

Power Saving Techniques in 3GPP 5G New Radio: A Comprehensive Latency and Reliability Analysis

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Abstract—Energy efficiency is critical for future sustainable cellular systems. Power saving optimization has been a key part of the fifth generation (5G) new radio specifications. For 5G-advanced and future 6G, with the anticipation of a trillion internet of things (IoT) devices with non-rechargeable or low-density batteries, device power efficiency is rather essential. There are numerous contributions from industry and academia which present the potential power saving gains of the various 5G power saving techniques; however, there is a lack of art on the performance cost paid to achieve such power saving gains. Therefore, this paper presents a comprehensive evaluation of the radio latency and reliability cost, which is lost due to a certain 5G new radio power saving feature. A thorough review of the state-of-the-art 5G power saving techniques is introduced. Extensive system level simulations are performed to evaluate the latency and reliability cost of the considered power saving features. The paper offers valuable recommendations for supporting power-efficient latency-critical traffic for beyond 5G-advanced systems.

Index Terms—Power efficiency; power saving; URLLC; 5G NR; 6G; DRX; Paging; Scheduling; 3GPP.

I. INTRODUCTION

The fifth generation (5G) new radio (NR) is driven by the deterministic ultra-low latency use-cases, i.e., the ultra-reliable and low-latency communications (URLLC) [1]. Those support a wide variety of industrial internet of things (IIoT) deployments of intelligent sensors, actuators, robots, and machines [2]. To support the critical industrial applications, the majority of the IIoT URLLC communications demand a stringent set of the radio latency and reliability, which is comparable to that is of the Ethernet-based communications, i.e., a one-way radio latency of 1-5 ms with a success probability of 99.999%.

For beyond 5G-advanced systems, i.e., beyond 3GPP release-20 (6G), it is envisioned to deploy a trillion IIoT devices with the requirement of a prolonged battery lifetime, i.e., beyond 10-year of operation [3]. Furthermore, it has been seen, from field deployments and lab tests, that such battery requirement is infeasible in practice and accordingly, the typical IIoT device lifetime becomes much more longer than that is of the battery. In particular, those battery targets assume the IIoT devices are deep sleeping for extended periods of time and only waking up when there is a payload for transmission. This is not appropriate for mobile terminated services, where devices need to at least periodically search for potential incoming traffic. Thus, despite the battery lifetime assumptions, it leads to millions of IIoT devices removed and manually recharged or completely thrown-away per day, which imposes a significant expenditure overhead and hazardous environmental waste, respectively [4].

Those power efficiency challenges have been well reflected by a variety of state-of-the-art contributions from 3GPP partners and academia. Specifically, energy efficient radio communications are recognized as a vital design target of the upcoming 6G cellular networks. For 5G new radio, there has been an extensive work on device power saving procedures [5], including power optimizations for idle, inactive and connected modes. On another side, and away from the power efficiency targets, the feasibility of the URLLC latency and reliability requirements is investigated for macro deployments with frequency division duplex (FDD) [6], time division duplex (TDD) [7], and for industrial factory TDD deployment [2], respectively. Furthermore, smarter scheduling algorithms [8, 9] are vital to achieve the challenging URLLC targets, particularly in coexistence deployments with various quality of service (QoS) classes on the same spectrum. However, there is lack in the state-of-the-art literature on the performance cost, i.e., radio latency and reliability, paid in order to fulfill a power efficient operation at the device side.

In this work, the state-of-the-art 3GPP power saving techniques have been extensively investigated and reviewed. Those include the power efficient RRC inactive state, the flexible discontinuous reception (DRX), the cross-slot scheduling, the paging early procedures, small data transmission without RRC state transition, and dynamic reference signal sharing, respectively. Accordingly, an extensive set of realistic system-level simulations are carried out to evaluate the achievable latency and reliability performance for each of the considered power saving feature. The paper offers valuable recommendations on the current power efficiency challenges towards 6G systems.

This paper is organized as follows. Section II briefly presents the system model of this work while Section III surveys the state-of-the-art power saving techniques until the current 3GPP release-17. Section IV introduces the simulation results. Finally, the paper is concluded in Section V.

II. SYSTEM MODEL

An indoor industrial factory deployment is considered in this work, where C cells are deployed to offer coverage to the factory area and each serves K uniformly-distributed UEs. Both downlink and uplink directions are separately considered. The URLLC-alike FT3 traffic is considered with small and sporadic payload transmissions, where the offered traffic load per cell is calculated in line with [9].

The 3GPP methodology for URLLC system-level simulations is followed in this work. UEs are dynamically multi-

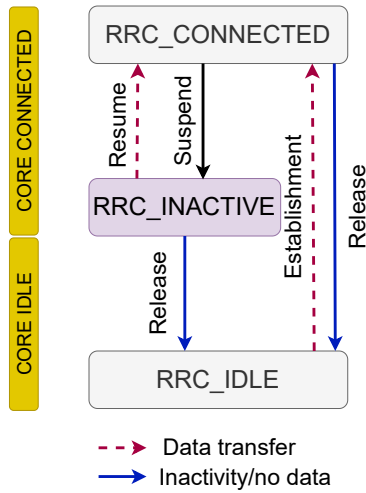


Fig. 1. RRC state transition in 5G new radio.

plexed using the orthogonal frequency division multiple access (OFDMA), with each physical resource block (PRB) of 12 successive sub-carriers. A short transmission time interval (TTI) duration of 4-OFDM symbols is considered alongside with 30 KHz sub-carrier spacing for faster URLLC transmissions. The performed system-level simulations include the majority of Layer 1 and 2 functionalities, in a realistic setup, such as dynamic UE scheduling (using proportional fair), dynamic hybrid automatic repeat request (HARQ) re-transmission and combining, indoor industrial factory channel modeling, and dynamic link adaptation, respectively. The major performance key indicator of this work is the outage latency [7], where it denotes the achievable radio latency of each transmitted payload until it is successfully decoded by its intended receiver, for a certain perceived outage probability. That is, including the inter-UE scheduling queuing delay, cell and UE processing delays, HARQ re-transmission delay, RRC state transition from IDLE/Inactive modes to connection mode, and paging detection delay.

III. 5G NEW RADIO: POWER SAVING TECHNIQUES

A. RRC Inactive State

The RRC Inactive state [5] has been introduced since 3GPP release-15, with the objective of reducing the UE power consumption and the connection establishment control overhead, respectively. With the RRC Inactive state, the UE core-network context information is kept alive at the last known gNB, i.e., anchor gNB. Therefore, as depicted by Fig. 1, when the UE transitions back to RRC connected mode, for payload transmission or reception, the current selected gNB acquires the UE context from the anchor gNB, and the RRC connection is established accordingly. The RRC Inactive state therefore enables a faster RRC connection establishment without the need to establish the core-network connection and respective security keys. This is useful for URLLC services for which sporadic and frequent traffic arrivals are foreseen such that UEs avoid the RRC connection establishment overhead.

Upon data inactivity, The gNB triggers an RRC suspend command to the UE and the UE enters the RRC Inactive

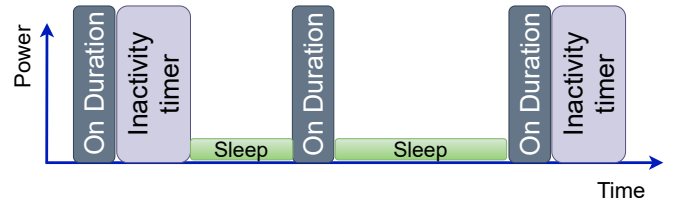


Fig. 2. Connected-DRX (C-DRX) for power critical 5G devices.

state, with the core-network context information kept active. For both the RRC IDLE/Inactive states, the UE monitors the configured paging occasions. When a true paging indication is detected and decoded, the RRC IDLE mode UE must transition to the RRC connected mode before the payload transmission or reception; however, the RRC Inactive mode UE may transmit or receive a small payload without transitioning to RRC connected mode.

B. Flexible Discontinuous Reception (DRX)

DRX is a legacy measure for connected-mode UEs to sleep and shut down their transceiver chains for extended periods of time, accordingly, avoiding the excessive battery consumption. A DRX cycle is defined by a periodic set of wake-up times over which the UE shall wake-up/turn on its receiver, and hence, attempt decoding the configured PDCCH control channels, for detecting a possible scheduling grant. There are long and short cycled DRX. The short DRX cycle spans from 2 ms to 640 ms while the long DRX cycle is from 10 ms to 10.24 s. Clearly, the long DRX cycle offers better UE power saving gain, at the expense of longer radio latency, i.e., the device is not reachable during the DRX OFF periods.

Therefore, the UE, according to its own implementation, decides the sleep state which it shall trigger between the DRX ON opportunities. As part of 3GPP release-17, there are three sleep states defined for 5G devices as: deep sleep, light sleep, and micro sleep. Each state denotes that UE shuts down certain components of its RF chain. For instance, a UE within the deep sleep state implies that UE RF chain is completely shutdown and the UE can not monitor or receive control or data channels. Thus, to transition from one state to another, the UE consumes an amount of power and processing delay until it fully transitions to the required state. For example, to transition from deep sleep to active state, the UE consumes an average of 20 ms until it is fully available for reception [5].

Thus, as shown by Fig. 2, 3GPP has introduced an extended inactivity timer [5] as part of the connected-mode DRX operation. Upon detecting a control channel grant during the DRX ON period, the UE stays active for the duration of the configured inactivity timer in order to continue monitoring the control channel for possible following grants of further incoming and/or buffered traffic payload at the gNB. This way, the UE does not transition quickly between states, and hence, avoiding the power and delay overhead of the state transition.

C. Cross-Slot Scheduling

The 5G new radio, since the early release-15 development, has introduced a flexible resource allocation for latency-critical

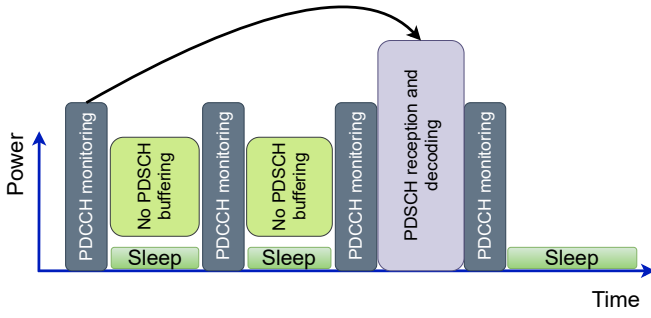


Fig. 3. Cross-slot scheduling and resource allocation.

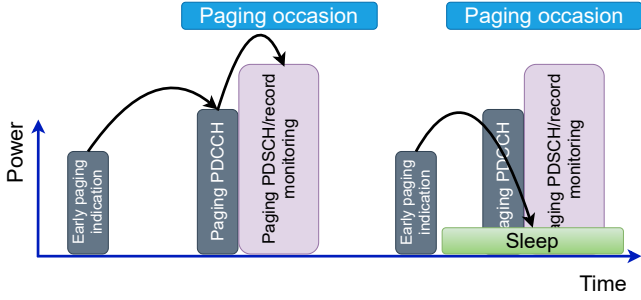


Fig. 4. Power-optimized early paging indication.

QoS UEs. That is, by dynamically allocating the control and data channels within a sub-slot duration. For instance, a UE may receive the resource grant in a slot while the actual allocated data resources are within the same slot, and possibly, concurrent with the control channel resources. Thus, UEs, which are configured to monitor a certain PDCCH control channel search space, will always receive and buffer the concurrent PDSCH data resource within the same slot, in case they have an immediate grant, and which they become aware of after fully decoding and processing the PDCCH channel resources. In case UEs do not detect active resource allocations, they flush/erase the buffered PDSCH payload. However, the buffering requirement of the data channels requires a larger buffer size at the UEs, which accordingly, is not suitable for Reduced Capability UEs, and hence, imposes an unnecessary power consumption for latency-non-critical QoS payload.

Therefore, as depicted by Fig. 3, a cross-slot scheduling solution is introduced [5]. UEs are configured, by high level signaling (RRC, SIB), with the minimum scheduling offset. This offset implies the minimum delay, in number of symbols and/or slots, between receiving a resource grant and the actual data resources the UEs should expect. This removes the need for UEs to buffer concurrent data payload during the decoding of the PDCCH control channel, and hence, offering a clear UE power saving gain and relaxing the requirement on the buffer size of the UEs. The gNB may enable dynamic cross-slot scheduling where UEs dynamically identify, from decoding the control channel, on which slots they should expect receiving the actual data payload. The latter dynamic procedure still fulfills the configured minimum scheduling offset such as UEs completely avoid the unnecessary data buffering.

D. Early Paging Indication

For mobile terminated communications, the UEs need to periodically monitor the configured paging channels to detect upcoming traffic. Thus, a set of periodic paging occasions (POs) is configured, where the IDLE/Inactive UEs monitor various POs. A PO is defined by a PDCCH search space and an associated paging PDSCH record. That is, UEs monitor the PDCCH search space of the configured PO, and in case there is a paging indication present, the UEs receive and decode the paging record (PDSCH) and become aware of the listed identifiers, e.g., I-RNTIs, of the UEs which are actually paged. Accordingly, paged UEs trigger the connection establishment procedure while other UEs transition back to the deep sleep state. The major challenge is that all IDLE/Inactive UEs must monitor and decode the paging PDCCH and PDSCH even though if they are not actually paged, which consumes unnecessary power of the non-paged UEs.

Thus, there have been several paging enhancements during release-17. As presented by Fig. 4, the control channel of an early paging indication (EPI) is introduced [5]. The EPI implies a limited-size downlink control information (DCI) search space or a sequence, transmitted from the gNB prior to each PO. IDLE/Inactive UEs monitor the search space of the EPI, and upon detection of a present EPI indication, the UEs monitor the next PO. Otherwise, the UEs /deep sleep and skip detecting the PO. The achievable power saving gain is due to the more limited EPI search space, compared to the actual paging PDCCH. Hence, the EPI reduces the number of unneeded PO decoding, i.e., reducing paging false alarms, for UEs which are not paged. Furthermore, the EPI DCI or sequence could be defined for a certain group of IDLE/Inactive UEs. Particularly, IDLE/Inactive UEs are sub-grouped in several paging groups, by several introduced grouping means, and the EPI DCI is scrambled in a group-specific manner. Thus, when an IDLE/inactive mode UE calculates a wrong cyclic redundancy check (CRC) after decoding the EPI DCI with its own paging-group scrambling code, it assumes that the transmitted EPI is meant for one or more of the other paging groups, and accordingly skips the PO, leading to a further reduction of the paging false alarms.

E. Paging-Specific Assistance Reference Signals

For IDLE/Inactive UEs to decode the PO, UEs need to be first synchronized with the RAN interface. Due to the long sleep periods among each two successive POs, the IDLE/Inactive are likely to be out of the RAN synchronization. Thus, as shown by the top schematic in Fig. 5, IDLE/Inactive UEs must wake up to detect several synchronization signal blocks (SSBs) prior to each PO, to retain RAN synchronization. The exact number of SSBs required for paging pre-synchronization depends on the signal-to-interference-noise ratio (SINR) of the UE. For instance, UEs with good SINRs require a single SSB detection while UEs of low SINRs demand at least 3 SSBs prior the PO. For the latter case, the IDLE/Inactive UEs must wake up 80 ms before the PO, assuming a standard 20-ms SSB periodicity, leading to a significant power consumption.

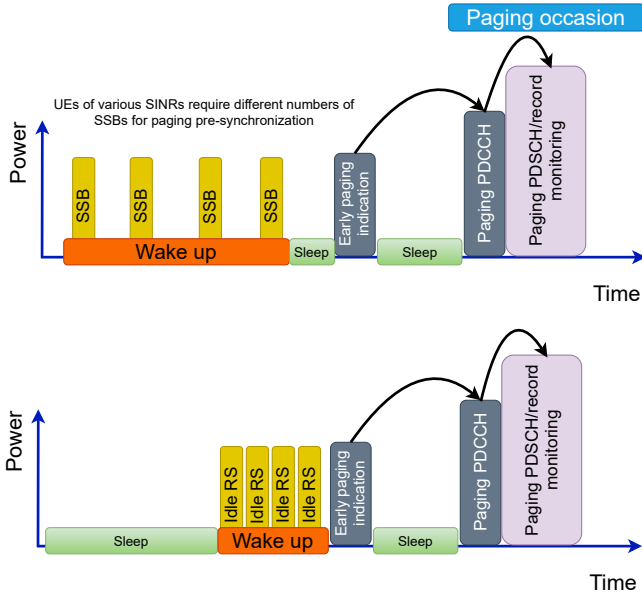


Fig. 5. Idle/inactive mode assisting reference signal.

Hence, paging assisting reference signals (RS) have been proposed. This denotes that gNB may transmit one or more of the IDLE/Inactive-specific RS sequences slightly before the POs such that IDLE/Inactive UEs wake up for shorter periods of time. That is, instead of waking up for detecting several SSBs with the longer periodicity, as shown by Fig. 5. The presence of the paging-specific RSs is signaled to the IDLE/Inactive mode UEs such as they can reliably skip detecting the needed SSBs. However, such procedure increases the network overhead over the paging bandwidth part, i.e., default bandwidth part, due to the almost-always-ON RS transmission (LTE-alike). To avoid such overhead, connected-mode RSs (TRS, CSI-RS), which are naturally available for ongoing connected-mode traffic prior to the PO, can be shared to IDLE/Inactive mode UEs as well, hence, reducing the number of paging dedicated RS transmissions. However, as the connected-mode RSs are only available when there is an ongoing traffic, it is a challenging task to rapidly signal IDLE/Inactive UEs with their presence.

F. Inactive Uplink Small Data Transmissions

For IDLE/Inactive UEs to transmit an uplink payload, they first need to transition to the RRC connected state by performing the random access procedure (RACH), and the RRC connection establishment procedure, respectively. For URLLC services, the useful payload is typically small-sized, e.g., 50 bytes, while the needed RRC signaling is hundreds of bytes as well as to the incurred latency. Therefore, uplink small data transmission (SDT) for Inactive mode UEs has been introduced [5]. Therefore, Inactive UEs may multiplex the small uplink payload as part of the RACH procedure, i.e., 2-step and 4-step RACH procedures. That is, as part of the RRC configuration signaling, e.g., RRC resume setup message. In another option, configured grant can be utilized, where pre-configured uplink resources and transmission configuration are adopted for quick uplink SDT.

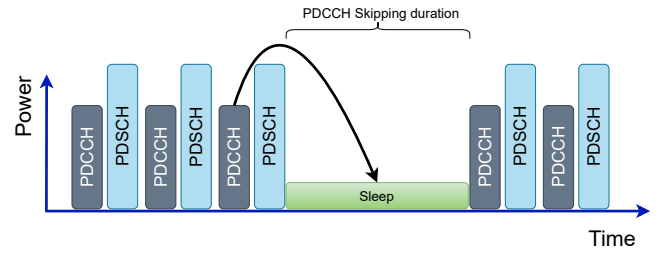


Fig. 6. PDCCH skipping of 5G new radio.

G. Control Channel Skipping and Search Space Set Switching

It has been understood, during release-16 evaluations, that the majority of the UE power consumption is paid for monitoring the control PDCCH channel during IDLE/Inactive/Connected modes [5]. This is simply because, particularly for IDLE/Inactive PDCCH, it requires a blind decoding operation. Therefore, Search Space Set Switching (SSSS) has been introduced. With SSSS, several search spaces are defined with various periodicity, monitoring duration, certain DCI formats to monitor for (to reduce number of blind decoding's), and number of symbols. For latency critical QoS, an SSSS with a shorter periodicity is activated; although, for power-limited UEs, an SSSS with a larger periodicity and shorter duration is signaled.

SSSS procedure may result in overlapping PDCCH search spaces with different configurations and an increased signaling overhead size. Accordingly, it leads to a complicated network implementation. Therefore, PDCCH control channel skipping is proposed as an alternative [5]. With PDCCH skipping, as depicted by Fig. 6, the network dynamically signals the power-limited UEs with an indication to safely skip monitoring the configured PDCCH control search space for either a certain duration or until they receive further indication to activate back PDCCH monitoring. This way, different UEs may be configured with the same PDCCH search space but with various monitoring patterns. Therefore, UEs, which have been configured of PDCCH skipping, assume that no traffic will be transmitted during the skipping duration.

IV. PERFORMANCE EVALUATION

Extensive system level simulations, using MATLAB, are performed to comprehensively evaluate the achievable latency-reliability performance for each of the considered device power saving feature. The main simulation parameters are listed in Table I, in line with [10]. The industrial factory deployments is considered with the 3GPP-compliant industrial channel mode. A 4 x 4 antenna setup is adopted for the gNB and UE. The simulation methodology, followed in this work, is inline with [11], where the majority of the 5G NR functionalities of Layer 1 and 2 are explicitly considered.

The impact of the scheduling delays on the latency-reliability performance is first investigated, for connected-mode UEs. Fig. 7 depicts the complementary cumulative distribution function (CCDF) of the achievable downlink (DL) radio latency, in a DL-only deployment. Four various scenarios of the scheduling configurations are considered. The

Table I
SIMULATION PARAMETERS.

Parameter	Value
Environment	3GPP industrial factory, 18 cells
UL/DL channel bandwidth	20 MHz, SCS = 30 KHz, FDD
Channel model	InF-DH (dense clutter and high BS)
BS and UE transmit power	BS: 30 dBm, UE: 23 dBm
Carrier frequency	4 GHz
BS and UE heights	BS: 10 m, UE: 1.5 m
Antenna setup	4×4
Average UEs per cell	5, 10
URLLC Traffic model	FTP3, packet size = 50 Bytes
DL/UL receiver	L-MMSE-IRC

instant scheduling denotes that the control PDCCH and data PDSCH channels are assumed always available for the UEs to receive their DL grants. The fixed offset scheduling implies configuring a minimum fixed cross-slot scheduling among a control channel opportunity and the actual PDSCH resources, while the dynamic offset scheduling scheme means a varying cross-scheduling offset, different for various UEs, and all possible offsets are larger than the configured minimum cross-slot scheduling offset. Finally, PDCCH skipping scheme is considered for a randomly selected sub-set of active UEs, where the skipping period is 5 slots.

As can be observed from Fig. 7, with instant scheduling, the stringent URLLC target of 1 ms at the 10^{-5} outage probability is fulfilled. However, it comes at the expense of the UE receivers assumed to be always active in order to monitor the always-ON PDCCH channel, while buffering the concurrent PDSCH resources, leading to a significant battery power consumption. The fixed offset scheduling is implementation and power friendly due to avoiding the buffering the PDSCH payload which is concurrent with configured PDCCH search space(s). Although, it obviously introduces an additional queuing delay compared to instant scheduling. The dynamic offset scheduling exhibits ~180% increase of the outage latency, compared to the instant scheduling. This is attributed to the additional cross-slot scheduling delay, where the URLLC UEs on the cell-edge suffer the most, i.e., represented by the longer tail distribution, because of the additional delay needed for the likely multiple HARQ re-transmissions.

The PDCCH skipping clearly degrades the outage latency performance since UEs, during the skipping duration, are considered completely unreachable. Therefore, with sporadic fast packet arrivals, which arrive during the skipping period, the gNB buffers the payload, triggers a DCI grant over the configured PDCCH search space after the skipping period is expired, and finally, the payload is transmitted on the allocated data resources, leading to a significant buffering delay.

Similarly, the uplink (UL) outage latency performance is analyzed, as shown by Fig. 8. Several UL transmission schemes are considered as follows. RRC based UL transmission is adopted, where UEs, of a newly arriving UL payload, need to establish an RRC connection prior to the payload transmission. Furthermore, UL small data transmission without RRC state transition is considered with configured grant (CG) and RACH schemes, respectively. The former implies a CG is used, where UEs transmit their new UL payload immediately on

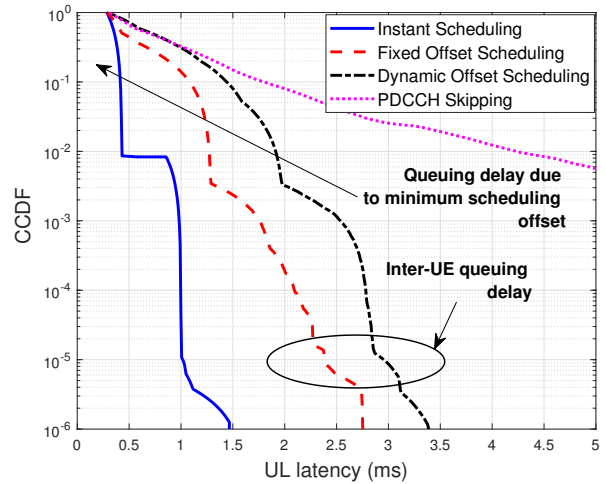


Fig. 7. Downlink outage latency: impact of scheduling delay.

a pre-configured set of resources, alongside with a configured preamble for the gNB to differentiate concurrent transmissions from various UEs. The latter option, i.e., the RACH-based SDT, implies that UEs, when a new UL payload is available, triggers a temporary RACH procedure and multiplex the UL payload with the RRC signaling. Accordingly, upon successful UL payload reception at the gNB, the UE shall not transition to RRC connected state.

As can be seen, the RRC-based UL inflicts the worst outage latency performance due to the requirement of the connected establishment before payload transmission. Two scenarios of the CG based SDT are presented. An error free CG is adopted, where the number of the CG preambles is made sufficient enough (i.e., larger than the number of active UL UEs), accordingly, it is enforced that various CG UEs to select dedicated preambles, i.e., UE-specific preamble, and hence, avoiding CG collisions. An error non-free CG implies a probability that at least two UEs select the same preamble, hence, the CG transmissions are collided and will be repeated over the next CG opportunity. As depicted by Fig. 8, both CG and RACH based UL offer a similar outage latency performance, where the latter introduces a slight increase of the outage latency due to the processing delay of receiving and transmitting RACH preambles before the UL payload is received as part of the RRC resume message. It is also clear that the RACH and CG collisions lead to a significant degradation of the outage latency, e.g., by employing CG UL with an increasing number of active UL UEs (5 to 10 UEs), than the available CG preambles. Thus, the error non-free RACH and CG based UL approach the outage latency performance of the conventional RRC-based UL.

Finally, the CCDF of the wake up time for RRC IDLE/Inactive mode UEs is depicted by Fig. 9, for various IDLE/Inactive mode power saving features. The wake up time is defined as the total time the UE transceiver stays active from the moment it synchronizes with the RAN interface, detects a true paging, and successfully receive the corresponding payload. As shown by Fig. 9, the DRX with SSB assistance for synchronization exhibits the longest outage wake up period,

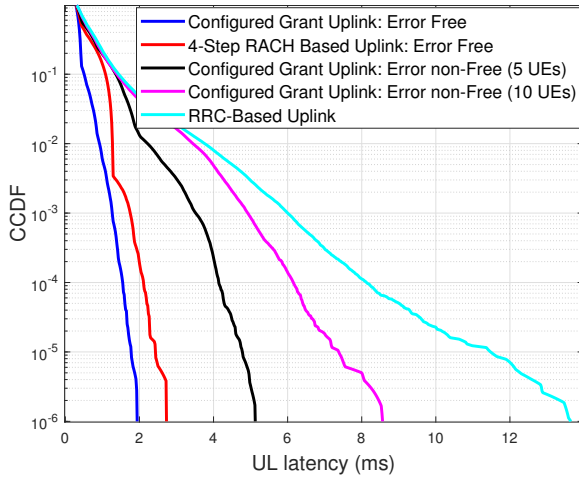


Fig. 8. Uplink outage latency: impact of RRC, CG and RACH based UL SDT.

i.e., up to 23 ms. This is because UEs, and particularly cell-edge UEs of weak SINRs, need to detect several SSBs for synchronization before the configured POs. If UEs are not actually paged, such longer wake up period is unnecessary. The EPI configurations are considered with three options. Common EPI denotes an EPI transmission that is meant for all active UEs, i.e., a single paging UE group. Group-based EPI implies the transmission of an EPI DCI/sequence that indicates only a single group of UEs to be paged, i.e., multiple paging groups. IDLE RS assisted EPI means that the transmitted EPI is prefixed by one or more paging-specific RSs, hence, IDLE/Inactive UEs do not need to wake up and detect the former SSBs of a longer cycle before the POs.

As can be clearly seen, the group-based EPI with assisting IDLE RSs offers the best shortest wake up time needed for IDLE/Inactive UEs to receive the respective payload. This is attributed for multiple reasons as: (1) UEs only wake up shortly before the EPI occasion, and synchronize with the RAN interface using the IDLE RSs, and (2) UEs which belong to a paging group rather than the detected EPI group shall deep sleep and skip decoding the actual PO. The IDLE DRX with SSB assistance obviously mandate IDLE UEs to wake up for extended periods of time for PO pre-synchronization and decoding. Moreover, the group-based EPI decreases the UE wake up duration by ~50% compared to the common EPI transmission, i.e., a single paging group, due to the reduced paging false alarms.

V. CONCLUDING REMARKS

In this work, a comprehensive review of the state-of-the-art 3GPP device power saving features is presented, including paging DRX, paging early indication, IDLE assistance reference signals, control channel skipping, small data transmission without RRC state transition, and cross-slot resource scheduling, respectively. Extensive system level simulations have been performed to evaluate the impact of the various power saving features on the achievable outage latency performance, for latency-critical URLLC services. The major

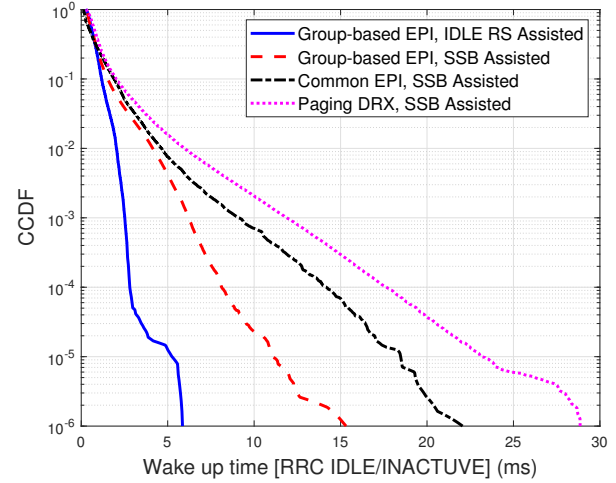


Fig. 9. Wake up time: impact of 5G NR paging procedures.

recommendations of this work are as follows: (1) control PDCCH channel skipping is vital for a power efficient UE operation; however, it is not proper for latency-critical URLLC services of frequent and sporadic packet arrivals, due to the additional buffering delays, (2) configured grant and RACH based uplink transmissions are vital for reducing the end-to-end delay of uplink packet transmissions. Although, preamble design and collision avoidance measures must be guaranteed to achieve the promised latency gain, and (3) For IDLE/Inactive mode UEs, the early paging indication, which is scrambled with a paging-group-specific code, alongside IDLE assisting reference signals are of a significant importance to drastically minimize the corresponding wake up time, and the paging false alarms, respectively.

REFERENCES

- [1] *Service requirements for 5G System*, TS 22.261, V18.3.0, June 2021.
- [2] A. A. Esswie and K. I. Pedersen, "Analysis of outage latency and throughput performance in industrial factory 5G TDD deployments," in *Proc. IEEE VTC*, 2021, pp. 1-6.
- [3] *Framework and overall objectives of the future development of IMT for 2020 and beyond*, Recommendation ITU-R, M.2083-0, IMT Vision.
- [4] *Study on ultra-low power wake up signal in Rel-18*, RWS-210169, 3GPP, release-18 workshop, VIVO.
- [5] *Study on User Equipment (UE) power saving in NR*, 3GPP, TR 38.840 (release-16), V16.0.0, June 2019.
- [6] A. A. Esswie and K. I. Pedersen, "Opportunistic spatial preemptive scheduling for URLLC and eMBB coexistence in multi-user 5G networks," in *IEEE Access*, vol. 6, pp. 38451-38463, 2018.
- [7] A. A. Esswie and K. I. Pedersen, "On the ultra-reliable and low-latency communications in flexible TDD/FDD 5G networks," in *Proc. IEEE CCNC*, 2020, pp. 1-6.
- [8] E. de Olivindo Cavalcante, G. Fodor, Y. C. B. Silva, and W. C. Freitas, "Distributed beamforming in dynamic TDD MIMO networks with BS to BS interference constraints," *IEEE Wireless Commun. Lett.*, vol. 7, no. 5, pp. 788-791, Oct. 2018.
- [9] A. A. Esswie, K. I. Pedersen and P. E. Mogensen, "Online radio pattern optimization based on dual reinforcement-learning approach for 5G URLLC networks," in *IEEE Access*, vol. 8, pp. 132922-132936, 2020.
- [10] K. Pedersen et al., "Advancements in 5G new radio TDD cross link interference mitigation," in *IEEE Wireless Communications*, June 2021.
- [11] G. Pocovi, K. I. Pedersen and P. Mogensen, "Joint link adaptation and scheduling for 5G ultra-reliable low-latency communications," in *IEEE Access*, vol. 6, pp. 28912-28922, 2018.