5G reduced capability devices

White paper

Contents

Executive summary

Internet of things (IoT) refers to the interconnection and autonomous exchange of data between devices. Three main IoT categories include massive IoT, critical IoT and broadband IoT. In addition, the industry has identified mid-range IoT use cases that are beyond the capabilities of massive IoT devices yet do not require broadband or critical types of services. Examples of these use cases include industrial wireless sensors, video monitoring and wearables such as smart watches and medical monitoring devices. These use cases will benefit from having a new device type that is lower in cost compared to high-end broadband and critical IoT devices. Furthermore, device designs supporting compact form factors are an important requirement for these use cases.

3GPP in Release 17 of the 5G standard (hereafter Rel-17) started standardization development work for reduced capability (RedCap) NR (5G new radio) devices. In this white paper, we provide an overview of the new device type and describe new complexity reduction and power saving features being introduced to support mid-range IoT use cases. Our analysis shows that significant complexity reduction can be achieved. When compared to reference Rel-17 NR devices, it is seen that a total complexity reduction of approximately 70% for FR1 (FDD and TDD) and 50% for FR2 (TDD only) can be achieved.[1]

In addition, the white paper presents network coverage analysis to show the impact from the introduction of RedCap devices. Coverage analysis based on typical NR deployment scenarios and target cell edge data rates shows that coverage compensation is generally not needed despite the performance loss from complexity reduction features.

Similarly, network capacity analysis shows that the impact to system spectral efficiency and capacity is minor when the system is not heavily loaded. There is also only minor impact to the performance of enhanced mobile broadband (eMBB) users.

Rel-17 specification work for RedCap devices is targeted to be completed by September 2022. Commercial deployment may be expected 18–24 months after completion of the specifications.

The evolution of RedCap devices will continue with Rel-18, which is the first release of 5G-Advanced. Rel-18 content can be grouped into four areas as shown in Figure 1: Experience (providing new levels of experience), Extension (extending networks into new areas), Expansion (expanding mobile networks beyond connectivity) and Excellence (providing excellent operational support). Providing further complexity reduction in FR1 bands, the goal is to introduce lower-tier devices between massive IoT and Rel-17 RedCap devices, which will be an important part of the Extension block of features.

1 FDD stands for "frequency division duplex" and TDD for "time division duplex". FR1 and FR2 represent the two frequency ranges in 5G. FR1 is sub-6 GHz spectrum and FR2, mmWave. Bandwidths include 5–100 MHz (FR1) and 50/100/200/400 MHz (FR2).

Figure 1. 5G-Advanced evolution in four areas

5G IoT and reduced capability devices

Internet of Things (IoT) refers to the interconnection and the autonomous exchange of data between devices and can also be described as a network of physical objects that are connected and exchanging data between themselves via the internet. IoT use cases can be grouped into three categories.

Massive IoT: This refers to IoT use cases or applications that are delay-tolerant and require low data rates. Massive IoT requires low-cost devices, devices with low energy consumption for extended battery life, extended network coverage, and support of massive numbers of devices in the network. Example use cases include asset tracking, telematics, remote monitoring, smart grid and smart city applications. These applications are supported using LTE-M (long-term evolution for machines) and Narrowband IoT (NB-IoT) based on 4G cellular technology [1]. LTE-M is intended for IoT applications requiring higher data rates and can support voice and video services, while NB-IoT can provide very deep coverage and support low-cost devices.

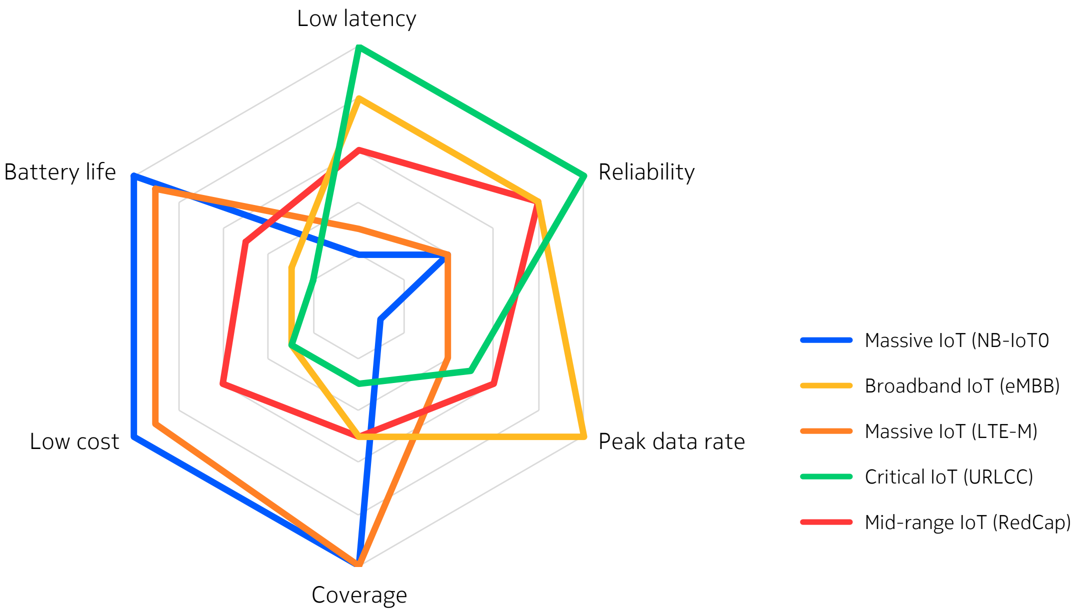
Critical IoT: This refers to IoT use cases or applications that require time-critical data delivery with strict delay constraints and high reliability. Example use cases include factory automation, industrial control, robotics, augmented reality and virtual reality. In 5G NR, these applications are supported using ultra-reliable low-latency communication (URLLC) features. These features have been designed to deliver very high reliability (99.999% uptime) with very low delay (~1 ms end-to-end). Low power consumption, however, is not critical for this IoT category.

Broadband IoT: This refers to IoT use cases or applications that require high data rates and lower delay that are typical of mobile broadband services. Example use cases include industrial gateways, hot spots, and wearables. In general, broadband IoT devices have capabilities similar to consumer mobile broadband devices. For instance, 5G industrial gateways can deliver peak data rates of 4.2 Gbps in the downlink (DL) and 0.45 Gbps in the uplink (UL).

In addition to the above categories, the industry has identified mid-range IoT use cases that are beyond the capabilities of massive IoT devices yet do not require broadband or critical services. Examples of these use cases include industrial wireless sensors, video monitoring and wearables such as smart watches and medical monitoring devices. These use cases will benefit from having a new device type that is lower in cost compared to high-end broadband and critical IoT devices. Furthermore, device designs supporting compact form factors are an important requirement for these use cases. The device requirements for the various IoT categories are illustrated in Figure 2.

Furthermore, ambient power-enabled IoT (also referred to as passive IoT) is being considered in 3GPP. Passive IoT refers to devices without battery or with limited energy storage that are powered by energy harvesting (e.g., from radio waves, light and motion). Examples include radio frequency identification (RFID) tags and near-field communication (NFC) smart cards. Passive IoT is not meant as a replacement to LTE-M and NB-IoT, but to address massive IoT market segments requiring ultra-low power consumption and ultra-low device cost. In the Service and System Aspects group, a study on ambient power-enabled IoT has been approved. The study aims to first study use cases and potential service requirements for passive IoT and then to perform gap analysis between passive IoT and existing requirements. Further studies will be undertaken by the RAN plenary in Rel-19 to identify deployment scenarios and design targets such as coverage, data rate, power consumption, cost and positioning accuracy.

Figure 2. IoT device requirements



In light of the above, 3GPP in Rel-17 started standardization development work for RedCap NR devices. The goal is to deliver lower-cost IoT devices that satisfy the design requirements for mid-range IoT use cases as provided in Table 1. This will allow important categories of use cases such as wearables, industrial sensors and video transmission to be served by lower-cost NR devices thus enabling cost-effective IoT solutions to be deployed in various vertical industries. The design must also support compact form factors. Core specifications to support RedCap devices were completed in March 2022, while performance-related specifications are expected to be completed by September 2022. Commercial deployment may be expected 18–24 months after completion of the specifications.

Table 1. Requirements for NR IoT use cases

Specifications	Critical IoT	Massive IoT	Mid-range IoT
Latency	1 ms	10 seconds	5–10 ms for safety reports, 100 ms for others
Reliability	99.999%	99–99.9%	Up to 99.99%
Peak data rates	N/A	LTE-M: 2.4 Mbps DL, 2.6 Mbps UL NB-IoT: 127 Kbps DL, 159 Kbps UL	Up to 150 Mbps DL, 50 Mbps UL
Battery life	N/A	10 years	1–2 weeks for wearables, several years for industrial sensors
Coverage	N/A	164 dB (maximum coupling loss)	Same as 5G eMBB
Frequency range support	FR1, FR2	FR1	FR1, FR2
Core network support	5GC	EPC and 5GC (for devices supporting N1 mode)	5GC – Standalone
Use case examples	Factory automation, industrial control, robotics, remote surgery	Asset tracking, telematics, remote monitoring, smart grid, smart city, security, healthcare	Wearables, industrial sensors, video transmission

Use cases and opportunities

RedCap devices are designed for use cases that are beyond the capabilities of massive IoT technology such as LTE-M and NB-IoT. This means that they can support high data rates and low latency as shown in Table 1. Some representative use cases include:

- Video transmission for traffic monitoring and security cameras
- Wearables such as smart watches, goggles, smart glasses, on-body health sensors and medical devices
- Industrial wireless sensors for temperature, pressure, proximity, smoke, level and vibration
- Connected car applications like infotainment, telematics, real-time high-definition maps and software upgrades
- Drones for command and control and video transmission

Some of these use cases are illustrated in Figure 3 in the context of smart city and smart factory.

Figure 3. IoT use cases for RedCap devices

Currently, broadband IoT use cases are typically supported using LTE due to wide availability of LTE networks and devices. 5G connectivity for IoT remains nascent due to high device cost and network focus on the broadband segment. The introduction of RedCap devices will help expand the IoT opportunities for the operators, including helping to:

- Expand the addressable IoT market for 5G NR using the existing network footprint by making lower-cost devices available and enabling network software updates
- Support the re-farming of LTE spectrum to NR by providing cost-effective device solutions for IoT service migration
- Provide NR-based IoT solutions to complement time-critical URLLC components in Industry 4.0 for better integration and improved network efficiency.

Reduced capability devices

In this section, we provide an overview of the features introduced to support RedCap devices. They include device complexity reduction techniques, how to support them in the network, and power saving features.

In addition, RedCap devices can operate only in standalone mode and with single connectivity (i.e., no dual connectivity support), and they can only operate in a single band at a time (i.e., no carrier aggregation support). Also note that Rel-15 SSB bandwidth is reused, and physical layer changes are kept to a minimum.

Complexity reduction

In 3GPP, a study was conducted to evaluate different complexity reduction techniques with respect to amount, performance impact, specification impact, and co-existence with legacy devices [2]. The study defined reference NR devices for complexity comparison purpose and included both NR frequency ranges (FR1 and FR2). The evaluation methodology for complexity analysis considers radio frequency (RF) and baseband parts, and the reduction is expressed as a relative cost compared to the reference NR device. The baseband part includes analog-to-digital and digital-to-analog converters (ADC/DAC), fast Fourier transforms and inverse fast Fourier transforms (FFT/IFFT), data buffer, transmitter/receiver processing block, encoder/decoder, etc. Complexity is evaluated based on required baseband operations. The RF part includes power amplifier, filters, transceiver and duplexer. The cost reduction can be achieved by either removing the component or replacing it with a less expensive component.

Based on the outcome of the study, the following complexity reduction techniques were agreed to be introduced.

Reducing the user equipment (UE) RF bandwidth: Reducing the RF bandwidth (BW) can reduce complexity significantly since this option reduces both the ADC/DAC and FFT/IFFT complexity as well as the peak data rates that can be supported by the device. The reduction amount scales with the BW, therefore it is beneficial to select the smallest BW possible. To allow the RedCap UE to continue to operate with legacy channels and signals, the bandwidth can only be reduced to 20 MHz for cmWave (FR1) and 100 MHz for mmWave (FR2). For FR1, reducing the bandwidth from 100 MHz to 20 MHz reduces device complexity by approximately 30%. For FR2, reducing the bandwidth from 200 MHz to 100 MHz reduces device complexity by approximately 15%.

Reducing the number of receive (Rx) branches: This can result in a large complexity reduction as each RF chain constitutes a large percentage of the RF cost. Having only a single receiver chain can reduce the UE complexity by as much as 15–30%, compared to having two, and by as much as 46%, compared to having four. It results, however, in performance degradation for the device in the downlink. In addition to reducing the RF cost, having only a single receiver chain eliminates the need to support spatial multiplexing MIMO (multiple input, multiple output). This can further simplify the baseband operations at the cost of reduced throughput in the downlink.

Half-duplex FDD operation: Half-duplex operation allows for the removal of the duplexer in the RF. The complexity reduction is minor, estimated to be up to 7% per frequency band. However, the saving can be substantial as the device will likely support many bands and so the duplexer can be removed for each supported band.

Relaxing the maximum modulation order in FR1: In NR FR1, legacy devices support 256-QAM (quadrature amplitude modulation) in the downlink. For IoT devices, such very high modulation is not usually necessary and baseband processing savings can be achieved by supporting up to 64-QAM only. This results in a small complexity reduction of approximately 6%. While the complexity reduction is minor, the impact of this relaxation is negligible, therefore, it was agreed to be supported. Note that, in FR2, the maximum modulation order is 64-QAM, thus there is no relaxation in FR2.

Table 2 illustrates the relative complexity reduction in comparison to reference NR devices. From the table, it is seen that total complexity reduction of approximately 70% and 50% can be achieved for FR1 and FR2 devices, respectively.

Table 2. Complexity reduction analysis

	Relative complexity reduction		
Complexity reduction technique	Frequency range 1 (cmWave) FDD	Frequency range 1 (cmWave) TDD	Frequency range 2 (mmWave) TDD
Reducing the UE RF bandwidth	31.9%	33.4%	15.6%
Reducing the number of Rx branches	25.5%	46.0%	30.6%
Half-duplex FDD operation	6.8%	N/A	N/A
Relaxing the maximum modulation order	5.8%	6.3%	N/A
Total device complexity reduction	67.1%	70.7%	47.5%

Table 3 summarizes the key characteristics of RedCap devices including optional capabilities. In FR1, the full duplex FDD (FD–FDD) RedCap device is capable of peak data rates of 85 Mbps in the downlink and 91 Mbps in the uplink. Half-duplex (HD) and TDD devices will have their peak rates reduced accordingly. In FR2, the TDD RedCap device in the 50:50 downlink-to-uplink time split is estimated to be capable of peak data rates of 213 Mbps in the downlink and 228 Mbps in the uplink.

Table 3. Reduced capability NR devices

	Frequency range 1 (cmWave)	Frequency range 2 (mmWave)
Device bandwidth	20 MHz	100 MHz
Antenna configuration	1Tx–1Rx 1Tx–2Rx (optional)	1Tx–1Rx 1Tx–2Rx (optional)
Downlink MIMO support	Yes for device with 2Rx branches	Yes for device with 2Rx branches
Duplex operation	FD–FDD, HD–FDD, TDD	TDD
Maximum modulation	DL: 256-QAM (optional), 64-QAM mandatory UL: 64-QAM	DL: 64-QAM UL: 64-QAM
Peak data rate	FD–FDD, 1Rx: 85 Mbps DL/91 Mbps UL TDD 50:50 DL/UL split, 1Rx: 42 Mbps DL, 45 Mbps UL	TDD 50:50 DL/UL split, 1Rx: 213 Mbps DL, 228 Mbps UL

From the 3GPP point of view, RedCap devices can be supported with moderate changes to the specifications. Key modifications are summarized below.

Reducing the UE RF bandwidth

Due to the reduced device RF bandwidth, RedCap can operate only in a Bandwidth Part (BWP) that is no larger than the device bandwidth. As a result, separate BWP may need to be configured for the RedCap device. In NR, a BWP is a contiguous set of frequency resources that can be configured for a UE. For instance, in FR1, if the carrier BW is 40 MHz, a separate BWP no larger than 20 MHz must be configured for the RedCap device. Legacy UE, however, can continue to use the entire BW and can be configured with another BWP spanning the entire 40 MHz. The Rel-15 specification already supports configurations of BWP, however, some enhancements were introduced for RedCap devices, as explained below.

In the downlink, a separate BWP may be configured that may not contain the entire cell-defining synchronization signal block (CD-SSB) and control resource set #0 (CORESET#0). This BWP can be used for initial access and when the device is in a connected state. If this BWP is used by the UE in a radio resource control (RRC) connected state, it should contain a non-cell-defining SSB (NCD-SSB). The NCD-SSB may be transmitted less frequently than the CD-SSB, thus lowering the additional overhead. In addition, some devices may have the optional capability to operate without requiring an NCD-SSB. In this case, they can rely on the channel state information reference signal (CSI-RS) for relevant operations.

In the uplink (UL), a separate BWP can also be configured for use both during initial access and in the connected state. The network can disable intra-slot physical uplink control channel (PUCCH) frequency hopping within this BWP so that the physical uplink shared channel (PUSCH) resource is not fragmented.

Reducing the number of Rx branches

The specification mainly impacts the UE performance requirements by reducing the number of Rx branches. In case the RedCap device has two Rx branches, the existing radio access network (RAN4) requirements can be reused. For a device with one Rx branch, new requirements for both RF and radio resources management (RRM) will be defined. They include, for example:

- The reference sensitivity for devices with 1Rx is based on 2Rx reference sensitivity with relaxation (2.5 dB for TDD, FDD; 2.5 dB for 5MHz; 3 dB for 10/15/20 MHz)
- New handover requirements are needed for 1 Rx UE for the following cases: NR FR1–FR1, NR FR2–FR2, NR–E-UTRAN, E-UTRAN–NR , NR FR1–FR2, NR FR2–FR1
- The number of samples for synchronization signal detection for FR1 is extended
- The accuracy level is relaxed for SSB-based layer 3 (L3) measurement with 1 Rx.

Half-duplex FDD operation

Half-duplex (HD) devices cannot transmit and receive simultaneously in FDD. The specification impacts from HD–FDD operation include switching times for the device and device behavior in case of collision between transmission and reception. On the first point, Rel-15 switching times for UE not capable of full-duplex communication are reused for HD-FDD devices. In FR1, the switching times for transmit-receive (Tx-Rx) and Rx-Tx are 13 μs. On the second point, collision handling behaviors have been defined for HD-FDD devices.

The defined behaviors are based on the existing Rel-15 behaviors for TDD UE and can be summarized, as follows. Where there is a collision between:

- Dynamically scheduled downlink reception and semi-statically configured uplink transmission, prioritize the dynamically scheduled downlink reception
- Semi-statically configured downlink reception and dynamically scheduled uplink transmission, prioritize the dynamically scheduled uplink transmission
- Semi-statically configured downlink reception and semi-statically configured uplink transmission, it is an error case and not expected by the device
- Dynamically scheduled downlink reception and dynamically scheduled uplink transmission, it is an error case and not expected by the device
- SSB and uplink transmission, prioritize SSB
- Random access and downlink reception, leave for UE implementation.

Relaxing the maximum modulation order in FR1

There is negligible specification impact from this relaxation. The existing specifications can be reused to support this feature.

Power saving

Two power saving features will be introduced in Rel-17: extended discontinuous reception (eDRX) and radio resource management (RRM) measurement relaxations for neighboring cells.

In NR, devices in idle or inactive mode must wake up periodically to check for paging and perform measurements. For many IoT use cases, devices may have infrequent data transmissions, thus there is no need to wake up frequently. The first power saving feature is an eDRX procedure that allows them to remain in a power-efficient deep sleep state longer for reduced power consumption. In Rel-17, eDRX is being specified for devices in radio resource control (RRC) inactive and idle states. Two maximum eDRX cycles will be supported: 10.24 s and 10485.76 s.

The eDRX feature is optional for any next-generation NodeB (gNB), which means the gNB implementation must explicitly support eDRX. The eDRX configurations can be different for RRC_IDLE and RRC_INACTIVE. Based on the objectives in the Rel-17 work item description, the paging time window (PTW) and paging hyper-frames (PH) will not be used in eDRX cycles up to 10.24 s, For eDRX cycles longer than 10.24 s, however, the eDRX feature, including the related parameters such as PTW, PH, and the corresponding paging operation defined for E-UTRAN are used as the baseline for both RRC_IDLE and RRC_INACTIVE in NR/5GC. The lower bound for eDRX configuration in RRC_IDLE and RRC_INACTIVE is 2.56 seconds. It is up to the RAN to configure the PTW length for RAN paging, and the RAN PTW length can be different from the core network (CN) PTW length. The maximum PTW length is 40.96 s when the IDLE eDRX cycle is longer than 10.24s. The minimum PTW length is 1.28 s and the step length or granularity of the PTW length is 1.28 s when the idle eDRX cycle is longer than 10.24 s.

The second power saving feature is RRM measurement relaxations for neighboring cells. Two important characteristics for many IoT use cases are that, first, the device is stationary and, second, the device is mostly in an idle or inactive state with infrequent data transmissions. In idle mode, power consumption is dominated by RRM measurements. Therefore, enhancements are being made to allow the UE to relax RRM measurements for neighboring cells. Specifically, new stationarity criteria and not-at-cell-edge criteria will be defined for RedCap devices to allow them to prolong the time between neighbor cell measurements. This RRM relaxation is under network control and can be configured on a device basis.

Device definition and identification

The RedCap device type is based only on the maximum device bandwidth (20 MHz in FR1 and 100 MHz in FR2) and therefore only one device type is defined. Other features, such as the number of Rx branches, can be acquired by the network as part of the UE capability signaling.

In NR, device capability can be acquired by the network in Msg5 of the random-access procedure. Hence, the network would be able to determine whether a device is a RedCap device and its associated capability (e.g., number of Rx branches) in Msg5. The network, however, can configure RedCap devices for early identification using Msg1 or Msg3. For Msg1 early identification, dedicated random access occasions or dedicated random access preambles can be reserved for RedCap devices. For Msg3 early identification, reserved MAC logical channel IDs can be used. Note that, with early identification, the network would only know that the RedCap device has limited bandwidth. It does not know of other limitations such as the number of Rx branches or whether the device is half duplex or full duplex. Additional limitations like these, can be discovered by the network using the RRC UE capability enquiry procedure.

In 3GPP, it was further discussed how to prevent RedCap devices from using radio capabilities not intended for them (e.g., as low-cost eMBB devices). It was agreed that this can be left up to the network. For example, the network can perform subscription validation during RRC connection setup to ensure that the requested services are specific to RedCap devices. Also, the network can use system information block type one (SIB1) to bar RedCap devices.

Coverage analysis

One of the studies on RedCap devices involved analyzing coverage of RedCap devices to determine whether coverage compensation would be needed. It may be noted that the complexity reduction features described in the previous section degrade downlink performance. Furthermore, in some of the use cases under consideration, such as wearables, the device may also have a small form factor. This may limit the antenna efficiency, which then causes an additional coverage loss.

The following complexity reduction features can result in performance loss for a RedCap device compared with a reference NR device.

Reduced number of Rx branches: a RedCap device with fewer receiver antenna branches than a reference NR device would suffer a degradation in downlink performance due to a reduction in combining gain and receive diversity gain.

Reduced UE BW: A RedCap device with smaller BW than a reference NR device may experience some loss in frequency diversity, resulting in performance loss.

Reduced antenna efficiency: Devices with a small form factor may have a small antenna with reduced efficiency, resulting in a loss compared with an NR device. For evaluation purpose, it was agreed that the loss can be up to 3 dB [2].

Three different coverage metrics were used in the link budget analysis for RedCap devices: maximum isotropic loss (MIL), maximum path loss (MPL), and maximum coupling loss (MCL). MIL incorporates antenna gains, thus it enables analysis of the impact of reduced antenna efficiency on coverage. Coverage of the following channels and messages was considered based on a target performance requirement.

- PDCCH – Physical downlink control channel
- PDSCH – Physical downlink shared channel
- PUCCH – Physical uplink control channel
- PUSCH – Physical uplink shared channel
- PRACH – Physical random access channel
- Msg2 – Message 2 of initial access carried on PDSCH
- Msg3 – Message 3 of initial access carried on PUSCH
- Msg4 – Message 4 of initial access carried on PDSCH

The main assumptions for the coverage analysis are listed in Table 4, breaking out the assumptions related to complexity for a reference NR UE (Reference) and a RedCap UE (RedCap). Scenarios in FR1 and FR2 were considered. The target performance metric specified for the uplink (UL) and downlink (DL) data channels was throughput. On the other hand, for the downlink control channel and a few other channels, a block error rate (BLER) was specified as the target metric. The link budget calculations used the signal-to-noise ratio (SNR) required to achieve the target performance metric.

Table 4. Scenarios and assumptions for coverage analysis

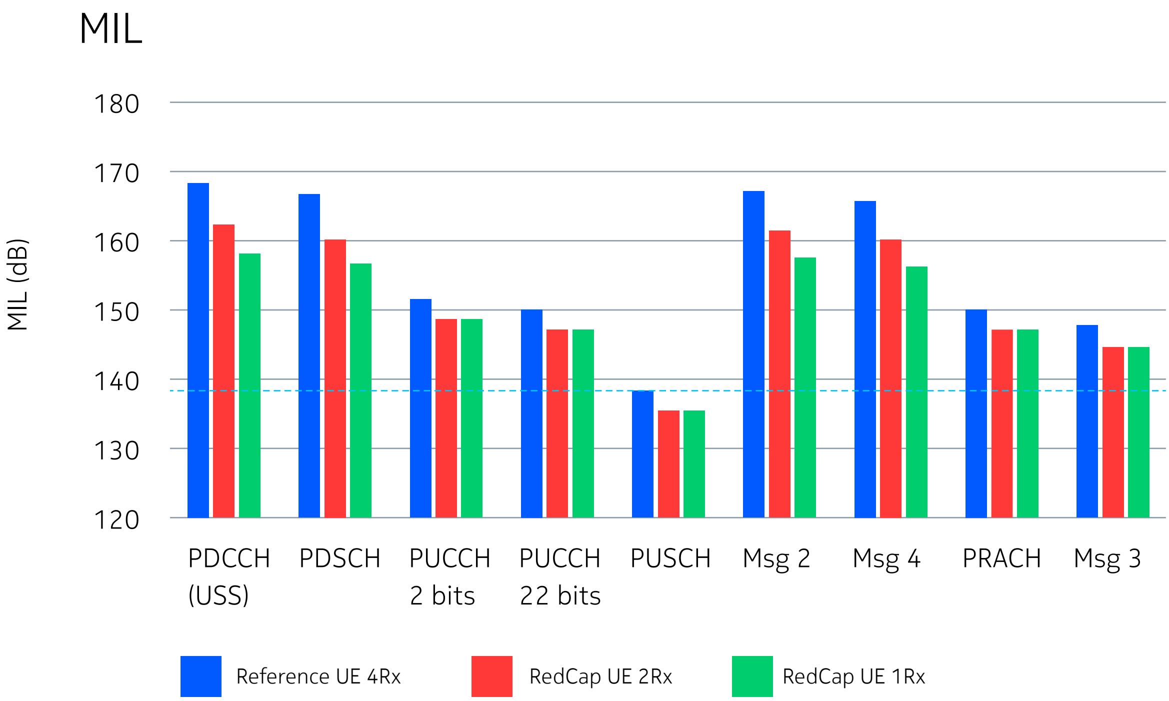
Scenario parameters		FR1		FR2
Scenario		Urban	Rural	Indoor
Carrier frequency		2.6 GHz and 4 GHz	700 MHz	28 GHz
Duplexing		TDD	FDD	TDD
Subcarrier spacing		30 kHz	15 kHz	120 kHz
UE bandwidth	Reference	100 MHz	20 MHz	100 MHz
	RedCap	20 MHz	20 MHz	100 MHz
Number of UE antennas	Reference	4 DL, 1 UL	2 DL, 1 UL	2 DL, 1 UL
	RedCap	1 or 2 DL, 1 UL	1 or 2 DL, 1 UL	1 DL, 1 UL
UE antenna element gain	Reference	0 dBi	0 dBi	5 dBi
	RedCap	-3 dBi	-3 dBi	5 dBi
PDSCH target throughput	Reference	10 Mbps	1 Mbps	25 Mbps
	RedCap	2 Mbps	1 Mbps	25 Mbps
PUSCH target throughput	Reference	1 Mbps	100 kbps	5 Mbps
	RedCap	1 Mbps	100 kbps	5 Mbps

In the following, we consider the MIL for the following three scenarios.

1. Urban 2.6 GHz (TDD)
2. Rural 700 MHz (FDD)
3. Indoor 28 GHz (TDD)

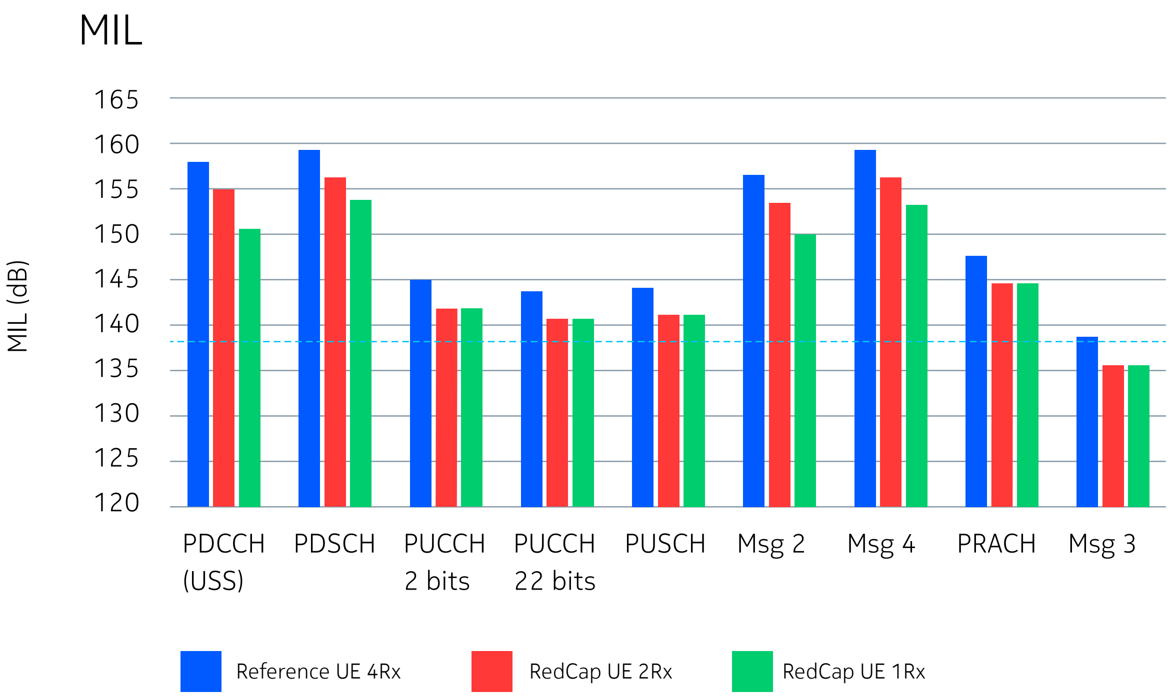
The MILs for all the considered channels in the Urban 2.6 GHz scenario are shown in Figure 4 for both a reference UE and a RedCap UE. RedCap UE with one Rx antenna and two Rx antennas are separately considered. The observed degradation of 3 dB in MIL for uplink channels of the RedCap UE is due to reduced antenna efficiency. On the other hand, reducing the number of Rx antennas causes additional degradation of the MIL on the downlink channels — the total MIL loss is about 10 dB for a RedCap UE with one Rx antenna. To determine the amount of coverage recovery that is needed for the RedCap UE, the limiting channel is identified. This is the channel for the reference UE with the smallest MIL value. As seen from the figure, the PUSCH is the limiting channel in this case, and the corresponding reference MIL is marked with a horizontal red line. Coverage recovery for a RedCap UE is required for a particular channel if the MIL is less than the reference MIL. Thus, in this case, a coverage recovery of 3 dB is seen to be necessary for PUSCH for RedCap UEs with either one Rx antenna or two Rx antennas. For all the other uplink channels, the MIL is better than the reference MIL by a significant margin and hence no coverage recovery is required. Likewise, no coverage recovery is required for downlink channels in this scenario, despite the performance loss due to reduced antenna efficiency and fewer Rx antennas. With more stringent downlink power assumptions, however, it was found that coverage recovery is required for some downlink channels.

Figure 4. Reference NR UE and RedCap UE link budget for different channels in the urban 2.6 GHz (TDD) scenario



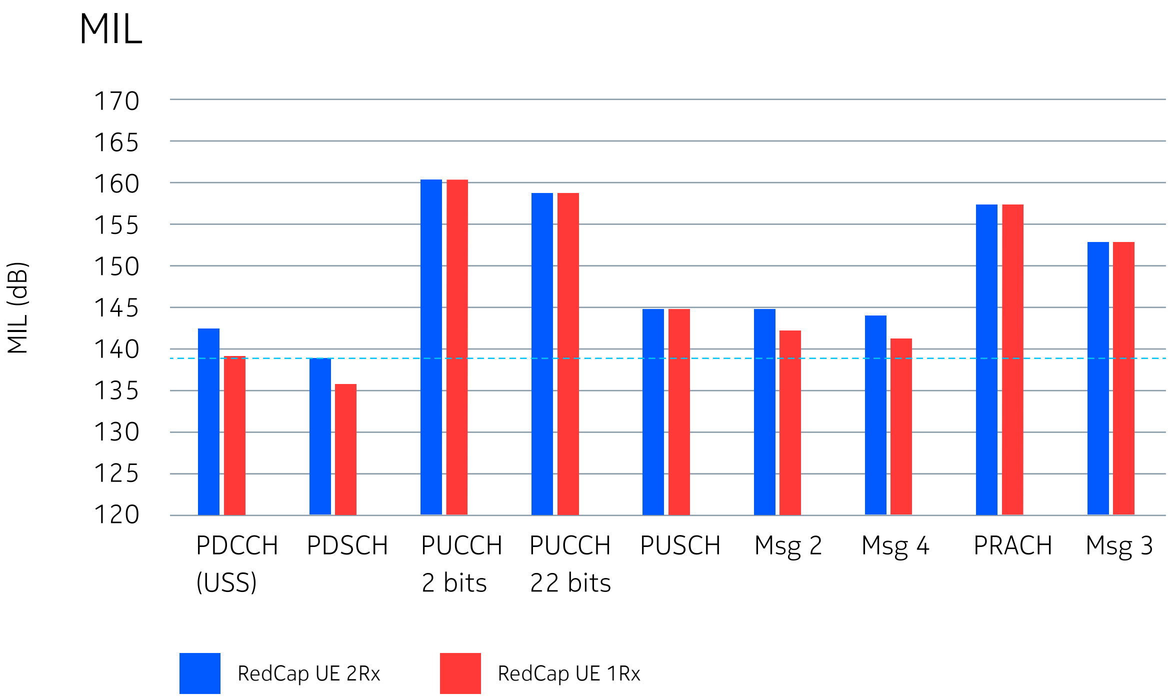
A similar plot of the MIL for the Rural 700 MHz scenario is shown in Figure 5. In this case, it is seen that Msg3 is the limiting channel for the reference NR UE. Therefore, a coverage recovery of 3 dB is required for Msg3 transmission for the RedCap UE corresponding to the amount of reduced antenna efficiency. Again, due to the vastly better MIL for the downlink channels of the reference NR UE, performance loss for the RedCap UE is not enough to cause the MIL to fall below the reference MIL, and hence coverage recovery is not required for the downlink channels.

Figure 5. Reference NR UE and RedCap UE link budget for different channels in the rural 700 MHz (FDD) scenario



The MIL is shown in Figure 6 for the indoor 28 GHz scenario. It is seen that PDSCH is the limiting channel in this scenario primarily due to the transmit power assumptions. For this channel, the RedCap UE experiences a loss of about 4.3 dB, which is the amount of coverage recovery necessary. The channel that has the next larger MIL is PDCCH, but the MIL for the RedCap UE is about the same as the reference MIL and hence coverage recovery is not required. Most of the uplink channels have a significantly higher MIL. At FR2, there is no assumption of reduced antenna efficiency for the RedCap UE. As a result, the MIL for the uplink channels is the same as for the RedCap UE. The MIL of the downlink channels is degraded due to performance loss from reducing the number of Rx antennas to one. The figure shows, however, that the loss experienced by channels other than PDSCH does not reduce their MIL below that of the reference MIL.

Figure 6. Reference NR UE and RedCap UE link budget for different channels in the indoor 28 GHz (TDD) scenario



Various techniques can be considered for improving the performance and recovering coverage of the data and control channels. Among them, the important ones for the data and control channels are as follows:

- Data (PDSCH and PUSCH) use repetition and frequency hopping to increase the received SNR
- Control (PDCCH) uses repetition and large aggregation levels to increase the received SNR and compact scheduling grants to reduce the number of bits to be transmitted.

Based on an extensive link budget analysis, it was determined that in the scenarios considered, a coverage recovery of up to 3 dB may be required for PUSCH and/or Msg3 for a RedCap UE. It was determined, however, that it is not necessary to specify coverage recovery solutions for RedCap devices. Thus, the work item for RedCap device specification does not include any objectives for coverage recovery. There is a separate Rel-17 NR Coverage Enhancement work item, and it was noted that uplink coverage enhancement solutions specified in that work item shall be assumed to also be available to RedCap UEs for coverage recovery.

In summary, RedCap UEs may experience some coverage loss due to their RedCap features. However, the coverage loss can be recovered through legacy NR features as well as Rel-17 coverage enhancement features specified for NR devices. Thus, current network deployments that provide full coverage to NR UEs can also provide full coverage to RedCap UEs. Therefore, site densification will not be necessary to provide full coverage to RedCap UEs.

Performance analysis

The impact of UE complexity reduction on the system-level performance is studied by using the Nokia 5G simulator. The simulation environment is an urban macro-cell network of seven sites with three sectors per site with the inter-site distance of 500 m. The simulations measure the system-level performance of uplink and DL. We assume a TDD system where eight and two subframes, respectively, are allocated for downlink and uplink operations. For simulations, the total system bandwidth of the network is 100 MHz, the subcarrier spacing is 30 kHz, and the carrier frequency is 2.6 GHz. Also, we run simulations for full buffer and file transfer protocol model 3 (FTP3) data traffic models, respectively.

For RedCap UE and enhanced Mobile Broadband (eMBB) UE, the different sets of parameters are used. RedCap UE and eMBB UE, respectively, use 20 MHz and 100 MHz of the total system bandwidth. Also, RedCap UE is assumed to have one or two receiving antennas, and eMBB UE use four receiving antennas. Then, for both RedCap UE and eMBB UE, it is assumed that the number of downlink layers equals the number of receiving antennas. Next, RedCap UE use 64-QAM in downlink and 16-QAM in uplink, and eMBB UE use 256-QAM in downlink and 64-QAM in uplink.

We first run simulations to measure the UE throughput with different RedCap UE ratios (expressed as a percentage of all UE) from 0% to 100%. In the simulations, we use the FTP3 model for bursty traffic with a file size of 500 Kbytes. Also, the traffic arrival rate is adaptively set so that the cell utilization level is medium (resource utilization is between 30% and 50%). First, we observe the 50th percentile user packet throughput of all UE. When the RedCap UE ratio is 0% and 100%, the throughput of all UE is 300.05 Mbps and 22.28 Mbps in downlink and 35.77 Mbps and 7.15 Mbps in uplink, respectively. The results show that deploying additional RedCap UE can decrease the user packet throughput of all UE in the network. Also, we observe the 50th percentile user packet throughput of eMBB UE. When the RedCap UE ratio is 25% and 50%, the eMBB UE's throughput in downlink is 407.42 Mbps and 413.37 Mbps and in uplink, 35.71 Mbps and 36.16 Mbps, respectively. Therefore, the results show that the deployment of RedCap UE has less impact on the downlink and uplink user packet throughput of eMBB UE on the same network. Additional results may be found in [3].

The cell average spectral efficiency is then analyzed for eMBB and RedCap UE in downlink and uplink with the different RedCap UE ratios. In the analysis, FTP3 traffic model is used. The definition of the cell average spectral efficiency is given by:

Spectral efficiency [bps/Hz] = (cell average throughput) / (bandwidth x resource utilization)

As a result, the cell average spectral efficiency can be reduced as more RedCap UE are deployed on a network. For instance, the uplink spectral efficiency of all UEs decreases by 20.4% if the RedCap UE ratio changes from 0% to 100%. Also, the downlink spectral efficiency can decrease up to 64.1% if the network only consists of RedCap UEs. Therefore, the deployment of RedCap UEs has less impact on uplink spectral efficiency than on downlink spectral efficiency.

Figure 7. Cell average spectral efficiency of eMBB UE and RedCap UE with full buffer traffic model in downlink and uplink

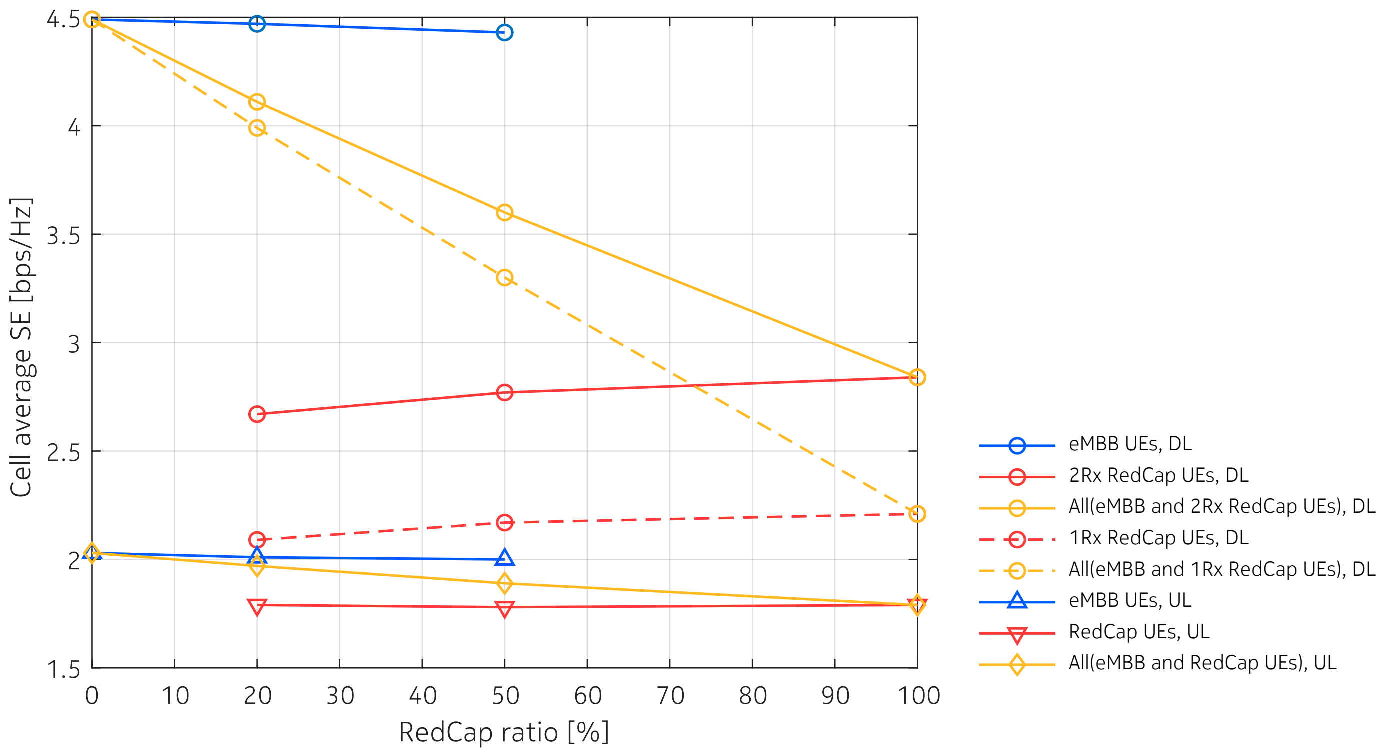


Figure 7 shows the uplink and downlink cell spectral efficiency when the full buffer traffic model is used with the different RedCap UE ratios ranging from 0% to 100%. In Figure 7, we can see that the cell spectral efficiency increases with the number of RedCap UE receiving antennas. For instance, if RedCap UEs increase the number of receiving antennas from one to two, the cell spectral efficiency increment can be up to 27.7% when the simulation environment has the same number of eMBB and RedCap UE on the network.

Figure 7 also shows that the cell spectral efficiency of eMBB UEs is less impacted by the ratio of RedCap UEs on a network especially when increasing the RedCap UE ratio from 0% to 50%, which decreases the downlink spectral efficiency by 1.3% for eMBB UEs. Also, in Figure 7, the cell spectral efficiency of RedCap UEs can increase with the RedCap ratio. For instance, if a network increases the ratio of RedCap UEs from 20% to 50%, spectral efficiency can increase up to 6.4% for RedCap UEs with two receiving antennas in downlink.

Reduced capability device evolution

Table 5 provides an overview of 5G IoT devices up to Rel-17. From the table, it is seen that there is still a large gap in the peak data rates of massive IoT devices compared to RedCap devices. For instance, LTE-M devices can support peak rates of 2.4 Mbps in the downlink and 2.6 Mbps in the uplink, while RedCap devices can support 85 Mbps in the downlink and 91 Mbps in the uplink. In Rel-18, 3GPP is studying further device complexity reduction in FR1. The goal is to introduce lower-tier devices between massive IoT and Rel-17 RedCap devices. The supported peak data rate for the new Rel-18 devices is expected to be around 10 Mbps.

Table 5. 5G IoT Devices

	Massive IoT				Critical IoT	Mid-range IoT	
	LTE-M		NB-IoT		URLLC	RedCap	
	Cat-M1	Cat-M2	Cat-NB1	Cat-NB2		FR1	FR2
Downlink peak rate	300 kbps*	2.4 Mbps*	27 kbps	127 kbps		85 Mbps	209 Mbps (50:50 DL/UL)
Uplink peak rate	475 kbps*	2.6 Mbps*	62 kbps	159 kbps		91 Mbps	229 Mbps (50:50 DL/UL)
Coverage (maximum coupling loss)	164 dB					144 dB	
Maximum cell size	100 km		120 km			100 km	
Battery life	10 years						
Latency	Up to 10 s for successful delivery of an application layer packet from the device to RAN				1 ms User plane latency	5-10 ms safety sensor, 100 ms others User plane latency	
Reliability	99% - 99.9%				99.999%	99.99%	
UE bandwidth	1.4 MHz	5 MHz	200 kHz	200 kHz		20 MHz	100 MHz
UE power class	14/20/23 dBm					23 dBm	
Frequency range	FR1					FR1, FR2	

* HD-FDD

Potential solutions for Rel-18 RedCap FR1 devices include device bandwidth reduction to 5 MHz, restricting the bandwidth of the data channels, and relaxed UE processing timelines. Our preliminary analysis shows that approximately 25–30% complexity reduction with respect to Rel-17 device is possible. The lower-complexity device includes 5 MHz bandwidth, half-duplex and supports 64-QAM on the downlink and 16-QAM on the uplink. Further restrictions such as limiting peak data rates can be considered to provide additional cost reduction.

Note that reducing the device bandwidth to 5 MHz will have some impacts. First, when SSB is deployed using sub-carrier spacing (SCS) of 30 kHz, the physical broadcast channel (PBCH) occupies 7.2 MHz, which is beyond the device bandwidth. It is still possible for the device to decode the PBCH using only signals that fall within 5 MHz but the performance will be degraded. Second, only CORESET#0 with 15 kHz SCS and 24 physical resource blocks (PRBs) in size can be supported, so this limits the configuration of CORESET#0.

Conclusions

In this paper, we provide an overview of RedCap devices being introduced in 3GPP Rel-17 to support mid-range IoT use cases such as industrial wireless sensors, wearables and video surveillance. Our analysis shows that significant complexity reduction can be achieved. When compared to reference Rel-17 NR devices, it is seen that a total complexity reduction of approximately 70% for FR1 (FDD and TDD) and 50% for FR2 (TDD only) can be achieved. The specification changes required to support complexity reduction features are seen as moderate, with most modifications related to BWP operations, half-duplex operations, and new requirements for devices with one Rx branch and for NCD-SSB operations.

Network coverage analysis shows that the impact from the introduction of RedCap devices is small. Coverage analysis, based on typical NR deployment scenarios and target cell edge data rates, shows that coverage recovery is generally not needed despite the performance loss in the downlink. This is because the coverage of the downlink channels is significantly better than the bottleneck uplink channel, thus coverage is not impacted even with some performance loss. In FR1, however, reduced antenna efficiency due to device size limitations may mean that coverage recovery is needed. Coverage recovery can be achieved using techniques introduced in another Rel-17 work item on coverage enhancement.

Network capacity analysis shows that the impact to system spectral efficiency and capacity is minor when the system is not heavily loaded. Furthermore, there is also minor impact to the performance of eMBB users.

In addition to complexity reduction, two power saving features — eDRX and RRM relaxation — are also introduced to provide additional power consumption reduction. The first feature can provide significant power savings to devices with infrequent data transmission, while the second feature is beneficial to stationary devices.

Technical specifications for RedCap devices are expected to be completed by September 2022, with commercial deployment expected 18–24 months thereafter. Currently, wearables such as smart watches and goggles are seen as the most attractive initial use case. On the network side, gNBs can simply be upgraded via software to support RedCap devices. Coexistence with other NR devices is seamless since they share the same NR design. Furthermore, the existing network footprint can be used based on our network coverage analysis.

In Rel-18, 3GPP is studying further device complexity reduction in FR1. The goal is to introduce lower-tier devices between massive IoT and Rel-17 RedCap devices. The supported peak data rate for the new Rel-18 devices is expected to be around 10 Mbps.

Abbreviations

3GPP	Third-generation partnership project
5GC	5G core
BLER	Block error rate
BW	Bandwidth
BWP	Bandwidth part
CD-SSB	Cell-defining synchronization s ignal block
cmWave	Centimeter wave
CORESET	Control resource set
CSI-RS	Channel state information reference signal
DL	Downlink
DRX	Discontinuous reception
eDRX	Extended discontinuous reception
eMBB	Enhanced mobile broadband
EPC	Extended packet core
EUTRAN	Evolved UTRAN
FD	Full duplex
FDD	Frequency division duplex
FR1	5G frequency range 1 (sub 6 GHz)
FR2	5G frequency range 2 (mmWave)
gNB	Next generation NodeB
HARQ	Hybrid automatic repeat request
HD	Half duplex
IoT	Internet of things
LTE-M	Long term evolution for machines
MAC	Medium access control
MCL	Maximum coupling loss
MIL	Maximum isotropic loss
MIMO	Multiple-input multiple-output
mmWave	Millimeter wave
MPL	Maximum path loss
Msg	Message
NB-IoT	Narrowband internet of things
NCD-SSB	Non-cell-defining synchronization signal block
NFC	Near-field communication
NR	New radio
PBCH	Physical broadcast channel
PDCCH	Physical downlink control channel
PDSCH	Physical downlink shared channel
PH	Paging hyper-frame
PRACH	Physical random-access channel
PTW	Paging time window
PUCCH	Physical uplink control channel
PUSCH	Physical uplink shared channel
QAM	Quadrature amplitude modulation
RedCap	Reduced capability
RF	Radio frequency
RFID	Radio frequency identification
RRC	Radio resource Control
RRM	Radio resource management
Rx	Receive
SIB1	System information block type one
SNR	Signal-to-noise ratio
SSB	Synchronization signal block
TDD	Time division duplex
Tx	Transmit
UE	User equipment
UL	Uplink
UMTS	Universal mobile telecommunications system
URLLC	Ultra-reliable low-latency communications
UTRAN	UMTS terrestrial radio access network

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