# Ensuring Energy Efficient 5G User Equipment by Technology Evolution and Reuse

Lauridsen, Mads; Berardinelli, Gilberto; Sørensen, Troels Bundgaard; Mogensen, Preben

*Published in:*
I E E E V T S Vehicular Technology Conference. Proceedings

*DOI (link to publication from Publisher):*
10.1109/VTCSpring.2014.7022914

*Publication date:*
2014

*Document Version*
Accepted author manuscript, peer reviewed version

Accepted for publication at IEEE VTC Spring 2014.

# Ensuring Energy Efficient 5G User Equipment by Technology Evolution and Reuse

Mads Lauridsen, Gilberto Berardinelli, Troels B. Sørensen, Preben Mogensen
Department of Electronic Systems, Aalborg University, Niels Jernes Vej 12, DK-9220 Aalborg Øst
{ml,gb,tbs,pm}@es.aau.dk

***Abstract*—Research on fifth generation (5G) radio access technology (RAT) is ramping up, with the goal of significantly improving user data rates and latency compared to previous RAT generations. While energy efficiency (EE) of the user equipment (UE) was not a key optimization parameter for the current wireless standards, it is anticipated to become a distinguishing factor for 5G.**

**In this paper, we analyze established and emerging technological solutions for features such as waveform, frame structure, duplexing and multiple antenna transmission from an EE perspective. Our contribution is to identify and discuss the features' pros and cons in achieving high performance in terms of data rate and/or latency while limiting their effect on the UE power consumption. Based on the discussion we give general recommendations for an energy efficient 5G design in the context of a previously proposed RAT concept.**

## I. Introduction

The large improvements in terms of data rate and latency from 2nd generation (2G) to 4th generation (4G) RAT have led to a significant increase in UE power consumption [1]. Recent measurements [2] showed a modern smartphone's cellular subsystem can consume half of the total power, and therefore a new energy efficient 5G RAT design may significantly improve the UE battery life.

Energy efficiency (EE), defined as the amount of energy required to transfer one byte of data, was identified as a key 5G requirement in [3], but until now little research has been devoted to UE EE. Current 5G projects such as METIS [4] and 5GNOW [5] are following a clean slate approach to RAT design, and since EE is a significant design motivation for 5G it justifies a novel disruptive design. Conversely backwards compatibility requirements prohibit substantial changes to standards like Long Term Evolution (LTE), which is partly in a deadlock with several releases, providing limited EE improvements. For instance the LTE release 11 Enhanced Physical Downlink Control Channel (EPDCCH) even has a negative effect on EE.

The EE of existing RAT standards have been discussed in a few contributions. In [6], the impact of Radio Resource Management, deployment strategies, Multiple Input Multiple Output (MIMO) antenna technologies and Multiple Access (MA) schemes on the EE of the network was analyzed, but recommendations for future 5G designs were not provided. The impact of the EE improvement on other significant parameters such as bandwidth and network delay was discussed in [7]. However, [7] only focused on network power consumption due to its effect on global $CO_2$ emissions and operators expenditure, while omitting the effect on UE battery life.

In this paper, we provide concrete recommendations on the design of an energy efficient 5G RAT. We base our

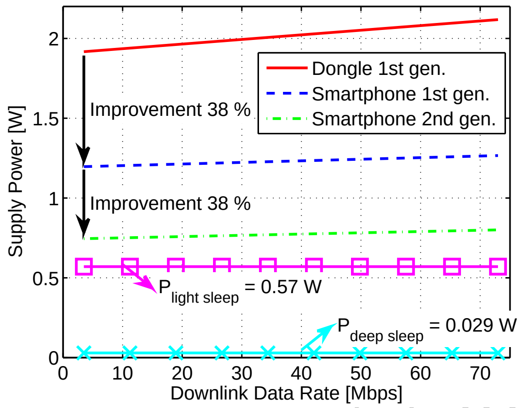


Fig. 1: UE power consumption based on [2], [9].

recommendations on a discussion, made with the UE EE perspective, of the main technology features of the previous RAT generations and emerging solutions. We then compare our recommendations with a 5G RAT, proposed in a conceptual form in [8]. The RAT design is still under research and therefore our EE recommendations, which among others include suggestions for choice of waveform, duplexing scheme, frame structure and interference management, are useful inputs to the researchers, such that their design can fulfil the 5G UE EE requirements.

The paper is structured as follows: sec. II presents a discussion on the technology features adopted by the current RAT standards, with particular focus on their pros and cons from an UE EE perspective. The recommendations for an energy efficient 5G design are given in sec. III. Finally, sec. IV presents the conclusions and ideas for future work.

## II. Energy Efficiency of existing RATs

This section presents a discussion on the most significant technology features of the existing RAT standards, with the aim of identifying their pros and cons in terms of UE EE. We refer to GSM release 7 as 2G, HSPA+ release 8 as 3G, and LTE release 11 as 4G, hence mature versions of the standards [10]. Tab. I displays the main technology features of which we will discuss a selection in the following subsections.

### A. Bandwidth and Data Rate

The downlink (DL) demodulation complexity has increased steadily with the introduction of each RAT generation due to higher order modulations and increased bandwidth; 200 kHz (2G), 5 MHz (3G), 20 MHz (4G). The possibility of boosting the data rate enabled by the larger bandwidth induces a faster baseband processing at both transmitter and receiver, hence

TABLE I: Overview of key Radio Access Technology Parameters. (cl refers to the UE class)

| Method | 2G | 3G | 4G | 5G |
|---|---|---|---|---|
| Specification | GSM rel. 7, band 850/900 | HSPA+ rel. 8 | LTE rel. 11 | 5G concept [8] |
| Duplex | FDD, HD | FDD, FD (some TDD exist) | FDD, FD (some TDD exist) | TDD (synchronization needed) |
| Multiple access | TDMA/FDMA | CDMA | OFDMA | OFDMA |
| Bandwidth | 200 kHz | 5 MHz | 1.4-20 MHz | 10-200 MHz |
| Frame/subframe size | 4.615 ms (comprising 8 slots) / - | 10 ms / 2 ms | 10 ms / 1 ms | - / 0.25 ms |
| Equalizer | Time | Time | Frequency | Frequency |
| Antennas | 2 Rx, 1 Tx | 2 Rx, 1 Tx | 4 Rx, 4 Tx | 4 Rx, 4 Tx |
| Control/data pos. | Initial paging, then fixed BW | One slot spacing | No gap | One frame offset |
| Sleep mode | CM DTX | CM DTX+DRX | CM DTX+DRX | CM DTX+DRX |
| Frequency reuse | 3 (varying) | 1 | 1 | 1 |
| DL modulation | GMSK, 8PSK, 16QAM, 32QAM | QPSK, 16QAM, 64QAM | QPSK, 16QAM, 64QAM | LTE like |
| Multiple carriers | 2 | 2 | 5 | Possible |
| Link Adaptation | AMC using RxQual | AMC using CQI | AMC using CQI | AMC |
| UL modulation | GMSK, 8PSK, 16QAM, 32QAM | QPSK, 16QAM | QPSK, 16QAM, 64QAM | LTE like |
| UL PAPR | 3.2 dB | 6-8 dB | 11 dB | LTE like |
| Max. UL transmit power (sum of antennas) | 33 dBm (cl4) +/-2 dB, -3 to -9 dB if 2-8 time slots are allocated | 24 dBm +1/-3 (cl3), additionally CuM-1 for some channels | 23 dBm +/-2 dB (cl3), -1 to -2 dB depending on MCS and #PRBs | 10-15 dBm per antenna |
| Minimum UL power | 5 dBm +/- 5 dB | -50 dBm | -40 dBm | -20 dBm |
| Dynamic range | 28 dB | 74 dB | 63 dB | $\sim$30 dB |
| UL power control | 2 dB step, 16.67 Hz | 1, 2, 3 dB step, 1500 Hz | FPC, open+closed loop, $\leq$1000 Hz | Not yet specified |

higher power consumption. Fig. 1 illustrates the evolution of the supply power as a function of the DL data rate for three generations of LTE devices. The dongle measurement is from our first LTE measurements made in 2011 [9], while the measurements on the smartphone 1st generation [2] and on the recently released smartphone 2nd generation were made in 2012 and 2013, respectively. Increasing the data rate by a factor of 10 only increases the power consumption by 10 %. This entails the UE can receive a data file much faster and then turn off its receive chain i.e. enter a low power sleep mode to conserve energy. The EE of the 2nd generation 4G smartphone is $\sim$0.8 W/10 Mbps=80 nJ/bit, whereas 2G achieves 3.5 $\mu$J/bit and 3G 450 nJ/bit [11, Fig.8], hence the increased data rate has a positive effect on UE EE.

This is also the case when using multiple carriers as shown in [12]. Downlink Dual Carrier (2G), Dual Cell (3G) and Carrier Aggregation (4G) have been defined to enable the UE to connect to multiple carriers and achieve a load balancing gain, resulting in improved capacity and data rates. The cost, which affects the power consumption, is the need for a second receiver and an extra Local Oscillator if the multiple carriers operate in different frequency bands.

Fig. 1 also shows that, when moving from one generation to another, the power consumption is reduced by a factor of $\sim$38 %. This is partly due to technology node scaling, i.e. voltage scaling and reduction of switched capacitance, which according to Intel [13] will continue. Previously, [14] has predicted a similar power reduction of 30-40 % per node change. The reduction is also due to device maturity i.e. the chipset design is optimized throughout the standard's lifetime.

### B. Sleep Modes

In the previous section it was discussed how higher data rates allows the UE to power off its receive chain and enter sleep mode. Several types of sleep mode have been defined in the RAT standards. They can be divided into two groups where the UE is either in Idle or Connected mode.

In Idle mode the UE is unable to receive or transmit data. Instead it performs measurements on neighbor cells and monitors system information and a periodic paging channel, which notifies it about incoming calls. To save energy the UE only monitors a subset of the channels and sleeps for the rest of the period. This sleep mode is called Idle mode Discontinuous Reception (DRX), and is available in all the RAT generations.

The 2G standard includes the Connected mode Discontinuous Transmission (CM-DTX), because 2G was mainly designed for voice calls where silent periods are frequent. To save energy the UE can choose not to transmit any information during these silent periods that are identified by a Voice Activity Detection mechanism [15]. The CM-DTX also reduces the interference footprint in the network.

The initial 3G specifications did not include CM-DTX, thus forcing the UE to transmit the control channel even when no user data was available. However, later 3G releases re-introduced this feature. Later Connected mode DRX (CM-DRX) was implemented with the aim of saving energy in the receiver, because the need for receive energy savings became apparent as the amount of DL data increased.

The 4G standard includes both CM-DRX and CM-DTX, because it is focused on packet switched data, which can handle the inherent delays introduced by sleeping. Different CM-DRX settings may lead to light or deep sleep modes; measurements [2] on LTE UEs using CM-DRX have shown that the deep sleep power consumption is 30 mW (see fig. 1), which corresponds to 1/35 of the active mode power. The 4G frame structure also allows for micro sleep, see sec. II-F.

### C. Duplexing

The term duplexing describes a point-to-point system where communication can flow in both directions. The duplexing method affects the energy consumption due to hardware requirements and the impact on data rate and latency.

The 2G RAT utilizes Frequency Division Duplexing (FDD) and Half Duplexing (HD); i.e. communication can only flow in one direction at a time, and different carrier frequencies are used for the DL and the uplink (UL). Therefore the duplexer in the Radio Frequency (RF) Front End (FE) can be removed, resulting in a lower component cost and a lower attenuation between the antenna and the RF FE [16]. Lower attenuation allows the Power Amplifier (PA) to reduce its transmit power, with benefits in terms of overall power consumption. The drawback of HD is the need for guard time to avoid power leakage of the transmitter into the receive slot. The guard time is pure overhead and therefore has a negative effect on EE.

The 3G RAT is mostly deployed as FDD but utilizes full

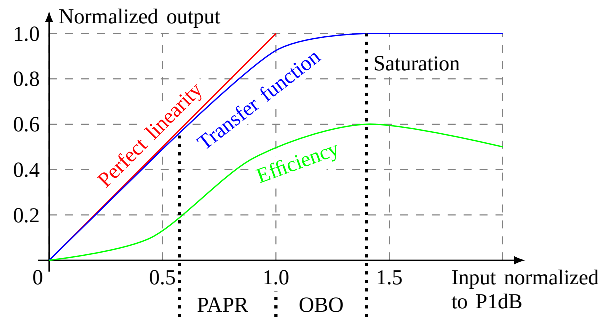

Fig. 2: Power amplifier operation, based on [16, Fig. 2.30].

duplexing (FD) i.e. simultaneous transmission and reception, and therefore a duplexer is needed. Conversely, the guard time is substituted with a guard band in frequency. Furthermore the combination of FDD and FD entails strict Third-Order Intercept Point (IP3) requirements, because the UE's transmit signal can be mixed with external signals leading to a blocker in the receive band. Improving the IP3 performance leads to increased UE power consumption. In 4G both FDD and Time Division Duplexing (TDD) have been specified; TDD is by default HD since UL and DL transmissions are scheduled in different time slots, while the FDD design allows for FD.

### D. Uplink Waveform

The UL modulation scheme choice impacts the Peak to Average Power Ratio (PAPR), which affects the obtainable PA efficiency. High PAPR forces the PA to operate far from its saturation point; this increases the dissipation of DC supply power and therefore impacts the EE as illustrated in fig. 2. If the PA is saturated the signal is distorted and out-of-band harmonics occur, which impacts the Adjacent Channel Leakage Ratio (ACLR). Increased ACLR affects data rates negatively and thus the EE due to decreased sleeping opportunities.

In the first version of 2G the Gaussian Minimum Shift Keying (GMSK) modulation was used. Since the GMSK pulse has a constant envelope [16] the PA can operate close to the saturation region, where the EE peaks as shown in fig. 2. However, the GMSK waveform suffers from low spectral efficiency since only 1 bit/symbol is supported. In current 2G RAT versions higher level PSK is used to increase the data rate. The cost is increased sensitivity to distortion and therefore Output Back Off (OBO) is applied to ensure operations in the linear region as shown in fig. 2.

Initially, the 3G waveforms had PAPR properties similar to the 2G waveforms, but later releases have led to a higher PAPR due to the introduction of more advanced UL channels as shown in fig. 3. Furthermore, the Code Division MA (CDMA) scheme used in 3G is often coupled with the Rake receiver whose complexity increases with the number of multipath components and antennas. This increases the baseband processor power consumption [14]. As in 2G, the bandwidth is not scaled with respect to the needed data rate.

In 4G DL, the usage of Orthogonal Frequency Division Multiplexing (OFDM) has led to significant computational complexity reduction due to the efficient single-tap equalization in the receiver [17]. However, OFDM has a large PAPR due to the possibility of co-phasing multiple narrowband signals in the time domain. The usage of Single Carrier-Frequency Division Multiplexing (SC-FDM) in 4G UL decreases the PAPR compared to OFDM up to 4 dB. Unfortunately SC-FDM suffers from noise enhancement at the receiver which degrades

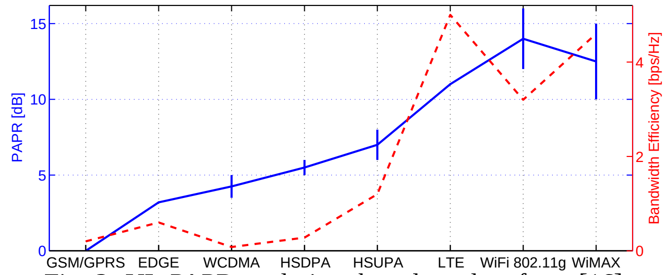

Fig. 3: UL PAPR evolution, based on data from [16].

the link performance [18] thus lowering the data rate and EE as discussed in sec. II-A. Furthermore, the PAPR of SC-FDM increases with high order modulations such as 64QAM, but a significant improvement over OFDM is preserved.

### E. Transmit Power and Control

The UE transmit power obviously affects the overall UE power consumption, because the PA is the major power consumer in the UE cellular subsystem [2].

The high transmit power of 2G (33 dBm) is necessary because the UE is active only in one out of eight slots [15]. In later releases the UE was allowed to occupy a larger set of time slots, and therefore reduce its transmit power to achieve the same detection performance as shown in tab. I.

In 3G the transmit power is 24 dBm, but since the RAT is FDD and FD the average transmit energy is the same as for 2G. Due to the mentioned PAPR increase from WCDMA to HSUPA, see fig. 3, the maximum transmit power was reduced in order to enable reuse of the previous releases' PAs. The reduction is based on the Cubic Metric (CuM) [19] which represents a measure of the expected intermodulation distortions introduced by the PA. This can lower the PA power consumption because the transmit power may be reduced by 1 dB, for $0 \leq$CuM$\leq 3.5$ dB, [20].

The maximum transmit power of 4G is 1 dB lower than 3G. The allowed transmit power reduction is 0-2 dB [21] and it depends on the Modulation and Coding Scheme (MCS) and the number of allocated resource blocks in the channel.

If the transmit power is not adjusted to a specific scenario's needs energy is wasted and the battery time reduced; an UL power control (UPC) technique is therefore critical for EE. Slow UPC is applied in 2G because the Time Division MA (TDMA) / Frequency Division MA (FDMA) + FDD structure ensures zero intra-cell interference. Slow UPC lowers the control overhead, but may result in high transmit power because it only adapts to pathloss and shadow fading. Furthermore excessive transmit power increases inter-cell interference.

The near-far CDMA problem in 3G leads to the necessity of using a faster UPC; its rate is fixed at 1500 Hz with steps of 1, 2, and 3 dB. By using a fast UPC the UE can track the channel conditions (fast fading) at the expense of a large control overhead. The UPC is closed loop because for FDD the channel is not reciprocal, hence the UE needs to inform the base station (BS) of the channel condition perceived in the DL and vice versa for the UL.

In 4G the UPC can update every ms, but the average rate is estimated to be 50-200 Hz depending on the channel type and conditions. The UPC consists of an open loop, where the UE compensates for a fraction of the experienced pathloss based on parameters which are set by the network, and a closed loop where the network dictates power adjustments until a certain Signal-to-Interference-plus-Noise-Ratio (SINR) is achieved.

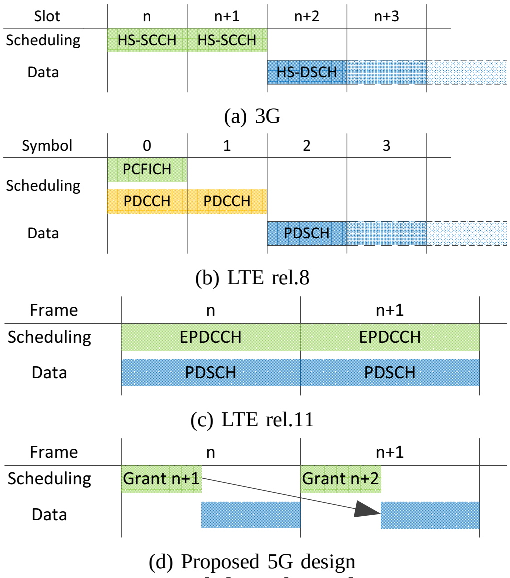


Fig. 4: Control/data channel position.

### F. Frame Structure

The frame duration, more specifically the time domain scheduling granularity, has been reduced with the introduction of every new RAT generation from 4.615 ms (2G) to 1 ms (4G). Shorter frame size entails a lower latency, but may also result in a larger overhead in case each frame preserves the same amount of control information. As described in sec. II-A it is beneficial to transfer data as fast as possible, and therefore it is important to minimize the control overhead.

The relative position of control and data channels affects the control channel decoding procedure, which is used to determine if the UE is scheduled or can power down.

Initially 2G was designed as a circuit switched RAT, where a certain amount of resources was allocated to the user for the entire call duration even though the user might not need such resources in every slot. Later releases introduced packet switched data while preserving dedicated channels for each session. For instance, the UE can be allocated slots 0-3 of every TDMA frame, but they may be unused causing excessive power consumption due to reception of useless data.

In 3G, the High-Speed Shared Control Channel (HS-SCCH) is used to provide information to the UE on how to demodulate the High-Speed Downlink Shared Channel (HS-DSCH) [14]. The HS-SCCH is located in slot $n$ and $n+1$, while data is in slot $n+2$ and onwards as illustrated in fig. 4a. The first part of slot $n$ indicates the modulation format and which data codes the UE must despread. The second part, in slot $n+1$, contains redundancy information, Automatic Repeat Request (ARQ) process number and a retransmission indicator. This design is beneficial from an energy consumption perspective, because it informs the UE of the necessity of decoding the data mapped in slot $n+1$ and onwards upon detection of slot $n$. This eliminates the buffering of unused data.

In 4G the UE decodes the Physical Control Format Indicator Channel (PCFICH), which indicates the number of symbols used for the Physical Downlink Control Channel (PDCCH) [17]. Simultaneously, the UE receives and decodes the PDCCH which reports the used MCS and the location of the potentially allocated resources. The PDCCH is immediately followed by the Physical Downlink Shared Channel (PDSCH), which carries data. The UE needs to buffer PDSCH because there is no time available for decoding between the allocation indication and the actual data, as illustrated in fig. 4b. The micro sleep concept [22] has been introduced with the aim of minimizing the energy waste in case of unused buffered data. The main idea of the micro-sleep is to perform fast decoding of the control channel, and then power down the receiver in case the UE has no scheduled data. The cost is that the Reference Signals which are allocated at the end of the subframe are not received. This may lead to a degradation in the channel estimation, which may affect the throughput.

In LTE release 11 the EPDCCH has been standardized. The idea is to achieve a frequency selective scheduling gain by allocating the EPDCCH across an entire frame (see fig. 4c) and limit it to the frequency subcarriers which experience the most advantageous channel conditions. However, the expected SINR improvement comes at the expense of higher power consumption, since the usage of micro sleep is made impossible.

### G. MIMO

The usage of multiple receive antennas entails the UE can exploit receive diversity to improve the link budget, but also enhances the interference cancellation/mitigation capability. Furthermore the BS can transmit multiple data streams to boost the data rate. The power consumption will increase with the introduction of the extra RF circuitry which is needed to accommodate multiple transmit/receive chains. Furthermore MIMO requires larger baseband processing capabilities to deal with multiple data streams. However, as explained in sec. II-A the increased data rate leads to longer, efficient sleep modes.

In 2G the UE receive diversity is specified, while 3G and 4G allow for both receive diversity and DL multistream MIMO. Even though a maximum of 4 streams is specified in 4G, the number of codewords is limited to 2; this enables the implementation of Successive Interference Cancellation (SIC) receivers with feasible complexity. Newer versions of 4G also include transmit diversity and UL multistream MIMO.

### H. Frequency Reuse and Interference

Frequency Reuse is a widely used technique for dealing with inter-cell interference. The presence of interference may severely limit the data rate, thus also affecting the energy consumption since UEs need longer active time for transmitting/receiving their data as discussed in sec. II-A.

In 2G a frequency reuse factor of 3 or more is used. This allows for significant reductions of the inter-cell interference experienced by the cell edge users at the cost of a lower spectral efficiency from a system perspective. Intra-cell interference can also occur if the frequency channels are not properly filtered; since the potential improvement in SINR translates to higher data rates, interference cancellation techniques have been proposed. The widely used Single Antenna Interference Cancellation method has feasible complexity [23].

In 3G reuse factor 1 is applied, hence the users can experience interference from neighbor cells. Since the spreading codes adopted by neighbor BSs are not completely orthogonal, the users may experience Multiple Access Interference (MAI). UEs can apply interference cancellation/mitigation methods, which estimate and subtract the interference from the desired signal. As in 2G, these methods have high complexity, but also significant advantages when the MAI is high [14].

The 4G RAT primarily applies a frequency reuse factor of 1 and therefore cell edge users may experience inter-cell interference. Methods such as soft and fractional frequency reuse have been proposed [17] along with the previously discussed power control strategies.

## III. Recommendations for EE 5G

A 5G RAT shall be designed with the aim of minimizing the power consumption at the UE while maintaining high performance in terms of data rate and latency. In the light of the discussion on the technology features presented in the previous section, we now provide our recommendations, summarized in tab. I, for an energy efficient 5G design.

Our target 5G RAT was proposed in a conceptual form in [8]; since the envisioned design has not yet been finalized, we believe that our EE recommendations can significantly influence it. The concept aims at peak data rates of 10 Gbps, short latency below 1 ms and wake-up time from inactive to active in the order of 10 ms. The ambitious data rate requirement is to be achieved by using a 200 MHz bandwidth, TDD mode, a frame of 0.25 ms and multistream transmission, as well as established technology features such as Adaptive Modulation and Coding (AMC), Hybrid ARQ (HARQ), and efficient time/frequency scheduling. Since most of the data traffic is expected to be generated in an indoor environment, the 5G RAT will be optimized for a local area (LA) scenario rather than for macro area as is the case for the 4G RAT.

TDD has clear cost advantages over FDD as duplex mode for 5G as it allows for a flexible spectrum assignment (no need for paired spectrum as in FDD), flexible duplexing of UL and DL, which is beneficial for asymmetric data, and simple support for backhauling and device-to-device communication. Its drawback is the need for a tight time synchronization to avoid mutual interference among UEs due to a misaligned UL/DL switching point. From an energy consumption perspective, TDD allows for discarding of the duplexer, which reduces the insertion loss in the RF FE by up to 3 dB (in both directions). Furthermore, in TDD mode the UE's transmit signal is not present during reception, hence the IP3 requirements can be relaxed since the undesired harmonics will not interfere the reception, with benefits in terms of power dissipated in the mixer. In addition, the possibility of exploiting the channel reciprocity between UL and DL may avoid the transmission of channel feedback from the UE to the BS, thus also saving transmit power.

Research on novel modulation/MA schemes for 5G is ongoing. For instance Non-Orthogonal MA, which combines Superposition Coding and OFDM [24], has drawn attention. This scheme requires a complex SIC receiver as baseline detector, and its EE properties are still unclear. Moreover, the Superposition Coding principle works best when the channel gain difference between UEs is large, which may not be the case in the LA scenario targeted by 5G [8]. The Filter Bank Multicarrier (FBMC) modulation [25] can be seen as a generalization of OFDM where the simple square window which is applied at each subcarrier, is replaced by a filter. FBMC allows removing the Cyclic Prefix and significantly reduces the out-of-band emissions. However, the computational complexity and thus the power consumption is significantly larger due to the time domain processing; moreover, the extension to MIMO is not as straightforward as in OFDM.

The usage of OFDM on both link directions allows for efficient resource allocation and UE implementation. The high PAPR, which represents the main drawback of OFDM modulation, should not be considered a significant limitation in the future. The reason is that novel techniques for the supply of PAs have gained attention and could considerably improve PA efficiency. One technique is Envelope Tracking (ET), which adjusts the PA supply voltage in accordance with the input signal (the modulated low power signal) to allow the PA to operate closer to the saturation region. According to [26] 20 MHz bandwidth is already supported, but it is an open question when and how the 200 MHz 5G bandwidth can be accommodated. If ET is realisable, the PAPR effect on the PA power efficiency is minimal hence OFDM can be implemented in an energy efficient manner.

When considering the benefits in terms of complexity and flexibility of OFDM and the reduced impact of its PAPR drawback, we believe OFDM modulation is the strongest candidate for energy efficient 5G.

While the 5G RAT is expected to be similar to the 4G standard for what concerns multiplexing and modulation format, the major difference is the 10 times increase in bandwidth. Moreover, 256QAM modulation is intended to be included to boost the spectral efficiency in favorable channel conditions. The larger bandwidth is not believed to impose a complexity problem. The reason is that the complexity of LTE scales linearly with the bandwidth [17], and the same is expected for an OFDM-based 5G RAT. Furthermore, the turbo decoding complexity is a linear function of the data rate [17]. The complexity of the 5G RAT is therefore expected to be 10 times higher, but if Moore's law continues to be valid the performance is supposed to increase by a factor of $10 - 30$ within the next decade, i.e. the complexity can be handled. Similarly, the power consumption is not expected to be affected due to Gene's law [27], which states the power dissipation per Million Instructions Per Second is halved every 18 months.

Note that, as the bandwidth becomes larger, the attenuation of the adjacent channels decreases. The reason is that wideband analog filters have a larger transition bandwidth with respect to narrowband filters. The related out-of-band emissions on the adjacent channels affect the dynamic range of the Analog to Digital Converter (ADC), which may cause it to consume more power. The baseband complexity is also increased because better digital filters are needed to remove the unwanted signals. Conversely, the wider bandwidth is not expected to have a significant effect on the RF power consumption.

A potential reduction of the maximum transmit power to the range 10-15 dBm, has to be taken into consideration given the LA scenario targeted by 5G. This would lead to huge power savings, and possibly to the removal of the external amplifier stage in current UE transmitters. In addition to the power savings this could entail less costly and less bulky UEs. We believe the UPC for 5G should be similar to 4G, because it represents a good tradeoff between control overhead and SINR control, with no significant penalty on the power consumption.

Clearly the control data channel design of 3G results in better energy efficiency when compared to 4G (as shown in fig. 4a and 4b), since useless data is not buffered. Therefore the 5G frame structure should be designed such that the scheduling information for frame *n+1* arrives in frame *n* as illustrated in fig. 4d. This allows the UE to determine in adequate time whether it is scheduled or not, hence it can power down and save energy when possible. The cost is an increased delay, but due to the short frame size this is not a major issue. The CM-

DRX and CM-DTX sleep modes should also be included given their obvious power reduction benefits. It is worth to mention that the usage of deep sleep modes may however increase the latency since the UE needs to spend some time waking up, before tight synchronization can be re-acquired. The design of energy efficient wake up and re-synchronization methods are important further studies.

When 5G is ready for deployment it is expected that the technological evolution allows for 4x4 MIMO implementation in the UE. The multistream transmission boosts the data rate, and therefore increases the sleeping opportunities. We foresee that the low power sleep will compensate the extra power consumed by the extra RF circuitry and baseband processing.

The 5G RAT envisioned in [8] targets LA scenarios with uncoordinated deployment of small cells; in such scenarios inter-cell interference is a significant limiting factor. In case neighbor cells are time synchronized, such interference can be suppressed/cancelled by using Interference Rejection Combining (IRC) or SIC receivers. The usage of advanced receivers obviously leads to increased complexity, which however translate again to the possibility of boosting the data rate and then increase the sleeping opportunities. This can also be accomplished by autonomous interference coordination techniques; 5G BSs can sense interference from neighbor cells and select their frequency resources accordingly, as well as notify their neighbors about the interference they may generate.

Based on this discussion we conclude that a future 5G RAT can be made energy efficient, and that the proposed concept [8] is beneficial from UE EE perspective. It is however important that UE EE is included as a design parameter in the clean slate designs, and not only as a buzz word.

## IV. Conclusions and future work

The 5th generation (5G) radio access technology aims at increased user data rates and lower latency compared to the previous generations, while reducing the user equipment (UE) power consumption. In this work existing technology features, generally recognized as necessary for achieving the 5G requirements, have been discussed considering their effect on UE energy efficiency. Based on that we gave recommendations for an energy efficient design of a previously proposed 5G concept, which is still under research.

We foresee significant advantages in the usage of TDD mode given the related simple and low power hardware design. Multiple access based on OFDM has several advantages such as low computational complexity and considering the ongoing improvements in power amplifier efficiency, the large PAPR can be handled with good UE energy efficiency. We further predict that the local area scenario targeted by 5G allows for a significantly lower transmit power, with obvious benefits on the overall power consumption. Features like MIMO antenna schemes and multiple carrier transmission allow shortening the active time of the device; this leads to higher energy efficiency, by use of low power sleep modes, despite of the increased computational complexity. Finally, a novel control channel design allows for effective micro sleep, which has to be supplemented with Discontinuous Reception and Transmission sleep modes.

We predict that the main key to achieve high UE energy efficiency in 5G is the combination of high data rates and low power sleep modes.

Future open problems, from an energy efficiency perspective, include the design of low complexity interference cancellation receivers, sleep mode and synchronization procedures, as well as the analysis of the wide bandwidth's effect on the power consumption of Analog to Digital Converters and filters.

## Acknowledgement

The work is partly funded by the Danish National Advanced Technology Foundation and the 4th Generation Mobile Communication and Test Platform project.

## References

[1] J.D.Power and Associaties, "J.D. Power Insights: Battery Life: Is That All There Is?" http://tinyurl.com/l9mft9n, 2012.
[2] M. Lauridsen, P. Mogensen, and L. Noel, "Empirical LTE smartphone power model with DRX operation for system level simulations," *VTC Fall, IEEE 78th*, September 2013.
[3] P. Demestichas, A. Georgakopoulos, D. Karvounas, K. Tsagkaris, V. Stavroulaki, J. Lu, C. Xiong, and J. Yao, "5G on the Horizon: Key Challenges for the Radio-Access Network," *Vehicular Technology Magazine, IEEE*, vol. 8, no. 3, pp. 47–53, 2013.
[4] Metis, "Mobile and wireless communications Enablers for the Twenty-twenty Information Society," www.metis2020.com, 2013.
[5] 5GNOW, "5th Generation Non-Orthogonal Waveforms for Asynchronous Signalling," www.5gnow.eu, 2013.
[6] D. Feng, C. Jiang, G. Lim, J. Cimini, L.J., G. Feng, and G. Li, "A survey of energy-efficient wireless communications," *Communications Surveys Tutorials, IEEE*, vol. 15, no. 1, pp. 167–178, 2013.
[7] Y. Chen, S. Zhang, S. Xu, and G. Li, "Fundamental trade-offs on green wireless networks," *ComMag, IEEE*, vol. 49, no. 6, 2011.
[8] P. Mogensen, K. Pajukoski, B. Raaf, E. Tiirola, E. Lähetkangas, I. Kovacs, G. Berardinelli, L. Garcia, L. Hu, and A. Cattoni, "B4G local area: High level requirements and system design," in *Globecom Workshops, 2012 IEEE*, 2012, pp. 613–617.
[9] A. Jensen, M. Lauridsen, P. Mogensen, T. Sørensen, and P. Jensen, "LTE UE Power Consumption Model - for System Level Energy and Performance Optimization," *VTC Fall, IEEE 76th*, September 2012.
[10] 3GPP, "3GPP Technologies," www.3gpp.org/Technologies, 2013.
[11] L. Wang and J. Manner, "Energy Consumption Analysis of WLAN, 2G and 3G interfaces," in *IEEE/ACM GreenCom*, 2010, pp. 300–307.
[12] M. Lauridsen, H. Wang, and P. Mogensen, "LTE UE Energy Saving by Applying Carrier Aggregation in a HetNet Scenario," in *VTC Spring, IEEE 77th*, 2013.
[13] M. Mayberry, "Enabling Breakthroughs in Technology," Intel, 2011.
[14] H. Holma and A. Toskala, *WCDMA for UMTS - HSPA Evolution and LTE*, 5th ed. John Wiley & Sons, Ltd., 2010.
[15] R. Steele, C. Lee, and P. Gould, *GSM, cdmaOne and 3G Systems*. John Wiley and Sons, 2001.
[16] E. McCune, *Practical Digital Wireless Signals*, ser. The Cambridge RF and Microwave Engineering Series. Cambridge University Press, 2010.
[17] H. Holma and A. Toskala, *LTE for UMTS, OFDMA and SC-FDMA Based Radio Access*. John Wiley & Sons, Ltd., 2009.
[18] B. E. Priyanto, H. Codina, S. Rene, T. B. Sørensen, and P. Mogensen, "Initial performance evaluation of DFT-spread OFDM based SC-FDMA for UTRA LTE uplink," *IEEE 65th VTC Spring*, April 2007.
[19] Motorola, "Comparison of PAR and Cubic Metric for Power De-rating," 3GPP TSG RAN WG1 #37 R1-040522, 2004.
[20] 3GPP, "UE radio transmission and reception," TS 25.101 v.8.16.0, 2012.
[21] ——, "UE radio transmission and reception," TS 36.101 V8.20.0, 2013.
[22] M. Lauridsen, A. Jensen, and P. Mogensen, "Fast Control Channel Decoding for LTE UE Power Saving," *VTC Spring, 75th*, May 2012.
[23] ETSI, "Feasibility study on SAIC for GSM networks," TR145.903 v7.0.1, 2007.
[24] Y. Saito, Y. Kishiyama, A. Benjebbour, T. Nakamura, A. Li, and K. Higuchi, "Non-Orthogonal Multiple Access (NOMA) for Cellular Future Radio access," *VTC Spring, IEEE 77th*, 2013.
[25] B. Farhang-Boroujeny, "OFDM versus Filter Bank Multicarrier," *Signal Processing Magazine, IEEE*, vol. 28, no. 3, pp. 92–112, 2011.
[26] Nujira, "High Accuracy Envelope Tracking for LTE' Smartphones and Modems," www.nujira.com/pages/files/Coolteq.L_Feb_2013.pdf, 2013.
[27] G. Frantz, "Digital signal processor trends," *Micro, IEEE*, vol. 20, no. 6, pp. 52–59, 2000.