5G-ACIA White Paper

Assessment of 5G Reduced Capability (RedCap) Devices for Industrial IoT

5G Alliance for Connected Industries and Automation

1 Executive Summary

3GPP has standardized a set of features called Reduced Capability (RedCap) in Releases 17 and 18 to support the development of 5G user equipment (UE) with reduced complexity and power consumption. As of this writing, solutions based on Release 17 are starting to enter the marketplace.

Many consider RedCap to be promising for a range of IoT use cases. This white paper aims to provide an industrial IoT perspective on this emerging technology.

In summary, this white paper makes the following observations:

- The RedCap functionality introduced in Releases 17 and 18 enables the development of UEs with reduced complexity and power consumption. RedCap is a 5G-only technology and does not depend on, nor is it backward compatible with, 4G and LTE.
- RedCap can be highly relevant for a variety of industrial use cases, especially in high-density sensor networks where device space is limited and/or specific power characteristics are required.
- On the network side, a software upgrade is necessary to allow RedCap UEs to connect. Additionally, the network must support 5G standalone (SA) operation.
- If there is a high traffic load from connected RedCap UEs, there may be an impact on overall spectral efficiency.
- Power-saving features in RedCap are comparable to those of 4G technologies (NB-IoT and LTE-M). Optimizations for power savings can be achieved for applications that meet the criteria outlined in Section 5. These power-saving optimizations are not dependent on RedCap.

About 5G-ACIA

The 5G Alliance for Connected Industries and Automation (5G-ACIA) was established to serve as the central and global forum for addressing, discussing, and evaluating relevant technical, regulatory, and business aspects with respect to 5G for the industrial domain. It reflects the entire ecosystem and all relevant stakeholder groups, including the operational technology (OT) industry (industrial automation companies, engineering companies, production system manufacturers, end users, etc.), the ICT industry (chip manufacturers, network infrastructure vendors, mobile network operators, etc.), academia, research institutes, and other relevant players. The paramount objective of 5G-ACIA is to ensure the best possible applicability of 5G technology and 5G networks to the industrial domain. 5G-ACIA's mission is to make sure the interests and needs of the industrial domain are adequately considered in 5G standardization and regulation and that ongoing 5G developments are understood by and effectively transferred to the industrial domain.

2 Table of Content

3 Introduction: What is RedCap?

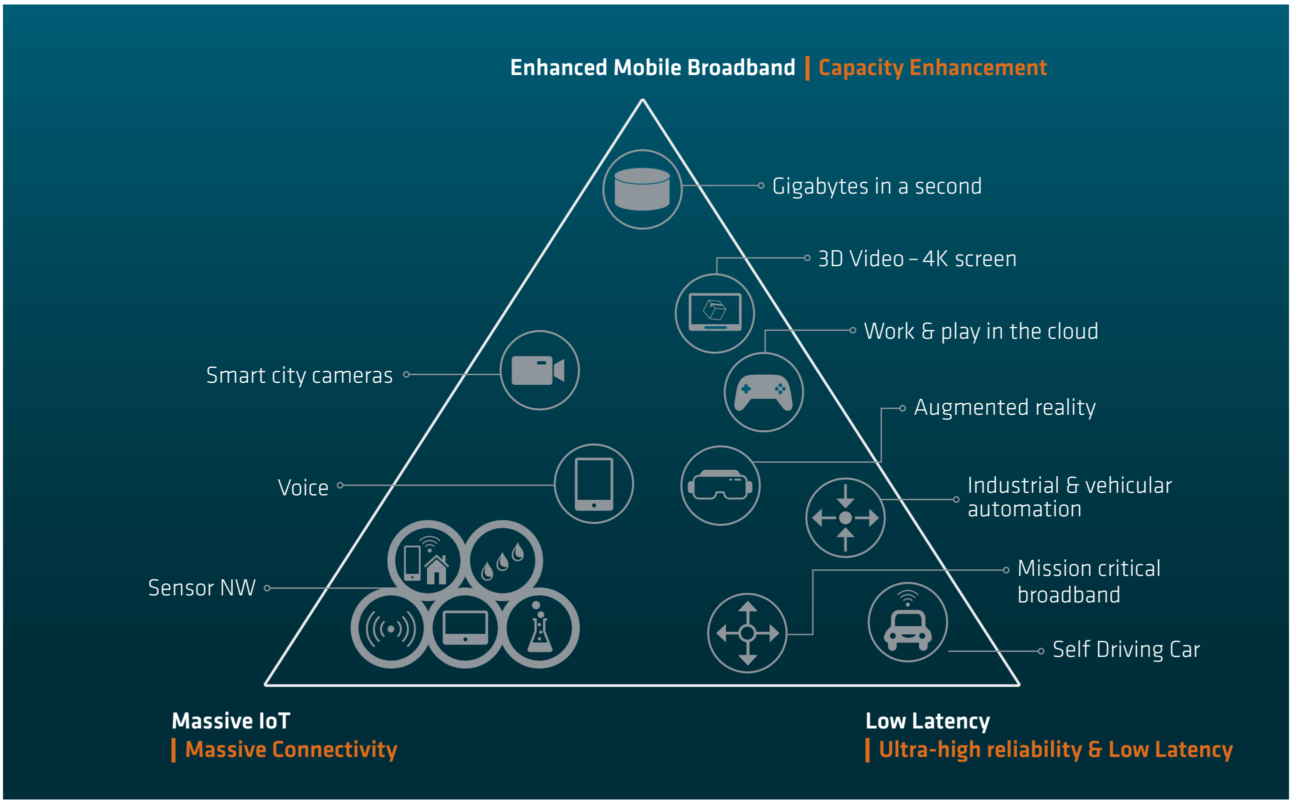
The three cornerstones of the 3GPP use case triangle for 5G are enhanced mobile broadband (eMBB), ultra-reliable low-latency communication (URLLC), and massive machine-type communication (mMTC). Each of these use case categories has distinct requirements for data rate, capacity, latency, and power consumption. The triangle concept originated from the ITU-R's set of 5G requirements, titled "IMT for 2020 and beyond," and a version of it is shown here.

3GPP has developed standards to address these three use case segments. The eMBB and URLLC use cases were covered by the 5G New Radio (NR) standard introduced in Release 15, while the mMTC use cases were addressed by the NB-IoT and LTE-M standards, which were introduced in Release 13. However, new use cases have since emerged that require a different combination of 5G requirements and capabilities than those represented in the triangle in Figure 1.

These new use cases are depicted in the center of the enhanced diagram in Figure 2. This evolution is one of the reasons why 5G Reduced Capability (RedCap) was developed and formally defined in Release 17, with further enhancements introduced in Release 18. The commercial deployment of Release 17 RedCap UEs and networks has already begun, and it is expected to accelerate in the coming years.

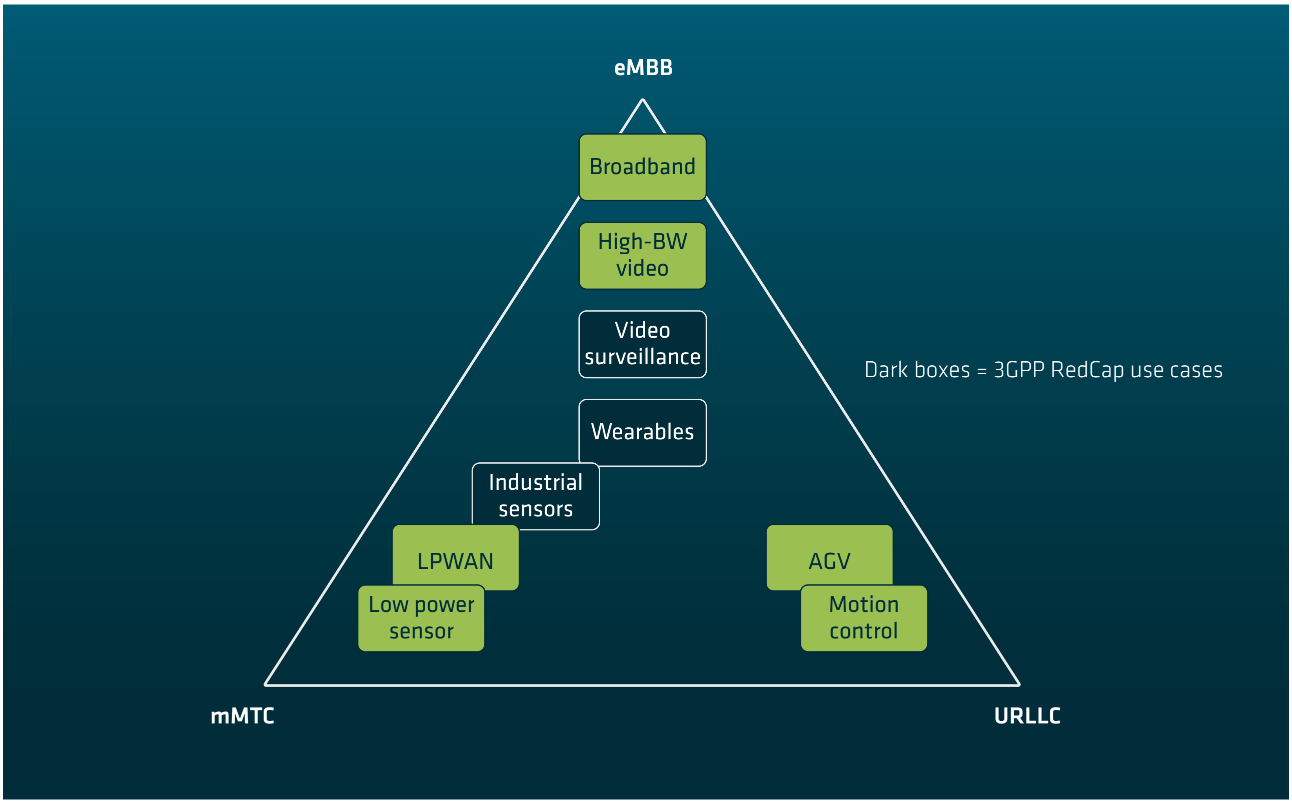
Comparisons can be drawn between RedCap and the use cases and UEs that fall under the 4G LTE Category 1 (see Table 4), which was first introduced in Release 8 and targeted lower-end UEs and mobile phones. However, the deployment of Category 1 was eventually driven by IoT use cases. These use cases can be effectively served by UEs with reduced complexity, which helps lower costs and increases their relevance for large-scale IoT deployments. Despite the reduced complexity, these endpoints can still support sufficient bandwidth

Figure 1: ITU-R IMT for 2020 Triangle



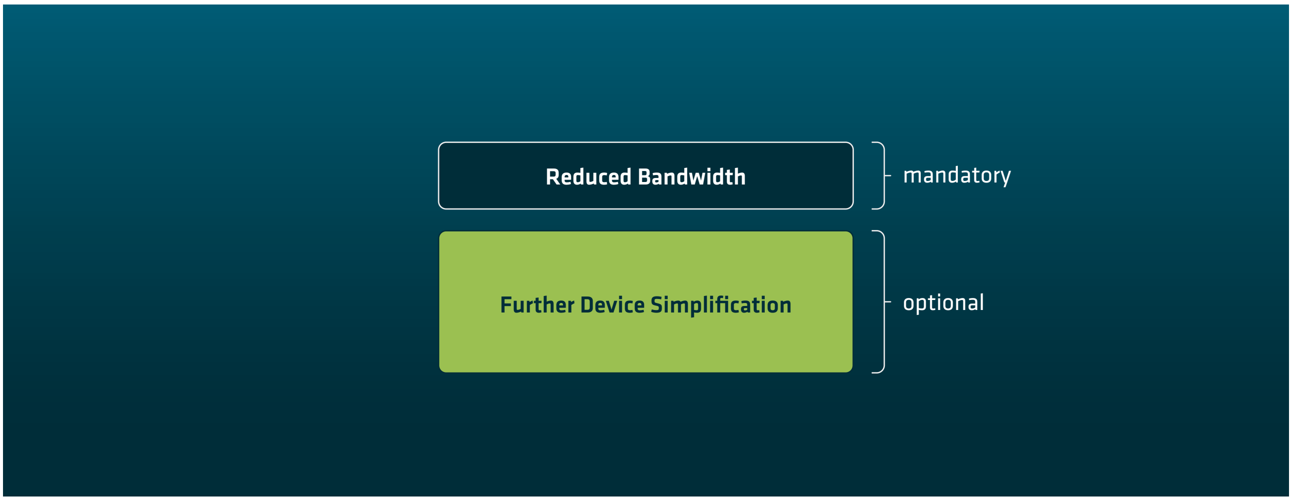
Source: 5G-ACIA / ZVEI e. V.

Figure 2: Enhanced IMT Triangle



Source: 5G-ACIA / ZVEI e. V.

Figure 3: RedCap UE complexity reduction techniques



Source: 5G-ACIA / ZVEI e. V.

for many vertical-specific applications. The use cases initially identified by 3GPP include wearables, industrial wireless sensors, and video surveillance.

RedCap consists of several techniques for reducing UE complexity, which will be explained in detail in Section 4. As shown in Figure 3, reduced bandwidth is the only mandatory complexity reduction technique for all RedCap UEs. All other complexity reduction techniques are optional, as described further in Section 4. This flexibility allows industrial device manufacturers to choose the most relevant complexity reduction techniques for their specific application and use case.

In addition to the new lower-complexity UE types, Release 17/18 introduces new techniques for reducing UE power consumption. These techniques are not exclusive to RedCap UEs; they can be implemented in any 5G UE, although they are particularly relevant for RedCap UEs and their intended use cases. These techniques, which are described in Section 5, can significantly extend UE battery life, potentially lasting weeks or even years. However, the actual battery life achievable will depend on the specific use case, as detailed in Section 5.

As a result, it is expected that various implementation examples will emerge. Section 6 will provide an overview of this landscape, derived from multiple OT sources, along with insights into potential additional areas where the adoption of 5G has not yet been realized in the market.

4 New UE types with lower complexity

4.1 RedCap UEs (Release 17)

As mentioned in the introduction, several IoT use cases have been identified that would benefit from a 5G UE type offering a different trade-off between capabilities and complexity compared to standard 5G UEs—specifically, trading reduced capabilities for reduced complexity.

To address this need, 3GPP Release 17 introduced a new reduced-capability UE, or RedCap UE. A RedCap UE implements one or more complexity reduction techniques that enable the development of simpler and smaller UEs [1]. These techniques, along with their impact on the supported peak rate, are described below.

- **Reduced Maximum Bandwidth:** For a RedCap UE, the maximum bandwidth for transmission or reception is 20 MHz for low/mid bands and 100 MHz for high bands, which is less than that for ordinary 5G UEs (see Table 1). RedCap UEs are not allowed to support larger bandwidths, nor are they capable of supporting carrier aggregation (CA) or dual connectivity (DC). These UEs, with reduced maximum bandwidth, are managed using the existing bandwidth part (BWP) concept with some minor updates. For example, additional synchronization signal blocks (SSBs) may be transmitted to ensure that the UE can receive SSBs in its BWP while in the Connected state.
- **Reduced Antenna Configuration:** A RedCap UE only needs to implement a single receive antenna branch for low/mid bands or a single antenna panel for high bands, which is fewer than what ordinary 5G UEs require (see Table 1). This configuration needs explicit configuration in the RAN to enable these UEs. For high bands, a UE with a single antenna panel implements a lower transmit power class, known as power class 7. Optionally, a RedCap UE can support two receive antenna branches for low/mid bands or two panels for high bands.
- **Reduced Supported Number of Downlink Layers:** A RedCap UE only needs to support a single downlink layer, meaning it does not require multiple-input multiple-output (MIMO) support, unlike ordinary 5G UEs (see Table 1). Optionally, a RedCap UE can support

dual-layer transmission if it has two receive antenna branches.

- **Reduced Maximum Downlink Modulation Order:** A RedCap UE only needs to support up to 64QAM modulation, which is lower than that for ordinary 5G UEs (see Table 1). Optionally, a RedCap UE can support 256QAM.
- **Half-Duplex Operation:** A RedCap UE does not need to support full-duplex operation when operating in a paired (FDD) band. In this case, the RAN must be explicitly configured to support half-duplex operation, meaning the UE does not need to transmit and receive simultaneously. Optionally, a RedCap UE can support full-duplex operation.

According to the evaluation in 3GPP TR 38.875 [2], these complexity reduction techniques collectively were estimated to reduce the UE modem complexity by approximately 50 % to 70 %, depending on the frequency band.

It was also estimated that these techniques could be deployed without significantly impacting network coverage or capacity, provided that the traffic load from RedCap UEs remains small compared to the total traffic load. However, it should be noted that if a very high number of RedCap UEs are deployed, or if RedCap UEs are used for traffic-intensive, high-throughput use cases, the reduced downlink performance of RedCap UEs—due to the reduced number of receive antennas—could have a more significant impact on network capacity and spectral efficiency.

The table below compares the typical properties of ordinary 5G UEs and RedCap UEs across different bands.

Table 1: Typical properties for ordinary 5G UEs and RedCap UEs in different bands

	Low frequency bands (410 – 2,495 MHz)		**Mid frequency bands (2,496 – 7,125 MHz)**		**High frequency bands (24,250 – 52,600 MHz)**	
	Ordinary 5G UE	**RedCap UE**	**Ordinary 5G UE**	**RedCap UE**	**Ordinary 5G UE**	**RedCap UE**
Maximum bandwidth	≥ 100 MHz	20 MHz	≥ 100 MHz	20 MHz	≥ 200 MHz	100 MHz
Antenna configuration	≥ 2 receive antennas	≤ 2 receive antennas	≥ 4 receive antennas	≤ 2 receive antennas	≥ 2 antenna panels	≤ 2 antenna panels
Supported number of downlink layers	≥ 2	Same as number of receive antennas	≥ 4	Same as number of receive antennas	≥ 2	1 or 2
Maximum downlink modulation order	256QAM	64QAM or 256QAM	256QAM	64QAM or 256QAM	64QAM or 256QAM	64QAM or 256QAM
Duplex mode	Full-duplex FDD	Full- or half-duplex FDD	TDD	TDD	TDD	TDD

Source: 5G-ACIA / ZVEI e. V.

Table 2: Example peak data rates in Mb/s in downlink (DL) and uplink (UL) for RedCap UEs

RedCap UE capabilities	Low frequency bands (410 – 2,495 MHz)		Mid frequency bands (2,496 – 7,125 MHz)		High frequency bands (24,250 – 52,600 MHz)	
	DL peak rate [Mb/s]	UL peak rate [Mb/s]	DL peak rate [Mb/s]	UL peak rate [Mb/s]	DL peak rate [Mb/s]	UL peak rate [Mb/s]
Single layer, peak rate calculated according to 16QAM	~55	~60	~35	~25	~160	~120
Single layer, 64QAM	~85	~90	~50	~35	~240	~175
Dual layers, 256QAM	~225	~90	~135	~35	~640	~175
	Assumptions: Full-duplex FDD operation 15 kHz subcarrier spacing		Assumptions: TDD DL/UL time split 60/40 % 30 kHz subcarrier spacing		Assumptions: TDD DL/UL time split 60/40 % 120 kHz subcarrier spacing	

Source: 5G-ACIA / ZVEI e. V.

Table 2 illustrates how the complexity reduction techniques impact the peak data rates. In the table, the row 'Dual layers, 256QAM' represents a relatively advanced RedCap UE that implements both downlink MIMO and 256QAM modulation. The row 'Single layer, 64QAM' represents a simpler RedCap UE that does not implement MIMO or 256QAM. Finally, the row 'Single layer, 16QAM' represents the simplest RedCap UE, where the peak data rates are calculated assuming 16QAM modulation (even though the UE can momentarily support 64QAM modulation, provided the peak data rate does not exceed the value calculated based on single-layer and 16QAM). Other combinations of optional features are possible, but as shown in the examples in the table, there are sufficient design choices to implement RedCap UEs with varying peak data rates.

For the TDD cases (in mid/high-frequency bands), it is important to note that the achievable downlink (DL) and uplink (UL) peak rates depend on the DL/UL time split used by the network. In the examples in Table 2, it is assumed that 60 % of the time is allocated to DL and the remaining 40 % to UL. If, for example, a larger fraction of time is allocated to DL and a smaller fraction to UL, the achievable peak rate would be correspondingly larger in DL and smaller in UL.

Compared to ordinary 5G UEs, RedCap UEs have lower complexity and peak rates. However, compared to NB-IoT and LTE-M UEs, RedCap UEs have higher complexity and peak rates. RedCap is not optimized for the low-end IoT use cases currently served by NB-IoT and LTE-M. This is illustrated in Figure 2, where NB-IoT and LTE-M target the lower-left mMTC corner, while RedCap targets the center of the use case triangle. Therefore, these technologies are designed to complement each other.

Network support for RedCap UEs is expected to be introduced through software upgrades of existing 5G networks. If the network is a 5G non-standalone (NSA) network, it must also be upgraded to a 5G standalone (SA) network in order to support RedCap UEs.

Since RedCap UEs have reduced capabilities compared to standard 5G UEs, the network may need to identify whether a UE is a RedCap UE early on to ensure proper scheduling.

As such, a RedCap UE always identifies itself as a RedCap UE during one of the first messages transmitted by the UE during the initial access procedure (referred to as message 1 or message 3). Furthermore, RedCap UEs are only allowed to access a cell if the cell broadcasts system information indicating that RedCap UEs are permitted to connect. The cell may allow access based on different configurations for RedCap UEs, such as varying numbers of antennas (1 or 2) or different FDD duplex modes (HD-FDD or FD-FDD).

The reduced capabilities of RedCap UEs only affect their processing power, meaning that RedCap UEs will still support the same high-level security procedures as other 5G UEs.

4.2 eRedCap UEs (Release 18)

As mentioned in the previous section, Release 17 introduced support for RedCap UEs with reduced capabilities and complexity compared to standard 5G UEs. These RedCap UEs have peak data rates (see Table 2) that are comparable to 4G LTE UE Category 4 (see Table 4). This may be considerably higher than what is required for some IoT use cases, such as those currently served by 4G LTE UE Category 1, which offers a lower peak data rate.

To address this, Release 18 takes a further step by introducing support for even simpler RedCap UEs, known as eRedCap UEs, targeting a peak data rate of 10 Mb/s [3]. This target refers to the instantaneous peak data rate, so for TDD, the effective DL and UL peak rates depend on the DL/UL time split used by the network.

The functionality introduced in Release 17 is reused to the greatest extent possible to minimize the impact on specifications and implementations. As a result, the peak data rate is limited, and the baseband bandwidth of physical data channels (PDSCH and PUSCH) can optionally be limited to 5 MHz. However, other physical signals and channels remain unchanged compared to Release 17. These new eRedCap UEs are only specified for low/mid bands and exhibit performance and complexity similar to 4G LTE UE Categories 1 and 1bis (see Table 4).

According to the evaluation in 3GPP TR 38.865 [4], the complexity reduction techniques for eRedCap may result in the simplest eRedCap modem being approximately 10 % less complex than the simplest RedCap modem. A more significant difference in complexity may be observed when comparing other specific configurations, such as the simplest eRedCap HD-FDD modem with the simplest RedCap FD-FDD modem.

5 New techniques for reduced power consumption

5.1 Extended sleep time (Release 17/18)

The most significant power consumption reduction feature introduced in Release 17 is an enhancement to the existing discontinuous reception (DRX) feature. 5G UEs can be configured with a DRX cycle, which determines how often the UE must listen for potential attempts from the network to reach it when the UE is in a low-activity state (Inactive or Idle state). Between these monitoring occasions, the UE can sleep to save power. The maximum DRX cycle length that could be configured in earlier releases was 2.56 seconds.

Release 17/18 RedCap work items introduced much longer extended DRX (eDRX) cycles in the Idle/Inactive state, aimed at further reducing UE energy consumption. Ultimately, 3GPP decided that these longer eDRX cycles would be supported as optional features not only for RedCap UEs but also for standard 5G NR UEs. However, the longer eDRX cycles in the Idle/Inactive state were introduced as part of the RedCap work items, and they are most likely to be implemented early on by RedCap UEs.

Release 17 took the first step by introducing the ability to configure UEs with these longer eDRX cycles [1]. The new maximum for the Inactive state is 10.24 seconds, while the new maximum for the Idle state is 10,485.76 seconds, which is almost 3 hours. If both the UE and the network support the feature, the UE can request to be configured with an extended DRX cycle. The network can either accept the requested value or select a different value for the UE.

Release 18 further advances this by introducing support for as long extended DRX cycles in the Inactive state as in the Idle state—up to almost 3 hours in both low-activity states [3]. The main change from the network's perspective, compared to Release 17, is that the core network is notified when a UE, configured with a long eDRX cycle, transitions to the Inactive state. This allows the core network to buffer the downlink data until the UE becomes available again after the sleep cycle.

A longer eDRX cycle means fewer transmission opportunities in the downlink. While this enables the UE to sleep more and save power, it also increases downlink latency. Therefore, the configuration of the eDRX cycle should consider the trade-off between power saving and downlink latency.

Additionally, it should be noted that the eDRX cycle does not affect uplink transmission opportunities. This means that the eDRX cycle does not impact uplink latency for UE-triggered traffic. However, if the traffic is characterized by frequent uplink transmissions, the uplink contribution to the UE's power consumption may dominate, preventing the UE from sleeping much—regardless of whether a long eDRX cycle is configured.

Therefore, it is important to consider both downlink packet latency tolerance and uplink packet interarrival time expectations when selecting an appropriate eDRX cycle length and assessing the expected power savings.

For use cases with high downlink packet latency tolerance and long uplink packet interarrival times, the power consumption reduction features enable extensive UE modem sleep time. In such cases, if the UE modem constitutes the majority of the device's power consumption, the overall device power consumption can be significantly reduced, potentially extending battery life to several years (see Annex E in TR 38.875 [3] for examples).

5.2 Relaxed measurements (Release 17)

Another power consumption reduction feature introduced in Release 17 concerns the relaxation of radio resource management (RRM) measurement requirements for neighboring cells. 5G UEs periodically perform measurements on the serving cell as well as neighboring cells to ensure they are connected to the optimal cell. These RRM measurements on downlink signals can significantly impact the UE's energy consumption, especially when traffic is relatively infrequent. If the use case and scenario allow for some relaxation of the measurement requirements for neighboring cells—meaning the measurements can be performed less frequently—this could help improve battery life.

Some relaxations were already introduced in Release 16, allowing standard 5G UEs in the Idle/Inactive state to perform neighbor-cell measurements less frequently, provided the UE has limited mobility or is not near the cell border. If the UE exhibits both limited mobility and is not near the cell border, it may be allowed to refrain from measuring neighboring cells for a certain period. The network enables this feature by configuring the UE with specific criteria that the UE uses to determine whether the measurement relaxations can be applied.

Release 17 introduces additional RRM measurement relaxations specifically for RedCap UEs [1]. For the Idle/Inactive state, the maximum time between measurements and the maximum duration without measurements are extended. Additionally, two new criteria—stationarity and not-at-cell-edge—can be applied to RedCap UEs. Furthermore, some support for relaxed RRM measurements in the Connected state is also introduced for RedCap UEs. When a RedCap UE identifies that it is in a low-mobility scenario, it can report this to the network. The network can then configure the UE with a measurement configuration that is appropriate for the scenario.

5.3 Wake-up receivers (Release 19)

Release 19 will take another step toward even lower UE energy consumption by introducing support for low-power wake-up receivers (LP-WUR) [5]. The benefit comes from the reduced power required by the UE to monitor the downlink, as the full receiver does not need to be activated. In this approach, a new downlink signal, called the low-power wake-up signal (LP-WUS), is transmitted by the base station shortly before the regular downlink signals. This signal informs the UE whether it needs to wake up the main receiver to receive the regular signals. The UE only requires the LP-WUR to detect the LP-WUS, which results in significantly lower energy consumption since, for the majority of the time, the UE is not being paged, allowing the main receiver to remain in a sleep state. Both RedCap UEs and standard 5G UEs will be able to implement this feature.

The features for reduced power consumption are summarized in Table 3.

Table 3: Feature names and the 3GPP release in which they were introduced to reduce power consumption

Feature name	Release	Description
Extended sleep time	Release 15	Support for DRX cycles up to 2.56 seconds
	Release 17	Support for eDRX cycles up to 10.24 seconds in Inactive state and up to 10485.76 seconds in Idle state
	Release 18	Support for eDRX cycles up to 10485.76 seconds in Idle/Inactive state
Relaxed measurements	Release 16	Possibility to perform neighbor-cell RRM measurements less often in Idle/Inactive state
	Release 17	Further RRM measurement relaxations for neighboring cells in Idle/Inactive/Connected state
Wake-up receivers	Release 19	Support for low-power wake-up receivers (LP-WUR)

Source: 5G-ACIA / ZVEI e. V.

6 Industrial use cases that can leverage RedCap

6.1 Wearables

6.1.1 Wearable sensors

The 'Wearables' use case, chosen as part of the 3GPP study for RedCap, is captured in [2] with the following text:

Wearables use case includes smart watches, rings, eHealth related devices, and medical monitoring devices etc. One characteristic for the use case is that the device is small in size. […]

Wearables: Reference bitrate for smart wearable application can be 5–50 Mb/s in DL and 2–5 Mb/s in UL and peak bit rate of the device higher, up to 150 Mb/s for downlink and up to 50 Mb/s for uplink. Battery of the device should last multiple days (up to 1–2 weeks).

Many wearable sensors on the market are designed for healthcare and fitness applications. However, several manufacturing use cases could also benefit from the use of RedCap UEs.

An example is a scanner attached to a glove or worn elsewhere on the body to identify products in a warehouse. These types of wearables aim to simplify the movement of the individual by reducing the number of devices they need to carry manually. Proximity scanning technologies, such as RFID, may be used for local scanning, but most systems will send the scanned ID to an application or retrieve information from the application once the ID is determined.

6.1.2 Safety wearables

Wearable safety IoT devices are becoming increasingly popular in manufacturing and process industries. These devices are designed to help workers stay safe in hazardous environments by monitoring various aspects of their physical well-being, such as body temperature, heart rate, and breathing rate. They can also track the worker's location, movements, and proximity to hazardous equipment or substances. This information can be used to identify potential safety risks and take preventative measures, especially in environments with Automated Mobile Robots in operation.

An important consideration for wearable safety IoT devices is battery life. These devices must be able to operate for extended periods without the need for frequent recharging or replacement. Battery life can be extended by optimizing the device's power consumption, and RedCap features can help optimize the use of radio resources and enhance battery efficiency.

Examples of wearable safety IoT devices include smart helmets, gloves, and glasses, each equipped with a unique set of safety features for monitoring impact, temperature, capturing video, and connecting with colleagues. Given their compact size, these wearables often require the modulation and antenna components to be minimized or limited in the device's architecture.

The largest use of wearable sensors is in petrochemical and chemical environments, where gas detection can indicate leaks or, in worse cases, pose a serious risk to human life. The criticality of these detections requires the devices to be highly reliable, but also to run on batteries, making them suitable for continuous wear. Typically, additional fixed detectors are installed around the facility to monitor the environment. In such cases, wearables may not require an ultra-low-latency connection and could be served by a connectivity solution with RedCap complexity reduction.

6.1.3 Body cameras

Battery-operated body cameras have become standard equipment in public safety, primarily used to document incidents for legal purposes. Following this concept, it is expected that body cameras will also have widespread applications in industry. They can simplify and accelerate process documentation. For example, repair and maintenance operations typically require detailed written reports and photographs. Body cameras can replace and automate these tasks by recording videos of the operations performed.

A second application field is the logistics sector. Currently, the condition of incoming goods at the receiving department is manually documented through pictures taken by workers to identify damaged packaging. Body cameras could assist in this process. The video data can be uploaded to a mobile edge server, where pattern detection software analyzes it, detects anomalies, and generates reports on the goods' condition.

The data throughput required for video streaming applications depends on factors such as resolution, video codec, scene complexity, object movement, and frame rate. A typical H.264 stream requires a data throughput of 0.5 to 6 Mb/s, with the higher value supporting a full HD stream at 1920x1080. Additionally, if supported by the hardware, H.265 can further reduce throughput by about half. Video streaming applications via body cameras are therefore expected to be fully supported, despite the throughput limitations of RedCap, as discussed in Section 4.

Body cameras may be active either continuously or intermittently, depending on demand. If the camera is always on, it may not benefit significantly from the power-saving measures introduced in Release 17 (see Section 5). However, RedCap can help lower the cost of end-user devices and reduce their size. This is particularly advantageous when one or more body cameras are attached to a worker, as it will not disrupt the worker's operations.

6.2 Industrial wireless sensors

The 'Industrial Wireless Sensors' use case and requirements, chosen as part of the 3GPP study for RedCap, is captured in [2] with the following text:

Devices in such environment include e. g. pressure sensors, humidity sensors, thermometers, motion sensors, accelerometers, actuators, etc. It is desirable to connect these sensors and actuators to 5G radio access and core networks. […]

The requirements for these services are higher than LPWA (i. e. LTE-MTC/NB-IoT) but lower than URLLC and eMBB. […]

Industrial wireless sensors: Reference use cases and requirements are described in TR 22.832 and TS 22.104: Communication service availability is 99.99 % and end-to-end latency less than 100 ms. The reference bit rate is less than 2 Mb/s (potentially asymmetric e. g. UL heavy traffic) for all use cases and the device is stationary. The battery should last at least few years. For safety related sensors, latency requirement is lower, 5–10 ms (TR 22.804).

It is worth noting that the proposed 5–10 ms latency requirement for safety-related sensors was only captured in a technical report (TR 22.804) and was ultimately not included in the relevant normative technical specification (TS 22.104 [6], Table 5.2–2).

Industrial wireless sensors are widely used in process automation. In a 5G-ACIA white paper on industrial 5G devices [7], two process automation use cases were presented, which are briefly described below.

The first process automation use case is process monitoring, where multiple sensors are installed in a production facility to provide insights into processes, environmental conditions, or inventories. Data is transmitted to displays for observation and/or to databases for logging and trend monitoring. In this use case, sensors generate periodic measurements of continuous values (e. g., temperature, pressure, flow rate) or waveform measurements (e. g., vibration sensors). Even though waveform measurements are continuous, these sensors typically buffer and transmit the data periodically (e. g., every second) to save battery by enabling discontinuous transmission.

The second process automation use case is plant asset monitoring. To keep a plant running smoothly, it is essential to maintain assets such as pumps, valves, heaters, and instruments. These assets are monitored for early detection of any degradation (e. g., leakage in pipes and valves, wear and tear of bearings) to support and plan maintenance work. Smart sensors (e. g., vibration, temperature, and acoustic sensors, video cameras, gas and flame detectors) are used to detect abnormal conditions in the assets.

Next, we can categorize the industrial wireless sensor domain into three main areas: natively wireless sensors, transmit-only sensors, and clusters of sensors connected physically to an industrial fieldbus gateway. We will discuss these areas individually, as the use cases and implementation requirements tend to differ. However, the relevance of RedCap UEs in these areas could overlap.

6.2.1 Natively wireless sensors

Natively wireless sensors combine operational sensing technology with an integrated UE, enabling direct connection to the 5G network. These sensors can be powered by either a battery or an external power source and can be deployed virtually anywhere. Consequently, they are particularly relevant for use cases that involve remote locations or large geographical areas with varying sensor densities.

RedCap complexity reduction can be beneficial in this context for several reasons, depending on the device's specific characteristics. RedCap features can support and alleviate size limitations, making them particularly useful for devices with space constraints. Coupled with the power-saving features introduced in Release 17, the combined effect offers an appealing solution for wireless sensor manufacturers.

Sensor reporting can be conducted in either push mode or pull mode. In push mode, reporting can be event-driven (including alarms) or periodic (on a regular, scheduled basis). The payload can be binary (e. g., presence or general state, when the sensor is uniquely associated with a specific state or event) or scalar (e. g., temperature, pressure, level, and similar measurements).

6.2.2 Transmit-only sensors

For a relevant set of industrial use cases, such as in process, batch, and factory automation, sensors are typically used in push mode only. In this case, the sensors only require transmit capabilities and determine when to enter "sleep mode." Transmit-only sensors can offer significant energy savings since the device is only active during transmission. These devices can also send scheduled "keep-alive" messages to either maintain an application connection state or ensure the device remains connected to the gNodeB.

Transmit-only devices have limitations, primarily that no information can be pulled by an application. This means there is no connectivity from a northbound controller or application to request data, request retransmissions, or enable active monitoring solutions to verify availability. Additionally, transmit-only sensors lack over-the-air configuration and firmware upgrade capabilities. While these are notable limitations, they may be acceptable for use cases requiring simpler devices in a lower cost bracket, especially when paired with a simpler radio connection.

All RedCap UEs have both transmit and receive capabilities, but if it is known that a UE only handles uplink traffic, its configuration can be optimized to minimize power consumption related to downlink reception.

6.2.3 Clustered industrial sensors

As described in the 5G-ACIA white paper on industrial 5G devices [7], Section 3.3.14, in this common scenario, sensors that serve multiple functions within a small area, such as inside a machine, are connected using low-cost physical connections within the system to a central I/O gateway device. The I/O gateway then connects to the transport medium, which carries traffic up to the application. These I/O gateway devices can leverage the 5G network by incorporating a UE that provides connectivity to all the connected sensors.

Ultimately, the I/O gateway devices may benefit from the same aspects of RedCap that a standalone connected sensor and UE can.

In cases where the I/O gateway must meet low-latency or extremely high-reliability requirements, the features for UE complexity reduction may have a negative impact. Therefore, it is important to assess sensor and application requirements in advance to ensure that the I/O gateway controller with a 5G connection has the necessary capabilities. There are scenarios where a 5G RedCap I/O gateway device is appropriate, and others where a full 5G UE is required to support advanced capabilities such as TSN or high-bandwidth demands.

6.3 Video surveillance

The 'Video Surveillance' use case and requirements, chosen as part of the 3GPP study for RedCap, is captured in [2] with the following text:

The smart city vertical covers data collection and processing to more efficiently monitor and control city resources, and to provide services to city residents. Especially, the deployment of surveillance cameras is an essential part of the smart city but also of factories and industries. […]

Video Surveillance: As described in TR 22.804, reference economic video bitrate would be 2–4 Mbps, latency < 500 ms, reliability 99 %-99.9 %. High-end video e. g. for farming would require 7.5–25 Mbps. It is noted that traffic pattern is dominated by UL transmissions.

The 3GPP use case captured here describes a CCTV-type service, where video is monitored either by humans or analytics software to automate the detection of behavioral events and trigger corresponding actions. In cases where continuous real-time video capture is required, which can be streamed over the network, a relatively high-bandwidth and resilient connection may be necessary.

Further use cases involve surveillance cameras with onboard compute functionality, allowing the captured video stream to be processed through a lightweight dedicated software module. This module extracts events from the stream and compresses the resulting data into a much smaller form for storage or further transmission to a northbound application. These types of cameras typically require mains power or power supplied via a wired Power-over-Ethernet (PoE) connection.

It is possible that use cases may emerge where the simplification features of RedCap could be leveraged alongside this embedded form of image processing, perhaps on smaller-scale mobile robots.

6.4 Handheld radio devices

Voice communication is essential for enabling workers inside a factory to coordinate production processes and respond to unforeseen events. Today, two approaches are commonly used to support voice applications:

1. License-free spectrum is available for use by various radio devices. This is known as PMR446 in Europe and FRS in the US, operating in the 400 MHz band. Communication is typically ad-hoc, with no infrastructure required.
2. Exclusive licenses are used to set up private trunked radio systems. Different standards exist for utilizing the spectrum, with TETRA being the most well-known in Europe. Communication in this setup is carried out using a private radio infrastructure that must be set up and managed. TETRA is highly spectrum-efficient due to its 25 kHz channels and supports group calls in broadcast mode.

Private 5G networks are expected to replace voice-centric radio technologies in the future. Managing and maintaining a single infrastructure will help reduce costs. Moreover, small-band technologies like TETRA are focused on voice communication and are not well-suited for exchanging arbitrary data. The high throughput capabilities of 5G could enable new applications, allowing workers to exchange data of any size in a reasonable timeframe whenever needed. The 3GPP standard that is expected to be used for this purpose is MCx (Mission

Critical Services), which facilitates the transmission of voice, messages, and data in broadcast mode across groups using any IP-based communication technology. The scope of this document does not include MCx.

So far, ruggedized small-band handheld devices for PMR446 or TETRA have benefited from low pricing. RedCap can help bridge this gap through more affordable 5G integration, making these devices competitive. It may also enable the development of smaller devices that better match user and application requirements.

6.5 5G mobile tracker

According to the 5G-ACIA white paper on industrial 5G devices [7], Section 3.3.12, this use case is highly relevant for RedCap because:

- There are **high-density requirements** for monitoring transported goods, pallets, and other transport mediums.
- The data requirements are **small volume**, with periodic bursts of approximately 100 kb/s.
- **Deep sleep mode** can be utilized in some cases due to the periodic nature of the data.

Mobile trackers present challenges in roaming, particularly when crossing international borders. Products will transition from public network connectivity during transport to private networks at enterprise sites, which may have both indoor and outdoor facilities. RedCap does not affect this challenge, provided that all networks support the RedCap UE type.

7 Conclusion

This 5G-ACIA white paper aims to provide an industry perspective on the RedCap feature sets and how these features are relevant to industrial use cases. It covers the necessary considerations for implementation, such as breaking down the features in the standards and how industrial device manufacturers can selectively choose the most relevant features for their specific use cases.

In summary, the following key points have been observed:

- The RedCap functionality introduced in Releases 17 and 18 enables the implementation of UEs with reduced complexity and power consumption. RedCap is a 5G-only technology and does not depend on or offer backward compatibility with 4G and LTE.
- RedCap can be relevant in multiple industrial use cases, especially in high-density sensor networks, where device space is limited and/or where certain power characteristics are present.
- On the network side, a software upgrade is required to allow RedCap UEs to connect, and the network must support 5G standalone (SA) operation.
- There may be an impact on overall spectral efficiency if there is a high traffic load from connected RedCap UEs.
- Power-saving features are generally on par with 4G technologies (NB-IoT and LTE-M). Power-saving optimizations can be achieved for applications that meet the prerequisites outlined in Section 5. These optimizations are not specifically dependent on RedCap.

RedCap radio chipsets bring lower complexity to the market, helping achieve the low cost needed for affordable and widespread sensor deployment. In cases where the cost of communication is a significant portion of the overall device cost, RedCap can help significantly reduce the overall cost.

For industrial sensors, particularly at the smaller end of the scale, space is often limited. RedCap offers specific benefits, such as reducing the number of antennas required and simplifying the integration and assembly of the antenna system. If a half-duplex application and system are implemented, the added weight and complexity of duplexing circuitry can be avoided.

Power consumption is a key feature of RedCap, but substantial savings can only be achieved if the industrial endpoint application meets the prerequisites described in Section 5. Therefore, a thorough analysis of the use case is recommended to determine the suitability and the potential power savings from the specified power-saving features.

In conclusion, many industrial use cases stand to benefit from the lower complexity, cost, size, and power consumption offered by RedCap UEs. However, it is crucial to conduct a detailed assessment to determine the extent to which these benefits will be realized for each specific use case.

3GPP
The 3rd Generation Partnership Project (3GPP) is a collaborative project that brings together standardization organizations from around the world to create globally accepted specifications for mobile networks. As its name implies, it was first created to establish such specifications for the third generation (3G) of mobile communication systems. It has continued its work for subsequent generations, including the one considered here, the fifth generation (5G).

5G-ACIA
5G-ACIA is the globally leading organization for shaping and promoting Industrial 5G.

8 Abbreviations

3GPP	Third Generation Partnership Project
5G-ACIA	5G Alliance for Connected Industries and Automation
AGV	Automated guided vehicles
BW	Bandwidth
BWP	Bandwidth part
CA	Carrier aggregation
CCTV	Closed-circuit television
DC	Dual connectivity
DL	Downlink
DRX	Discontinuous reception
eDRX	Extended DRX
eMBB	Enhanced mobile broadband
eRedCap	Enhanced RedCap
FDD	Frequency division duplex
FD-FDD	Full-duplex FDD
HD-FDD	Half-duplex FDD
ICT	Information and communications technology
IMT	International Mobile Telecommunications
I/O	Input/output
IoT	Internet of things
LTE	Long-Term Evolution
LTE-M	LTE for MTC
LPWA	Low-power wide-area
LP-WUR	Low-power wake-up receiver
LP-WUS	Low-power wake-up signal

MCx Mission critical services
MIMO Multiple-input and multiple-output
mMTC Massive machine-type communication
MTC Machine-type communications
NB-IoT Narrowband IoT
NR New Radio
NSA Non-standalone
PDSCH Physical downlink shared channel
PUSCH Physical uplink shared channel
OT Operational technology
QAM Quadrature amplitude modulation
RedCap Reduced capability
RFID Radio-frequency identification
RRM Radio resource management
SA Standalone
SSB Synchronization signal block
TDD Time division duplex
TR Technical report
TS Technical specification
UE User equipment
UL Uplink
URLLC Ultra-reliable low-latency communication

9 Annex

Table 4 Downlink and uplink peak rates for a selection of 4G LTE UE categories as defined in 3GPP TS 36.306 [8]

4G LTE UE category	DL [Mb/s]	UL [Mb/s]
Categories 1 & 1bis	10	5
Category 2	50	25
Category 3	100	50
Category 4	150	50
Category 5	300	75

Source: 5G-ACIA / ZVEI e. V.

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[7] 5G-ACIA white paper *"Industrial 5G Devices – Architecture and Capabilities"*, March 2022, https://5g-acia.org/whitepapers/industrial-5g-devices-architecture-and-capabilities/

[8] 3GPP Technical Specification 36.306, *"Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio access capabilities"*, V8.9.0, March 2013, https://www.3gpp.org/ftp/Specs/archive/36_series/36.306/36306-890.zip

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