CELLULAR IoT IN THE 5G ERA

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ABSTRACT

Almost every industry can be transformed with cellular IoT. The connectivity needs of all industries can be addressed by four multi-purpose IoT segments, which efficiently co-exist in one 5G network. These segments are Massive IoT, Broadband IoT, Critical IoT and Industrial Automation IoT. This paper presents a clear evolution plan for addressing all 5G-IoT use cases, from basic to the most complex, in a cost-efficient, smooth and future-proof way.

KEYWORDS: *IoT, 5G, Ericsson, LTE.*

INTRODUCTION

The 3GPP-based global cellular networks are connecting things-to-things and things-to-persons across borders. Many industries are experiencing the benefits of cellular IoT, for example in the consumer electronics, automotive, railway, mining, utilities, healthcare, agriculture, manufacturing and transportation sectors.

There are over 1 billion cellular IoT connections today in 2020, and Ericsson forecasts around 5 billion connections by 2025[1].

With 5G in the market, almost every industry is exploring the potential of cellular connectivity for fundamentally transforming businesses. In some regions, governments are encouraging adoption of IoT via direct and indirect incentives to promote sustainability, innovation and growth.

Mobile network operators (MNOs) have long been successful in the mobile broadband (MBB) market and are also best positioned to create and capture value in the emerging IoT market with their regional and global footprint. Unlike MBB, the IoT usage scenarios have extremely diverse requirements.

For maximizing returns on investments, MNOs will have to systematically evolve cellular networks for addressing the needs of the rapidly increasing IoT use cases across multiple industries. This paper shows a clear evolution plan for addressing all 5G-IoT use cases, from basic to the most complex, in a cost-efficient, smooth and future-proof way.

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The wireless connectivity across various industries can be grouped into four distinct sets of requirements. To address these requirements, Ericsson has defined four IoT connectivity segments [2]: Massive IoT, Broadband IoT, Critical IoT and Industrial Automation IoT, as illustrated in Figure 1. Each IoT connectivity segment addresses multiple use cases in multiple industries.

Today, 4G networks are supporting Massive IoT based on Cat-M/NB-IoT and Broadband IoT based on LTE. Massive IoT continues to evolve with Cat-M/NB-IoT access in 5G-enabled networks, and Broadband IoT is being further enhanced with the introduction of 5G radio and core networks. With powerful, ultra-reliable and/or ultra-low latency capabilities, 5G networks are going to enable Critical IoT for time-critical communications. To seamlessly integrate 5G networks with Ethernet-based industrial wired communications networks, 3GPP has standardized additional capabilities that would be offered by Industrial Automation IoT connectivity.

The four IoT connectivity segments can co-exist in one 5G network, whether deployed for public or non-public access. Some devices may need multiple IoT connectivity segments for executing one or more use cases, for example, an autonomous vehicle with rich requirements [3].

Massive IoT

Massive IoT connectivity targets a large number of low-cost, narrow-bandwidth devices that infrequently send or receive small volumes of data. These devices can be situated in challenging radio conditions requiring extreme coverage and may rely solely on battery power supply. LTE-M and NB-IoT have been co-existing with LTE in 4G networks since 2017 and fulfill all 5G requirements from ITU and 3GPP for massive machine type communications [4-6].

LTE-M extends LTE to support machine-type communications, including access for the low-complexity device category series named Cat-M. NB-IoT is a standalone radio access technology based on the fundamentals of LTE. At the start of 2020, over 120 commercial networks supported NB-IoT and Cat-M access globally [7]. with millions of commercial users [1]. Forecasts indicate more than 2.5 billion connections will be in place by 2025 [1]. Commercial devices span various types of meters, sensors, trackers and wearables in many different industries, including utilities, automotive, transport, logistics, agriculture, manufacturing, healthcare, warehousing and mining [8].

There are two dominating types of Cat-M/NB-IoT modem in the market: single-mode NB-IoT modems, which are suitable for ultra-low cost devices, and dual-mode Cat-M1/NB-IoT modems, suitable for diversity of use cases with low-cost devices. The dual-mode modem combines the best attributes of the two technologies in terms of throughput, coverage, mobility, voice support and device positioning, as summarized in Figure 2.

The dual-mode devices use Cat-M1 mode in Cat-M1 signal coverage and can switch to NB-IoT access when out of Cat-M1 coverage. Cat-M1 has two coverage extension (CE) modes in the 3GPP standard: a mandatory CE mode A (for up to 10dB CE) and an optional CE mode B (for up to 20dB CE, on a par with NB-IoT).

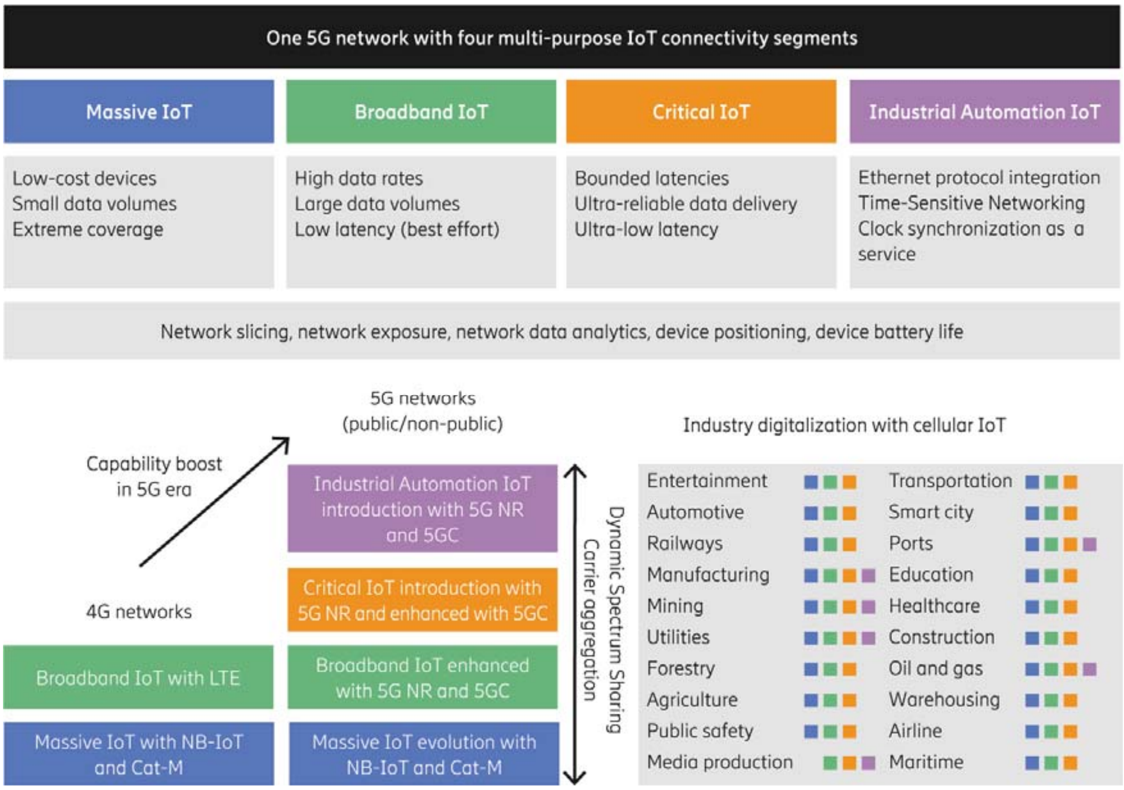
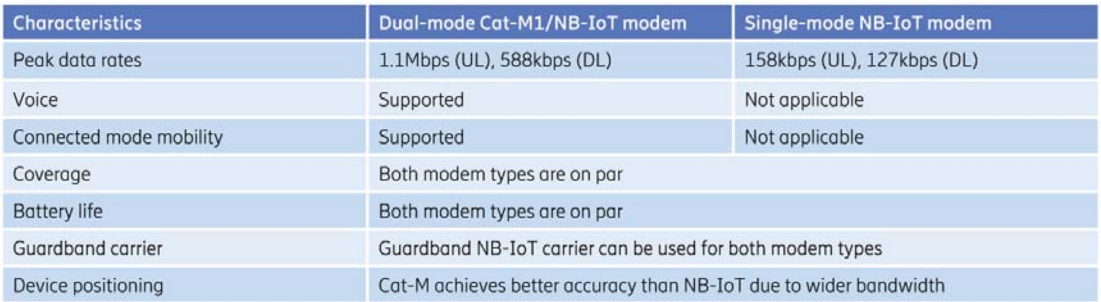


Figure 1. Industry digitalization with cellular IoT in the 5G era



Characteristics	Dual-mode Cat-M1/NB-IoT modem	Single-mode NB-IoT modem
Peak data rates	1.1Mbps (UL), 588kbps (DL)	158kbps (UL), 127kbps (DL)
Voice	Supported	Not applicable
Connected mode mobility	Supported	Not applicable
Coverage	Both modem types are on par	
Battery life	Both modem types are on par	
Guardband carrier	Guardband NB-IoT carrier can be used for both modem types	
Device positioning	Cat-M achieves better accuracy than NB-IoT due to wider bandwidth	

Figure 2. Comparison of Massive IoT modems (assuming half-duplex FDD and 3GPP Rel-16)

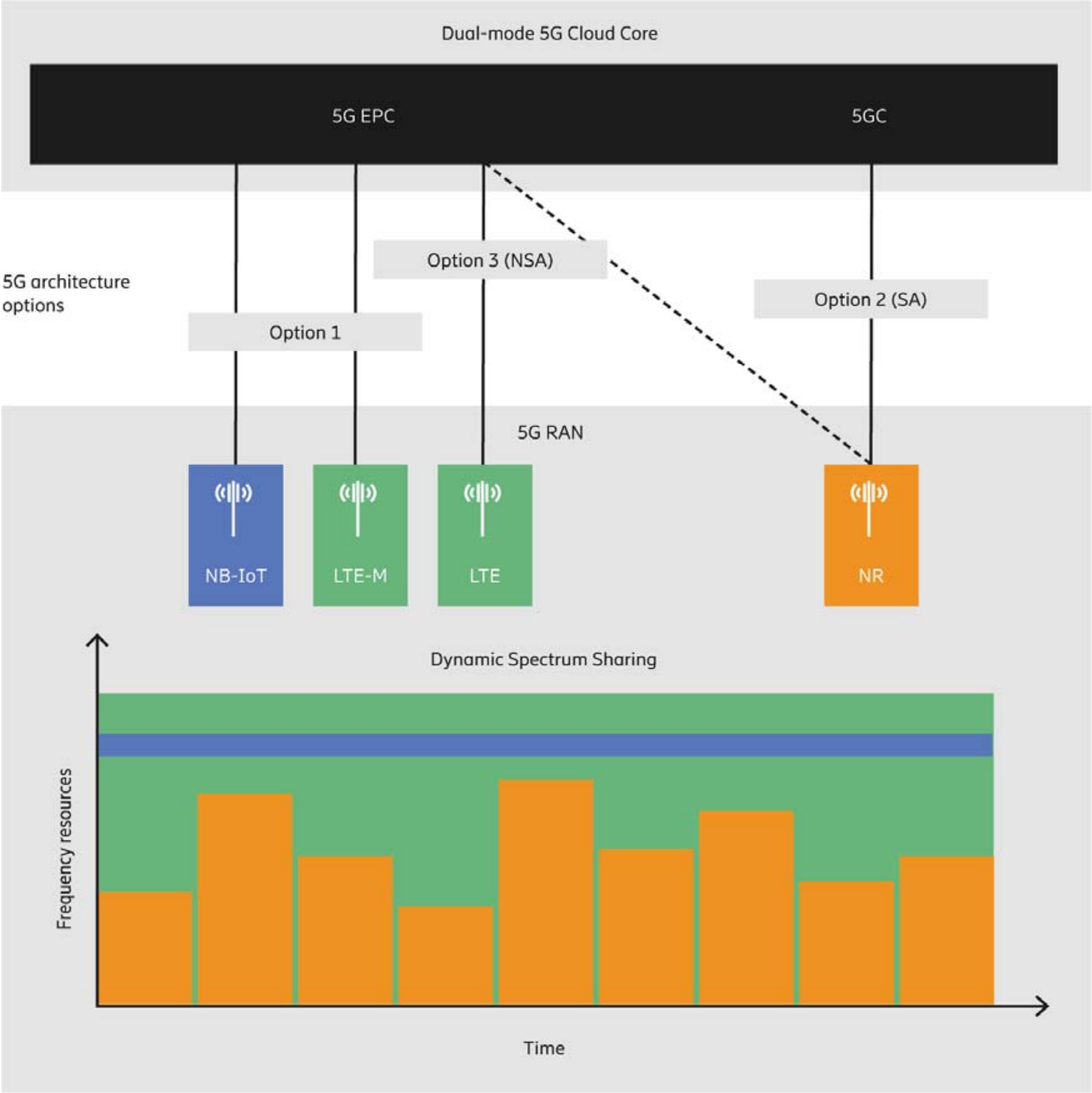


Figure 3. Cat-M and NB-IoT have a smooth and future-proof evolution in the 5G era

The performance benefits of Cat-M1 vanish when using CE mode B, due to fundamental trade-off between coverage and throughput. There is major spectrum resource consumption due to hundreds of subframe repetitions in CE mode B. Provided that the dual-mode modem can switch to NB-IoT access and leverage guardband NB-IoT carriers in extremely poor coverage scenarios, there is no commercial advantage in using CE mode B.

The peak data rates in Figure 2 are valid for commercially available Cat-M1 modems, which have 1.4MHz bandwidth. The 5MHz bandwidth Cat-M modem (known as Cat-M2) and the full-duplex operation mode have not been included, since these are currently not realized in the ecosystem due to the price-sensitive Massive IoT device market and their negative impact on device power consumption.

Cat-M1 and NB-IoT have a smooth and future-proof evolution in 5G networks when combined with Dynamic Spectrum Sharing [9], dual-mode 5G Cloud Core [10] and continued standardization in 3GPP [6]. NR is being deployed in the new 5G frequency bands, as well as in the 4G frequency bands, where Cat-M1, NB-IoT and LTE devices are operational.

With Dynamic Spectrum Sharing, all technologies co-exist efficiently, as shown in Figure 3.

Dual-mode 5G Cloud Core includes 5GC and 5G EPC. The existing and future Cat-M1/NB-IoT devices can connect to 5G EPC (known as 5G architecture Option 1) [11]. 3GPP Rel-16 is also specifying an option for connecting Rel-16 compatible Cat-M/NB-IoT devices to 5GC; however, this would be challenging for the cost-sensitive Massive IoT market, due to not only increased complexity, but also market fragmentation.

Broadband IoT

Broadband IoT connectivity adopts the capabilities of MBB for IoT to provide much higher data rates and lower latencies than Massive IoT, while enabling additional capabilities for IoT, such as extended device battery life, extended coverage, enhanced uplink data rates and enhanced device positioning precision.

Broadband IoT is relevant for all industries. There are more than 500 million Broadband IoT users in 2020, primarily with LTE access [1]. Commercial usage today is dominated by personal cars, commercial vehicles, trains, wearables, gadgets, cameras, sensors, actuators and trackers. These devices can leverage MBB connectivity; however, their requirements and traffic patterns are sometimes very different from typical MBB usage. For example, traffic patterns can be more uplink-heavy and/or periodic, while requirements on battery life, signal coverage and device positioning can be more challenging than for MBB.

LTE has a range of device categories (LTE Cat-1 and above) with wide bandwidths well suited for diverse, wide area use cases. LTE achieves Gbps data rates and RAN (best effort) latency down to around 10ms (round-trip time). With the introduction of 5G NR in old and new spectrum, Broadband IoT is set to enable tens of Gbps.

The signal coverage per base station can be enhanced if requirements are relaxed on data rate and latency; for example, an LTE device can dynamically switch between LTE and LTE- M access depending on the signal coverage. Device battery life can be significantly improved, leveraging user-specific traffic patterns. Network-based device positioning accuracy can be improved with NR since the positioning accuracy typically depends on signal bandwidth, and NR can operate in much wider bandwidths than LTE.

Uplink data rate is boosted with high-order modulation, multi-antenna transmission [12] and carrier aggregation. When using TDD, uplink and downlink capacities are fundamentally dependent on the TDD transmission pattern. Typically, MNOs have to agree on a common static TDD configuration in order to avoid interference according to regional regulations.

The TDD configurations deployed today are often downlink-heavy to optimize for MBB usage. However, with uplink-heavy IoT usage taking off, MNOs will have to reconsider mutual agreements on TDD configurations in order to achieve a good balance between uplink and downlink capacity, as well as low latency.

One of the 5G fundamentals is tight interworking between LTE and NR that allows 5G modems to simultaneously access LTE and NR carriers, known as non-standalone (NSA) 5G (Option 3 in Figure 3). A 5G-capable modem connects with NR (when in NR coverage) to experience a boost in performance while maintaining its LTE connection. This approach ensures that 5G deployments deliver value for wide area MBB and IoT users from day one [3].

Standalone (SA) 5G (Option 2 in Figure 3) is the long-term target architecture, as well as the ideal choice for usage scenarios with localized coverage needs (e.g. local industrial deployments) in the near term, from both performance and complexity standpoints.

To broaden the use cases addressable with NR, 3GPP Rel-17 will diversify NR device capabilities by introducing support for relatively less-complex modems with power-saving capabilities as part of the work on reduced capability NR devices; [13] example uses include industrial sensors and wearables.

Critical IoT

Critical IoT connectivity is for time-critical communication. It enables data delivery within desired latency bounds. It includes 5G's most powerful capabilities for ultra-high reliability and/or ultra-low latency communication at a variety of data rates. The reliability here is defined as the probability of successful data delivery within a specified time duration [14]. In contrast to Broadband IoT, which achieves low latency on best effort basis, Critical IoT can deliver data within specified latency bounds with required guarantee levels, even in heavily loaded networks.

Typical use cases with demanding combinations of reliability, latency and data rates include AR/VR, autonomous vehicles, mobile robots, real-time human machine collaboration, cloud robotics, haptic feedback, real-time fault prevention, and coordination and control of machines and processes [14-17]. Such use cases are relevant in almost every industry. Some industries are piloting these applications with 5G, for example, in the entertainment, automotive, manufacturing, mining, harbor, airport, construction and utilities sectors.

To enable demanding Critical IoT use cases, all components (networks, devices and applications) may have to step up in terms of latency and reliability. From a pure network perspective, end-to-end latency is the sum of individual latency contributions from radio, transport and core networks, and the overall reliability cannot be higher than the reliability of the weakest link.

5G NR and 5GC have been standardized for ultra-reliable and low latency communication (URLLC) from day one (Rel-15) with further evolution in Rel-16 and Rel-17 [6]. With URLLC capabilities, 5G NR can achieve latencies down to 1ms and reliability up to 99.9999 percent. Latency within the core network is typically below 1ms. The transport network can be a major contributor to the end-to-end latency. Transport network latency varies widely between regions, depending on distances and the transport solutions used. A general trend is that transport latency is being optimized by higher availability of fiber and fewer router hops. As an example, the round-trip time between 2 cities in a European country (city distance 1,300km) is today just 16ms (theoretical minimum optical fiber latency is 13ms), which is less than half of the latency of 5 years ago.

Edge computing is needed to reduce transport latency for demanding Critical IoT use cases. Distributed anchor points, local break-out or on-premise full-core deployments are key scenarios to achieve low to ultra-low latency, as illustrated in Figure 4 with typical latencies. Core user plane distribution reduces latency by keeping the user traffic as local as possible and is therefore typically distributed on more local sites than control plane network functions. For use cases that require very high reliability, the core control plane and network exposure can be further distributed to limit network disturbances, even in the rare event of a major incident or disaster scenario. Real-time mobility, group management and network monitoring could also drive decentralized control plane to optimize for reduced latency. Core control plane and network exposure are typically recommended to be located at the same site to avoid so-called signaling flow tromboning. Another driver for edge computing is data offload, which is beneficial for both MBB and IoT [18, 19].

On-premise, full-core deployment enables dedicated resources, ultra-low latency and ultra- reliability, providing autonomous operation with local subscriber data. The local area network can also be interconnected with a public network, allowing mobile IoT devices to roam between the networks.

Critical IoT can be demanding in terms of bandwidth, since any major gains in reliability and latency typically require substantial spectrum resources. NR operates in a wider range of frequencies with larger bandwidths and far greater capabilities than LTE, which makes NR the technology of choice. LTE may never be enhanced for Critical IoT due to multiple factors, such as the timing of commercial use cases, the continued capability expansion of NR URLLC in 3GPP, the momentum on NR and the available option of software upgrading existing LTE sites with NR (in the LTE spectrum bands).

With flexible spectrum assets, MNOs are best positioned to provide Critical IoT coverage not only in wide area deployments, but also for local industrial deployments. NR enables URLLC in all 5G (FDD/TDD) frequency bands [2]. Figure 5 illustrates examples of spectrum band combinations, along with key characteristics of different bands in terms of URLLC capacity and coverage for addressing wide and local area users. Considering that there is very limited bandwidth in sub-1GHz bands, these should be leveraged for high-value, wide area users.

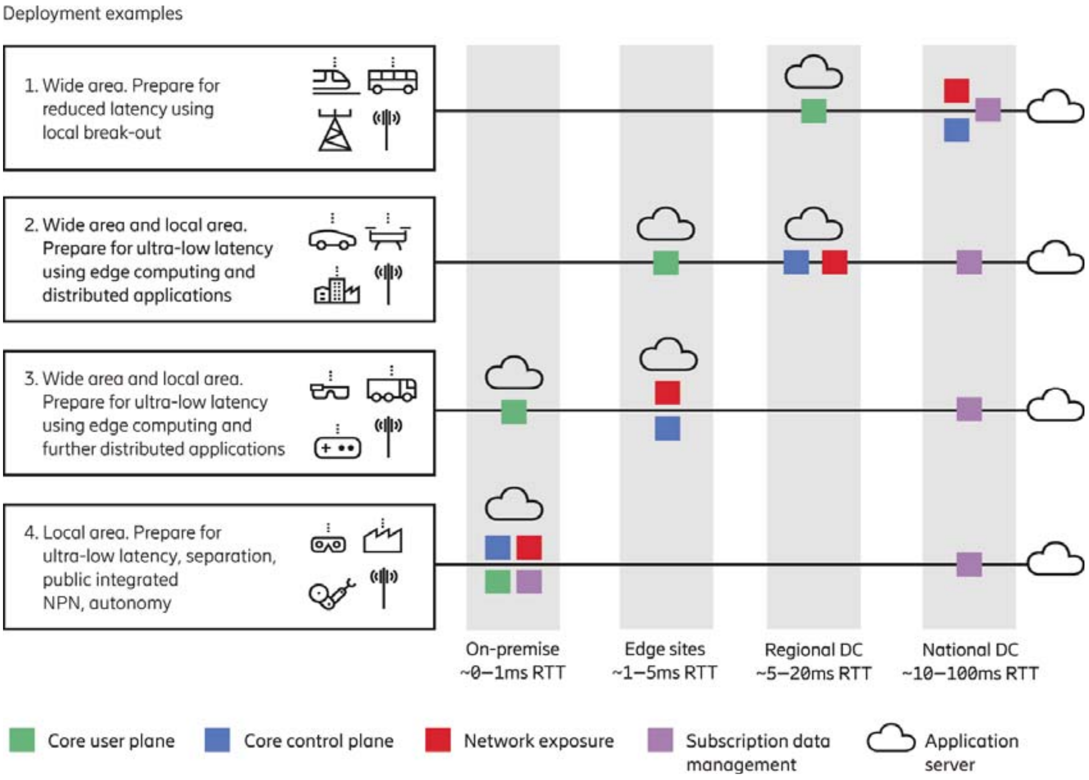


Figure 4. Core network deployment examples to support Critical IoT use cases

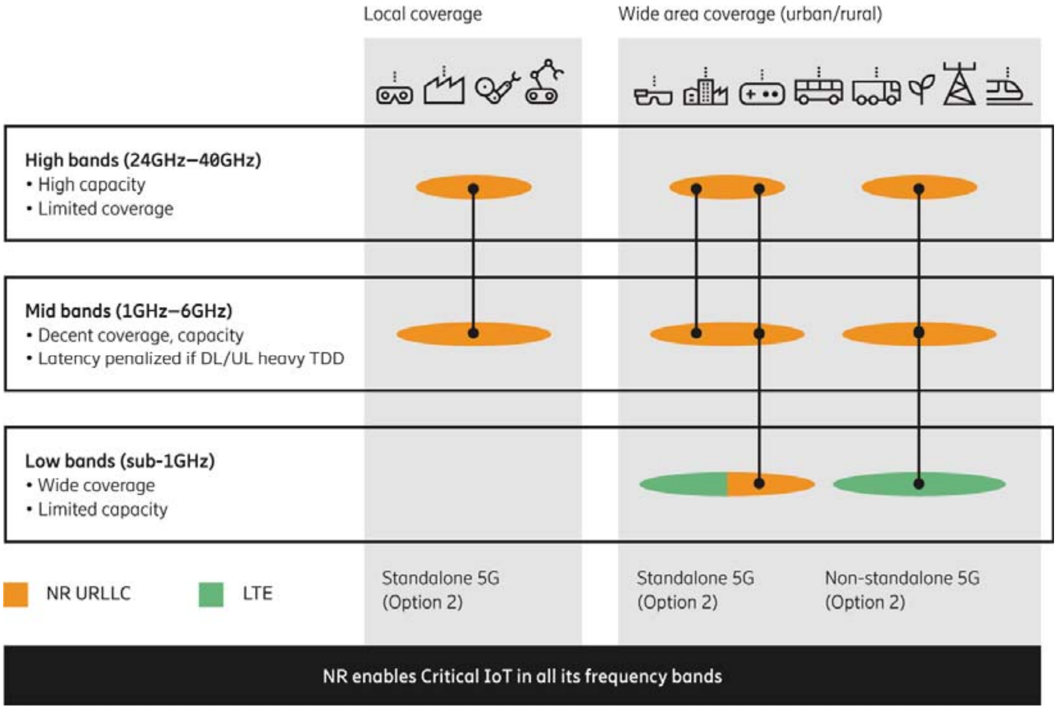


Figure 5. MNOs are best positioned to enable Critical IoT with their flexible spectrum assets

When using TDD, RAN latency is fundamentally dependent on TDD transmission patterns. A downlink- or uplink-heavy TDD configuration negatively impacts latency, especially in sub-6GHz [2, 20].

SA 5G is ideal for fulfilling the challenging Critical IoT requirements. 5GC is better than 5G EPC in terms of ultra-reliability mechanisms, advanced service differentiation, flexible edge computing, network data analytics, advanced Quality of Service (QoS), Ethernet connectivity, and end-to-end network slicing capabilities which can be important for critical use cases. Provided that LTE is also not enhanced for Critical IoT, NSA 5G does not offer full potential for URLLC from both radio access and core network perspectives. For use cases with local coverage needs, such as local industrial sites, NSA 5G deployments would not be beneficial, as discussed earlier. However, in wide area coverage, 5G deployments would be initially NSA and could leverage NR user plane capabilities for URLLC to enable less demanding Critical IoT use cases. Over time, NSA 5G deployments will transition to SA 5G, achieving the full potential of Critical IoT in wide areas.

Industrial Automation IoT

Industrial Automation IoT aims at enabling seamless integration of cellular connectivity into the wired industrial infrastructure used for real-time advanced automation. It includes capabilities for integrating 5G systems with real-time Ethernet and Time-Sensitive Networking (TSN) used in industrial automation networks.

Cellular connectivity offers great benefits in term of mobility, flexibility, cost-cutting and digitalization compared to wired communication. However, in some industrial deployments, wired networks may migrate to wireless connectivity in such a manner that different parts of an industrial system may switch to wireless connectivity gradually over time. Even if an industrial system is within 5G coverage, certain components of the system might stay connected with cables due to various factors; for example, not having a major need for a wireless solution, having long life cycles, or having extreme performance needs that are beyond 5G's current capabilities (for example, micro-second level deterministic latency). It is important that 5G supports seamless integration into the current and evolving wired infrastructure [21].

A number of industries use wired communication for advanced automation; for example, the mining, utilities, construction, ports, oil and gas sectors. There are several industrial Ethernet solutions supporting deterministic communication for real-time automation; for example, PROFINET, EtherCAT, Sercos, EtherNet/IP, Powerlink and Modbus. 3GPP has standardized support for Ethernet sessions in Rel-15. In Rel-16, Ethernet header compression has been introduced for spectral efficiency. Reliable data delivery within strict latency bounds is achieved with 5G URLLC (enabled by Critical IoT). With Rel-16, a 5G virtual network can be set up over a 5G system providing 5G LAN-type service (e.g. VLAN) by which on-demand connection of UE to UE (user equipment), multicast and broadcast private communications is supported between members of the same 5G virtual network [22]. In order to overcome challenges with the fragmented industrial Ethernet market, a common open standard is emerging: Ethernet with TSN support [23]. TSN is designed for diverse QoS requirements, including both deterministic and best-effort latencies. TSN was standardized within IEEE and its profile for industrial automation is being developed jointly by IEC and IEEE. To enable seamless integration of 5G with TSN, 3GPP has standardized a feature set in Rel-16 as part of the Industrial IoT work item.

The 5G-TSN integration is illustrated in Figure 6, where a 5G system is integrated into a TSN network as a bridge [24]. TSN Translators (TT) are introduced in the 5G system for the user plane and control plane. The user plane translators are placed at the UPF (Network TSN Translator, NW-TT) and at the UE (Device Side TSN Translator, DS-TT).

TSN is managed centrally by the TSN Central Network Controller (CNC). A TSN Application Function (AF-TT) is placed at the 5G control plane to expose 5G system capabilities (e.g. list of ports at DS-TT and NW-TT and the transfer delay between them) to the TSN CNC, for configurating and scheduling TSN flows across the 5G system bridge. Hold and forward (de-jitter) buffering at NW-TT and DS-TT is used for delivering traffic streams with deterministic latency based on the time-aware scheduling information obtained from CNC.

The TSN nodes are time-synchronized with a master clock using the generalized Precision Time Protocol (gPTP) [IEEE 802.1AS] [24]. The 5G system bridge can either support forwarding of the gPTP synchronization information or use its internal clock as a grandmaster for providing a time-reference to the TSN nodes. The 5G system can also deliver clock synchronization as a service to industrial applications that operate synchronously; for example, synchronized coordination between multiple controllers in a system.

Key enablers for cellular IoT

Network slicing

Network slicing allows creation of multiple logical networks using a common shared network infrastructure across radio, core and transport networks, which is essential for cost efficiency, scaling and flexibility [25]. An operator can either deploy end-to-end network slices per cellular IoT segment serving consumers and multiple enterprises, or create separate network slices for different enterprises where each slice may include multiple IoT connectivity segments, as shown in Figure 7.

A network slice includes required network resources configured and connected across radio, transport and core network. The resources can be physical or virtual, either dedicated to a slice or shared between slices. The slices can be dynamically created on an as-needed basis. A slice service Orchestrator automates the creation, modification and deletion of the individual slices, while also handling the assignment of the underlying resources. By continuously monitoring slice performance, the Orchestrator is able to accurately configure and adjust slice resources.

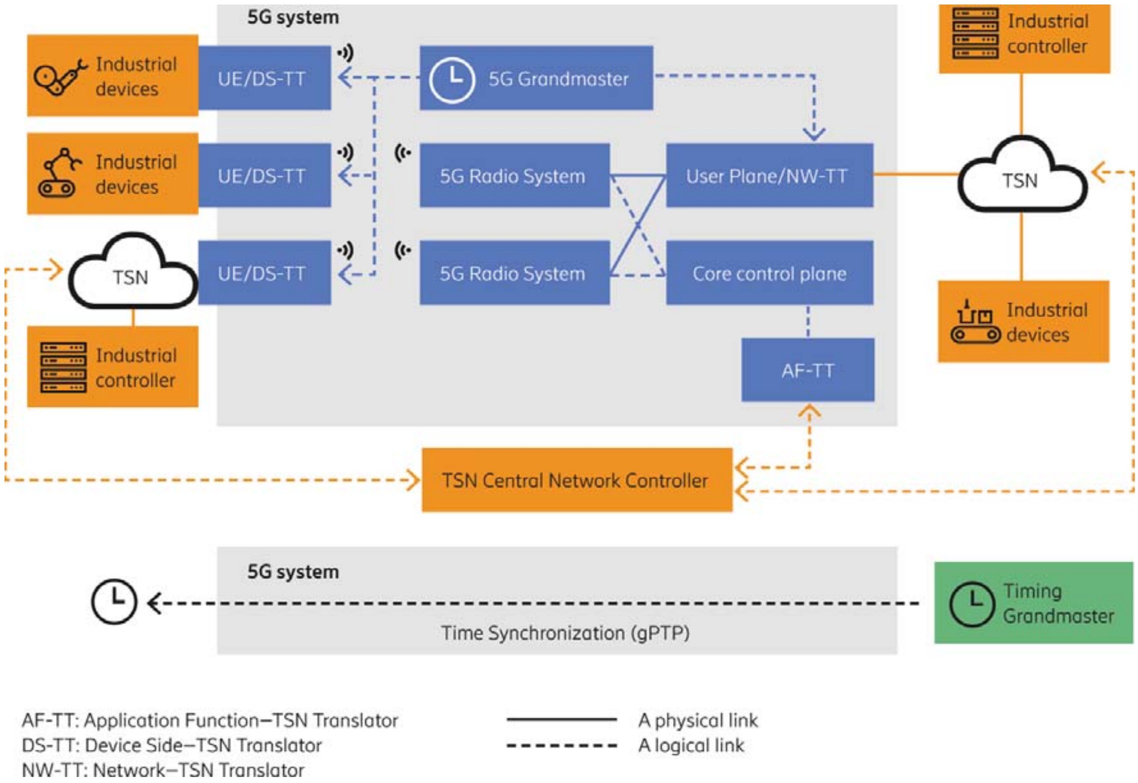


Figure 6. 5G-TSN integration and clock synchronization as a service

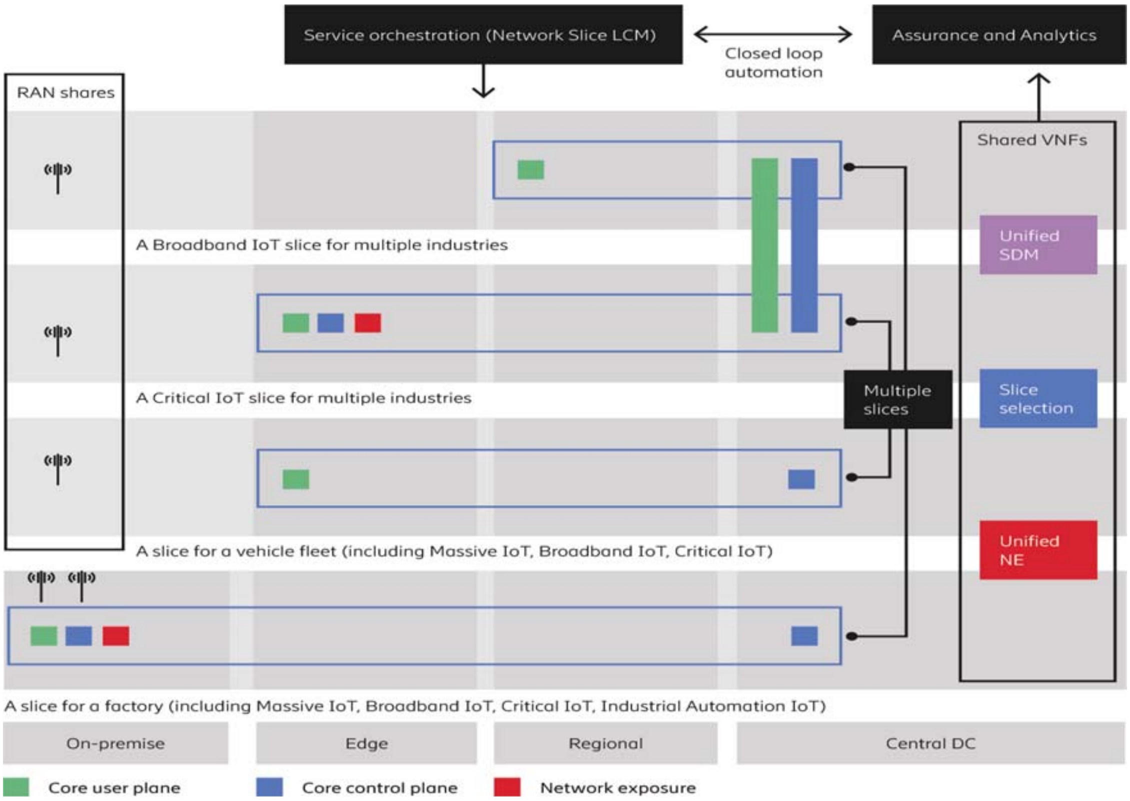


Figure 7. Dynamic network slicing with closed-loop life cycle management

Network exposure

Network exposure with RESTful APIs securely exposes network capabilities, enabling network programmability. The main types of service exposure for IoT connectivity are:

- network monitoring, including network publishing information as real-time statuses, event streams, statistics and analytics insights
- device-related APIs for provisioning, onboarding, triggering, device and connectivity management, connectivity monitoring and location information
- network control and configuration, involving control services that request configuration changes including network resource management, group management and application function influencing traffic routing (local breakout)
- payload interfaces for small data delivery, non-IP data delivery and background data transfer

Network Data Analytics

Network Data Analytics leverage the consolidated data from status monitoring of the network, applications and devices for extracting valuable network insights and optimizing the network for improved performance. The Network Data Analytics Function has been introduced in the 5G system architecture in 3GPP Rel-15 [26] with enhancements in Rel-16, which enables:

- the detection of misbehaving devices by observing abnormal traffic patterns;
- deriving a suitable policy for background data transfer by analysis of, for example, traffic volume, congestion level, load status information in the specific network area;
- dynamic traffic routing to the edge by analyzing network status (for example load information based on time and space), which service is available at the edge, and the device's location;
- assisting applications with predictable network performance by analyzing speed, direction and location of devices and network status;
- network automation by collecting and analyzing the status of network slices and assisting the network slice Orchestrator to scale up or scale down the resources for IoT network slices.

SIM flexibility

Traditionally, the cellular network subscription credentials are provided to devices using physical SIM cards. However, it can be difficult to physically access the SIM cards in various IoT devices after they are produced and sold. During production of devices, it is often not known which cellular subscription(s) would be used and the subscription(s) may also change multiple times during the device's life. To address this, GSMA has specified an Embedded SIM (eSIM) solution for remote provisioning of the subscriber credentials without physically touching the device [27]. For optimizing device cost, form factor and power consumption, an Integrated SIM (iSIM) solution embedded into a device's chipset hardware exists in the market that builds on the eSIM functionality [28].

3GPP Rel-16 has standardized non-SIM authentication (a certificate-based EAP-TLS authentication principle) for 5GC [29]. The non-SIM authentication is useful for non-public networks where devices may not need subscription. A device accessing both public and non-public networks may still use SIM functionality for the public network and the non-SIM feature for accessing the non-public network. The non-SIM authentication is also attractive for low-cost NB-IoT and Cat-M1 devices, and is therefore also relevant for 5G EPC.

Conclusion

MNOs are uniquely positioned to transform almost every industry with cellular IoT. The connectivity needs of all industries are addressed with four multi-purpose IoT segments which co-exist efficiently within one 5G network, leveraging complementary capabilities of multiple radio access and core network technologies, with cost-efficiency, flexibility and scale.

Firstly, Cat-M and NB-IoT are formally 5G Massive IoT technologies with global coverage and a clear evolution plan. There is tremendous potential for realizing truly Massive IoT with continued investment in the existing Cat-M1 and NB-IoT ecosystem.

Secondly, Broadband IoT has a natural head start with 4G and initial 5G MBB roll-outs. Its long-term success depends on addressing the IoT-specific challenges, such as signal coverage, device battery life, device positioning, uplink-heavy traffic and diversifying capabilities of 5G devices.

Thirdly, almost every industry has time-critical communication needs. 5G powered with URLLC capabilities is the most suitable wireless technology for realizing Critical IoT. However, a systematic end-to-end co-development in the ecosystem is essential for realizing Critical IoT gradually over time.

Finally, Industrial Automation IoT with support for real-time Ethernet and TSN is an enabler for seamless integration of 5G into the existing and evolving industrial deterministic networks used for real-time automation. These capabilities, in conjunction with other IoT segments, enable the Industry 4.0 revolution to meet its promise for full digitalization.

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