

# Wake-up Radio based 5G Mobile Access: Methods, Benefits and Challenges

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**Abstract**—Future mobile networks will enable new use cases, requiring further enhanced data rates, latency, coverage, capacity and reliability. In this article, to emphasize sustainable energy consumption and improved device battery lifetime, the concept, benefits and challenges of utilizing wake-up radio based access in 5G networks are reviewed and discussed. To this end, the operating principle and associated wake-up signal structures are first reviewed, together with the corresponding power consumption and buffering delay trade-offs. Then, the applicability of wake-up methods at mmWave bands and beamforming systems is addressed and highlighted. Additionally, an energy-efficient mobility management procedure for wake-up radio based devices is described and demonstrated, utilizing narrowband uplink reference signals. Overall, the article provides an overview of wake-up based access in 5G systems as a promising power-saving mechanism, and discusses the associated prospects, benefits and challenges.

## I. INTRODUCTION

THE advent of 5G New Radio (NR) [1], [2], specified by 3GPP, offers a new world of prospects and opportunities for the mobile communications ecosystem. The 5G NR networks will provide a diverse set of services with specific emphasis on enhanced mobile broadband (eMBB), ultra-reliable low latency communication (URLLC), and massive machine-type communication (mMTC). However, the associated high-bandwidth communication and advanced processing methods consume considerable amount of energy, and can thus exhaust the mobile devices battery capacity very quickly. The slow technological progress in battery capacities cannot reach such advocated requirements [3], and therefore different energy-saving mechanisms are becoming increasingly important. For enhanced sustainability and device usability, enhancing the user equipment (UE) battery lifetime is of fundamental importance, and thus 3GPP has introduced the so-called 'days-of-use profile' to quantify the remaining UE battery lifetime in terms of days [4]. Enhancing the UE power-saving capabilities is also the main theme of this article.

The main technical power-saving approach in 3GPP mobile radio networks is, currently, the so-called discontinuous reception (DRX). The DRX allows the UE to reduce its energy consumption by turning some components of the cellular subsystem off, into sleep mode, for a certain period of time, while decoding the physical downlink control channel (PDCCH) only in short active periods. Due to the existence of relatively long start-up/power-down periods, at the events of unscheduled DRX cycles, considerable amount of energy

is wasted. As a result, from power-saving point of view, it is preferable to select long DRX cycles. This is also motivated by the experimental results in [4], showing that YouTube, Google hangout and Web browsing traffic have unscheduled PDCCH for 25%, 75% and 40% of time, respectively.

On the other hand, with respect to latency requirements, it is beneficial to process PDCCH in a very short DRX cycle to receive uplink (UL) grants or downlink (DL) data. In general, the PDCCH rendering is known to be computationally very intensive and power consuming, with the baseband processor (BBP) corresponding to about 74% of the overall PDCCH processing power consumption [5]. This indicates that large power-savings are available, by switching off the BBP, if redundant or unscheduled PDCCH processing could be avoided.

Motivated by the above reasoning, there is a clear need for further power-saving enhancements, beyond DRX, applicable at all radio resource control (RRC) states. Recently, the so-called wake-up radio based access (or wake-up scheme, WS, in short) has started to raise increasing interest in cellular network context. A WS that enhances the power-efficiency of MTC devices is introduced in 3GPP LTE Release-15 [6], building on narrowband signaling, and is currently considered also in 3GPP 5G NR standardization work [7].

This article provides an overview of the WS operating principle in 5G and beyond mobile networks. First, the fundamental WS signal structures and representative numerical examples regarding UE power consumption and latency are described and provided. Then, the WS applicability and potential limitations in mmWave beamforming networks with UE mobility is assessed. After this, a novel energy-efficient uplink-based mobility procedure is described and show-cased. Finally, the general benefits, challenges and trade-offs are discussed and summarized. Overall, the article provides a timely overview on wake-up based 5G mobile access, while also presents new associated technical concepts and corresponding quantitative results, that pave the way towards further technology development and innovations in this field.

## II. TECHNOLOGY OVERVIEW

### A. Principle of Operation

In order to eliminate the unnecessary start-up/power-down procedures and unscheduled PDCCH processing, different wake-up based concepts have been recently considered, e.g., in [3] and [8]. These approaches build on the utilization of narrowband wake-up signaling (WuS) and the corresponding wake-up receiver (WRx), detecting and decoding the WuS. The WRx can be designed as a standalone receiver or as a submodule in the main receiver. An innovative RFIC based

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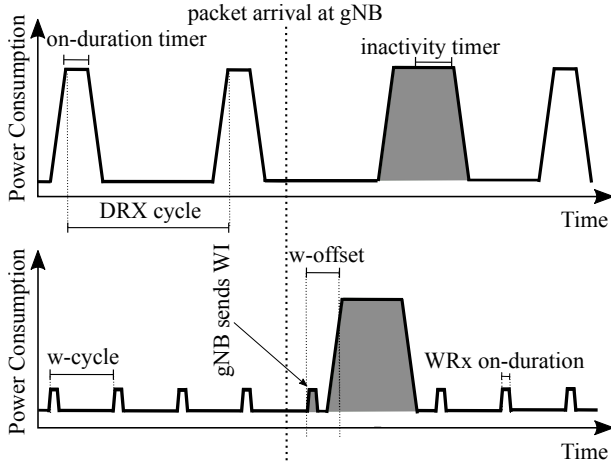


Fig. 1: Representative power consumption profiles of DRX (top) and WS (bottom). Grey areas indicate power consumption under scheduled PDCCH.

WRx can also be pursued [8], allowing the BBP to remain in sleep mode as long and often as possible, seeking thus to maximize the energy-efficiency of WuS detection.

The main WS operating principle is that in every wake-up cycle, called  $w$ -cycle, the WRx monitors a set of specified subcarriers for a short duration of time to determine whether it receives a wake-up indicator (WI) or not. Through the WI, the network informs the UE to decode the PDCCH with specified time offset, called  $w$ -offset. Once the WRx successfully detects the WI, the BBP will be switched on. After that, the BBP decodes the PDCCH messages at active state for a preconfigured on-duration period, followed by initiation of its inactivity timer. After the inactivity timer is initiated, and if a new PDCCH message is received before the timer expiration, the BBP re-initiates its inactivity timer. However, if there is no PDCCH message received before expiration of the inactivity timer, a sleep period starts, the UE switches to its sleep state, and WRx operates according to its  $w$ -cycle.

In general, due to its dedicated nature, the start-up/power-down periods for WRx are much shorter than those of the normal BBP. Furthermore, the WuS processing requires only a few OFDM symbols and a few subcarriers in each  $w$ -cycle, in contrast to DRX, where the BBP needs to operate over the full bandwidth and for multiple symbols to process the PDCCH. Thus executing the WRx is much more energy-efficient compared to normal PDCCH decoding in DRX [8]. Moreover, the narrowband nature of WuS facilitates improved sensitivity due to its low in-band noise level. As illustrated in Fig. 1 at principal level, the WS reduces the UE energy consumption compared to baseline DRX as the energy consumption related to decoding unscheduled PDCCHs is avoided. Moreover, since the  $w$ -cycle can be short without essentially increasing the energy consumption, the buffering delay can be reduced compared to DRX.

To facilitate efficient multiuser operation, the 5G base-station, called gNB [1], can multiplex multiple WIs, called WS group, over the preconfigured set of subcarriers through orthogonal codes [8]. All the WS parameters and configurations can in general be signaled by higher layers.

## B. Synchronization and Wake-up Signals

To assure reliable WI decoding, the WRx needs to acquire and keep synchronization successfully, despite the main receiver/BBP sleeping regularly. Depending on the specific considered WuS structure, the WRx may need to demodulate the generic network synchronization signals, namely the primary and secondary synchronization signals (PSS, SSS) which are sent periodically or, as an alternative, retain the synchronization through other WRx-specific signal structures. The following potential scenarios can thus be envisioned.

1) *PSS and SSS based operation*: WRx acquires synchronization through the existing NR synchronization mechanisms. However, due to the power consumption related to normal processing of PSS and SSS, the achievable power-saving factor can eventually be low. Additionally, depending on how the network is configured in terms of broadcasting the PSS and SSS, the synchronization latency can be large.

2) *Preamble-based operation*: In this case, the network sends a specific signal structure every  $w$ -cycle, containing the actual WI signal as well as a preamble that allows the WRx to carry out timing and frequency estimation. Such approach calls for reserving some radio resources from the NR frame structure to facilitate the preamble.

3) *WuS with embedded synchronization*: The scheme proposed in [8] is based on the gNB transmitting a set of orthogonal sequences over dedicated subcarriers, carrying set of code-multiplexed WIs along with an embedded synchronization sequence. Employing such an embedded synchronization sequence assists WRx to obtain or retain time and frequency synchronization simultaneously while detecting and decoding the WuS. This reduces the synchronization delay, while can also provide flexibility for WRx to obtain synchronization in every  $w$ -cycle without waiting for PSS and SSS that are commonly broadcast fairly infrequently.

A detailed description of a WuS for 5G control plane using embedded synchronization signaling is given in [8]. The corresponding extensive link-level results show that with such signal structure and with SNRs as small as  $-4$  dB, the WuS misdetection, false alarm and synchronization failure rates are less than 1%, 10% and 1%, respectively, indicating very high reliability in WuS detection.

## C. Example Performance Results

System-level simulations are conducted to evaluate and compare the performance of WS and DRX, in terms of the energy consumption and power-delay trade-off. For WS, we consider the WuS structure, hardware settings and detection performance following those in [8], while for DRX we assume the optimized parameterization from [9]. Specifically, the basic 20 MHz carrier bandwidth case with 15 kHz subcarrier spacing is considered. Additionally, each WS group has 7 users, utilizing Zadoff-Chu sequences with length of 117 subcarriers and root index of 31. Furthermore, we consider a classical Poisson packet arrival model parameterized with the packet arrival rate ( $\lambda$ ), and consider values for  $\lambda$  that correspond to realistic IoT/MTC and eMBB applications. The on-duration timer and inactivity timer of 2 ms and 8 ms, respectively,

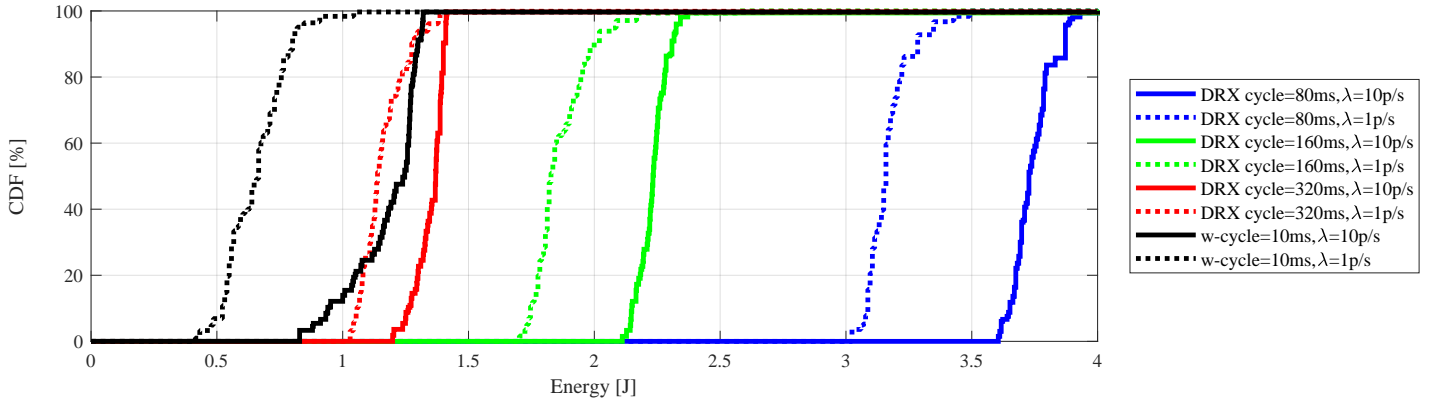


Fig. 2: Simulation-based empirical UE energy consumption CDFs with DRX and WS for two different packet arrival rates. The x-axis represents the total energy consumption of the UE during 10-second session for corresponding packet arrival rates.

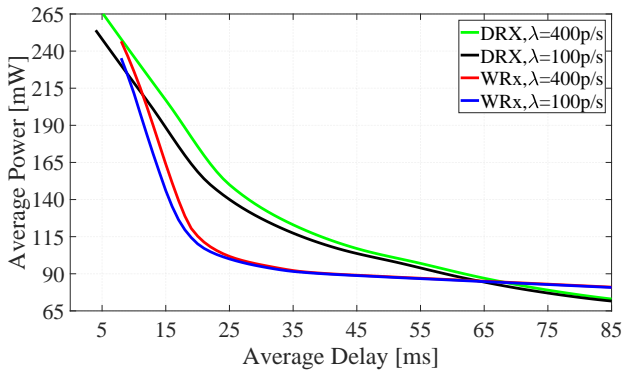


Fig. 3: Simulation-based power-delay operating characteristics curves for DRX and WS under two different mean packet arrival rates.

are assumed. Additionally, we assume that the BBP start-up period, power-down period, active power consumption and sleep power consumption are 15 ms, 10 ms, 850 mW and 10 mW, respectively [3], [8]. We also assume that the average power consumption of RFIC-based WRx is 57 mW [8].

1) *Energy consumption*: Fig. 2 depicts empirical cumulative distribution functions (CDFs) of the UE energy consumption for 1000 sessions each with a duration of 10 seconds for packet arrival rates ( $\lambda$ ) of 1 and 10 packets per second (p/s). Such packet arrival rates are representative in different sensor/MTC applications [7]. As can be observed, the WS with w-cycle of 10 ms can facilitate substantially lower energy consumption compared to DRX with different DRX cycles. Moreover, for a given delay requirement and power-saving mechanism, the power consumption for the higher packet arrival rate is observed to be larger than that for the lower packet arrival rate. This is mainly because the larger value of  $\lambda$  implies more packets arriving at gNB during the session. This, in turn, makes the BBP more likely to stay in the active state, leading to a higher power consumption for a given delay constraint.

2) *Power-delay trade-off*: Fig. 3 shows the achievable average power consumption versus the average delay, for two different values of the mean packet arrival rates. Here, for the purpose of diversity in the evaluations, we have deliberately

used larger packet arrival rates that in practice can correspond to video streaming or other similar eMBB services [3], [7]. We can observe that when the w-cycle and the DRX cycle are increased, from 5 to 250 ms and from 15 to 340 ms, respectively, the average packet delay increases while the power consumption reduces. This is natural because when increasing the w-cycle or the DRX cycle, the sleep ratio increases, and thus the power consumption is reduced but at the cost of an extra delay.

Additionally, as can be observed in Fig. 3, for delay requirements within 10 ms to 60 ms, the wake-up enabled UE power consumption is substantially lower than the DRX-based one. For instance, if the buffering delay constraint is 25 ms, by utilizing DRX, mobile device may achieve average power consumption of 140 mW, while when employing the WS, this can be reduced down to 100 mW at  $\lambda = 100$  p/s. This represents power-savings in the order of 30%, which is a substantial number. It is also observed that DRX works better for applications which can tolerate very long delays (large sleep-ratio), the reason being that the wake-up-enabled UE consumes more energy in the sleep state than the DRX based UE in the deep sleep state of long DRX cycle. Finally, based on Fig. 3, we also acknowledge that DRX can better satisfy very short delay requirements, mostly due to the fact that the start-up time of cellular subsystem for short-DRX cycle is less than 1 ms [3], [9]. In case of the wake-up enabled UE, due to start-up period, achieving such very low latencies in the order of 1-5 ms is difficult. Additionally one can observe that for tighter delay constraints, both methods result to consuming higher amounts of energy, the main reason being that the cellular subsystem remains in active state more often than in case with longer delay constraints.

### III. BEAMFORMING OF WAKE-UP SIGNALS

One of the key technological advances of 5G NR is to allow each transmission/reception point (TRP) to have a large number of antenna elements [10], thus facilitating efficient beamforming. Currently, NR beam management is based on synchronization signal blocks (SSBs) and channel state information reference signals (CSI-RSs) [2]. The SSBs are transmitted in bursts by the network whose periodicity

can be configured to take place between 5 and 160 ms. By receiving and measuring such beamformed SSB bursts, the UE can determine its reception (Rx) beams and report the best serving transmission (Tx) beams to the network. This kind of procedure is also known as beam-sweeping. Beam management can be also based on CSI-RSs, where the UE measures CSI-RSs, which are transmitted from different antenna ports. This allows for applying codebooks for channels measured by the UE in order to determine suitable beams for communication [10].

#### A. Wake-up Signaling at mmWaves

In general, the adoption of NR technology at mmWave bands relies heavily on beamforming in order to tackle the high path losses [11]. Hence, beam sweeping for WuS will be required in order to reach the desired UE after a sleep period. In spite of beamforming, it is expected that mmWave communications can provide a decent coverage only up to some 200 m from the TRP [11]. Therefore, when a moving UE is configured with WS, participation of multiple TRPs to the WuS beam-sweep is potentially required. However, in order to reduce latency, energy waste and resource consumption, the network should be able to optimize the number of beams in a single WuS burst utilized for waking up the UE.

#### B. mmWave Evaluation Setup

In order to analyze the challenges of beamformed WuS at mmWave frequencies, the raw received signals corresponding to WuS are accurately emulated with a realistic 5G NR system-level simulator on Madrid-map [12] using a ray tracing channel model and a 30 GHz carrier frequency, with further details available in [12]. For this purpose, 9 sites each comprising of two panel-arrays with patch elements, are placed at 10 m height with mechanical downtilt of 15 degrees, while each array is directed towards the street direction in azimuth domain. Then, 50 randomly rotated UEs, with a single dual-polarized WRx patch antenna, are dropped randomly at the beginning of each simulation realization. UE mobility of 30 km/h is considered, corresponding to cars or other vehicles moving in the considered urban environment. Each individual simulation run consists of 10 seconds of real time, while 100 independent simulation runs with random initial drops are carried out. It is also assumed that orthogonal non-interfering sequences are used for WIs within served WS group while all other TRPs are causing interference for the received signals.

The beamforming weights for each TRP are obtained according to the multi-user MIMO (MU-MIMO) codebook for dual-polarized 4x4 panel arrays with 32 antenna ports, as specified in [13]. Transmission power of a single panel array is assumed to be +46 dBm per 20 MHz of bandwidth. Furthermore, a single beam or 4 best beams are selected for each UE before the UE enters the sleep period. In case of multiple beams, the best beams are selected from the grid of beams of single or multiple TRP(s).

#### C. Performance Results of Beamformed Wake-up Signals

When investigating the ray-tracing based received signals, it was first perceived that received wake-up signals at the con-

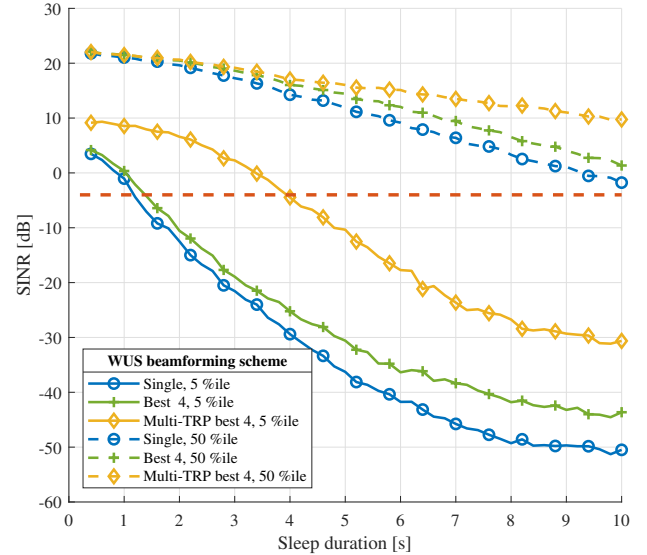


Fig. 4: Simulation-based raw signal-to-interference-plus-noise ratio (SINR) of the best received WuS, within a beamformed WuS burst, when operating at 30 GHz mmWave band, after varying sleep durations of UEs moving at 30 km/h. Also the  $-4$  dB SINR limit is illustrated, shown in [8] to still facilitate reliable WuS decoding.

sidered mmWave frequency and TRP-UE distances are mostly noise limited. Furthermore, beamformed wake-up signals were able to reach almost all UEs right after the best beam is selected for each UE as shown in Fig. 4. However, when the sleep duration is increased, a single serving beam per UE is not anymore able to wake-up reliably the 5th percentile UE after approximately 1.2 seconds, when considering the  $-4$  dB minimum SINR requirement established in [8] for reliable WuS decoding. On the other hand, if the WuS is transmitted with the 4 best beams from a single TRP, the reliability is increased only slightly. In order to achieve significantly better reliability for these UEs at the edge of TRP's reach, the usage of multiple TRPs for selecting the best 4 serving beams is notably advantageous, as can be observed in Fig. 4. In such case, the 95% of UEs are reliably waken up after up to 4 second sleep period. For the average 50th percentile user, all beamforming schemes are able to achieve decent reliability after 10 seconds of sleep duration, which is the maximum DRX cycle length in the current 5G NR connected state. These results provide thus new quantitative information and insight regarding the applicability of WuS and wake-up based access in mmWave networks.

## IV. ENERGY-EFFICIENCY AND MOBILITY MANAGEMENT

### A. WS and Handover Measurements

Periodically measuring and reporting multiple neighbouring gNBs are the approach adopted in LTE and NR networks to support reliable mobility. To extend the battery lifetime, such measurements and reports should be triggered only when necessary, i.e., when the serving cell's radio conditions deteriorate severely. However, with fast moving UEs, the radio conditions can also vary fast, and thus frequent measurements are needed. Specifically, as discussed in [14],

the high-speed UEs' channel measurements are no longer valid if the measurement and reporting interval is long, in the order of hundreds of milliseconds. Therefore, DRX-based UEs need to frequently trigger on the BBP to perform the mobility procedures including computationally-expensive and time-consuming task of cell selection and camping. As a result, fast moving UEs cannot necessarily benefit from or adopt long DRX cycles, thus reducing the DRX energy-saving capabilities. There exists thus, overall, a trade-off between the UE energy efficiency and the reliability of mobility.

Similar to the existing mobility schemes, the WRx can measure the received WuS power, and if observed to be low, provide the measurements to the BBP. This can in practice happen only after the BBP is in the active state, after which the BBP can trigger the mobility procedure. Alternatively, to reduce the UE energy consumption also in mobility related procedures, UL measurements could be adopted. In such enhanced mobility scheme, the WuS is complemented with dedicated UL reference signals, in order to avoid unnecessary BBP triggering and thus to save energy. Unlike the legacy DL schemes, the enhanced WuS+UL scheme overcomes the need for the BBP to (i) decode the unscheduled PDCCHs, and (ii) to perform time and energy consuming DL measurements and report them back to the network, while at the same time enabling reduced handover delay. This is particularly relevant for future ultra dense networks, where handovers can happen very frequently, which in turn can increase the handover failure rate and UE power consumption [15].

Such novel energy-efficient mobility concept builds on the transmission of specific narrowband UL reference signals just before the wake-up instant with a configurable period, referred to as the u-cycle, as illustrated in Fig. 5. This allows the network to accurately track mobile UEs, while being in deep power-saving state. By receiving, detecting and measuring the narrowband UL reference signals, potentially at several surrounding gNBs or TRPs, the measurements can be subsequently processed in a central node. This node can select the serving gNB or TRP with the highest signal quality for a given UE, and track the location of such user in the event of incoming scheduled data.

On the hardware implementation side, similar to WRx, the transmission of the narrowband UL reference signal every u-cycle can be embedded directly to RFIC without using the BBP. Since the reference transmitter and WRx operate in time division manner, both can also partially share same hardware resources. The power consumption of the reference transmitter is likely to be somewhat higher than that of the WRx, the main reason being the power amplifier. According to our pre-design estimation, the RFIC-embedded narrowband reference transmitter consumes approximately 80 mW of power, when including both the RF and digital processing.

### B. Example Numerical Results

Next, example numerical results are provided, to assess the suitability and efficiency of the envisioned WuS+UL mobility scheme. The simulation-based evaluation environment is similar to the one adopted in Section III-B, while in this

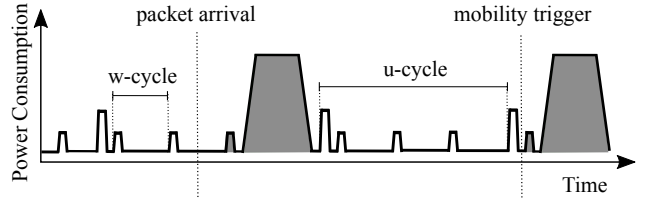


Fig. 5: Illustration of power consumption profile and timings when WuS is complemented with narrowband UL reference signals for mobility measurements.

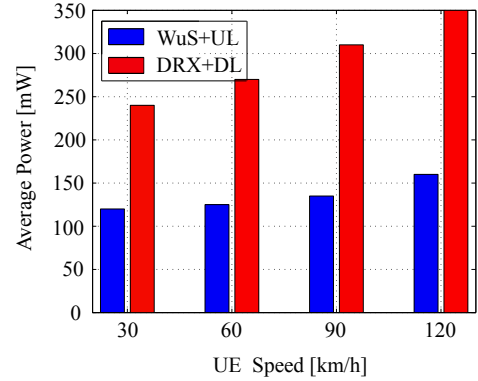


Fig. 6: Simulation-based power consumption of the two considered mobility schemes for given handover failure rate of 5%, maximum delay bound of 25 ms and packet arrival rate of 100 p/s.

case the network is assumed to operate at 3.5 GHz band. Specifically, we analyze the power consumption of the conventional DRX+DL and the novel WuS+UL mobility methods for given handover failure rate of 5% and maximum average delay bound of 25 ms. The power consumption values are calculated based on the optimal DRX and WS parameters, using extensive simulation results such that both the handover failure rate and the maximum delay are satisfied. For both schemes, we utilize unfiltered handover measurements, and carry the evaluations for varying UE speeds. In case of DRX+DL, the UE measures the DL received signal strength which is averaged over the considered reference symbols within the measurement bandwidth of 1.25 MHz, while the handover measurement period is equal to the UE DRX cycle. In the WuS+UL case, the measurement bandwidth and averaging are configured similarly. Furthermore, the scenarios and triggering events in 3GPP TS 36.331 are adopted.

The obtained quantitative results are illustrated in Fig. 6. In general, in the DRX case, the handover failure rate is dependent on the DRX cycle. More specifically, it degrades with increasing DRX cycle, therefore with increasing speed, the DRX cycles need to be reduced for a given target handover failure rate, and as a result the power consumption increases. Thus for each measurement instance, the BBP wastes considerable amount of energy for start-up/power-down stages.

However, in the case of WuS+UL, the UE transmits a narrowband reference signal, and thus avoids measuring multiple gNBs or TRPs, while also allowing the BBP to sleep as long and often as possible for maximum energy-efficiency. For WuS+UL, the mobility failure rate is mainly dependent on the value of the u-cycle. This makes the parameter optimization

of the WS-enabled system overall fairly simple, i.e., the w-cycle can be set based on delay bound and packet arrival rate, while the u-cycle can be configured based on UE speed and mobility requirements.

## V. BENEFITS, CHALLENGES AND TRADE-OFFS

### A. Benefits

1) *Sustainable energy consumption*: The WS reduces the UE energy consumption through three different aspects. Firstly, by removing the unnecessary PDCCH monitoring which is computationally expensive and power hungry. Secondly, because of the novel signal structure, the WS removes the start-up/power-down related energy wasting. Lastly, when combined with narrowband UL reference signaling, even high-speed UEs can reside in the sleep state for long periods, while not increasing the handover failure rate.

2) *Short buffering delay*: DRX-based UEs with long DRX cycles can suffer from high buffering delays. However, in case of WS, the UE is only subject to a maximum delay of w-offset plus w-cycle.

3) *Synchronization assistance*: Owing to the fact that at every wake-up instant, the WRx acquires coarse synchronization, it can directly assist the main receiver/BBP in synchronization. This reduces the BBP synchronization latency.

4) *Increasingly traffic agnostic*: DRX requires reconfiguration per traffic type, and is easily subject to increased energy consumption and buffering delays if its parameters are not optimized. Furthermore, DRX fits well to periodic traffic patterns, however, it is a sub-optimal mechanism for non-periodic traffic, such as augmented or virtual reality. WS, in turn, reduces the need for reconfiguration of wake-up parameters for broader range of realistic unsaturated traffic scenarios.

5) *Less signaling overhead*: The WS allows to reduce the signaling overhead in multiple ways. Firstly, because being more traffic agnostic, it reduces the need for traffic type based reconfiguration and reoptimization. Secondly, for unsaturated cell deployments, WS can reduce the need for transmitting DL broadcast or reference signals, and thus reduce the energy consumption of cellular network itself while potentially allowing for cell-level sleep modes. Furthermore, in mMTC applications, group-specific WuS could be utilized, instead of UE-specific, which further reduces the signaling overhead. Lastly, the combination with UL reference signals reduces the channel measurement and signaling reports performed currently by the UEs for mobility purposes.

### B. Challenges

1) *Packet scheduling and parameter optimization*: WS may complicate the radio resource management and UE scheduling in the network due to the sleep patterns. For certain parameter settings and traffic characteristics, the power overhead of too frequent packet scheduling in wake-up instants can reduce the potential power-savings. As an extreme example, if the gNB has data at most of the wake-up instants, the UE would perform WuS decoding as well as the regular PDCCH decoding correspondingly, thus increasing the start-up/power-down

energy overhead. To solve this, the network should deploy a real-time WS-aware scheduler to schedule packets aiming to meet the energy-saving and buffering delay requirements of the target device. In such a method, WS parameters should be embedded into the scheduling determinants.

2) *Costs and complexity*: If the WuS and WRx were to utilize different frequency band than the main receiver/BBP, the hardware complexity and cost of UEs would increase. However, since the considered concept builds on inband operation and RFIC-embedded WRx implementation, the increases in cost and complexity are negligible.

### C. Trade-offs

1) *Energy efficiency vs. latency*: While the WS energy consumption is less sensitive to latency constraints compared to DRX, there is still inherent dependence between the energy consumption and the length of the w-cycle. The exact behavior depends on the energy consumption of the WRx.

2) *Energy efficiency vs. handover reliability*: Increasing the sleep-ratio leads to a higher handover failure rate. However, the combination of WS with narrowband UL reference signals can achieve largely improved trade-off between energy-efficiency and handover failure rate through configurable u-cycle.

3) *Network capacity vs. WuS robustness*: The introduction of WS has two fundamental consequences, misdetection and false alarm, with further details in [8]. With longer code lengths, both false alarm and misdetection rates reduce for a given SNR. However, increasing the code length also increases the system overhead, while also reduces the number of UEs that can simultaneously support WS.

## VI. CONCLUSIONS

For improving the energy-efficiency of mobile devices, the concept, benefits and challenges of utilizing wake-up radio based access in 5G networks were reviewed. Wake-up signaling methods and the corresponding power consumption and buffering delay trade-offs were discussed and assessed, while the applicability at mmWave bands and beamforming systems was also addressed. Additionally, energy-efficiency of handovers and downlink vs. uplink based mobility management procedures were discussed and show-cased. Overall, the reported quantitative results show that wake-up based access has large potential in 5G and beyond networks with emphasis on sustainable energy consumption.

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