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Lauridsen, Mads; Berardinelli, Gilberto; Tavares, Fernando Menezes Leitão; Frederiksen, Frank; Mogensen, Preben Elgaard

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# Sleep Modes for Enhanced Battery Life of 5G Mobile Terminals

Mads Lauridsen[1], Gilberto Berardinelli[1], Fernando M.L. Tavares[1], Frank Frederiksen[2], Preben Mogensen[1,2]
[1] Department of Electronic Systems, Aalborg University, Denmark [2] Nokia, Aalborg, Denmark
{ml,gb,ft,pm}@es.aau.dk

***Abstract*—In addition to higher data rates and lower latency the 5G Radio Access Technology concepts are targeting to provide better battery life for mobile broadband and Machine Type Communication users. In this overview paper we analyze how microsleep, Discontinuous Reception and Transmission, and a wake-up receiver concept can be combined to enhance the battery life of 5G mobile terminals. Due to the short and pipelined 5G frame structure microsleep provides 20 % energy savings as compared to LTE. The Discontinuous Reception and Transmission modes also benefit from the new frame structure leading to faster connection setup and up to 80 % lower energy consumption depending on the traffic type. Finally we estimate that the wake-up receiver concept, when adapted to scheduled and cellular communication, can provide 90 % lower energy consumption and ensure a predictable and consistent latency.**

## I. Introduction

Industry and academia are currently collaborating on concept development for a future fifth Generation (5G) Radio Access Technology (RAT). The objective is to support the exponential increase in data traffic and new use cases such as Machine Type Communication (MTC), which are expected for 2020 and beyond. One proposal for a new RAT is the centimeter-wave 5G concept presented in [1], which targets 10 Gb/s peak data rate, sub-ms over-the-air latency, and enhanced battery life. Extending the mobile terminal battery life is a fundamental design target for 5G as Long Term Evolution (LTE) and other previous generation RATs initially de-emphasized this parameter. In addition the previous RATs were neither optimized for MTC, which in some use cases target 10 years of battery life. The key to achieve long battery life is the use of sleep modes where the mobile terminal saves energy by powering OFF unused components for a period of time [2]. On the contrary, achieving low latency (e.g. for connection setup) requires the mobile terminal to remain connected and consequently harm the battery life. Our key idea is thus for the mobile terminal to be active when there is data to transfer and sleep otherwise by use of efficient and flexible sleep modes, which address the trade-off between latency and battery life.

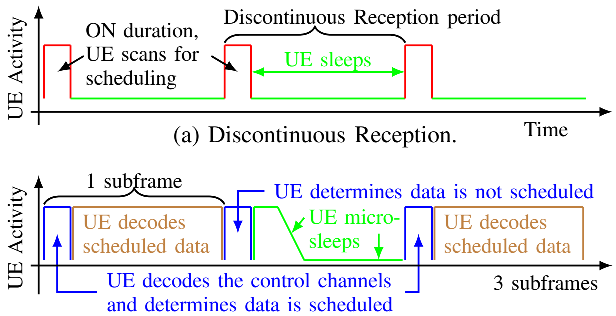
In this paper we combine new and known sleep modes to enhance the battery life of 5G mobile terminals. We use the short and pipelined frame structure in [1] as our reference, which among others targets to enable efficient sleep modes. We first present the microsleep concept, which we previously proposed for LTE use [3], and the LTE standardized Discontinuous Reception (DRX) [4]. We then show how the 5G frame structure facilitates the use of microsleep and improves the applicability and energy saving potential of DRX as compared to LTE. Further, to the best of our knowledge, we are the first to propose how the wake-up receiver (WuRx) concept, developed for unlicensed and contention-based channel access [5], [6], can be adapted to a scheduled cellular 5G RAT to enhance the battery life.

The paper is structured as follows. A review of sleep modes in High Speed Packet Access (HSPA) and LTE is carried out in Sec. II. We then present a reference 5G concept and examine three applicable sleep modes in Sec. III. Finally we compare the sleep modes, discuss future challenges, and provide our conclusion in Sec. IV and V, respectively.

## II. Sleep Modes in HSPA & LTE

In HSPA & LTE the mobile terminal is either in a Radio Resource Control (RRC) connected mode where it continuously monitors if it is scheduled, or an idle mode where it periodically monitors the paging channel [4]. The mobile terminal is only able to receive and transmit data in the connected mode and therefore it must change from idle to connected if such a transfer is imminent. The idle mode is useful because the periodic monitoring entails the mobile terminal can apply a sleep mode to minimize the energy consumption. However, changing RRC mode requires a significant amount of control signalling which increases latency and consumes energy. For example [7] estimates that after the LTE mobile terminal has transferred some data packets it takes a few to tens of seconds before it moves from connected to idle mode. This tail time is implemented to avoid the signalling involved in switching RRC mode too often, but it entails the mobile terminal remains in the energy consuming connected mode. Therefore the connected mode DRX, hereafter referred to as DRX, has been standardized in HSPA release 7 and LTE [4]. When DRX is configured the access point informs the mobile terminal of a certain periodic time duration in which it is expected to listen for data, as illustrated in Fig. 1a. Therefore it can sleep during the remainder of the period, and in [2] it was measured that the mobile terminal in DRX sleep consumes less than 1/50 of the connected mode power primarily because a low-power clock is used while the Radio Frequency (RF) subsystem and parts of the baseband (BB) processor are powered OFF. The DRX can be configured with a periodicity between a few milliseconds and multiple seconds while the ON duration and an inactivity timer after successful data reception can also be adjusted [4], [7]. However, DRX settings are usually not adapted to changing traffic patterns making the latency and energy savings suboptimal [7]. Similarly Discontinuous Transmission (DTX) is available for uplink communication.

In addition to DRX the mobile terminal can apply the unstandardized microsleep [3] when it is connected, but not scheduled as illustrated in Fig. 1b. In this sleep mode the mo-




(a) Discontinuous Reception.

(b) Microsleep.

Fig. 1: Sleep modes in LTE.

bile terminal quickly decodes the Physical Downlink Control Channel to determine if it is scheduled. Given that data is not imminent the mobile terminal can apply a low-power sleep mode for the rest of the subframe. In HSPA there is a gap between control and data [4], and thus the mobile terminal knows in advance whether it must receive the data channel, but in LTE the data follows immediately after the control channels and thus forces the mobile terminal to buffer the data channel while decoding the control channel. In [3] we estimated the LTE mobile terminal must be ON the first 6 symbols after which it may microsleep, consuming about half of the ON power, for the remaining 8 symbols of an LTE subframe.

## III. Sleep Modes for 5G

In this section we recall the 5G concept's main principles [1] and analyze how microsleep and DRX can be applied and their potential energy savings compared to LTE. At last we discuss the novel use of a WuRx in scheduled and licensed cellular bands. The modes are studied in relation to the specific concept, but they can be generalized to other future RATs.

The 5G concept envisioned in [1] targets a peak data rate of 10 Gb/s, 100 Mb/s for the 5th percentile of users, a round trip time (RTT) below 1 ms, and inactive to active mode transition within 10 ms to resemble the mobile terminal being always-ON. This is to be achieved in an ultra-dense small cell network with 10-100 times more devices and 10000 times more traffic as compared to 2010. The envisioned RAT applies Orthogonal Frequency Division Multiplexing modulation in downlink and uplink combined with Time Division Duplexing (TDD) to utilize fragmented spectrum. The concept uses a 0.25 ms frame structure consisting of 14 symbols, each 17.67 $\mu$s including 1 $\mu$s cyclic prefix. The first symbol is dedicated to downlink control, the next to uplink control, and the final 12 to either uplink or downlink data. The frame structure, illustrated in Fig. 2, is designed such that a paging signal, including the data location, arrives in the downlink control part (in the illustrated example in frame 2) one frame ahead of the data (in frame 3), resulting in sub-ms RTT and allowing for pipelined decoding. A similar procedure is applied in uplink as shown in Fig. 4.

### A. Microsleeping Using the Proposed 5G Frame Structure

In 5G the control information and its associated data is separated by one frame, as illustrated in Fig. 2. This entails the mobile terminal knows whether it will receive or transmit data at the beginning of a frame and therefore it can apply pipelining and the microsleep mode, discussed in Sec. II. Given fast power ON and OFF of parts of the RF subsystem and BB

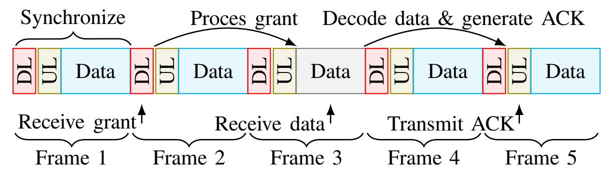



Fig. 2: Procedure for receiving data in 5G.

processor, the 5G mobile terminal can apply microsleep in 12 of 14 symbols per frame as compared to sleeping in 8 of 14 symbols in LTE [3]. The estimated energy consumption for LTE $E_{\mu\text{sleep,LTE}}$ and 5G $E_{\mu\text{sleep,5G}}$ microsleep is:

$$\begin{aligned} E_{\mu\text{sleep,LTE}} &= t_{\text{ON,LTE}} \cdot P_{\text{ON}} + t_{\mu\text{Sleep,LTE}} \cdot P_{\mu\text{Sleep}} \quad [\text{J}] \\ &= 6\,\text{ms} \cdot 1\,\text{W} + 8\,\text{ms} \cdot 0.5\,\text{W} = 10\,\text{mJ} \qquad (1) \\ E_{\mu\text{sleep,5G}} &= t_{\text{ON,5G}} \cdot P_{\text{ON}} + t_{\mu\text{Sleep,5G}} \cdot P_{\mu\text{Sleep}} \quad [\text{J}] \\ &= 2\,\text{ms} \cdot 1\,\text{W} + 12\,\text{ms} \cdot 0.5\,\text{W} = 8\,\text{mJ} \qquad (2) \end{aligned}$$

where $P_{\text{ON}}$ and $P_{\mu\text{Sleep}}$ are the ON and microsleep power consumption of the mobile terminal, defined relatively as $P_{\text{ON}} = 2 \cdot P_{\mu\text{Sleep}}$ according to [3]. The estimated ON time is $t_{\text{ON}}$ while the microsleep time is $t_{\mu\text{Sleep}}$, normalized such that 1 symbol is 1 ms independent of the RAT. The 5G mobile terminal can save $1 - 8/10 \Rightarrow 20\,\%$ energy in unscheduled frames compared to LTE microsleep, while saving $1 - 8/14 \Rightarrow 42\,\%$ compared to not applying microsleep at all.

### B. Re-using DRX and DTX in 5G

In LTE the periodic DRX and DTX sleep modes are essential to prolong the battery life and therefore we study their applicability for 5G in this section. The use of DRX in 5G is particularly important due to video streaming being a key user scenario for 5G. According to [8] it will constitute 72 % of all mobile traffic in 2019 and have a year-over-year growth rate of 66 %. Video streaming is made either by downloading the entire file at once, called a bulk transfer, or by initially using a buffer phase followed by ON-OFF periods as identified by [9]. However mobile terminals never use the bulk transfer when streaming video from Netflix and YouTube [9], possibly because capacity and energy is wasted if the user prematurely stops watching the video. From a battery life perspective the ON-OFF streaming can be efficiently combined with the use of DRX. In [9] both short ON-OFF periods of 0.2-5 s and longer periods up to 60 s were observed. In addition, voice calls have a packet arrival rate of 20 ms [4] and therefore DRX settings must span from 20 ms to at least 60 s to support video and voice. In [7] it was discussed to only apply RRC connected mode combined with DRX in LTE, and this is also our proposal for 5G to provide the user the always-ON experience. However [7] noted that DRX must be made more adaptive by standardizing that the mobile terminal reports the running applications and what type of traffic it expects to generate. This will increase the signalling, but also help optimize the DRX settings and thus reduce the energy consumption and latency.

In this section we compare the battery life for LTE TDD and 5G when the mobile terminal applies DRX and DTX. The LTE TDD version is selected to have a fair comparison with the TDD based 5G concept [1]. The target is to verify whether the short and pipelined 5G frame provides energy saving for different packet inter-arrival times. We assume that the data amount is small and transferable within one LTE subframe /

TABLE I: Model parameters for MTC mobile terminal in 2020. Modified model from [10] where the sleep power is 0 W.

| Description | Parameter | Value |
|---|---|---|
| Transmit power consumption | $P_{\mathrm{tx}}$ | 300 mW |
| Receive power consumption | $P_{\mathrm{rx}}$ | 100 mW |
| Clock power consumption | $P_{\mathrm{clk}}$ | 10 mW |
| Sleep power consumption | $P_{\mathrm{sleep}}$ | 0.01 mW |
| Time to power ON/OFF the transmitter & receiver | $t_{\mathrm{trx}}$ | 20 $\mu$s |
| Energy to power ON/OFF transmitter from/to clock level | $E_{\mathrm{clk-Tx}}$ | 3.1 $\mu$J |
| Energy to power ON/OFF receiver from/to clock level | $E_{\mathrm{clk-Rx}}$ | 1.1 $\mu$J |
| Battery capacity (3 V and 3 Ah) | $E_{\mathrm{bat}}$ | 32.4 kJ |

TABLE II: Frame configuration for LTE TDD, [11, Table 4.2-2]. A downlink subframe is denoted by D, an uplink subframe by U, and the special subframe by S.

| Configuration | Switching periodicity | Subframe number 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 5 ms | D | S | U | U | U | D | S | U | U | U |
| 1 | 5 ms | D | S | U | U | D | D | S | U | U | D |
| 2 | 5 ms | D | S | U | D | D | D | S | U | D | D |
| 3 | 10 ms | D | S | U | U | U | D | D | D | D | D |
| 4 | 10 ms | D | S | U | U | D | D | D | D | D | D |
| 5 | 10 ms | D | S | U | D | D | D | D | D | D | D |
| 6 | 5 ms | D | S | U | U | U | D | S | U | U | D |

5G frame and always successful received and acknowledged. Furthermore, we assume that the power consumption and other parameters are the same for both the LTE and 5G mobile terminal to ensure a fair comparison independent of device capabilities. The MTC power model, presented in Table I, is a modified version of [10] developed to estimate the battery life in 2020. The clock is assumed to be always-ON while the power ON/OFF of the transmitter and receiver from the clock level is a ramp function captured by $E_{\mathrm{clk-Tx}}$ and $E_{\mathrm{clk-Rx}}$.

LTE TDD differs from the Frequency Division Duplexing version in multiple areas, and one key aspect affecting DRX and DTX is the use of the 7 frame configurations in Table II. Note 1 LTE frame consists of 10 subframes each $t_{\mathrm{subframe}} = 1\,\mathrm{ms}$ long [4]. The special subframe S consist of a downlink timeslot with the same structure as a normal downlink subframe, a guard period, and an uplink timeslot, which only includes the Sounding Reference Signals and the Random Access Channel and thus precludes uplink data [11].

Due to the 7 frame configurations and the special subframe, which can only carry downlink data but has resources for both downlink and uplink requests, there is a multitude of combinations in which a data transfer can be made. Figure 3 provides an overview of the possible outcomes if the mobile terminal transmits a scheduling request in either subframe 1 or 2 of the first frame in configuration 0. The total time is then calculated as the sum of the individual steps, where it must be noted that the mobile terminal and access point are defined to have 3 ms of processing time, corresponding to 3 subframes. In addition, the mobile terminal is expected to spend 5 ms, before the transfer, for synchronization with the network because the LTE synchronization signals have a 5 ms periodicity [4].

This analysis has been performed for uplink and downlink using the configurations in Table II. The minimum number of subframes to transfer data, depending on in which subframe it is initiated, is given in Table III. The numbers are noted for downlink and uplink where "-" indicates a transfer cannot be initiated. In downlink 5-14 subframes + 5 subframes for synchronization and channel estimation are required to transfer

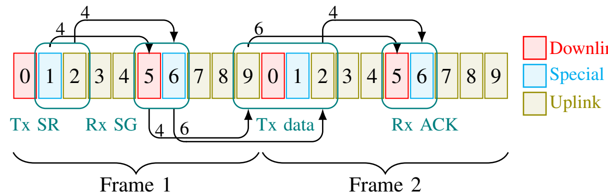



Fig. 3: Procedure for uplink transmission in LTE TDD using frame configuration 0 of Table II and 3 ms for processing.

TABLE III: Minimum number of subframes required to perform transfers in LTE TDD given 3 ms processing time.

| Configuration | Starting subframe number (downlink / uplink) 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Minimum DL | Minimum UL | Maximum DL | Maximum UL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 5/- | 7/15 | -/15 | -/18 | -/18 | 5/- | 7/15 | -/15 | -/18 | -/18 | **5** | 15 | 7 | 18 |
| 1 | 8/- | 7/16 | -/15 | -/17 | 5/- | 8/- | 7/16 | -/15 | -/17 | 5/- | 5 | 15 | 8 | 17 |
| 2 | 8/- | 7/16 | -/15 | 5/- | 9/- | 8/- | 7/16 | -/15 | 5/- | 9/- | 5 | 15 | 9 | 16 |
| 3 | 5/- | 12/16 | -/15 | -/14 | -/13 | 8/- | 7/- | 6/- | 5/- | 5/- | 5 | **13** | 12 | 16 |
| 4 | 13/- | 12/16 | -/15 | -/14 | 9/- | 8/- | 7/- | 6/- | 5/- | 5/- | 5 | 14 | 13 | 16 |
| 5 | 13/- | 12/16 | -/15 | 10/- | 9/- | 8/- | 7/- | 6/- | 5/- | 14/- | 5 | 15 | **14** | 16 |
| 6 | 5/- | 7/16 | -/15 | -/17 | -/16 | 8/- | 7/- | -/15 | -/19 | 5/- | 5 | 15 | 8 | **19** |

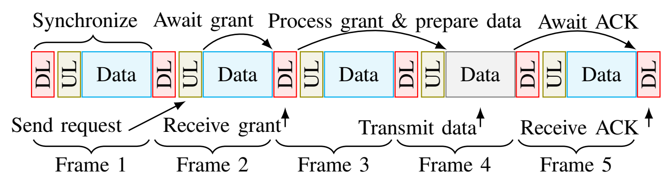



Fig. 4: Procedure for transmitting data in 5G.

data, while uplink requires 13-19 subframes + synchronization. The fastest transfer times are used for comparison with 5G.

Using the results of Table III a LTE TDD transmission $t_{\mathrm{txLTE}}$, including power ON and OFF, can be completed in:

$$\begin{aligned} t_{\mathrm{txLTE}} &= t_{\mathrm{syncLTE}} + 13 \cdot t_{\mathrm{subframe}} + 2 \cdot t_{\mathrm{trx}} \qquad [\mathrm{s}] \\ &= 5\,\mathrm{ms} + 13 \cdot 1\,\mathrm{ms} + 2 \cdot 20\,\mu\mathrm{s} = 18.04\,\mathrm{ms} \end{aligned} \tag{3}$$

where $t_{\mathrm{syncLTE}}$ is the time to synchronize [s] equal to 5 subframes. The energy consumption for a transmission is based on the number of receive and transmit states in Fig. 3:

$$\begin{aligned} E_{\mathrm{txLTE}} =& t_{\mathrm{syncLTE}} \cdot P_{\mathrm{rx}} + 2 \cdot t_{\mathrm{subframe}} \cdot P_{\mathrm{tx}} + 4 \cdot E_{\mathrm{clk-Tx}} + \\ & 2 \cdot t_{\mathrm{subframe}} \cdot P_{\mathrm{rx}} + 6 \cdot E_{\mathrm{clk-Rx}} + t_{\mathrm{txLTE}} \cdot P_{\mathrm{clk}} \; [\mathrm{J}] \\ =& 1499\,\mu\mathrm{J} \end{aligned} \tag{4}$$

For downlink $t_{\mathrm{rxLTE}} = 10.04\,\mathrm{ms}$ and $E_{\mathrm{rxLTE}} = 1009\,\mu\mathrm{J}$.

Assuming the mobile terminal is allocated the required resources a 5G transmission, see Fig. 4, is completed in

$$\begin{aligned} t_{\mathrm{tx5G}} &= t_{\mathrm{sync5G}} + 4 \cdot t_{\mathrm{frame5G}} + t_{\mathrm{symb}} + 2 \cdot t_{\mathrm{trx}} \qquad [\mathrm{s}] \\ &= 0.25\,\mathrm{ms} + 4 \cdot 0.25\,\mathrm{ms} + 17.67\,\mu\mathrm{s} + 2 \cdot 20\,\mu\mathrm{s} \\ &= 1.30767\,\mathrm{ms} \end{aligned} \tag{5}$$

where $t_{\mathrm{tx5G}}$ is the ON time for a 5G transmission [s], $t_{\mathrm{sync5G}}$ is the synchronization time [s], equal to one frame because the required synchronization signals occur every frame, $t_{\mathrm{frame5G}}$ is the frame length [s], and $t_{\mathrm{symb5G}}$ is the symbol duration [s] as defined in the introduction of this section according to [1].

Therefore a 5G transmission requires (based on Fig. 4):

$$\begin{aligned} E_{\mathrm{tx5G}} =& t_{\mathrm{sync5G}} \cdot P_{\mathrm{rx}} + t_{\mathrm{symb5G}} \cdot P_{\mathrm{tx}} + 2 \cdot t_{\mathrm{symb5G}} \cdot P_{\mathrm{rx}} + \\ & t_{\mathrm{data5G}} \cdot P_{\mathrm{tx}} + 4 \cdot E_{\mathrm{clk-Tx}} + 6 \cdot E_{\mathrm{clk-Rx}} + \\ & t_{\mathrm{tx5G}} \cdot P_{\mathrm{clk}} = 129.5\,\mu\mathrm{J} \end{aligned} \tag{6}$$

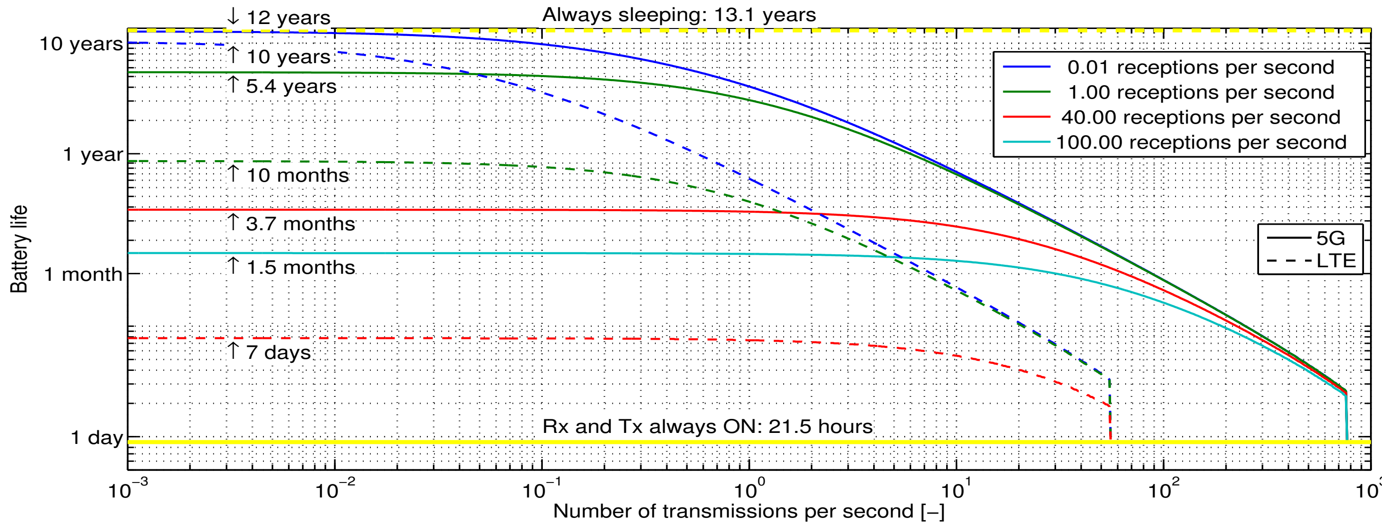



Fig. 5: MTC battery life estimation when using DRX and DTX in 5G and LTE. Power model assumptions are given in Table I.

Similar calculations are performed for the 5G reception time and energy illustrated in Fig. 2 resulting in $t_{\mathrm{rx5G}} = 1.07534\,\mathrm{ms}$ and $E_{\mathrm{rx5G}} = 74.6\,\mu\mathrm{J}$. The LTE transfers are thus 9-13 times longer and consume 12-14 times more energy.

Using the LTE and 5G energy consumption and time results on individual transfers the battery life as a function of number of receptions and transmissions per second is calculated. The battery capacity is given in Table I, and since the study includes infrequent transfers combined with low power consumption the battery self-discharge is modelled. According to [12] the battery discharges 5 % the first 24 hours after which it will discharge 2 % of the remaining capacity per month.

The estimated battery life is shown in Fig. 5 as a function of number of receptions and transmissions per second for the cellular subsystem of an MTC device, as defined in Tab. I. Note that the transceiver is set to be always ON when either the number of receptions or transmissions exceed the estimated time to transfer. For infrequent transmissions and receptions the battery life is dominated by the battery self-discharge and approaches 13.1 years. Contrary to that the mobile terminal may be always-ON for frequent transmissions and receptions resulting in just 21.5 hours of battery life. The LTE estimate, indicated with dashed lines, approaches this state for less frequent transfers because the ON time of a single transfer is 9-13 times longer. For a fast updating sensor transferring and receiving 1 packet a second the battery life improves from less than 1 month in LTE to almost a full year in 5G. On average the benefit of the short and pipelined frame structure is 5-15 times energy saved depending on the traffic type. Specifically there is a major benefit when the number of transfers per second exceed the minimum time to transfer for LTE, which was calculated to be 10-18 ms. The 5G concept can support traffic that is 10 times as frequent and thus yields prolonged battery life for devices which require or deliver many updates such as MTC for vehicles and industrial automation.

### *C. Supporting Aperiodic, Low Latency Traffic in 5G*

The DRX mode is based on trading latency and network scheduling complexity for extended OFF periods to achieve low-power sleep. For voice calls and video streaming the periodic nature of DRX is a good fit. However, other applications

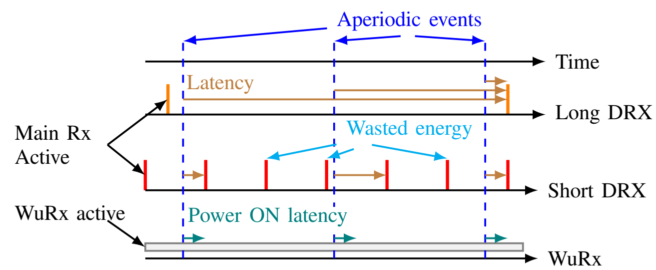



Fig. 6: DRX and wake-up receiver comparison.

such as sensors which are aperiodically polled by either a user or a machine will have to accept a longer latency or a shorter battery life. In 5G this issue must be addressed because MTC traffic has an estimated growth rate of 103 % per year, while the number of MTC devices will also increase to 3.2 billion in 2019, constituting 28 % of all connected devices [8].

The issue of supporting aperiodic events is illustrated in Fig. 6. If the DRX period is too long the latency between the occurrence of an event on the network side and until the mobile terminal is scheduled can become so long that the data is invalid, while if the DRX period is too short the mobile terminal may often power ON without receiving a scheduling signal. This reduces the latency, but harms the battery life. In addition, if a large number of devices apply DRX it complicates the access point's scheduling decision because the resource allocation freedom is limited by the predefined ON periods of the sleeping devices. Note this is only a downlink issue as devices can always apply the random access procedure to upload data.

In this section we thus propose how 5G can separate itself from existing cellular RATs, by ensuring both long battery life and low downlink latency. This is achieved by applying the WuRx concept, illustrated in Fig. 7, in the 5G small cells. The idea is to power OFF the main receiver while the low-power WuRx is scanning a pre-defined channel for incoming wake-up signals. If such a signal is detected the WuRx interrupts the main receiver, which then powers ON and receives the normal paging signal in accordance with the standard.

Two significant challenges are to achieve sufficiently low WuRx power consumption, and to develop a wake-up signal which can be reliably received faster than the latency

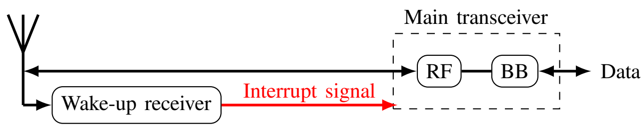


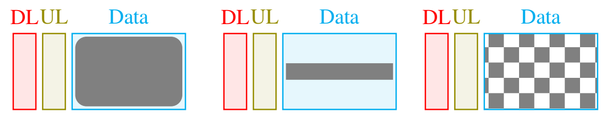

Fig. 7: Wake-up receiver principle.

TABLE IV: Examples of WuRx implementations and the low-power standards for Bluetooth (BT) and ZigBee.

| Ref. | Power | Rate | Wake-up Signal | Sensitivity | Frequency |
|---|---|---|---|---|---|
| [13] | 2.4 $\mu$W | 10 kb/s | 7 ms | -71 dBm | 868 MHz |
| [6] | 19 $\mu$W | 50 kb/s | - | -53 dBm | 2.4 GHz |
| [15] | 25.4 $\mu$W | 2.73 kb/s | 12.5 ms | -53 dBm | 868 MHz |
| [5] | 1 mW | 100 kb/s | 1.4 ms | -82 dBm | 2.4 GHz |
| [14] | 7 mW | 19.2 kb/s | 3.07 ms | -95 dBm | 915 MHz |
| BT 4.0 LE [16] | 53.7 mW | 1 Mb/s | - | -88 dBm | 2.4 GHz |
| ZigBee [17] | 103 mW | 250 kb/s | - | -92 dBm | 2.4 GHz |

requirement of a given application. The WuRx concept has previously only been studied for use in ISM bands for non-scheduled systems e.g. WiFi. Table IV provides an overview of selected WuRx implementations from literature and the existing low-power standards Bluetooth and ZigBee. However, Bluetooth and ZigBee target a higher data rate than the WuRx implementations and thus consume more energy making them less applicable for the WuRx concept. The most efficient WuRx implementations [13], [6] achieve power consumption levels which are 500-1000 times lower than the current lowest LTE DRX power consumption level of 10 mW, known as deep sleep [2]. This is achieved by reducing the signal rate and sensitivity as compared to more power consuming implementations [5], [14]. However, a high rate signal is important because the WuRx mainly rely on a processing gain to limit the number of active RF components and thus reduce the energy consumption. The implementations [5], [14] achieve a sensitivity which is 10-20 dB lower than LTE mobile terminals [4], [2] and an ON power which is 1.5-10 times lower than LTE DRX deep sleep. However, the 5G concept is targeting a small cell deployment and therefore the path loss and the sensitivity requirement are reduced. Note that the duration of the wake-up signals are all shorter than 10 ms, which entails that the 5G requirement of always-ON experience may be fulfilled [1].

Based on Table IV the WuRx concept is feasible from a hardware perspective, but it has not been discussed in literature how the wake-up signal can be accommodated in a scheduled and licensed cellular band. In order to avoid purchasing new spectrum we propose the wake-up signal is allocated in-band with the regular data, and thus it is important to minimize the effect on the existing control and data channels. Since the uplink and downlink control channels of the 5G concept only span 1 symbol each we suggest to allocate the wake-up signal within the 12 symbol data part of the frame, when it is used for downlink information. The signal can either be implemented as a wideband signal co-located with the main data by use of a spreading code or as a narrowband signal occupying a few subcarriers as illustrated in Fig. 8a and 8b, respectively. The first option will limit the signal to noise ratio of the normal receivers and require time synchronization, while the latter will entail some subcarriers are not available for normal data transfers. A third option illustrated in Fig. 8c is to periodically allocate the signal either narrow- or wideband, but this will increase the wake-up time. Finally frame length modulation was proposed by [18], but this is not applicable for the fixed




(a) Wideband (b) Narrowband. (c) Periodic.

Fig. 8: Allocation of the wake-up signal (gray color).

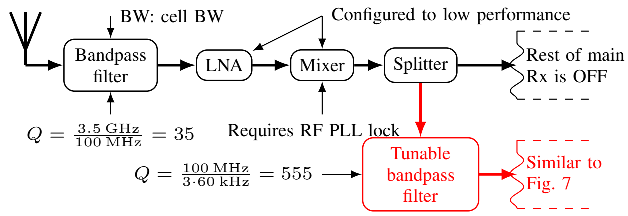



Fig. 9: Simplified block diagram for a narrowband WuRx, in red, partly reusing the main receiver's front end.

5G frame structure studied in this work.

In this study we examine the narrowband design in further detail, while the other designs are for future study. To limit the effect on cell throughput we propose to use 3 subcarriers, each 60 kHz wide for the wake-up signal. This results in $3 \cdot 60\,\text{kHz}/100\,\text{MHz} \Rightarrow 0.18\,\%$ frequency capacity loss for a 100 MHz 5G carrier. The narrowband implementation must rely on coding gain in the time domain and thus either an orthogonal code or a code with zero-autocorrelation and limited crosscorrelation is desired. Without synchronization the number of candidate codes are limited and therefore the number of individually addressable codes must be limited. Ideally each WuRx uses an individual code, but the devices can also be grouped using a single code. It is out of scope to suggest codes in this work, but provided that an applicable code exists it can be implemented using ON-OFF-Keying (OOK), which e.g. is suggested in [13]. The OOK modulation, where the carrier wave is either ON or OFF, can be combined with an envelope detector to receive a binary code by limiting the bandwidth to the carrier frequency. The received binary code is then correlated with a pre-defined code, identifying the specific WuRx or a group, after which the WuRx must decide whether to send an interrupt to the main receiver. As suggested in [13] time synchronization can be avoided by using $2^N - 1$ correlators, where $N$ is the code length. The narrowband WuRx is illustrated in Fig. 9 and a key challenge is to limit the bandwidth to the OOK carrier. This requires a high filter quality factor $Q$, which is the ratio between filter center frequency and the filter bandwidth. Therefore we propose to reuse parts of the main receiver's front end, where a bandpass filter is readily available. After down conversion to BB the signal can be passed to the WuRx where a tunable filter with a quality factor requirement in the order of 500 is needed as illustrated in Fig. 9. Reusing parts of the main receiver will increase the WuRx energy consumption but also decrease the power ON time of the main receiver.

Based on Table IV we estimate that a cellular WuRx with sufficiently high rate, short signal duration, and high sensitivity consumes about 1 mW. Assuming that the power ON procedure is similar to when the mobile terminal exits DRX deep sleep the overall energy consumption is estimated to be 10 times lower because this is the ratio between DRX deep sleep and WuRx consumption. The cost of the estimated $90\,\%$ savings is the allocation of the wake-up signal in-band.

TABLE V: Sleep modes for 5G compared to LTE.

| Sleep mode | Application | Energy saving | 5G advantage |
|---|---|---|---|
| Micro | Frequent traffic with unscheduled frames | ≥20 % | Microsleep opportunities are known a priori |
| DRX & DTX | Periodic traffic | ≥80 % | Shorter sleep periods are applicable |
| WuRx | Aperiod traffic | ≥90 % | Predictable and consistent latency |

## IV. Discussion

The three sleep modes discussed in this paper are applicable in different scenarios depending on the traffic type and user requirements. Table V provides a comparison of the modes, which are complementary because microsleep is applicable for frequent traffic where some frames are occasionally not scheduled, while DRX and DTX can be used for periodic traffic such as video streaming and keep alive messages. Finally the WuRx applies to aperiodic traffic e.g. caused by sensors. Each of the modes provides energy savings in the order of 20-90 % as compared to LTE. In addition, the modes provide advantages in terms of more predictable sleeping opportunities and latencies, while also allowing for more frequent periodic traffic to be combined with sleeping.

However, there are multiple challenges that must be addressed in future 5G development. They include optimization of power ON and OFF sequences related to sleep modes, because this defines which power level can be achieved and the amount of energy that can be saved. In current LTE implementations the power ON sequence after DRX light and deep sleep is 0.7 and 10 ms respectively and thus further research is needed to make the sleep modes applicable to 5G [2]. The sequences have improved 2.5-12 times in the recent LTE smartphones [2] as compared to the first generation and therefore the outlook is promising. Another key challenge is implementation of the WuRx and the related signalling in a scheduled and licensed cellular band. The WuRx must be able to handle interference, deep fades, and other impairments that disturb the wake-up signalling. A final task is the development of useful codes for the wake-up signal and analysis of whether mobile terminals shall be addressed in groups or individually.

## V. Conclusion

A future fifth generation (5G) Radio Access Technology must provide enhanced mobile terminal battery life in addition to the general requirements including higher data rates, lower latency, and support for Machine Type Communication (MTC).

In this paper we proposed to combine microsleep, Discontinuous Reception and Transmission, and an aperiodic sleep mode. The reason is that the cellular subsystem being ON is amongst the main energy consumers and this can be reduced by optimized sleeping. By adapting the examined sleep modes to a 5G concept we estimate 20-90 % longer battery life compared to LTE depending on the traffic type and user requirements.

Microsleep addresses the ON time by enabling the mobile terminal to sleep during unscheduled frames, while Discontinuous Reception and Transmission allows the mobile terminal to only monitor the control and data channel periodically and sleep for the remainder of the time. Both benefit from the short and pipelined 5G frame structure, and we thus estimate that MTC devices can achieve the targeted 10 years battery life when performing one data transfer per 100 seconds.

However, there is a trade-off between achievable sleep power level and the latency in contacting the device. Therefore the use of a wake-up receiver is proposed to complement Discontinuous Reception, especially for unpredictable and aperiodic traffic, which may result due to user behaviour and infrequent polling of MTC devices such as sensors. We estimate potential energy savings up to 90 % compared to the existing Discontinuous Reception sleep mode.

For future work the wake-up receiver concept may be expanded to also address sleeping small cells, because this can limit both the energy consumption and interference footprint.

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