP has introduced a new demarcation, namely 5G-Advanced, which encompasses new planned 3GPP releases from Rel-18 onwards. This evolution builds upon the foundation established in previous releases, introducing new enhancements and capabilities to propel 5G networks even further.

The progress of 5G and 5G-Advanced development results from collaborative efforts and standardization within 3GPP¹. A diverse group of stakeholders, including network operators, equipment manufacturers, technology providers, and vertical industry partners, have worked together to develop a unified and globally accepted standard. The goal has been to ensure interoperability, scalability, and futureproofing of 5G networks.

Figure 1. 5G evolution toward 5G-Advanced: An Overview of 3GPP



With the parallel workflow system adopted by 3GPP, multiple releases are simultaneously under development. For 5G-Advanced, the plan is to span multiple releases, starting with Rel-18 as the first target release. Scoping in the Radio Access Network (RAN) for Rel-18, specifically for 5G-Advanced, began in the second half of 2021, with the core specification expected to be completed by the end of 2023. This timeline does not include the performance part in RAN4 or the UE conformance testing specification work that follows in RAN5.

2.2 Summary of Rel-17 Network and Device Enhancements

3GPP Rel-17 brings major enhancements to existing applications, complementing the previously mentioned enhancements. These include:

- **MIMO for NR:** Further improvements in MIMO for NR to enhance spectrum efficiency and wireless communication robustness. Techniques introduced in Rel-17 include a unified transmission configuration indicator (TCI) framework, multi-TRP (transmission reception point) transmission, sounding reference signal (SRS) enhancements, and optimization for high-speed communications like high-speed trains.
- **Improved Uplink Coverage:** Enhancements to uplink control and data channels, utilizing techniques such as enhancement repetitions, demodulation reference signal (DMRS) time domain bundling, and uplink data transport block distribution over multiple slots.
- **Enhanced Sidelink Communications:** Power-saving measures and reliability improvements for sidelink communications. Such improvements include partial sensing, discontinuous reception (DRX) enhancement, inter-UE coordination, sidelink DRX for broadcast/groupcast/unicast, and support for sidelink relay.

- **Positioning Enhancement:** Rel-17 focuses on improved positioning accuracy in horizontal and vertical dimensions, lower latency with shortened request and response, and improved efficiency at the network and device levels.
- **UE Power Saving:** Power-saving enhancements for both idle and connected modes. These power-saving enhancements include reduced paging false alarm rate, active bandwidth part (BWP) extension with physical downlink control channel (PDCCH) skipping, relaxed radio link monitoring (RLM) measurements, and various power-saving improvements specified in Rel-16.
- **URLLC/IIoT Enhancements:** Enhanced Hybrid Automatic Repeat Request Acknowledgment (HARQ-ACK) feedback for Semi-Persistent Scheduling (SPS) HARQ-ACK deferral, type3 HARQ-ACK, and Physical Uplink Control Channel (PUCCH) cell switch. Rel-17 extends URLLC operations in the unlicensed band and supports multiplexing behavior among HARQ-ACK/SR/Channel State Information (CSI) and PUSCH for different traffic priorities. Propagation delay compensation enhancements are introduced for timing-sensitive networks.
- **Integrated Access and Backhaul (IAB):** Enhancements to IAB in Rel-17 enable flexible and dense deployment of NR cells while reducing the need for wireline transport infrastructure. These enhancements improve robustness, load balancing, spectral efficiency, multi-hop latency, and end-to-end performance.
- **Non-Terrestrial Networks (NTN):** Rel-17 specifies enhancements for NTN, particularly for long propagation delays, large Doppler effects, and moving cells in non-terrestrial networks like Low Earth Orbit (LEO) and Geosynchronous Earth Orbit (GEO). Implicit compatibility is included to support scenarios involving high-altitude platform stations (HAPS) and air-to-ground (ATG) communications.

These enhancements in 3GPP Rel- 17 contribute to the comprehensive development of 5G networks, providing advancements in various areas such as MIMO, coverage, power efficiency, communications reliability, positioning, and support for non-terrestrial networks.

2.3 New Network and Device Features in 3GPP Rel-17

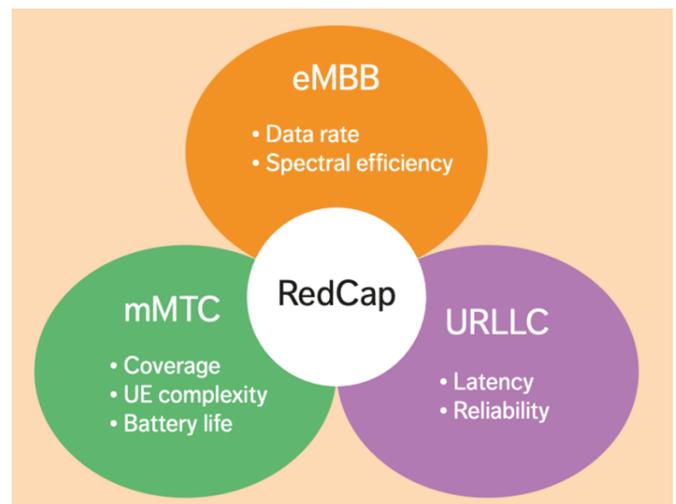
NR Rel-17 brings significant advancements to the 5G landscape, introducing a range of key features that enhance the capabilities and functionalities of the network. These features aim to address evolving industry requirements, enable new use cases, and extend the reach of 5G technology. From expanded spectrum utilization to improved coverage and specialized device capabilities, NR Rel-17 sets the stage for a more versatile and efficient 5G ecosystem. Let us explore some of the key features that make NR Rel-17 a pivotal milestone in the evolution of cellular networks.

Key Features of NR Rel-17:

- **Extended Spectrum Range:** NR Rel-17 extends the operational spectrum of NR, enabling operation above 52.6 GHz up to 71 GHz. This expansion unlocks new licensed and unlicensed frequency bands, facilitating greater spectrum availability for 5G deployments.
- **Reduced Capability NR Devices:** The 3GPP-based global cellular networks are experiencing widespread adoption, connecting various industries, and enabling communication between things-to-things and things-to-persons across borders. With the flexibility and scalability of 5G NR, timely enhancements can be introduced to address new use cases and expand the 5G ecosystem, connecting an ever-growing number of devices to the network. Industries such as consumer electronics, automotive, railway, mining, utilities, healthcare, agriculture, manufacturing, and transportation are benefiting from cellular Internet of Things (IoT).

3GPP Rel-17 introduces support for reduced capability (RedCap) NR devices to further accelerate industrial transformation and digitalization. These devices cater to use cases not adequately served by current NR specifications. RedCap bridges the gap between the relaxed requirements of massive machine-type communication (mMTC) and the stringent requirements of ultra-reliable low-latency communications (URLLC), as depicted in Figure 2.

Figure 2. Rel-17 RedCap addresses needs that fall between eMBB, mMTC, and URLLC for 5G NR.



Rel-17 expands the range of use cases for NR by introducing support for RedCap UE². RedCap UE provides performance comparable to Rel-8 LTE UE but offers additional benefits, such as improved latency and the ability to operate in NR frequency bands up to 52GHz. RedCap UEs are designed to be less complex than regular NR UEs, featuring a reduced number of radio receiver (RX) antenna branches, reduced RX and radio transmitter (TX) bandwidth, and operating in half-duplex mode. This reduced complexity is expected to result in a more affordable device price point,

supporting the use of NR in new applications like industrial sensor networks. Additionally, supporting a single antenna branch enables more compact device form factors, which is crucial in popular wearable applications such as smartwatches.

- **Enhanced Dynamic Spectrum Sharing:** NR Rel-17 improves Dynamic Spectrum Sharing (DSS) technology, enhancing the simultaneous operation of 4G LTE and 5G NR networks in the same frequency band. The enhancements optimize spectrum resource utilization and enable more efficient and flexible sharing of frequencies.
- **Enhanced Uplink Coverage:** NR Rel-17 incorporates enhancements to improve uplink coverage, ensuring reliable connectivity in challenging environments. These improvements extend the reach of uplink transmission, enhancing the overall user experience.
- **Multi-SIM Devices:** NR Rel-17 introduces support for multi-SIM devices, accommodating multiple SIM cards. This feature offers users flexibility in choosing different network operators or services and enables seamless switching between networks.
- **Advanced Side-link Communications:** Rel-17 enhanced the capabilities of side-link communications, facilitating efficient and reliable direct communication between nearby devices. These enhancements support device-to-device coordination, proximity-based services, and collaborative use cases.
- **Small Data Transmission (SDT) Capabilities:** NR Rel-17 focuses on optimizing the transmission of small data packets, improving efficiency and reliability. These capabilities cater to Internet of Things (IoT) applications, sensor networks, and other use cases involving frequent transmission of small data payloads.
- **Broadcast/Multicast Services within NR:** Rel-17 enables the delivery of broadcast and multicast services using the NR technology. This feature efficiently delivers content such as live TV, over-the-air software updates, and Internet of Things (IoT) solutions to many users simultaneously.
- **Support for Non-Terrestrial Networks:** The introduction of Non-Terrestrial Networks (NTN) in Rel-17 brings significant advancements to the 3GPP specifications. These networks utilize high-altitude platforms, low Earth orbit (LEO) satellites, and geosynchronous orbit satellites to expand network coverage in remote areas where terrestrial networks are absent. NTN works in conjunction with NR, Narrowband-Internet of Things (NB-IoT), and LTE for Machine Type Communication (LTE-M), enabling the implementation of NTN-based Mobile Broadband (MBB) and massive IoT services from Rel-17 onwards.

Building upon earlier studies conducted in Rel-15 and Rel-16, Rel-17 addresses the specific challenges associated with NTN. These challenges primarily revolve around the mobility and orbital height of satellites. The high altitude increases path loss and larger round-trip time (RTT). In the case of LEO satellites, their mobility introduces a significant

Doppler offset on the radio link and necessitates frequent changes in serving nodes for all devices involved. Rel-17 introduces fundamental mechanisms and specifications that support NTNs based on NR, NB-IoT, and LTE-M technologies to tackle these challenges.

The inclusion of NTN in Rel-17 enhances network capabilities and opens new possibilities for global connectivity. By utilizing high-altitude platforms, LEO, and geosynchronous orbit satellites, NTN offers network coverage in areas beyond the reach of traditional terrestrial networks. This development paves the way for improved mobile broadband services and enables seamless connectivity for a wide range of IoT devices. As the 3GPP continues to evolve and expand its specifications, Rel-17 is a significant milestone in bridging the gap between terrestrial and non-terrestrial networks.

NR Rel-17 represents a significant leap forward in the evolution of 5G, introducing a host of features that enhance the network's capabilities and expand its applicability across various industries and use cases. From extending the spectrum range to introducing specialized devices and optimizing data transmission, NR Rel-17 empowers the 5G ecosystem to address emerging needs and connect an ever-growing number of devices. These advancements pave the way for a more versatile, efficient, and inclusive 5G landscape, fueling digital transformation and innovation across sectors.

2.4 Security Enhancements and Features in Release 17

Rel-17 brought forth a comprehensive array of cutting-edge enhancements and features aimed at bolstering the security of end-to-end networks. Key security enhancements and features introduced in this release encompass:

- **User Plane Integrity Protection:** User plane, handling data traffic like web browsing and video streaming, is now fortified with integrity protection. This security measure enables base stations and mobile devices to ascertain whether received messages have been tampered with by malicious actors. While User Plane Integrity Protection was initially integrated into 5G during Rel-15 for standalone deployments (Option 2), Rel-17 extends this protection to the deployment options involving 4G core over LTE and NR radios (Options 1 and 3), offering a choice to CSPs for activation.
- **Security for 5G Proximity-Based Services:** Typically, mobile phone traffic traverses the network, but proximity-based services facilitate direct communication between mobile devices in close proximity, enabling device-to-device connectivity.

Rel-17 standardizes these services for 5G New Radio (NR) and concurrently introduces security mechanisms to safeguard the discovery of mobile devices and the ensuing communications between them.

- **Security for Industrial IoT:** As 5G caters to diverse use cases, including Industry 4.0, the need for deterministic communication is paramount. Rel-17 enhances support for time-sensitive networking (TSN), ensuring precise packet delivery timings. Additionally, it fortifies the 5G system with robust time synchronization and time-sensitive communication (TSC) mechanisms, including secure interfaces, authentication, and authorization.
- **Protection Against False Base Stations:** False base stations pose a significant security threat in radio access networks. Rel 17 undertakes a comprehensive study to mitigate security and privacy issues arising from these fraudulent stations. While final solutions are pending, a new protection mechanism for safeguarding mobile phone capabilities has been swiftly integrated into industry standards.
- **3GPP Security Assurance Specifications:** Rel-17 introduces new security assurance specifications to encompass a wider range of Network Functions (NFs). These include Service Communication Proxy (SCP), 5G Network Data Analytics Function (NWDAF), Non-3GPP InterWorking Function (N3IWF), and Network Slice-Specific Authentication and Authorization Function (NSSAAF).
- **Non-Public Networks (NPN) Access:** Rel-17 enhances Standalone Non-Public Networks (SNPNs) by enabling User Equipment (UE) access using external credentials (e.g., from a public network or another SNPN), facilitating SNPN UE onboarding, and ensuring support for emergency services.
- **Mission Critical Security Phase 2:** Building on previous releases, Rel-17 introduces Mission Critical security enhancements in Phase 2. This comprehensive security architecture encompasses confidentiality, integrity, user authentication, service authorization, and overall security for Mission Critical services, including Mission Critical Push-to-Talk (MCPTT), MCVideo, MCData, MC Location, MC Interworking, MC Interconnection, and MC Railway, with further clarifications and corrections provided in TS 33.180: Security of the Mission Critical (MC) service Rel-17.

In a nutshell, Release 17 has introduced substantial security enhancements and features to fortify end-to-end network communication. Next, we will delve into Release 18 and explore its significant developments. We will discuss key use cases, such as the metaverse and other emerging communication scenarios. Additionally, we will touch upon the integration of AI/ML, highlighting their transformative potential in shaping the future of network technology and communication systems.

3. Key Technology Use Cases in 5G-Advanced

In this section, four elements of 5G-Advanced Use Cases are explored: Metaverse, Extended Reality (XR), Reduced Capability (RedCap), Integrated Sensing and Communication (ISAC), and Ambient Internet of Things (IoT). This examination will illuminate recent advancements, industry standards, and emerging technologies, offering a comprehensive understanding of both the current state and the future direction of this field.

3.1 Metaverse Evolution

The metaverse is a dynamic and evolving concept in the realm of digital technology, characterized by its capacity to transcend strict definitions. It represents a partial or fully immersive digital networked experience that seamlessly interconnects people, places, objects, and information in real time, going beyond the confines of the physical world. At its core, the metaverse holds vast potential to augment the human experience, impacting social interactions, healthcare, education, gaming and creating new avenues for business through virtual economies and currencies³.

Originating from Neal Stephenson's "Snow Crash" and gaining prominence with Meta's vision, the metaverse is a social phenomenon, emphasizing deeply immersive social interactions where avatars engage on a human level, facilitating eye contact, body language, and even physical gestures.⁴ Its virtual narrative can manifest primarily in the digital realm, as seen in VR experiences like Fortnite, or it can integrate with the physical world, employing AR and mixed reality (MR) to overlay digital content. In fact, from a 3GPP viewpoint, the "mobile metaverse" is defined as the user experience enabled by the 5G (and beyond) system of interactive and/or immersive eXtended Reality (XR) media, including haptic media.

As such, the metaverse experience is accessible through a variety of XR /3D devices or conventional 2D screens using WebXR technologies. The metaverse's essence lies in its ability to transform our digital interactions and experiences, promising to reshape the way we live, work, and connect in the modern age.

Within the cellular realm and the framework of 5G-Advanced networks, the metaverse finds a transformative platform enabled by a suite of XR services and the concept of digital twins. These technologies, poised to redefine our digital interactions, play pivotal roles in seamlessly connecting us to the metaverse, offering immersive experiences and bridging the gap between the physical and digital worlds. Essentially, XR technologies, encompassing VR, MR, and AR, are driving innovation across various sectors, from entertainment and gaming to education and healthcare. Their ability to blend digital content with our immediate surroundings relies on the capabilities of cellular networks, the evolution of today's 5G network and next-generation networks providing ultra-low latency, high bandwidth, and dependable connectivity for enhanced metaverse interactions. In fact, 3GPP dedicates a comprehensive study to the localized metaverse, scrutinizing use cases and key solutions for this exciting digital frontier.

In this exploration, we will first delve into the world of XR, examining their key challenges and solutions proposed by 3GPP, we will then shed light on novel RAN enhancements proposed by 3GPP. We will finally conclude with an important use case on spatial mapping that acts as a bridge between tomorrow's metaverse and XR as well as the network's distributed sensing and communication capabilities.

3.1.1 XR Evolution: Key Challenges

This discussion will first address the XR challenges from a 3GPP lens. These challenges encompass a wide range of complexities, from optimizing policy control and data synchronization to ensuring low latency and power efficiency in XR applications over cellular networks.

Coordinated Transmission for Multi-Modality Flows: Delivering XR experiences involves various data flows within a single UE, such as video, audio, haptic, and sensor data. Ensuring these related data streams are delivered simultaneously to enhance the immersive experience presents a policy control challenge. Such challenges relate to QoS policy coordination, policy control for application synchronization, and interaction between the Application Function (AF) and 5G System (5GS) for seamless coordination.

Multi-Modal Traffic Synchronization and QoS Coordination: Achieving synchronization and QoS policy coordination is paramount for multi-modal communication sessions across multiple UEs. This challenge involves delivering related tactile and multi-modal data (e.g., audio, video, haptic) to users at similar times. It necessitates QoS policy coordination and interaction between AF and 5GS to ensure synchronization and coordination among multiple UEs. Moreover, Table 1 showcases the typical QoS requirements that must be fulfilled so that the user's quality of experience (QoE) is met.

Table 1. Typical QoS requirements for multi-modal streams

	Haptics	Video	Audio
Jitter (ms)	≤2	≤30	≤30
Delay (ms)	≤50	≤400	≤150
Packet loss (%)	≤10	≤1	≤1
Update rate (Hz)	≥ 1000	≥ 30	≥ 50
Packet size (bytes)	64 - 128	≤ MTU	160 - 320
Throughput (kbit/s)	512 - 1024	2500 - 40000	64 - 128

5GS Information Exposure for XR and Media Optimization: Reducing latency, managing congestion, and ensuring a desired user experience in XR applications require interaction between applications and the 5GS. This challenge explores mechanisms to expose 5GS information, enabling XR application servers to adjust media codecs and traffic rates dynamically based on network conditions, including identifying use cases, enhancing the exposure framework, and specifying the information needed for codec/rate adaptation.

PDU Set Integrated Packet Management: Current 5GS QoS granularity treats all packets within a flow uniformly; however, XR services often demand coordinated handling of groups of packets, known as PDU Sets (e.g., video frames). These packets have inherent dependencies in the media layer. Addressing this challenge involves developing PDU Set integrated packet handling,

including supported PDU Set types, information provision to 5GS, QoS model enhancements, and network locations for PDU Set management.

Differentiated Handling of PDU Sets: XR services involve high data rates and diverse content within PDU Sets (e.g., I/B/P frames). Optimizing resource utilization necessitates differentiated QoS handling based on the importance of PDU Sets. This challenge explores mechanisms to identify PDUs within PDU Sets, determine importance and dependencies, and enhance QoS models and policy control.

Uplink-Downlink Transmission Coordination for Low Latency: To deliver low round-trip latency for real-time XR/media services, ensuring balanced uplink and downlink coordination is crucial. This challenge focuses on supporting coordination to meet round-trip latency requirements between the UE and the network. It includes interactions between AF and 5GS, QoS enhancements, and dynamic management of latency requirements.

Policy Enhancements for Jitter Minimization: Minimizing jitter is essential for high-quality XR and media services. This challenge involves studying policy enhancements to minimize jitter, including requirements from AF and potential extensions of PCC rules within the 5G system.

Power Efficiency for XR Services: Optimizing device battery life while maintaining low latency in XR services is a priority. This challenge explores improvements to power-saving schemes like Connected mode Discontinuous Reception (CDRX) to strike the right balance between latency and device battery lifetime

Balancing QoE and Power Savings: Efficient codecs and high throughput may increase power consumption. Balancing quality of experience (QoE) with power consumption is essential. This challenge addresses the trade-off between throughput, latency, reliability, and power consumption, especially for efficient codec usage and device battery life.

For comprehensive insights into the key solutions proposed by 3GPP for the challenges⁵ discussed, it is highly recommended that readers consult 3GPP TR 23.700 for a more detailed description.

3.1.2 XR RAN Enhancements and Standardization Pathway

In the context of 3GPP RAN enhancements for XR, XR Awareness plays a pivotal role in optimizing radio resources.

This optimization involves the use of PDU Sets and Data Bursts, as defined by the 3GPP SA Working Group 2. PDU Sets and Data Bursts allow the RAN to identify content units (e.g., portions of images or audio frames) and their transmission durations, respectively, enabling efficient resource allocation and management⁶.

- XR-aware RANs employ the PDU Set Integrated Handling Indication (PSIHI) to determine whether all PDUs in a set are essential for usage at the application layer. Consequently, RANs can halt the transmission of a PDU set as soon as a loss is detected, thereby conserving resources. Each PDU set can also be assigned an “importance” level, which guides the RAN behavior during congestion by prioritizing higher-importance sets.
- Power-saving techniques were evaluated during the Rel-18 XR study. Aligning the periodicity of UE Discontinuous Reception (DRX) with XR traffic proved critical for conserving power and optimizing capacity. New mechanisms were introduced to accommodate non-integer periodicities associated with XR frame rates. Techniques such as Search Space Set Group (SSSG) switching and PDCCH skipping adapt PDCCH monitoring to account for XR PDU arrival jitter and end data burst timing.
- Capacity enhancements for XR involve PHY-related techniques. These include the introduction of Configured Grant (CG) periods with multiple PUSCH occasions for uplink data transmission. UE can indicate unused PUSCH occasions in the UCI, allowing the gNodeB (gNB) to reallocate unused UL resources to improve overall cell capacity and save energy. No PHY-related enhancements were needed for downlink, as conventional dynamic grant scheduling was found to be flexible enough for XR services. At Layer 2, capacity improvements aim to enhance the gNBs awareness of what the UE needs to transmit, which is crucial due to the high bit rates and low latency requirements of XR services. Buffer Status reports are enhanced to minimize quantization errors, and the knowledge of buffered data with reduced delay is also reported.

These RAN enhancements for XR Awareness, Power Saving, and Capacity collectively contribute to the efficient and optimized delivery of XR services in 3GPP networks.

3.1.3 Use Case on Spatial Mapping and Localization Service Enabler and Joint Sensing and Communication in 5G-Advanced

Within the realm of the localized metaverse and XR, a pivotal use case study revolves around Spatial Mapping and Localization Service Enablers. This foundational use case establishes a critical connection between these services and the evolving landscape of Joint Sensing and Communication Systems within the realm of 5G-Advanced. These interconnected elements play an integral role in the

5G-Advanced ecosystem, seamlessly merging spatial awareness with advanced communication technologies.

Spatial mapping, a process that involves creating or updating maps for uncharted territories, is inherently entwined with the core concept of localization. Localization encompasses the continuous tracking of objects to precisely determine their location and orientation over time. In the context of the localized mobile metaverse use case, service providers and operators are tasked with the mission of delivering and utilizing spatial map information. This mission results in the creation of dynamic 3D maps for both indoor and outdoor environments. This dynamic use case underscores the paramount significance of spatial mapping and localization as catalysts for a diverse range of services.

3.2 RedCap

Supporting RedCap devices is introduced in NR Rel-17. The use cases that motivate the specification work on NR RedCap include wearables (e.g., smart watches, wearable medical devices, AR/VR goggles, etc.), industrial wireless sensors, and video surveillance. These three use cases put some generic requirements on the system, such as reduced device complexity, compact form factor, and support for FR1 and FR2. The table below specifies such use case specific requirements^{7 8}:

Table 2. Requirements of wearables, industrial wireless sensors, and video surveillance use cases

	Data rate	Latency	Availability/ reliability	Battery lifetime	Device size
Wearables	5 - 50Mbps DL, 2 - 5 Mbps UL	Relaxed	N/A	up to 1-2 weeks	Compact form factor
Industrial Wireless Sensors	< 2 Mbps	< 100 ms	99.99%	At least a few years	N/A
Video surveillance	2-4 Mbps for economic video, 7.5-25 Mbps for high-end video	< 500 ms	99%-99.9%	N/A	N/A

The enhancements forecasted on RedCap devices that are planned in 3GPP Rel-18 are to improve the support of the three use cases identified in Rel-17 as well as expand into a wider range of use cases such as smart grid. 5G-Advanced will also introduce positioning support in RedCap. The Rel-18 RedCap device is intended to be a lower-tier device with capabilities between a Low Power Wide Area (LPWA) (eMTC and NB-IoT) device and Rel-17 RedCap device. Table 3 shows the detailed capabilities of different types of devices. These enhancements are to be introduced keeping in mind the integrity of the RedCap ecosystem to maximize the economies of scale.

The scope of work for further reducing the complexity of NR RedCap in Release 18 encompasses the following objectives^{9 10}:

- Achieving a supported peak data rate of 10 Mbps for Release 18 RedCap.
- Reducing the User Equipment (UE) bandwidth to 5MHz in Frequency Range 1 (FR1).

- Lowering the UE peak data rate to 10 Mbps in FR1.
- Relaxing the UE processing timeline.
- Implementing the reuse of Release 15 Synchronization Signal Blocks (SSB) and minimizing modifications to the physical layer (L1).
- Considering the operation of RedCap within Bandwidth Part (BWP) configurations, both with and without SSB, as well as with and without RF retuning. It is noteworthy to point out that the study is focused on FR1, although certain solutions may also be applied to FR2 as well.

Table 3. Comparison of device capabilities¹¹

	R15/16 NR eMBB	R17 NR RedCap	R18 NR RedCap	LTE-M (Cat M1)	NB-IoT (Cat NB1)
UE BW	100 MHz (FR1), 200 MHz (FR2)	20 MHz (FR1) 100 MHz (FR2)	20 MHz or 5 MHz (FR1 only)	1.4 MHz	180 KHz
Duplex	FD-FDD, TDD	FD/HD-FDD, TDD	FD/HD-FDD, TDD	FD/HD-FDD, TDD	HD-FDD, TDD
UE Antenna	1T2R(FDD)/1T4R (TDD)	1T1R/1T2R	1T1R/1T2R	1T1R	1T1R
Max Modulation Order	256QAM for DL, 64QAM for UL	64QAM (256QAM optional)	64QAM (256QAM optional)	16QAM	QPSK
Peak Data Rate – DL	2.3 Gbps	220 Mbps	10 Mbps	588 kbps	26 Kbps
Peak Data Rate – UL	468 Mbps	120 Mbps	10 Mbps	1119 kbps	66 Kbps

3.3 Integrated Communication and Sensing (ICAS)

Joint communication and sensing (JCAS), on a high level, can be defined as integrating the functionalities of communication and sensing into the same system or network¹². The integration of sensing and communication with JCAS could be at different levels, from loosely coupled to fully integrated, shared spectrum, shared hardware, to shared signal processing module and network protocol stacks, and even using the same waveform for both communications and sensing. In this integrated way, sensing functionality can be introduced as a service with a low incremental cost as it leverages on equipment and spectrum anyway deployed for communication purposes.

Overall, JCAS can extend the capability of cellular network from “listen and talk” to “see and feel”. From a device perspective, they can sense their surroundings, and exchange their sensing results through communication links. From a network perspective, the widely deployed base stations for legacy cellular service could be re-used for wide area seamless RF sensing. In addition, combining the AI, communications, positioning and sensing capabilities, the cellular network could intelligently fuse the physical world with digital world and provide a variety of new services for consumers and industry customers.

Table 4. Performance requirements of sensing result for different use cases

Scenario	Sensing service category	Sensing service area	Confidence level [%]	Accuracy of positioning estimate by sensing (for a target confidence level)		Accuracy of velocity estimate by sensing (for a target confidence level)		Sensing resolution		Max sensing service latency [ms]	Refreshing rate [s]	Missed detection [%]	False alarm [%]
				Horizontal [m]	Vertical [m]	Horizontal [m/s]	Vertical [m/s]	Range resolution [m]	Velocity resolution (horizontal/ vertical) [m/s x m/s]				
Object detection and tracking	1 (use cases 5.1, 5.13 – level I)	Object to be detected indoor: Human, object to be detected outdoor: UAV	95	10	10	N/A	N/A	10 NOTE 2	10 NOTE 3	##	1	5	2
	2 (use cases 5.13 – level I, 5.6, 5.14)	Object to be detected outdoor: Human, UAV Factory (100m2), crossroad, highway, railway [air]	95	5	5	N/A	N/A	10 NOTE 2	10 NOTE 3	##	1	5	5
	3 (use cases 5.2, 5.7, 5.10, 5.11, 5.12, 5.23)	Object to be detected: Animal, Human, UAV, Vehicle NOTE 4	95	1	N/A	NOTE 5	N/A	NOTE 5	1 x 1. NOTE 9	NOTE 6	0.1 NOTE 11	2	2
	4 (use cases 5.20, 5.22, 5.25, 5.32)	Object to be detected: Animal, Human, UAV, AGV/AMR, Vehicle factory	95	0.5	0.5	0.1 Vehicle: 15	N/A	0.5m	5 x 5 for factories: 0.5 x 0.5	##	0	1	5
	5 (use cases 5.27, 5.28)	Object to be detected: Vehicle Public area safety, ADAS	95 Public safety: 99	0.1short-range radar: 0.02	0.5	0.03 Pedestrian: 1.5	Pedestrian: 1.5	0.4	0.1 x 0.6	50	0	1	1
Environment monitoring	5 (use cases 5.3 and 5.1)	Rainfall monitoring and flooding NOTE 14	95	10	NOTE 15	N/A	N/A	N/A	N/A	##	1<10min, application configurable	10	3
Motion monitoring	7 (use cases 5.15, 5.24)	Indoor human motion -sleep monitoring NOTE 12, sports monitoring NOTE 13,	95	N/A	N/A	N/A	N/A	N/A	N/A	##	60	5	5
	8 (use case 5.29)	Hand gesture recognition	95	0.2	0.2	0.1	0.1	0.375	0.3	5	0.1	5	5

However, it is still an open research problem to define a unified metric to evaluate the performance of JCAS systems. The design goals of JCAS systems depend on use cases. Particularly, 3GPP Rel-19 SA1 study on JCAS has defined the RF sensing performance key performance indicators (KPIs) per use cases.

To make JCAS a reality, there are several technique challenges. First, the strong self-interference due to limited space between Tx and Rx antennas/antenna panels may require advanced receiver algorithms for interference cancellation. The strong self-interference makes the detection of static or low speed targets particularly challenging since they share the same property of close to zero in the Doppler domain. Second, the reduced transmission power limits the maximum sensing range, especially for UE based RF sensing. Compared with UE positioning, the strong self-interference, the round-trip propagation path loss, and the loss due to reflections make the link budget in sensing even more challenging. Third, the rich clutter could degrade the sensing performance severely, as the antennas are pointing toward the ground in most use cases. The receiver's capability of clutter rejection plays a leading role in high accuracy and robust RF sensing in time-varying and multipath-rich cellular environments.

The key technologies that could potentially resolve the challenges to enable JCAS include but are not limited to the following:

- The service-based network architecture
- Flexible and efficient waveform
- Advanced signal processing at the network node

First, the network architecture could enable efficient coordination across the sensing nodes in the wide-area network, which is a key feature compared with classic radar sensing. A service-based architecture is the basis for the 5G core network, which could be further expanded into 6G for the RF sensing service. Particularly, there could be a network entity performing as a sensing server to coordinate the sensing nodes for sensing signal transmission and reception. For localization/tracking use cases, the multi-cell operation requires cross-cell coordination through the sensing server. For example, the sensing server could enable efficient gNB grouping during the target tracking. The sensing server could also mitigate the inter-cell interference through time/frequency/code/spatial domain multiplexing across the cells. Moreover, the sensing server could also collect extensive measurements from both the UE and gNBs to facilitate the AI-driven intelligent sensing service, such as target recognition and scene understanding.

Second, the standardized waveform and reference signals in cellular networks are another fundamental technique to facilitate RF sensing. The waveform and reference signal should enable both the mono-static and bi-static/multi-static RF sensing with delay/Doppler/angle estimation. From a hardware implementation point of view, the reference signal transmission across slots should guarantee phase coherency for the Doppler estimation. Besides, the dynamic range of the waveform is also critical for long-range sensing, especially for small-size targets such as drones. Hence, the low Peak-to-Average Power Ratio (PAPR) waveform is desirable.

Moreover, another desirable waveform property is to support efficient full-duplex sensing. In the 5G life cycle, the OFDM-based waveform could serve as the baseline for RF sensing, which could fully re-use the existing hardware. One enhancement could be using the Discrete Fourier Transform (DFT) spread OFDM with $\pi/2$ BPSK (Binary Phase Shift Keying) for the RF sensing purpose (for example, introducing the low PAPR PRS in 5G-Advanced). As 3GPP advances to 6G, further new waveforms¹³ could be considered to meet all the above desirable properties for RF sensing.

Lastly, advanced signal processing needs to deal with two fundamental challenges in cellular-based RF sensing: strong self-interference and rich clutter in the environment. The distribution of the self-interference and clutter in time, frequency, and angle domains could motivate some advanced receiver algorithms to reject the interference with acceptable implementation complexity. Some example algorithms are Doppler shift-based interference rejection, sensitivity time control (attenuate the nearby ground clutter which has an extremely large signal strength), moving target indication (moving target indication (MTI) uses signal processing to filter stationary and quasi-stationary clutter), space-time adaptive processing (adaptive weighting on the detected energy (signal, clutter, and/or noise), to discern the signal from clutter) and Constant False Alarm Rate (CFAR) detection (time-varying detection threshold that provides a constant false alarm rate to ensure that only the signals of interest are detected).

3.4 Ambient IoT

Ambient IoT represents an innovative device category that exclusively relies on harvested environmental energy, ensuring both cost-effectiveness and simplicity. These devices are intentionally designed without the need for battery replacements, alleviating the maintenance burden.

Ambient IoT stands as the most budget-friendly, uncomplicated, and power-efficient tier of devices. Its affordability facilitates the connection of numerous objects and items to networks, allowing for a multitude of applications, including:

- **Inventory Management:** Ideal for use in warehouses and supply chains.
- **Sensors for Smart Agriculture and Cities:** Perfect for monitoring and data collection in agriculture and urban environments.
- **Object Tracking:** Useful for tracking deliveries, managing electronic shelf labels, and locating lost items.
- **Remote Command and Control:** Empowering actuators and similar applications.

For in-depth exploration of use cases, you can refer to 3GPP specification TR.840¹⁴ and TR 38.848¹⁵. Ambient IoT devices can be categorized into three types based on energy storage and signal transmission methods:

- **Passive Devices:** Lack energy storage and rely on backscattering techniques for communication.
- **Semi-Passive Devices:** Feature energy storage and use backscattering for communication.
- **Active Devices:** Possess energy storage and actively generate signals, typically with a power amplifier.

The two pivotal technologies driving Ambient IoT include energy harvesting and storage techniques, as well as backscattering techniques.

Energy harvesting and storage can include diverse energy sources include RF signals, light, vibrations, and thermal energy. Different energy sources have varying levels of availability and energy density. Note that using RF signals may influence network and system design – and that energy harvesting techniques such as rectifiers and solar panels play a significant role.

The backscattering technique can involve a few different factors. Backscattering, combined with active signal generation (e.g., power amplifiers), minimizes power consumption in Ambient IoT devices. In backscattering, the transmitted signal is a reflection of continuous waves from a reader, modulated with information for communication. Ambient IoT's reliance on energy harvesting and backscattering holds tremendous potential in revolutionizing the world of low-cost, maintenance-free, and environmentally sustainable IoT solutions.

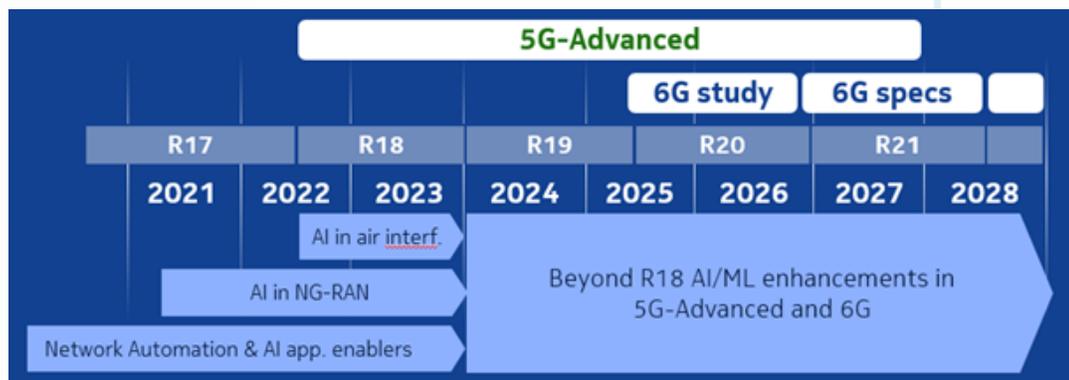
4. Artificial Intelligence (AI) and Machine Learning (ML) for 3GPP-Based Wireless Networks

This chapter distills the essence of AI/ML in 5G networks as defined by 3GPP standards, beginning with an exploration of their roles in enhancing network intelligence and efficiency. It delves into lifecycle management, outlining the processes for AI/ML model development, deployment, and maintenance to ensure robust network performance. Finally, it addresses the imperatives of trustworthy AI, focusing on ethical deployment, transparency, and security as the backbone of a reliable 5G infrastructure.

4.1 Overview of AI/ML in 3GPP

The initial foray of AI and Machine Learning into 3GPP began within the realm of network automation. In Release 15, the introduction of the Network Data Analytics Function (NWDAF) marked the advent of AI/ML, providing network slice analysis capabilities. Subsequently, it expanded its scope to include data collection and exposure within the 5G core in Rel-16, as well as facilitating UE application data collection in Release 17¹⁶.

Figure 3. The Evolution of AI/ML in 3GPP

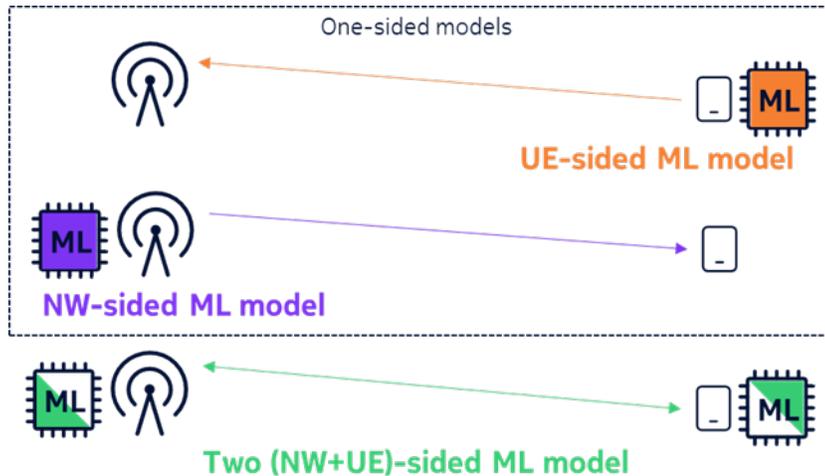


In Rel-17, the integration of Machine Learning further extended to the Next-Generation Radio Access Network (NG-RAN). The technical report TR 37.817 outlines the principles governing RAN intelligence empowered by ML. It delves into the functional framework and explores various use cases and solutions for ML-enabled RAN. The initial set use cases encompass:

- **Network energy savings:** This approach involves cell activation and deactivation, strategically offloading traffic within a layered structure to curtail energy consumption across the entire RAN. In cases where anticipated traffic volume falls below a predefined threshold, cells can be powered down, and connected UEs can be transferred to a different target cell.
- **Load Balancing:** With the proliferation of network traffic and the utilization of multiple frequency bands in commercial networks, achieving a balanced distribution of traffic becomes a complex challenge. Load balancing methods aim to equitably distribute the load among cells and various cell areas, carriers, or Radio Access Technologies (RATs). This can involve offloading users from congested cells or areas.
- **Mobility Management:** Machine Learning-driven solutions have been proposed to ensure seamless service continuity during mobility. These solutions minimize issues such as call drops, Radio Link Failures (RLFs), unnecessary handovers, and ping-pong effects. Beyond basic mobility management, optimization areas encompass dual connectivity, Cell Handover Optimization (CHO), and Dynamic Antenna Point Selection (DAPS), each presenting specific aspects for mobility enhancement.

Finally, in Rel-18, AI/ML spread to the new radio air interface¹⁷, as shown in Figure 4. This is a remarkable enhancement to be brought by 5G-Advanced¹⁸. More specifically, in the Rel-18 study, 3GPP is looking at ML solutions that require interactions between network (NW) and UE. 3GPP categorizes those solutions into one-sided models and two-sided models. The one-sided model means that inference of ML solution happens only at UE or only at NW. 3GPP refers to these as UE-sided models and NW-sided models accordingly.

Figure 4. One-sided and two-sided models



In the case of UE-sided models' the scope of standardization includes any new signaling needed to enable these use cases or make them more efficient compared to the 3GPP transparent option. As well as establish procedures for NW control over ML-enabled features. For NW-sided models, some extra signaling on the air interface may be needed to make the use cases work, e.g., assistance information from UE.

The two-sided model requires closer collaboration between the NW side and the UE side, since it assumes that UE and NW jointly run the inference of the ML model. Considering that many vendors prefer not to expose their models, 3GPP specifications need to ensure compatibility with ML counterparts when those are developed/trained separately.

In terms of the degree of collaboration between NW and UE and different amounts of specification impacts, the 3GPP Rel-18 study categorizes three different NW-UE collaboration levels:

- **Level x:** No collaboration; implementation-based only AI/ML algorithms without information exchange.
- **Level y:** Signaling-based collaboration without model transfer, where the NW is involved in managing functionalities/models at the UE side.
- **Level z:** Signaling-based collaboration with model transfer, where the NW is involved in managing functionalities/models at the UE side and where the models are transferred from NW.

The study considers three representative use cases.

- **Beam management:** includes beam prediction in the spatial and time domain. The main point is to reduce the number of measurements needed to select the best beam while system performance is not compromised.
- **CSI enhancements:** include CSI compression and CSI prediction. CSI compression is performed with a two-sided model. UE compresses CSI feedback with an ML encoder, and gNB decompresses that with an ML decoder. The goal is to either reduce feedback overhead at the same level of throughput performance or increase the throughput

performance with the same level of overhead – or a combination of those. CSI prediction in the time domain allows UE to skip a channel measurement and use prediction instead.

- **Positioning:** targeting improved accuracy and reduced overheads. Positioning considers direct methods when UE coordinates are derived from ML models and assisted methods, where ML models are incorporated in larger non-ML positioning estimation algorithms.

In 3GPP, the exploration of AI/ML use cases within the air interface domain is aimed at establishing a generalizable ML framework. This framework plays a pivotal role in enabling ML applications across the air interface, ensuring its versatility for accommodating additional use cases in forthcoming releases, including the evolution to 6G.

As we move into Rel-19, we anticipate the comprehensive incorporation of AI/ML use cases within the air interface, radio access network (RAN), and overall system architecture. In Release 20, the study of 6G technology will take center stage, with AI and ML seamlessly integrated into the system’s core. The advanced technologies, such as distributed learning, working in harmony with AI deeply embedded in both network infrastructure and user devices, will significantly enhance the overall performance and user experience.

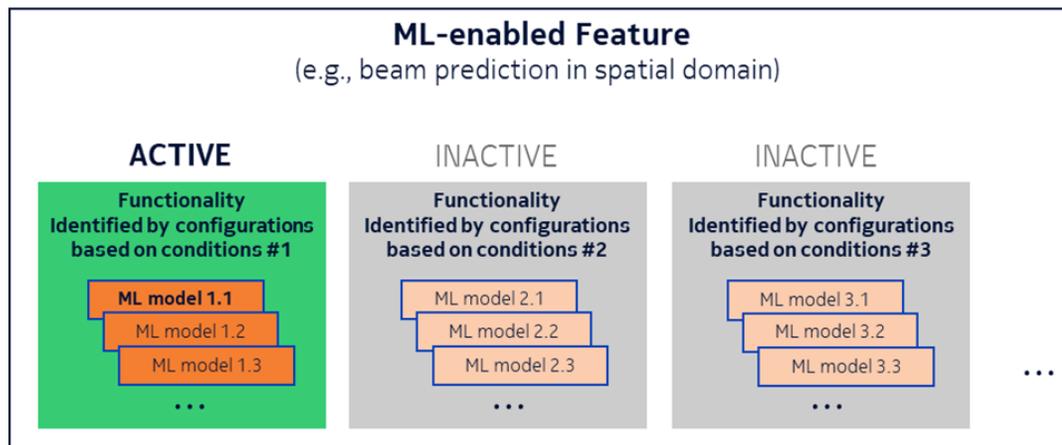
In this context, 6G stands out as a pioneering generation of mobile networks that are fundamentally driven by data, marking a paradigm shift in mobile communication technology¹⁹.

4.2 Life-cycle Management of an AI/ML Functionality

In the production industry, the term ‘product life cycle management’ is widely used to refer to the cyclic phases of a product, from conception to retirement. The product can be physical (hardware, machinery), computer software, a service, or any combination of these. In the AI/ML domain, the ML functionality life-cycle management is used to indicate a set of tools and procedures for enabling ML applications.

In some 3GPP discussions, the term ‘ML model life-cycle management’ is used even though in the latest discussions, it has become evident that the ML models themselves might not be possible, nor needed, to be fully managed using 3GPP specified mechanisms. The ML model needs some data pre-/post-processing to be integrated into the control pipeline to be operatable. Therefore, dealing with “functionality” instead of “model” is more accurate. The LCM procedure is studied on the basis that an AI/ML model has a model ID with associated information and/or model functionality, at least for some AI/ML operations. Figure 5 shows the relation between ML-enabled features, functionality, and model.

Figure 5. ML-enabled feature



Each feature may have more than one functionality. Different functionalities may be needed to deal with different scenarios (e.g., indoor and outdoor). Technically, functionalities can be different in pre-/post- processing algorithms, inference instructions, and underlying models.

To sustain and support the use of AI/ML models in the network, LCM procedures should be implemented. Those procedures may vary depending on the domain and use case. Commonly, they include:

- Data collection
- Model training and update
- Functionality registration and identification
- Inference operation
- Functionality/model monitoring
- Functionality, (de-)activation, switching, and fallback operation
- UE capability

The practical viability of ML solutions in air interfaces heavily depends on the scalability and generalizability²⁰ of ML models. In simple terms, it means how well one ML solution can work across different scenarios, devices, and configurations. To better illustrate the challenge, consider the CSI compression use case where the network vendor must manage multiple NW-side models per UE vendor. In this sense, we need to seek a scheme to facilitate a common NW-side model for multiple proprietary UE models. A mixed training dataset collected from multiple UE vendors can be one feasible option, but its performance and feasibility must be studied further.

Ideally, all possible scenarios could be covered by a single model. However, this can take a lot of work to achieve in practice. In addition to that, better model generalization often comes with a cost of higher complexity. Therefore, achieving a reasonable tradeoff between generalization and other KPIs is one of the key directions in ML study.

4.3 Trustworthy AI

As ML continues to proliferate throughout mobile networks, the issue of trustworthiness²¹ becomes increasingly paramount. Trustworthiness advocates a set of fundamental principles that should be inherently woven into the system's design:

- **Explainable Machine Learning:** This aspect pertains to the capacity of ML models to provide human-readable explanations for their decisions and predictions, facilitating transparency and understanding.

- **Fair Machine Learning:** Fairness in machine learning entails the identification and rectification of biases within ML models, ensuring equitable and unbiased outcomes.
- **Robust Machine Learning:** Robustness in machine learning addresses the ability to manage different types of errors, corruptions, and shifts in underlying data distributions autonomously, enhancing the reliability and adaptability of ML models.

These features are applicable across the entire ML process, spanning four key aspects:

- **Data Processing:** This phase involves data preparation for training, testing, and inference.
- **Training:** The training of ML models with data to establish their predictive capabilities.
- **Testing:** The evaluation of ML models to gauge their performance and accuracy.
- **Inference:** The practical application of trained models to make predictions or decisions in real-world scenarios.

Although ML trustworthiness is a burgeoning topic within 3GPP, the foundational design principles inspired by this paradigm have already been incorporated in 5G-Advanced. Notably, TR 28.908 underscores the necessity for managing AI/ML trustworthiness during the phases of ML training, testing, and inference, with a specific emphasis on ensuring that ML solutions are explainable, fair, and robust.

Furthermore, given the varying degrees of risk associated with ML's impact on different use cases, the trustworthiness requirements for ML may fluctuate accordingly. Consequently, the mechanisms related to trustworthiness must be individually configured and monitored for each specific use case to maintain the desired levels of reliability and integrity.

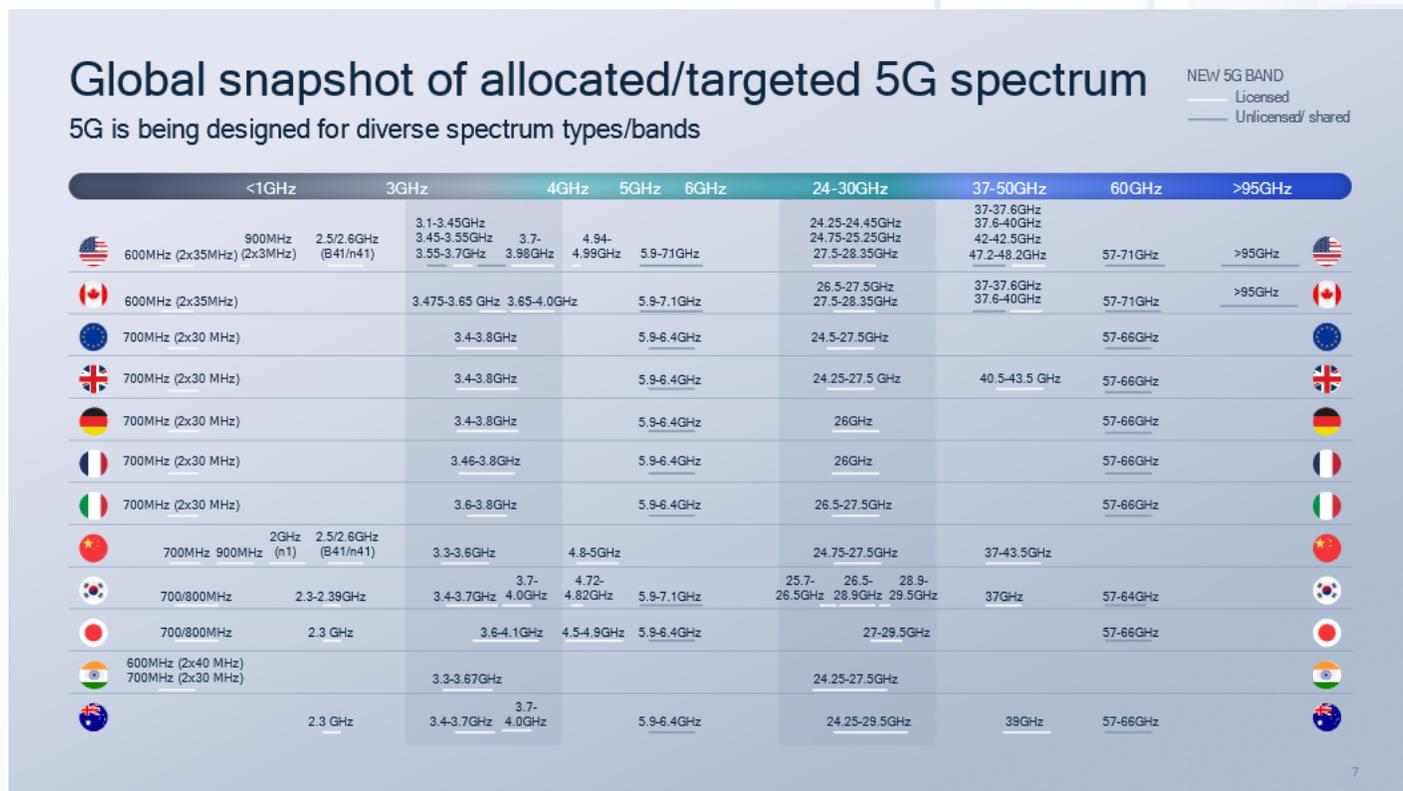
5. Spectrum and Air Interface in 3GPP

In this chapter on spectrum and the air interface, we dissect the complexities of deploying FR3 spectrum in 5G-Advanced, highlighting both the challenges of signal attenuation and hardware limitations, and the innovative solutions such as advanced beamforming and adaptive antenna systems. The discussion on carrier aggregation examines how it enhances the air interface by optimizing bandwidth and improving data rates across varied frequency bands. The section on multi-cell scheduling with a single Downlink Control Information (DCI) format unveils how it streamlines network operations by coordinating multiple cells efficiently, paving the way for more coherent and unified network management in dense 5G deployments.

5.1 FR3 Spectrum Deployment for 5G-Advanced: Challenges and Solutions

The introduction of new spectrum holds the promise of not only facilitating innovative applications but also enhancing the capabilities of existing ones within the realm of 5G-Advanced. Illustrated in Figure 5.1, the spectrum allocated for 5G-Advanced cellular deployments often occupies the upper midbands, notably spanning from 7.125 GHz to 24.25 GHz. In the context of this white paper, we have designated this frequency range as “FR3” spectrum, distinct from the previously established FR1 and FR2 spectrums. 3GPP may introduce specific frequency range designations for any newly defined 5G-Advanced spectrums in the future.

Figure 6. Global snapshot of allocated/targeted 5G spectrum²²



The “FR3” spectrum band boasts several key advantages, chief among them being its substantial bandwidth and its suitability for extensive geographical coverage, although it presents challenges distinct from those of FR1 deployments. Essentially, “FR3” holds the potential to combine the best aspects of both FR1 (for coverage) and FR2 (for wide bandwidth) bands. Furthermore, the ample coverage area coupled with the availability of wide bandwidth

renders this spectrum exceptionally promising for the enhancement of positioning and sensing capabilities. In essence, “FR3” could potentially emerge as the pivotal frequency range for the development and evaluation of critical 5G-Advanced technologies.

To fully harness the potential benefits offered by new spectrum, such as the FR3 spectrum, a range of significant challenges must be addressed, which are outlined below:

- **Propagation Loss Challenges:** FR3 has larger propagation loss than FR1. To guarantee similar coverage between FR1 and FR3, techniques to improve both DL and UL coverage in FR3 are essential for the success of FR3 deployment. One such technique is Gigantic MIMO, which scales up FR1 massive MIMO to gigantic MIMO antenna panels (>1K elements) to offer larger beamforming gain to overcome the larger propagation loss in FR3.
- **Coexistence with Existing Communication Systems:** Cellular communications in new spectrum, such as in FR3, might have to coexist with existing communication systems already deployed in those spectrums. For example, earth/satellite communications have been deployed in many spectrums in FR3. The incumbent of those existing communication systems might be government agencies such as the Department of Defense, which have very stringent requirements to suppress interference from other co-existing cellular communication systems to ensure the high reliability of the existing communications systems. One should notice that the two co-existence scenarios, cellular communication in FR3 co-existing with NTN and cellular communication in FR3 co-existing with existing communication systems of government agencies, are different.

In the former scenario, NTN is a commercial communication system operated by operators and standardized by 3GPP, which means 3GPP can develop techniques on both NTN and FR3 cellular communication systems, such as dynamic spectrum sharing, to make sure they coexist with each other nicely. For the latter co-existing scenario, due to the confidentiality of those communication systems of government agencies, it is unlikely to share spectrum and data between them and commercial cellular communications in FR3. Therefore, advanced interference management and suppression techniques must be developed on the FR3 cellular communication side to guarantee cellular communications and other communications systems can nicely coexist in new spectrum without interfering with each other.

- **New Transceiver Requirements:** The deployment of cellular communications within new spectrum bands advanced may necessitate the deployment of entirely new transceiver technologies. These novel transceivers could include advanced RF filters, high-performance power amplifiers, and innovative antenna designs for both UE and gNBs.

3GPP is expected to solve the above challenging problems and enable 5G-advanced deployment in the new spectrum. In the 3GPP Rel-19 workshop (June 15 - 16, 2023, Taipei), proposals related to FR3 were discussed. The discussion suggested starting the investigation on FR3 from the studying of channel model in FR3 to understanding the channel characteristics better, such as the channel delay spread, angular spread, path loss, outdoor to indoor loss, etc. The study of other aspects of FR3 can be conducted later after the channel model is established.

5.2 Carrier Aggregation and Air Interface

Carrier aggregation stands as one of the cornerstone technologies in 5G networks, enhancing the air interface by allowing multiple frequency bands to be combined, thus boosting data throughput and network capacity.

5.2.1 Multi-cell scheduling with a single DCI

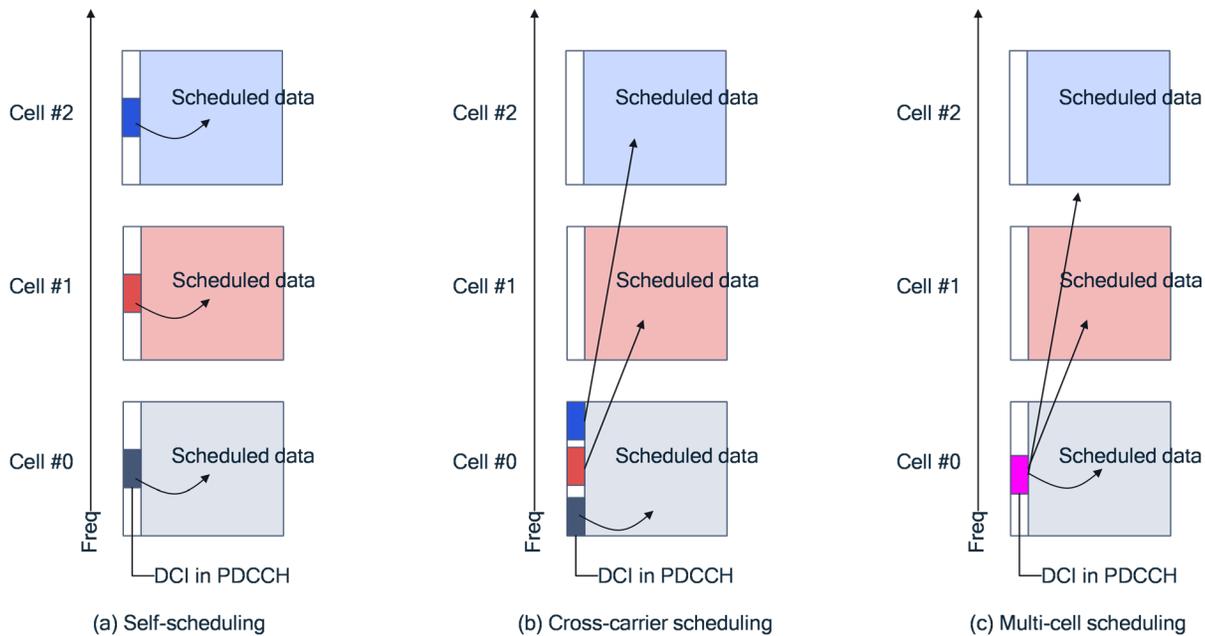
In the 5G-Advanced era, further increasing availability of spectrum is expected, including re-farming from previous generations and expansion of millimeter wave (mmW) bands. These spectra can be aggregated for a UE to increase data throughput for downlink and/or uplink. There are two modes in legacy carrier aggregation – self-scheduling and cross-carrier scheduling. For self-scheduling, downlink control information (DCI) that indicates scheduling information (resource allocation, link adaptation, etc.) of DL data (PDSCH) or UL data (PUSCH) on each carrier is delivered by a PDCCH on the same cell as for the scheduled data. For cross-carrier scheduling, a PDCCH and the scheduled DL or UL data can be transmitted/received on different cells. Cross-carrier scheduling further enables to transmit/receive PDCCH carrying multiple DCIs on a scheduling cell for DL data and/or UL data on multiple different cells.

When the number of cells in the carrier aggregation operation is small, cross-carrier scheduling will enable UE power efficient operation since the UE monitors PDCCH only on the scheduling cell. However, with the increased number of cells, it would be difficult to achieve the benefit of cross-carrier scheduling due to the following reasons:

- Many DCIs for multiple scheduled cells for the UE must be carried by a PDCCH of one scheduling cell. This consumes a lot of resources in the DL control of the cell and hence would block other UE’s scheduling opportunities.
- The UE must monitor a lot of PDCCH candidates in the scheduling cell, which consumes a lot of UE power.

The DL control overhead and UE power consumption issues were addressed, and it was agreed to support multi-cell PUSCH/PDSCH scheduling by a single DCI. Unlike legacy carrier aggregation, a single DCI provides scheduling information of DL data or UL data for multiple scheduled cells. For this feature, the most important open issue is how to design a DCI for multi-cell scheduling. Since the payload of a DCI is limited (e.g., up to 120 bits excluding CRC), it is not possible to concatenate all the existing indication fields of legacy DCIs for multiple scheduled cells to form a DCI for multi-cell scheduling. Moreover, a large payload of a DCI degrades the coverage performance of the PDCCH. On the other hand, reducing the number of bits of a DCI field loses scheduling flexibility in general. As such, the trade-off between DCI payload size and scheduling flexibility must be carefully considered.

Figure 7. Self-scheduling, cross-carrier scheduling, and multi-cell scheduling

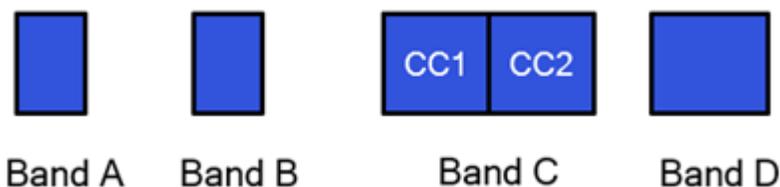


5.2.1.1 UL Tx switching

3GPP specified two band switching in Rel-16 and Rel-17, while Rel-16 is on 1Tx-2Tx switching and Rel-17 is on 2Tx-2Tx switching. As 5G deployment expands, operators plan to re-farm more 3G/4G spectrum for 5G and further require flexible switching among more than two bands.

Figure 8 illustrates combinations of switching bands when two or more bands are involved. Each band may be with 1 or 2Tx which depends on the supported antenna numbers. The Tx chain(s) could dynamically switch among different bands according to scheduling or configuration.

Figure 8. Switching band combination with more than two bands



Compared with switching between two bands, more than two bands switching would result in a more complicated switching band pair and RF combination. For example, without restriction, the switching could be from any band list and to another random band in the list. The overall band pair combination would be around ten, which is not affordable for UE implementation. Therefore, the design should target the switching complexity reduction as the priority. With extensive discussion, the complexity reduction includes three aspects:

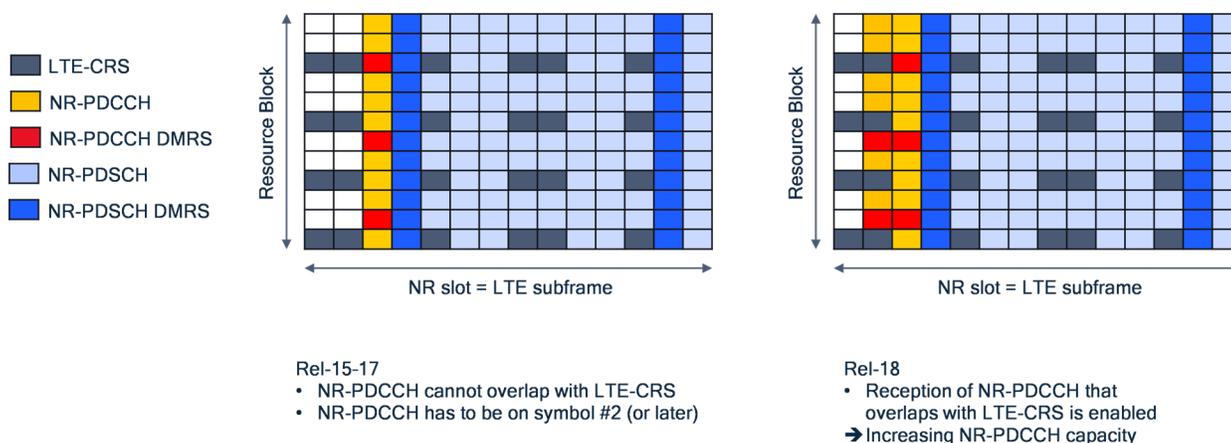
- Allowing UE to report only one Tx on certain band(s) within the band combination. This could reduce the RF memory and architecture complexity as the switching would only happen between parts of the Tx for the band combination.
- Allowing UE reports switching options (DualUL or SwitchedUL) for each band pair within the band combination. A UE could report DualUL for only one band pair within a four-band combination. This allows UE implementation flexibility and lowers the bar for a UE to support DualUL.
- When switching involves more than two bands within two consecutive slots, UE could report a minimum separation time (500us) for two consecutive switches, and BS would avoid back-to-back switching.

5.2.1.2 Rel-18 dynamic spectrum sharing (DSS)

3GPP introduced various features for NR for DSS operations since Rel-15. One of the key NR features introduced for DSS was to rate match NR physical downlink data channel (PDSCH) around LTE cell-specific reference signals (CRS) resource elements. LTE CRS is transmitted in every LTE downlink (DL) subframe. NR PDSCH rate-matching around LTE-CRS enables to transmit NR PDSCH on resources where LTE-CRS is transmitted.

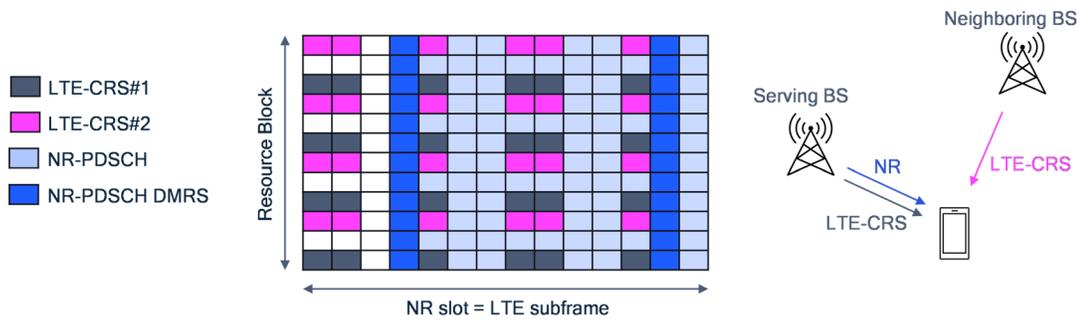
However, until Rel-17, NR physical downlink control channel (PDCCH) could not overlap with LTE CRS. For a DSS carrier, the network basically needs to configure NR-PDCCH for an NR UE such that NR-PDCCH is located on OFDM symbol where LTE CRS is not present (e.g., OFDM symbol #2). This limits the available OFDM symbol for NR-PDCCH transmission, causing limited NR-PDCCH capacity (see Fig 9). In Rel-18, NR-PDCCH reception on OFDM symbol(s) that has LTE-CRS is supported (see Fig 10). For this, the NR-PDCCH structure is kept unchanged. NR BS may puncture NR-PDCCH by LTE-CRS. NR UE may receive and decode the NR-PDCCH that may be punctured by LTE-CRS as if it is a regular NR-PDCCH that has no impact from LTE-CRS.

Figure 9. NR-PDCCH in Rel-15-17 (only on OFDM symbol #2) and Rel-18 (on OFDM symbols #2 and #3)



In addition, multiple LTE-CRS patterns on the same frequency (i.e., in the same resource block) for PDSCH rate-matching have also been supported in Rel-18. This enables to eliminate interference from LTE-CRS transmitted by a neighboring BS, as well as the one transmitted by the serving BS, as illustrated in Fig. 6.5. Such PDSCH rate-matching for multiple LTE-CRS patterns in the same resource block was already supported in Rel-16. However, the legacy PDSCH rate-matching for multiple LTE-CRS patterns in the same resource block was only for the case where the multiple LTE-CRSs are transmitted by different TRPs of the same serving BS. Rel-18 has no such limitation.

Figure 10. NR-PDSCH rate-matching around multiple LTE-CRS patterns



6. Sustainable Development

In the context of addressing climate change, an urgent priority is ensuring that 5G and advanced networks are deployed and operated sustainably. The gravity of this challenge is underscored by the record-breaking heat of July 2023, a stark reminder of the global climate crisis²³. As temperatures continue to rise, the consequences for the world's population are profound, affecting 81% of the global population²⁴. The science is clear: limiting global temperature rise to 1.5°C above pre-industrial levels is imperative, and the mobile industry plays a pivotal role in achieving this goal.

3GPP has a crucial role to play in supporting the sustainability of 5G and advanced networks. To this end, the 3GPP is diligently working on standards that encompass various facets of sustainability, including energy efficiency, resource optimization, circularity, and social responsibility. Moreover, these efforts extend beyond telecommunications, as 3GPP is actively crafting standards that enable wireless technologies to facilitate sustainability across multiple industries.

One notable area of focus is energy consumption²⁵, a substantial component of network operators' operational expenditures. Within the network infrastructure, the radio access network (RAN) and, specifically, the active antenna unit (AAU) stand out as primary sources of energy consumption. With this in mind, there is a compelling need to refine and develop energy-saving techniques with granular targeting for specific deployment scenarios, while also exploring the potential for user equipment (UE) support.

In the quest for energy efficiency within 5G networks, 3GPP has been incorporating criteria for communication services, enhancing transparency by disclosing energy consumption to clients, scrutinizing requirements to bridge existing gaps, and delving into security, billing, and privacy aspects. Addressing climate change and global energy scarcity necessitates collective efforts and a pronounced emphasis on energy efficiency.

In the pursuit of net zero emissions, the industry is fervently committed to balancing user experience with network efficiency. However, this endeavor requires access to vertical-specific data for further refinement. By offering energy efficiency as a service, end-users can make informed choices and assess their energy consumption. This approach also underlines the significance of fostering enhanced collaboration between applications and networks, as it holds the potential to improve both energy efficiency and user satisfaction. The concerted efforts within the 3GPP community exemplify the industry's unwavering dedication to sustainability and innovation in the ever-evolving landscape of advanced mobile communications.

6.1 Enhancing Energy Efficiency in the RAN²⁶

There are several methods for enhancing energy efficiency in radio access networks. Some of them include:

- **Optimizing Sleep Modes for gNB:** To bolster energy efficiency, it's crucial to allow gNBs to utilize deeper sleep modes by adjusting the transmission patterns of downlink common and broadcast signals, including SSB, SI, paging, and cell common PDCCH. Similarly, the transmission pattern and availability of uplink random access opportunities should be adapted. Eliminating unnecessary transmissions and receptions of UE-specific channels during low or no activity periods significantly reduces energy consumption. This enables gNBs to spend more time in sleep mode, particularly valuable in low-traffic areas.
- **Uplink Wake-Up Signals (WUS):** Minimizing gNB energy consumption involves reducing the time spent in an active state when channels or signals are not required. UEs can send

uplink wake-up signals (WUS) to prompt the gNB to transition from low-power mode to an active state for transmitting or receiving signals, conserving energy.

- **Dynamic Transmission Power Adjustment:** Improving network energy efficiency is achieved by dynamically adapting the transmission power of downlink signals and channels through UE feedback and configuration adjustments. This adaptive approach applies to PDSCH, CSI-RS, DMRS, and broadcast channels/signals (e.g., SSB, SI, paging). Power offset values between various signals and channels can be updated via lower layer signaling, enabling the network to reduce power for unnecessary signals and channels, leading to energy savings.
- **Multi-Carrier Energy Conservation:** Energy savings can be enhanced by transmitting SSBs and SIBs on only one carrier in a two-carrier deployment, leveraging the SSB-less operation feature. This not only reduces energy consumption for the gNB but also benefits UEs, as they no longer need to transmit or receive signals on both carriers.
- **Dynamic UE Group Pcell Switching:** The gNB can efficiently conserve energy by dynamically switching UEs between different Pcells using the UE-group Pcell switching feature. This prevents UEs from having to transmit or receive signals on all Pcells, contributing to energy savings.
- **Dynamic Bandwidth Adaptation:** Energy efficiency is also improved by dynamically adapting the bandwidth of a BWP for UEs through the BWP adaptation feature. By allowing UEs to transmit and receive signals only on the required bandwidth, unnecessary energy consumption is reduced.

Implementing these techniques can significantly enhance energy efficiency in RANs, reducing overall power consumption and contributing to a more sustainable and cost-effective network operation.

6.2 Energy Consumption as Performance Criterion for Best-Effort Communication and Support of Energy Related SLAs

The current landscape of 5G networks focuses on energy consumption and efficiency, albeit not as a primary performance criterion. Ongoing efforts have been dedicated to enhancing energy efficiency in system operations. However, as we evolve toward 5G-Advanced features, energy efficiency should stand as a core principle alongside security, privacy, and complexity. It is worth considering applying energy efficiency policies to best-effort traffic. At present, the 5G system efficiently supports services but does not incorporate energy consumption as a service-level parameter. This narrative explores the potential for using energy consumption as a novel service criterion for unconstrained mobile telecommunication services, ultimately leading to a more resource-efficient network.

In industrial campus settings, specialized networks are employed to achieve low latency and data protection. Nonetheless, the issue of energy consumption during periods of underutilization remains pertinent. To combat this, improved energy efficiency can be accomplished through replaceable Service Level Agreements (SLAs), dynamic energy states, and accommodating diverse energy requirements, such as supporting varying energy states and enabling charging based on these states. Facilitating access to energy consumption data for authorized parties becomes essential in promoting energy efficiency across a range of use cases.

6.3 Exposure of Energy Consumption and Efficiency Information

In this context, the exposure of energy consumption information is considered for various 5G network deployment scenarios, including dual connectivity, CU-DU deployment, and RAN sharing. The overarching goal is to acquire and disclose the energy consumption of the 5G network to industry customers, regardless of the deployment scenario.

The 5G network gathers information on energy consumption and provides it to customers upon request or subscription, irrespective of the NG-RAN deployment scenarios. Operators may offer varying energy-related SLAs based on the network's energy states, thus affording customers improved visibility into network services under diverse energy conditions. Network performance statistics can be configured by the customer, authorized third parties, or the operator and linked to energy usage data. In the deployment of 5G NPN, energy consumption monitoring is pivotal, especially in RAN sharing scenarios. The 5G Core Network delivers energy efficiency data to subscribing customers, allowing them to monitor energy consumption and adjust their behavior, while operators can enforce energy-related policies. Within this use case, new requirements emerge, including the monitoring of energy consumption and the establishment of energy credit limits for services.

- **Application Energy Efficiency Monitoring:** Next-generation mobile communication systems are gearing up to accommodate increasingly resource-intensive services, including immersive experiences and digital twins. Such use cases as well as the pervasive use of artificial intelligence and machine learning (AI/ML) in future network architectures will result in heightened energy consumption for both devices and network infrastructure. To uphold energy efficiency, we can employ application layer adaptation strategies, such as dynamically adjusting service levels based on the expected energy consumption within a specific geographical area.

- Within this context, the concept of Application Service Energy Efficiency (AEE) comes to the forefront. AEE can be effectively monitored and forecasted within the 5G system, empowering service providers to undertake well-informed measures to optimize energy usage. This process encompasses the consideration of pre-conditions, the management of service flows, and the evaluation of post-conditions, in addition to potentially necessitating the introduction of new prerequisites to ensure enhanced energy efficiency across mobile communication systems.
- **Temporary Coverage Layer Pooling for Energy Savings:** In the pursuit of energy savings within mobile networks, the implementation of coverage layer pooling can be a valuable strategy. This approach involves deactivating certain RAN nodes during periods of low usage, leaving only one active coverage layer. Agreements between operators can enable one network to provide coverage for subscribers from other networks during low-load periods, leading to network-wide energy savings. This strategy can also be extended between NPN operators and PLMN operators. The 5G system should support the temporary pooling of coverage layers, enable operators to serve users from other networks, and allow UEs to display their home operator network name during coverage layer pooling.
- **Energy as a Service Criterion for 5G Environment Adaptation:** Operators and cloud/data service providers face the dual challenge of reducing carbon emissions while offering optimal service plans to end-users. By diligently monitoring and controlling network functions based on energy consumption, operators can optimize energy usage without compromising service quality. The 5G system supports individual network function monitoring, registration, discovery, selection, load balancing, and overload control based on energy consumption. This enables operators to adapt, migrate, and scale network functions in line with energy efficiency requirements and strategic plans. By measuring and managing energy consumption, operators can achieve significant energy savings while maintaining high service quality, thereby accommodating diverse end-user service demands and advancing environmental sustainability.

Conclusion

In the dynamic world of telecommunications, innovation and progress continue to be the driving forces shaping our connectivity and communication landscape. The 3rd Generation Partnership Project (3GPP) stands as a beacon of our unwavering commitment to creating faster, more reliable, and more versatile networks, meeting the ever-evolving needs of our interconnected world.

Already, 5G networks have transformed our daily lives, and 3GPP is dedicated to taking them to new heights with 5G-Advanced. This next evolution promises faster data speeds, reduced latency, and enhanced reliability, opening a world of possibilities for industries, consumers, and the broader ecosystem. Our whitepaper delves into the core technologies, features, and use cases that will define the next chapter in wireless communication.

In our ongoing journey, 3GPP's Release (Rel)-17 introduced significant enhancements, laying the groundwork for the advancements to follow. These advancements include MIMO for NR, Improved Uplink Coverage, Enhanced Sidelink Communications, Positioning Enhancement, UE Power Saving, URLLC/IoT Enhancements, Integrated Access and Backhaul (IAB), and Non-Terrestrial Networks (NTN). These milestones propel the comprehensive development of 5G networks, advancing MIMO technology, power efficiency, communication reliability, positioning capabilities, and support for non-terrestrial networks. NR Rel-17 marked a pivotal milestone in cellular network evolution.

The journey of 3GPP Technology Trends continues into Rel-18, exploring cutting-edge topics such as the metaverse, RedCap devices, and the integration of communication and sensing within the same system or network (JCAS). The metaverse offers immersive digital experiences that transcend physical constraints, connecting people, places, objects, and information in real-time. RedCap devices, initially introduced in NR Rel-17, are set to support applications like wearables, smart grid technology, and industrial wireless sensors, with planned enhancements in Rel-18. AI and ML play a critical role in shaping the future of wireless communication, extending into the new radio air interface in Rel-18 and beyond.

As we look to the future, Rel-19 will see further expansion of AI/ML use cases, encompassing the air interface, RAN, and system architecture. Beyond that, Rel-20 will explore the possibilities of 6G, with AI and ML serving as integral components of the system. Advanced technologies, including distributed learning and deep AI integration within the network and devices, promise to significantly enhance system performance and usability.

Moreover, 3GPP remains adaptable to the ever-changing landscape of telecommunications. We may introduce specific frequency range designations for newly defined 5G-Advanced spectrums in the future, ensuring our commitment to meeting the evolving demands of the industry.

In conclusion, 3GPP continues to lead global technology trends, setting the stage for innovative connectivity, sustainable systems, and diverse modes of communication. Our dedication to minimizing resource usage, limiting environmental impacts, and increasing resource efficiency underscores our commitment to shaping the future of telecommunications and contributing to a more sustainable and interconnected world. We invite you to explore the comprehensive insights in this whitepaper of a data-driven mobile network era.

Appendix

Acronyms

AAU: Active antenna unit

AEE: Application service Energy Efficiency

AF: Application Function

AI: Artificial Intelligence

AI/ML: Artificial Intelligence and Machine Learning

AR: Augmented reality

ATG: Air-to-ground

BS: Base Station

BWP: Bandwidth Part

CDRX: Connected Mode Discontinuous Reception

CFAR: Constant False Alarm Rate

CRS: Cell-specific reference signals

CSI: Channel State Information

DAPS: Dual Active Protocol Stack

DCI: Downlink control information

DFT: Discrete Fourier Transform

DL: Down Link

DRX: Discontinuous Reception

DualUL: Dual Uplink

DSS: Dynamic Spectrum Sharing

GEO: Geosynchronous Orbit

HAPS: High-altitude platform stations

IAB: Integrated Access and Backhaul

ICAS: Integrated Communications and Sensing

IIoT: Industrial Internet of Things

IoT: Internet of Things

JCAS: Joint Communications and Sensing

KPI: Key performance indicators

LCM: Life Cycle Management

LEO: Low Earth orbit

LTE: Long Term Evolution

MBB: Mobile Broadband

MC: Mission critical

MIMO: Multiple Input and Multiple Output

mTRP: Multiple Transmission and Reception Point

ML: Machine Learning

MR: Mixed reality

MTI: Moving target indication

NF: Network Function

NG-RAN: Next Generation Radio Access Network

NPN: Non-Public Networks

NR: New Radio

Appendix

Acronyms

NTN: Non-Terrestrial Networks	RX: Radio Receiver
NW: Network	SDT: Small Data Transmission
NWDAF: Network Data Analytics Function	SIB: System Information Block
OFDM: Orthogonal Frequency Division Multiplexing	SIM: Subscriber Identity Module
OPEX: Operational expenditures	SLA: Service Level Agreement
PAPR: Peak-to-average-power	SNPN: Standalone Non-Public Network
PCC: Policy and Charging Control	SRS: Sound Reference Signals
PDCCH: Physical downlink control channel	SSB: Synchronization Signal Block
PDSCH: Physical downlink data channel	TCI: Transmission Configuration Indicator
PDU: Packet Data Unit	TRP: Transmission and Reception Point
PLMN: Public Land Mobile Network	TSC: Time-sensitive communications
PUCCH: Physical Uplink Control Channel	TSN: Time-sensitive networking
PUSCH: Physical Uplink Shared Channel	UAV: Unmanned Aerial Vehicles
QoE: Quality of experience	UE: User Entity
QoS: Quality of Service	UL: Uplink
RAN: Radio Access Network	URLLC: Ultra-reliable low-latency communications
RF: Radio Frequency	VR: Virtual Reality
RLM: Radio Link Mobility	WebXR: Web Extended Reality (Immersive)
RRC: Radio Resource Control	WUS: Wake-up signal
RTT: Round-trip time	XR: Extended Reality

Acknowledgements

5G Americas' Mission Statement: 5G Americas facilitates and advocates for the advancement of 5G and beyond throughout the Americas.

5G Americas' Board of Governors members include Airspan Networks, Antel, AT&T, Ciena, Cisco, Crown Castle, Ericsson, Liberty Latin America, Mavenir, Nokia, Qualcomm Incorporated, Samsung, Rogers Communications, T-Mobile USA, Inc., Telefónica, and VMware.

5G Americas would like to recognize the significant project leadership and important contributions of group leaders Dr. Christina Chaccour, Network Solutions Manager, Ericsson, and Orlett Pearson, Senior Specialist Standardization, Nokia, along with many representatives from member companies on 5G Americas' Board of Governors who participated in the development of this white paper.

The contents of this document reflect the research, analysis, and conclusions of 5G Americas and may not necessarily represent the comprehensive opinions and individual viewpoints of each particular 5G Americas member company. 5G Americas provides this document and the information contained herein for informational purposes only, for use at your sole risk. 5G Americas assumes no responsibility for errors or omissions in this document. This document is subject to revision or removal at any time without notice. No representations or warranties (whether expressed or implied) are made by 5G Americas and 5G Americas is not liable for and hereby disclaims any direct, indirect, punitive, special, incidental, consequential, or exemplary damages arising out of or in connection with the use of this document and any information contained in this document.

References

- 1 [Toward 5G-Advanced: overview of 3GPP releases 17 & 18 - Ericsson](#)
- 2 [Ericsson Reduced Capability \(RedCap\): NR Light software](#)
- 3 [The metaverse | Nokia](#)
- 4 [Why the metaverse-5G relationship is fundamental - Ericsson](#)
- 5 3GPP TR 23.700-60 Study on XR (Extended Reality) and media services (Release 18)
- 6 [eXtended Reality for NR \(3gpp.org\)](#)
- 7 Ericsson blog: "What is reduced capability (RedCap) NR and what will it achieve?"
- 8 3GPP RP-211574, "Revised WID on support of reduced capability NR devices", June 2021.
- 9 3GPP RP-213661, "Study on further NR RedCap UE complexity reduction", December 6 - 17, 2021
- 10 3GPP RP-232671, "Revised WID on Enhanced support of reduced capability NR devices", Sept 2023.
- 11 3GPP LTE and NR technical specifications and technical reports (e.g., TR 38.865, TR 38.875).
- 12 3GPP TR 22.837 Feasibility Study on Integrated Sensing and Communication (Release 19)
- 13 Chaccour, C., Soorki, M. N., Saad, W., Bennis, M., Popovski, P., & Debbah, M. (2022). Seven defining features of terahertz (THz) wireless systems: A fellowship of communication and sensing. *IEEE Communications Surveys & Tutorials*, 24(2), 967-993.
- 14 3GPP Technical report 22.840, Study on Ambient power-enabled Internet of Things, September 2023.
- 15 3GPP Technical report 38.848, Study on Ambient IoT (Internet of Things) in RAN, September 2023.
- 16 <https://www.3gpp.org/newsletter-issue-05-oct-2022>
- 17 RP-213599, "New SI: Study on Artificial Intelligence (AI)/Machine Learning (ML) for NR Air Interface" 3GPP RAN #94-e
- 18 Study on Artificial Intelligence (AI)/Machine Learning (ML) for NR air interface TR 38.843
- 19 [<https://www.nokia.com/blog/aiml-unleashes-the-full-potential-of-5g-advanced/>]
- 20 Chaccour, C., Saad, W., Debbah, M., Han, Z., & Poor, H. V. (2022). Less data, more knowledge: Building next generation semantic communication networks. *arXiv preprint arXiv:2211.14343*.
- 21 <https://www.ericsson.com/en/reports-and-papers/white-papers/trustworthy-ai>
- 22 Referenced by 5G Americas Member (Qualcomm)
- 23 <https://public.wmo.int/en/media/press-release/july-2023-set-be-hottest-month-record>
- 24 <https://www.latimes.com/environment/story/2023-08-02/heat-from-climate-change-affected-6-5-billion-people-in-july>
- 25 3GPP TS 28.310 Management and orchestration; Energy efficiency of 5GB (Release 18)
- 26 3GPP TR 38.864 Study on network energy savings for NR (Release 18)