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Reduced Capability Devices for 5G IoT

Rapeepat Ratasuk, Nitin Mangalvedhe, Gilsoo Lee, David Bhatoolaul
Nokia Bell Labs, Naperville, IL, USA
Email: {rapeepat.ratasuk, nitin.mangalvedhe, gilsoo.lee, david.bhatoolaul}@nokia-bell-labs.com

***Abstract*— The first release of 5G NR (Rel-15) supports Internet of Things (IoT) use cases including ultra-reliable low-latency as well as massive machine type communications. In Rel-17, reduced capability devices are being introduced to support mid-range IoT use cases such as industrial wireless sensors, wearables, and video surveillance. These use cases require low-cost devices to support high reliability, low latency, medium data rate, and long battery life despite being low complexity in design. In this paper, we provide an overview of these devices and describe important features being standardized in 3GPP for complexity reduction, coverage compensation, and power saving.**

Keywords—5G New Ratio (NR), Internet of Things (IoT), Reduced Capability (RedCap) Devices

I. Introduction

The communications industry is in the middle of transitioning to the fifth generation (5G) of wireless technology. In the 3rd Generation Partnership Project (3GPP), 5G has been given the name New Radio (NR). Three important types of services are supported – enhanced mobile broadband, massive machine type communications (mMTC), and ultra-reliable low latency communications (URLLC). Industrial IoT (IIoT) applications are supported using URLLC features, while mMTC applications are supported using LTE-M and Narrowband IoT based on fourth generation technology [1].

In Rel-17, 3GPP is introducing Reduced Capability (RedCap) devices [2] to support mid-range IoT/IIoT use cases with the goal to reduce device cost and complexity compared to normal NR devices. These devices are also colloquially referred to as RedCap or NR-Light devices. The requirements for these devices compared to other IoT devices are shown in Table I.

TABLE I. Requirements for NR IoT devices

Requirement	URLLC	mMTC	RedCap
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 rate	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 (Maximum Coupling Loss)	N/A	164 dB	Same as NR (~144 dB MCL)

Other use cases that fall within the requirements listed in Table I include live visual production control, process automation, remote vehicle operation, etc. Fig. 1 illustrates some IoT use cases and the related NR technology.

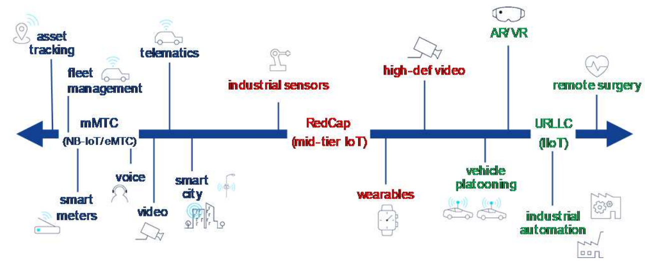

Fig. 1. Example of IoT use cases.

In addition to reducing complexity, the Rel-17 work to specify support for RedCap devices aims to satisfy additional objectives including –

- Device power saving and battery lifetime enhancement, including support for extended sleep and measurement relaxation.
- Early RedCap device identification to the network during initial access procedure and access restriction (e.g. access barring and access control).
- Device capabilities and restricting reduced capability devices to the intended use cases only.

Furthermore, RedCap devices may have compact form factor with reduced antenna efficiency (up to 3 dB lower antenna efficiency). In certain scenarios, coverage recovery techniques may be needed to ensure that RedCap devices enjoy the same coverage as legacy NR devices, This will allow RedCap deployment in existing cell sites.

The outline of the paper is as follows. In Section II, device complexity reduction analysis is provided together with specification impacts. Section III describes coverage analysis and needed recovery. Capacity impact from the introduction of RedCap devices is discussed in Section IV. Section V describes power saving analysis and features being introduced. Finally, conclusions are provided in Section VI.

II. Complexity Reduction

For cost and complexity reduction, a reference NR device is needed for comparison. A typical NR device would at a minimum have the following mandatory capabilities: 100 MHz radio frequency (RF) bandwidth for Frequency Range 1 (FR1, 410-7125 MHz) and 200 MHz for Frequency Range 2 (FR2, 24.25-52.6 GHz), one transmit antenna and multiple receiver antennas, and 2-layer MIMO. The approximate cost breakdown for a reference NR user equipment (UE) for evaluation is shown in Table II [3]. The device cost drivers can be broken down into two parts – RF and baseband. The RF components include antenna ports, RF transceivers (low-noise amplifier (LNA), mixer, local oscillator), power amplifier (PA), filters, duplexer, switches, etc. The baseband components include ADC/DAC, FFT/IFFT, data buffer, receiver processing block, low-density parity-check code (LDPC) coder/decoder, Polar coder/decoder, MIMO processing blocks, cell search processing block, etc.

TABLE II. REFERENCE NR DEVICE COST

Functional block	Cost breakdown		
	FR1 FDD 1Tx-2Rx	**FR1 TDD 1Tx-4Rx**	**FR2 TDD 1Tx-2Rx**
RF:baseband cost ratio	40:60	40:60	50:50
Antenna Array	-	-	33%
Power amplifier	25%	25%	18%
Filters	10%	15%	8%
RF transceiver (including LNAs, mixer, and local oscillator)	45%	55%	41%
Duplexer / Switch	20%	5%	0%
Total of RF	**100%**	**100%**	**100%**
ADC / DAC	10%	9%	4%
FFT/IFFT	4%	4%	4%
Post-FFT data buffering	10%	10%	11%
Receiver processing block	24%	29%	24%
LDPC decoding	10%	9%	9%
HARQ buffer	14%	12%	11%
DL control processing & decoder	5%	4%	5%
Synchronization / cell search block	9%	9%	7%
UL processing block	5%	5%	7%
MIMO specific processing blocks	9%	9%	18%
Total of Baseband	**100%**	**100%**	**100%**
Overall relative cost	**100%**	**100%**	**100%**

The following complexity reduction techniques have been studied in [3] and were recommended for RedCap devices –

- Reducing the number of Rx antennas: 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 (compared to two) can reduce the UE complexity by as much as 15-30%. It, however, can result in coverage loss for the UE in the downlink. In addition to reducing the RF cost, having only a single receiver chain eliminates the need to support spatial multiplexing MIMO. This can further simplify the baseband operations and the cost of reduced coverage and throughput in the downlink.
- Reducing the UE RF bandwidth: This can result in significant complexity reduction. However, the degree of the reduction depends on the relative reduction in the UE RF bandwidth compared to the reference NR UE. In this case, reducing the bandwidth from 100 MHz to 20 MHz can provide meaningful complexity reduction, estimated to be on the order of 10-20%. Note that, for the RedCap devices, support for existing synchronization signal block configurations is mandated. Therefore, the bandwidth can only be reduced to 20 MHz for FR1 and 100 MHz for FR2.
- Half-duplex FDD: This is expected to provide substantial complexity reduction, estimated to be up to 10% per frequency band. The saving can be substantial as the UE will likely support many bands and so the duplexer can be removed for each supported band.

When considered together, device complexity reduction on the order of 50-70% of the reference NR device may be achievable. Furthermore, the three techniques considered above can be implemented with minimum changes to the specifications. Other techniques such as relaxed device processing time and relaxed device processing capability were also considered. However, they did not provide meaningful reduction in complexity.

Subsequent to a comprehensive study on complexity reduction, it was agreed to define RedCap devices as shown in Table III. Note that only one type of RedCap devices will be defined per frequency range.

TABLE III. FEATURES OF REDUCED CAPABILITY DEVICES

	FR1		FR2	
	Reference NR UE	**RedCap UE**	**Reference NR UE**	**RedCap UE**
Device Bandwidth	100 MHz	20 MHz	200 MHz	100 MHz
Antenna Config	FDD: 1Tx-2Rx TDD: 1Tx-4Rx	1Tx-1Rx, 1Tx-2Rx	1Tx-2Rx	1Tx-1Rx 1Tx-2Rx
DL MIMO Support	Yes	Yes for 2Rx	Yes	Yes for 2Rx
Duplex Operation	FD-FDD, TDD	FD-FDD, TDD, HD-FDD	TDD	TDD
Maximum Modulation	DL: 256-QAM UL: 64-QAM	DL: 256-QAM (optional), 64-QAM mandatory UL: 64-QAM	DL: 64-QAM UL: 64-QAM	DL: 64-QAM UL: 64-QAM
Peak data rates	N/A	FD-FDD, 1Rx: 85 Mbps DL, 91 Mbps UL	N/A	50:50 DL/UL, 1Rx: 212 Mbps DL, 228 Mbps UL
Complexity Reduction	-	~50-60% (1Rx)	-	~50% (1Rx)

There are two key impacts from introducing RedCap devices – coverage reduction and capacity reduction. These two impacts are addressed in Sections III and IV. Other issues are related to required changes to 3GPP specifications to support these new devices [4]-[6]. They can be summarized as follow –

- Reducing the number of UE RF bandwidth: Existing specification can support UE with reduced RF bandwidth in wideband system via appropriate configurations of system parameters. 3GPP is studying several optimization

methods to address, e.g., offloading of RedCap devices into a different bandwidth part from broadband devices.
- Reducing the number of Rx antennas: Existing specification can already support 1 Rx antenna branches. The impact to coverage is addressed in Section III.
- Half-duplex FDD: Switching time between reception and transmission at the device of 13 μs has been agreed. The device will reserve the last symbol in downlink and/or uplink slot for this purpose. Potential collision cases (e.g. device being scheduled for downlink data reception at the same time it is configured to transmit channel quality report in uplink) are being studied and rules to resolve collisions will be defined if necessary. It is noted that most collision cases can be resolved by network implementation.

Further specification work will also address early identification of RedCap UE to the network, constraining RedCap UE to only intended use cases (i.e., IoT services), cell barring of RedCap UE, and UE capability report. In addition, higher-layer work related to power saving will introduce two enhancements – extended sleep and measurement relaxation to extend battery life [2]. Power saving is described in Section V. Note that specification work is still on-going in 3GPP.

III. Coverage Compensation

One objective of the NR-Light study item work was to analyze the coverage of RedCap UEs and study coverage recovery techniques to compensate for potential coverage loss from device complexity reduction. Note that only downlink coverage compensation is needed based on the techniques being considered in Section II. However, the NR-Light study also considered use cases where the RedCap device may have a small form factor, such as for wearables. In this case, there is an additional coverage loss, as explained below.

A RedCap UE can experience coverage loss compared with a reference NR UE due to the following complexity reduction features.

- 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. The loss can be up to 3dB.
- Reduced number of Rx antennas: A RedCap UE with fewer antennas than a reference NR UE would suffer a downlink performance loss.
- Reduced UE bandwidth: A RedCap UE with a smaller bandwidth than a reference NR UE may experience some loss in frequency diversity on the downlink in a coverage limited scenario.

Link budget analysis was undertaken using Maximum Isotropic Loss (MIL), Maximum Path Loss (MPL), and Maximum Coupling Loss (MCL) as metrics to evaluate coverage. Of these, since MIL also includes antenna gains, it allows for consideration of the impact of reduced antenna efficiency. The main assumptions for the coverage analysis are listed in Table IV for scenarios in FR1 and FR2. Coverage of the following channels was considered based on a target performance requirement.

- PDCCH – Downlink control channel
- PDSCH – Downlink data channel
- PUCCH – Uplink control channel
- PUSCH – Uplink data channel
- PRACH – 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

For physical downlink and uplink data channels, a target throughput was specified as shown in the table. For some channels, a target block error rate (BLER) was specified for carrying messages of a given size. For each channel, the required signal-to-noise ratio (SNR) to achieve the target performance was determined and used in the link budget calculations. The table shows the difference in assumptions between a reference NR UE (Ref.) and a RedCap UE and includes the aforementioned complexity reduction features.

TABLE IV. 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	Ref.	100 MHz	20 MHz	100 MHz
	RedCap	20 MHz	20 MHz	100 MHz
Number of UE antennas	Ref.	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	Ref.	0 dBi	0 dBi	5 dBi
	RedCap	-3 dBi	-3 dBi	5 dBi
PDSCH target throughput	Ref.	10 Mbps	1 Mbps	25 Mbps
	RedCap	2 Mbps	1 Mbps	25 Mbps
PUSCH target throughput	Ref.	1 Mbps	100 kbps	5 Mbps
	RedCap	1 Mbps	100 kbps	5 Mbps

Fig. 2 illustrates the MIL for various channels in the TDD Urban 2 GHz scenario for a reference NR UE (4Rx) and a RedCap UE (1Rx or 2 Rx). The MIL for uplink channels of RedCap UEs is degraded by 3 dB due to reduced antenna efficiency. The MIL for downlink channels is degraded even more (e.g., the loss is about 10 dB for 1Rx), due also to reduced number of Rx antennas. The amount of coverage recovery needed for RedCap UEs is determined based on the limiting channel for the reference NR UE, i.e., the channel with the poorest link budget (least MIL). It is seen that PUSCH is the limiting channel, as illustrated by the horizontal red line. Thus, a coverage recovery of 3 dB is necessary for PUSCH. While the other uplink channels for the RedCap UE also experience 3 dB loss, the MIL is still better than that of the limiting channel and

TABLE V. EXAMPLE OF CAPACITY ANALYSIS FOR FTP3 TRAFFIC WITH MEDIUM CELL LOADING

		50th percentile UPT (Mbps)				5th percentile UPT (Mbps)				Cell average SE (bps/Hz)			
	RedCap UE ratio	0%	25%	50%	100%	0%	25%	50%	100%	0%	25%	50%	100%
Downlink	eMBB UE	300.05	407.42	413.37	\	105.19	190.68	193.98	\	3.68	4.79	4.79	\
	RedCap UE (2Rx)	\	18.92	18.15	22.28	\	2.73	2.34	3.83	\	1.27	1.27	1.32
	All UEs	300.05	330.63	106.32	22.28	105.19	7.5	3.77	3.83	3.68	3.91	3.03	1.32
Uplink	eMBB UE	35.769	35.71	36.162	\	11.898	11.898	11.163	\	0.49	0.49	0.49	\
	RedCap UE (2Rx)	\	6.968	7.079	7.15	\	3.514	3.289	3.313	\	0.39	0.39	0.39
	All UEs	35.769	29.122	7.783	7.15	11.898	5.171	4.04	3.313	0.49	0.47	0.44	0.39

hence no coverage recovery is necessary for these channels. This is also the case for all the downlink channels. In other scenarios and with more stringent downlink power assumptions, it was found that some downlink channels also require coverage recovery.

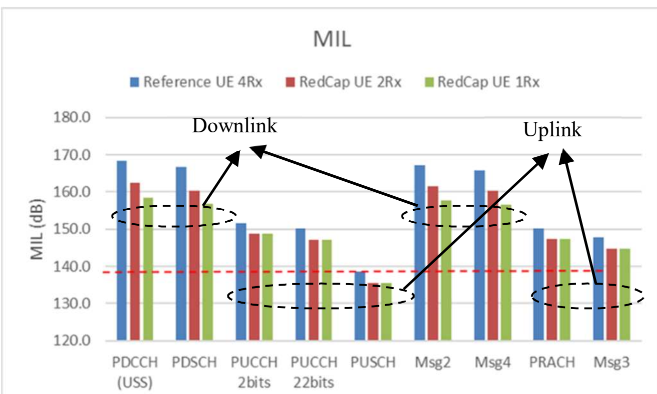

Fig. 2. NR UE and RedCap UE Link budget for different channels.

Key candidate techniques proposed in the study report for improving the performance of the data and control channels are as follows.

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

The work item does not include any specific objectives for coverage recovery, but 3GPP is discussing whether existing solutions can adequately provide coverage recovery where necessary.

IV. Capacity Analysis

Capacity evaluation is performed to study the impact of UE complexity reduction on system-level performance by using a 5G simulator [3]. For our simulations, we consider an urban macrocell network of 7 sites with 3 sectors per site with the inter-site distance of 500 m as shown in Fig. 3. The total system bandwidth of the network is 100 MHz. The simulations are carried out for both uplink and downlink. In the simulations, TDD system is assumed where 8 and 2 subframes, respectively, are allocated for downlink and uplink operations. The subcarrier spacing is 30 kHz, and the carrier frequency is 2.6 GHz. We have run simulations using full buffer and FTP3 data traffic models, respectively.

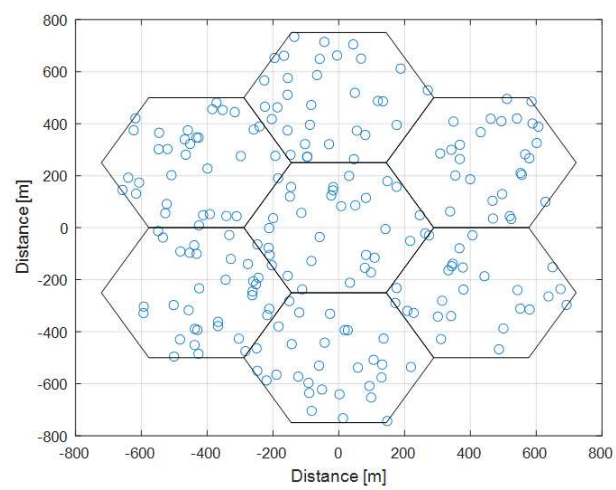

Fig. 3. Simulation environment example of 7 sites with 3 sectors per site.

In the simulations, RedCap UE and enhanced Mobile Broadband (eMBB) UE have different sets of parameters. In particular, the bandwidth of RedCap UE is assumed to be 20 MHz while the eMBB UE uses 100 MHz of the total system bandwidth. When RedCap UE has 1 or 2 receiving antennas, we assume that the number of downlink layers is equal to the number of receiving antennas. Also, eMBB UE is set to use 4 receiving antennas. Moreover, RedCap UE uses 64-QAM in downlink and 16-QAM in uplink whereas 256-QAM in downlink and 64-QAM in uplink are applied to eMBB UE.

Table V shows the throughput of eMBB UE, RedCap UE, and all UEs on a network with different RedCap UE ratios from 0% to 100%. In Table V, FTP3 traffic model is used to capture the effect of bursty traffic on the capacity performance of the network. For FTP3 model, the file size is 500 kbytes, and the arrival rate is adjusted in order that the network is operating at a medium load, i.e., the resource utilization of the network is between 30% and 50%. Table V first shows that user packet throughput (UPT) is reduced if the network has only RedCap UE. For instance, the 50th percentile UPT decreases from 300.05 Mbps to 22.28 Mbps in downlink if the type of UE on a network changes from eMBB to RedCap. Also, in Table V, the UPT of eMBB UE is less affected by deploying RedCap UE on the same network. For instance, the 50th percentile UPT of eMBB UE is similarly maintained when the RedCap UE ratio changes from 0% to 50%.

In Table V, we also observe cell average spectral efficiency of eMBB and RedCap UEs in downlink and uplink with the different RedCap UE ratios. When FTP3 traffic model is used, the cell average spectral efficiency is defined as:

$$\mathrm{SE\ [bps/Hz]} = \frac{\text{cell average throughput}}{\text{bandwidth } \times \text{resource utilization}}$$

The results show that the cell average spectral efficiency decreases if the network has only RedCap UE. For instance, deploying only RedCap UE on the network can result in 64.1% and 20.4% lower cell average spectral efficiency in downlink and uplink, respectively, than the network with eMBB UE. From the same results, we can also see that deploying RedCap UE has a less impact on the spectral efficiency of uplink than that of downlink.

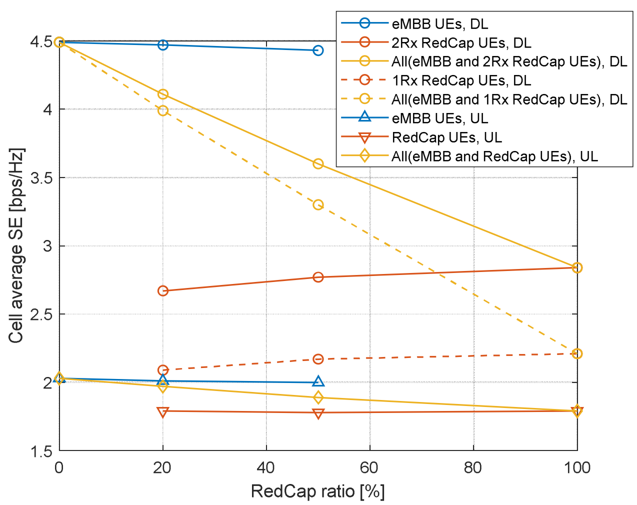

Fig. 4. Cell average spectral efficiency of eMBB UE and RedCap UE with full buffer traffic model in downlink and uplink.

In Fig. 4, we show the cell average spectral efficiency in uplink and downlink when full buffer traffic model is used with the different RedCap UE ratios from 0% to 100%. Fig. 4 shows that deploying the RedCap UE with a larger number of receiving antennas increases the cell average spectral efficiency. For instance, when a network has an equal number of eMBB and RedCap UEs, the spectral efficiency of all UEs in downlink can increase by 27.7% if the number of receiving antennas of RedCap UE changes from 1 to 2. Also, in Fig. 4, the results show that the ratio of RedCap UE has a marginal impact to the spectral efficiency of eMBB UE. For example, when the RedCap ratio increases from 0% to 50%, the spectral efficiency of eMBB UE in downlink is reduced by 1.3%. Moreover, from Fig. 3, we can see that the spectral efficiency of RedCap UE increases as the RedCap ratio increases on the network. For example, if the RedCap ratio increases from 20% to 50%, the spectral efficiency of RedCap UE with 2 receiving antennas in downlink can increase by up to 6.4%.

V. Power Saving

Another objective of the NR-Light work is to reduce power consumption in order to improve battery life. Techniques being considered for improving the battery life of NR-Light devices in this work include –

- Reducing the time the device would monitor the control channel for scheduling and other information.
- Extend discontinuous reception (DRX) time so that the device can sleep for longer.
- Measurement relaxation for stationary devices.

Given more generalized previous studies [7], the RedCap power saving study based on reduced PDCCH monitoring focused on the following 3 schemes.

- Scheme 1 is based on the concept of reducing the blind decoding required in connected mode on a per slot basis via either reducing the number of different sized DCIs the UE would be expected to monitor (alt. 1a) or via reducing the maximum number of blind decodes (alt.1b).
- Scheme 2 examined the impacts of extending the PDCCH monitoring gap between two consecutive PDCCH monitoring occasions.
- Scheme 3 focused on dynamic adaptation of the PDCCH monitoring parameters (e.g. the maximum number of PDCCH candidates).

The conclusion of the RedCap study with respect to these schemes was that they were not worth developing for Rel-17 RedCap, given the following observations:

- Limited power savings gains to be obtained that, even for the best-case scenarios simulated, were estimated to be in the range 0 to 12% [3] for those given slots, depending on factors such as the amount of blind decode candidate reduction and the traffic model.
- Increased blocking probability in some scenarios. Fig. 5 [8] shows the blocking probability experienced by a RedCap device monitoring a single slot configured with a 2-symbol 22 control channel element (CCE) PDCCH in good signal-to-interference-plus-noise ratio (SINR) conditions, operating within the FR2 range using 100 MHz and with a subcarrier spacing of 120 kHz. It can be seen that for that particular scenario, reducing the number of blind decode candidates by 50% can more than double the blocking probability experienced by UEs.
- Rel-16 expanded the range of existing power saving options already available, for example the Wake Up Signal (WUS).

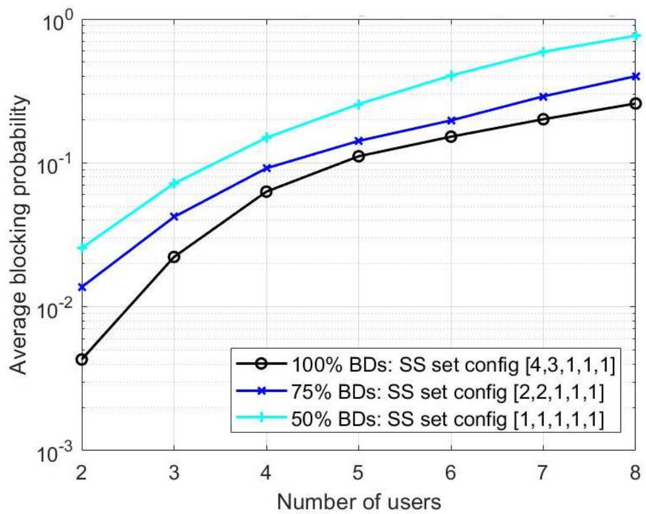

Fig. 5. Blocking Probability for FR2 range, 2 Symbol long, 22 CCE corset in good coverage scenario.

The studies into the application of extended DRX (eDRX) concluded that for both idle and inactive Radio Resource Control (RRC) modes, extending the cycle time beyond 10.24 s would in some important use case scenarios yield significant battery lifetime gains (see Table VI, from [3], Appendix E.1.2). These findings have led to the specification of this technique for eDRX cycles up to 10485.76 s to be included as an objective for the Rel-17 work item.

TABLE VI. POTENTIAL BATTERY SAVINGS FROM EXTENDING DRX

Use case	Mean Inter-Arrival Time	Payload Size	RRC_IDLE Battery Lifetime gain above 10.24s	RRC_INACTIVE Battery lifetime gain above 10.24s
Video Surveillance	≤1s	250 Bytes	up to 3.5%	up to 7%
Wearables	≤2s	72 Bytes	up to 7%	up to 16%
Industrial Wireless Sensor	100ms	72 Bytes	up to 0.38%	up to 1%
	1 min		up to 180%	up to 297%
	5 min		up to 340%	up to 419%

For those RRC Idle and RRC Inactive RedCap devices that are either low mobility or stationary, it was agreed during the study item phase that, given the potential power consumption savings, the Rel-16 NR radio resource monitoring (RRM) relaxation methods should be further studied and if agreed, then specified as part of the Rel-17 RedCap work item.

VI. CONCLUSION

In this paper, we provide an overview of reduced capability 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 with small impact to coverage. The impact to system efficiency and capacity is small when the system is not heavily loaded. Additional power consumption analysis shows that existing methods can already be used to ensure long battery life. Furthermore, two features – eDRX and RRM relaxation will be introduced to provide additional power consumption reduction.

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