

## AN EMPIRICAL LTE SMARTPHONE POWER MODEL WITH A VIEW TO ENERGY EFFICIENCY EVOLUTION

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*“The smartphone power consumption model includes the main power consumers in the cellular subsystem as a function of receive and transmit power and data rate...”*

*“...the combination of high data rates and long sleep periods is the optimal combination from a user equipment energy-saving perspective.”*

Smartphone users struggle with short battery life, and this affects their device satisfaction level and usage of the network. To evaluate how chipset manufacturers and mobile network operators can improve the battery life, we propose a Long Term Evolution (LTE) smartphone power model. The idea is to provide a model that makes it possible to evaluate the effect of different terminal and network settings to the overall user equipment energy consumption. It is primarily intended as an instrument for the network engineers in deciding on optimal network settings, but could also be beneficial for chipset manufacturers to identify main power consumers when taking actual operating characteristics into account. The smartphone power consumption model includes the main power consumers in the cellular subsystem as a function of receive and transmit power and data rate, and is fitted to empirical power consumption measurements made on state-of-the-art LTE smartphones. Discontinuous Reception (DRX) sleep mode is also modeled, because it is one of the most effective methods to improve smartphone battery life.

Energy efficiency has generally improved with each Radio Access Technology (RAT) generation, and to see this evolution, we compare the energy efficiency of the latest LTE devices with devices based on Enhanced Data rates for GSM Evolution (EDGE), High Speed Packet Access (HSPA), and Wi-Fi\*. With further generations of RAT systems we expect further improvements. To this end, we discuss the new LTE features, Carrier Aggregation (CA) and Enhanced Physical Downlink Control Channel (EPDCCH), from an energy consumption perspective.

Not surprisingly, the conclusion is that having the cellular subsystem ON, and in addition, transmit powers above 10 dBm, have the largest effect on UE power consumption, and that the combination of high data rates and long sleep periods is the optimal combination from a user equipment energy-saving perspective.

### Introduction

The battery life of smartphones has become shorter as smartphones have become more advanced, both due to slow battery capacity evolution, but also due to bigger displays, faster and more processor cores, and more complex Radio Access Technologies (RATs).

The power consumed due to use of various RATs depends on the hardware and software within the device, and in addition on the RAT network setup. To analyze and minimize the power consumption caused by suboptimal

network setup, the responsible network engineers require a model that describes the smartphone power consumption as a function of relevant parameters.

In recent literature the smartphone power consumption has been studied either by running a meter application on the phone<sup>[1][2]</sup> or by using a dummy battery<sup>[3][4][5]</sup>, which logs the current drain. The latter option seems to be the best because it does not introduce any additional signal processing and hardware routines in the smartphone. In some articles, the authors<sup>[4][2]</sup> have connected the smartphone to a live, commercial network, while others have performed conducted tests using a base station emulator in a laboratory.<sup>[3][5]</sup> The emulator setup is preferable because it provides the full control and logging of all relevant network parameters such as resource allocation and power levels, while also being a realistic “live” connection.

Few public measurements of LTE smartphones are available, and most of the literature unfortunately only reports power consumption for a limited number of parameters. One article<sup>[4]</sup> provides the power consumption as a function of data rates, but with no information about the transmit (Tx) and receive (Rx) power levels, while another<sup>[5]</sup> only reports power consumption as a function of Tx power. Therefore we decided to provide a new model, which includes the most relevant network parameters, that is Tx and Rx power levels and data rates. Our first LTE power model<sup>[6]</sup> was based on commercial Universal Serial Bus (USB) dongles, which were not optimized for low power consumption, but the model did not include DRX and cell bandwidth. Therefore we presented an updated model<sup>[3]</sup> where the power consumption of three different LTE smartphones, commercially available in fall 2012, was examined. Comparing our dongle and smartphone measurements, it is clear that the cellular subsystems develop fast and that the power consumption improves with each generation. Therefore it is of interest to examine how it has evolved with the launch of the latest LTE chipsets.

In this article we present our recent measurements on LTE smartphones and compare with the previous generations.<sup>[3][6]</sup> We also discuss the observed energy efficiency (EE) improvement and compare it with other wireless RATs. Finally we discuss how the LTE power consumption can be lowered in the future by use of micro sleep and Carrier Aggregation.

The article is organized as follows: in the next section we introduce our smartphone power consumption model, and in the following section, “Experimental Assessment,” we present the measurement campaign we have carried out to assign meaningful values to the model. Then we define energy efficiency (EE) and provide a comparison of EE in wireless RATs in the section “Energy Efficiency Evolution,” and in connection with this we discuss micro sleep and carrier aggregation as future power optimization possibilities in the section “Energy Efficiency Improvements.” In the last section we present our conclusions.

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*“...it is clear that the cellular subsystems develop fast and that the power consumption improves with each generation”*

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*“...the power consumption can be measured independently of the other blocks’ contributions by varying the block-specific parameter.”*

## Smartphone Power Consumption Model

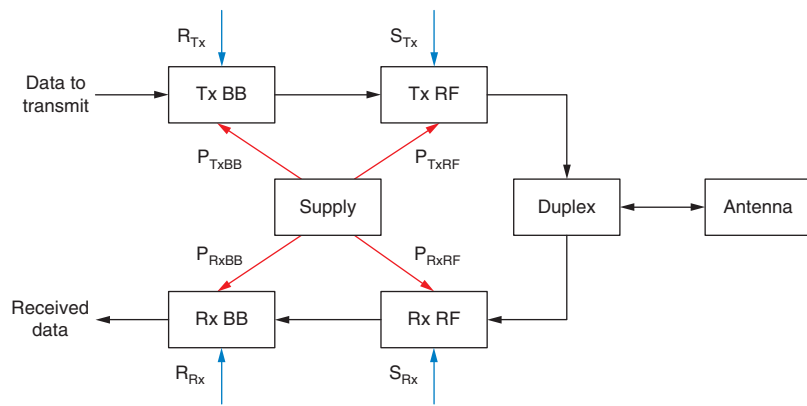
In this section the smartphone power consumption model, originally developed for the dongle measurements<sup>[6]</sup> but also applicable here, is presented.

The model covers the LTE cellular subsystem and the overall power consumption is defined as:

$$P_{\text{cellular}} = m_{\text{con}} \times P_{\text{con}} + m_{\text{idle}} \times P_{\text{idle}} + m_{\text{DRX}} \times P_{\text{DRX}} \quad [\text{W}] \quad (1)$$

where  $m$  is a binary variable describing whether the UE is in RRC\_connected (con), RRC\_idle (idle), or DRX mode. The associated  $P$  value describes the power consumption in the given mode as a function of mode specific parameters.

The power consumption model of RRC\_connected mode is divided into Tx and Rx Base Band (BB) and Radio Frequency (RF) functional blocks, which each define the power consumption as a function of either Tx or Rx power levels ( $S$ ) and data rates ( $R$ ). The model, sketched in Figure 1, was divided into those blocks<sup>[6]</sup> because they each have a distinct parameter, for example, transmit power  $S_{\text{Tx}}$  in the Tx RF, which primarily affects the power consumption of that block. Therefore the power consumption can be measured independently of the other blocks’ contributions by varying the block-specific parameter. Our empirical measurements<sup>[3][6]</sup> have consolidated this division.



**Figure 1:** LTE smartphone cellular subsystem power model  
(Source: Mads Lauridsen, Aalborg University, 2013)

The RRC\_connected mode power consumption is:

$$P_{\text{con}} = P_{\text{on}} + m_{\text{Rx}} \times (P_{\text{Rx}} + P_{\text{RxBB}}(R_{\text{Rx}}) + P_{\text{RxRF}}(S_{\text{Rx}})) + m_{\text{Tx}} \times (P_{\text{Tx}} + P_{\text{TxBB}}(R_{\text{Tx}}) + P_{\text{TxRF}}(S_{\text{Tx}})) \quad [\text{W}] \quad (2)$$

The constants  $P_{\text{on}}$ ,  $P_{\text{Rx}}$ , and  $P_{\text{Tx}}$  describe the power consumed when the cellular subsystem is ON, the receiver is actively receiving, and the transmitter is actively transmitting, respectively.

In RRC\_idle mode the UE is mainly in a low-power sleep mode. It wakes up periodically to see whether there is an incoming paging message from the network. The period is defined by the network-controlled paging cycle  $t_{pc}$ . This behavior resembles the DRX power consumption, and therefore the DRX model, which is presented in the next section, is used to calculate RRC\_idle mode power consumption  $P_{idle}$  of Equation 1. This is however an approximation because the number of tasks required in RRC\_idle is far less compared to RRC\_connected.

### DRX Power Consumption Model

Sleep modes are one of modern RATs' most important methods to achieve high EE. The Connected Mode DRX sleep mode is standardized in LTE, and has also been included in recent versions of 3G. The idea is that the UE is scheduled periodically by the network, hence it knows when to be active and when it can sleep. The LTE DRX allows for periods of 10–2560 ms, so the period can be well adjusted to the data type. Furthermore the network can specify how long the UE must remain ON during each period, known as the On Duration  $t_{onD}$ , and whether it must remain active for a certain period after successfully decoding data. The UE power consumption as a function of time, when using DRX, could therefore be expected to look as sketched in Figure 2.

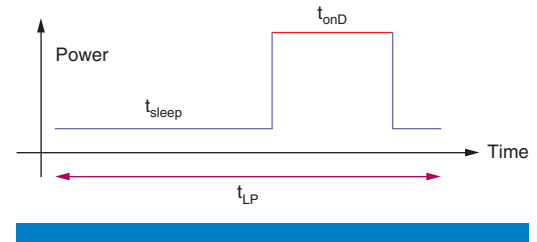
There are however multiple tasks that prevent the phone from performing as in Figure 2. They include but are not limited to<sup>[7]</sup>:

- The use of different clocks. In deep sleep mode the UE typically uses a low-power low-precision 32 kHz crystal to keep track of the System Frame Number (SFN), whereas it needs to power on a high-precision clock to achieve a proper phase reference for all clocks used when the cellular subsystem is ON.
- The wakeup phase. To enable demodulation, the UE obviously needs a phase lock of the BB Phase Locked Loop (PLL) synthesizer, but also a stable RF subsystem. The latter entails phase-locked RF PLL, stable Automatic Gain Control (AGC), programming of channel filters, and possibly a calibration of certain components.
- The synchronization phase. This requires demodulation of LTE's primary and secondary synchronization signals, which are sent every 5 ms, and possibly also decoding the Physical Broadcast Channel to get the SFN and other basic information. While this is being performed, channel estimation is also carried out.
- Power-down phase. In this phase the UE does not need to perform decoding, calibration, or any other time-consuming tasks, but powering down the components also takes time, and therefore the phase is included.

Due to the aforementioned tasks, the LTE DRX UE power consumption is as illustrated in Figure 3.

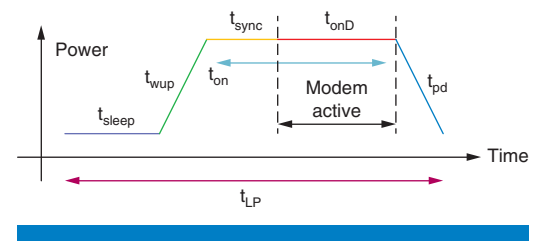
Comparing Figure 3 with Figure 2, you can see that the standardized  $t_{onD}$  remains the same while the sleep time  $t_{sleep}$  is shortened due to the introduction of the wakeup ( $t_{wup}$ ), synchronization phase ( $t_{sync}$ ), and power-down phase ( $t_{pd}$ ), all of which are functions of the DRX period  $t_{LP}$  because it is the deciding

*“Sleep modes are one of modern RATs' most important methods to achieve high energy efficiency.”*



**Figure 2: Ideal LTE DRX behavior**  
(Source: Mads Lauridsen, Aalborg University, 2013)

*“...the UE is scheduled periodically by the network, hence it knows when to be active and when it can sleep. The LTE DRX allows for periods of 10–2560 ms...”*



**Figure 3: Realistic LTE DRX behavior**  
(Source: Mads Lauridsen, Aalborg University, 2013)

factor for which sleep power level is used. The shorter sleep time means that the average power consumption is increased.

The sleep time is calculated as

$$t_{\text{sleep}}(t_{\text{LP}}, t_{\text{onD}}) = t_{\text{LP}} - (t_{\text{wup}}(t_{\text{LP}}) + t_{\text{sync}}(t_{\text{LP}}) + t_{\text{pd}}(t_{\text{LP}}) + t_{\text{onD}}) [s] \quad (3)$$

Combining it with the energy consumed during the wakeup, synchronization, and power-down phases  $E_{\text{wup/pd+sync}}(t_{\text{LP}})$ , the average DRX power consumption, excluding the power consumed in the On Duration, is

$$P_{\text{DRX}}(t_{\text{LP}}, t_{\text{onD}}) = (t_{\text{sleep}}(t_{\text{LP}}, t_{\text{onD}}) \times P_{\text{sleep}} + E_{\text{wup/pd+sync}}(t_{\text{LP}})) / (t_{\text{LP}} - t_{\text{onD}}) [W] \quad (4)$$

Combining this value with the power consumption and length of the On Duration, the total power and energy consumption of a DRX period can be calculated and applied in system level simulations.

The DRX model uses average power, and therefore the results cannot be used for Transmission Time Interval (TTI) simulations, but only system-level simulations with a longer time perspective. Note however that  $P_{\text{con}}$  is applicable on the TTI level.

## Experimental Assessment

Each of the proposed model's functional blocks depend on one specific parameter, and in this section it is described how the functions are derived using experimental measurements.

The assumption is that a given block's function can be assessed experimentally by varying the function-specific parameter, such as the  $R_{\text{Tx}}$  of the Tx BB, while keeping the other parameters  $S_{\text{Tx}}$ ,  $R_{\text{Rx}}$ , and  $S_{\text{Rx}}$  constant and at a level where they will influence the measurement the least.

The parameters are varied by adjusting the Modulation and Coding Scheme (MCS), number of Physical Resource Blocks (PRBs), and Rx and Tx powers  $S$ . For example the receive data rate  $R_{\text{Rx}}$  can be varied by adjusting the Downlink (DL) MCS and the number of DL PRBs.

A least one test case (TC) is then designed for each of the model's four functions (see Table 1), and to enable a comparison with our previous work<sup>[3]</sup> the same TCs are used. The varied parameter is shown in brackets. We have previously<sup>[3]</sup> applied the TCs in 10, 15, and 20 MHz cell bandwidth. The measurements showed a very linear relationship with bandwidth and therefore the TCs are only performed in 20 MHz cell bandwidth in this study.

The TCs in Table 1 are furthermore designed such that a common point exists. The point uses DL MCS 0, DL PRB 3/4, Uplink (UL) MCS 5/6, UL PRB 100, and constant powers. In addition TC 2 and 4 have an initial test point using 0 PRBs in either DL or UL. By comparing these three points the cellular subsystem ON power  $P_{\text{on}}$ , and the power consumption of having active reception  $P_{\text{Rx}}$  and transmission  $P_{\text{Tx}}$  can be determined.

*“The DRX model uses average power, and therefore the results cannot be used for Transmission Time Interval simulations, but only system-level simulations with a longer time perspective”*

Test Case		Downlink parameters			Uplink parameters		
		MCS	PRB	$S_{Rx}$	MCS	PRB	$S_{Tx}$
Rx BB	1	[0,28]	100	-25	6	100	-40
	2	0	[0,100]	-25	6	100	-40
Rx RF	3	0	100	[-25,-90]	6	100	-40
Tx BB	4	0	3	-25	6	[0,100]	-40
	5	0	3	-25	[0,23]	100	-40
Tx RF	6	0	3	-25	6	100	[-40,23]

**Table 1:** Measurement parameters. Tests are made for cell bandwidth of 20 MHz. In DL both 1 and 2 code words (CWs) are tested.

(Source: Lauridsen, Mads et al.<sup>[3]</sup>, 2013)

### Measurement Setup

In this study, measurements on two LTE Release 8 category 3 smartphones were performed to obtain updated and realistic values for the smartphone power model. The main characteristics of the Device Under Test (DUT) are listed in Table 2. They are both touchscreen phones running the Android\* OS, and are connected to LTE band 4 with carrier frequency 2145 MHz (DL UARFCN 2300).

*“In this study, measurements on two LTE Release 8 category 3 smartphones were performed to obtain updated and realistic values for the smartphone power model.”*

	UE1	UE2
OS	Android 4.0.4	Android 4.1.2
Launch date	June 2012	April 2013
Modem & CPU	Part #A	Part #B
Modem & CPU CMOS node	28 nm	28 nm
RF transceiver	Part #C	Part #D
RF transceiver CMOS node	65 nm	65 nm
Band 4 PA	Part #E	Part #F
LTE bands	4, 17	1, 2, 4, 5, 17

**Table 2:** DUT main characteristics

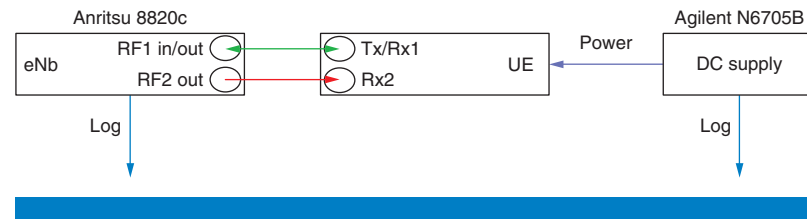
(Source: Laurent Noël, Vidéotron, 2013)

UE2 is one generation newer than UE1, which we previously have examined<sup>[3]</sup>, and therefore the UEs do not share modem and RF transceiver components as indicated in the table.

Power consumption measurements are performed under conducted test conditions, that is, the DUT is connected to an Anritsu 8820c eNodeB emulator via a pair of RF coaxial cables. A Faraday cage is used to ensure adequate DUT RF isolation from surrounding commercial LTE and HSPA+ networks. An Agilent N6705B power supply is connected to the DUT via the OEM's respective dummy batteries. Both supply voltage and current consumption are logged with microsecond time accuracy over at least 30 seconds per measurement point. Each power consumption log is then post-processed on a computer to determine the average power consumption. The accuracy of the measurement is estimated at  $\pm 10$  mW in cell-connected mode. The setup is illustrated in Figure 4.

*“UE2 is one generation newer than UE1 and therefore the UEs do not share modem and RF transceiver components...”*





**Figure 4: Measurement setup using the eNodeB emulator**  
(Source: Mads Lauridsen, Aalborg University, 2013)

Note that the use of a dummy battery, and especially the length and diameter of the connecting wires, have a non-negligible effect on the accuracy of the DRX time measurements, which is difficult to prevent.

### Uplink Characterization

The main contributor to cellular subsystem power consumption is the transmitter, and in this section the power consumption as a function of the two UL parameters in Equation 2 is reported.

*“The PA’s high gain mode is activated when the required transmit power exceeds a certain limit, and it entails a major increase in power consumption.”*

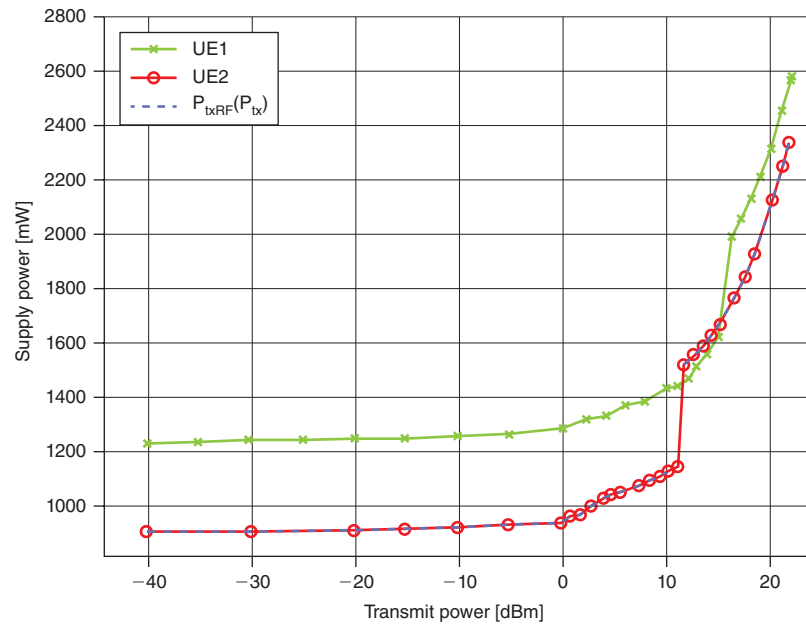
A transmitter is usually composed of a single chip RF transceiver and one external power amplifier (PA). The PA’s high gain mode is activated when the required transmit power exceeds a certain limit, and it entails a major increase in power consumption. We have however previously shown<sup>[8]</sup> that transmitting with high power and high data rates may be the most energy-efficient solution, depending on the type of data and propagation scenario.

Previous measurements<sup>[3][6]</sup> on older generations of LTE UEs, including UE1 of this study, have revealed a major power consumption increase when the transmit power exceeds 10 dBm. As illustrated in Figure 5, based on TC 6, this is also the case for the new UE2. Comparing the power consumption of UE1 and UE2, it is clear that the baseline power consumption has improved considerably in UE2. For transmit powers below 0 dBm the improvement is in the order of 35 percent. On the other hand, the PA used in UE2 is not as efficient as the one used in UE1, since the power consumption gap decreases for transmit powers above 10 dBm. This means the energy savings are reduced for high transmit power, but this may not be the case for other UEs because the PA is a component, which is available in many versions and designs, and because many tradeoffs are possible when specifying PA performance. For further information refer to the discussion in Holma et al.<sup>[7]</sup> on PAs.

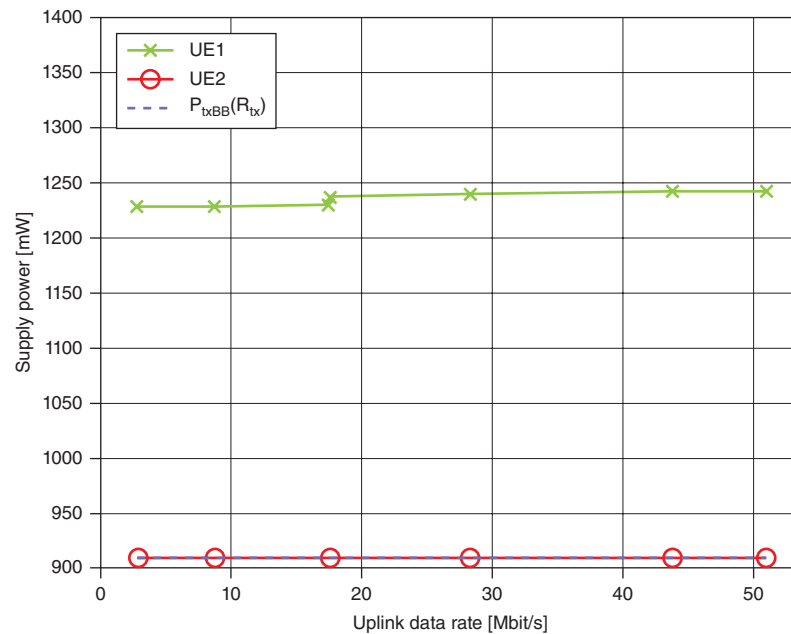
The blue dotted line in Figure 5 represents the model fit for the functional Tx RF block. The design of the fit and the function’s values are presented in the subsection “Model Parameterization.” Observe the blue dotted line is present in the following measurement results as well, and that it covers the related functional block fit.

*“...the UE2 power consumption is completely independent of the UL data rate.”*

The 35 percent power reduction between UE1 and UE2 is also observed when examining the power consumption as a function of UL data rate as in TC 4 and 5, where the transmit power and DL parameters are kept constant. The result of TC 5 is shown in Figure 6, and it illustrates that the UE2 power consumption is completely independent of the UL data rate. In some UEs,



**Figure 5:** Supply power consumption as a function of transmit power  
(Source: Mads Lauridsen, Aalborg University, 2013)



**Figure 6:** Supply power consumption as a function of UL data rate  
(Source: Mads Lauridsen, Aalborg University, 2013)

including the UE1, a step is observed when the modulation scheme is changed from QPSK to 16QAM. The reason is believed to be that certain PAs require a different bias/linearity setting to deliver the best compromise between power consumption and PA spectral emissions.

*“...certain PAs require a different bias/linearity setting to deliver the best compromise between power consumption and PA spectral emissions.”*



*“...network designers can aim for the highest UL data rate without affecting UE power consumption, but that transmit powers above 10 dBm must be avoided when possible.”*

*“...increasing the data rate by a factor 10, for example from 5 to 50 Mbit/s, only increases the power consumption about 5 percent.”*

Comparing the common point (UL MCS 6, UL PRB 100, Tx P -40 dBm) of Figure 5 and Figure 6, a maximum difference of 3.3 mW is observed, so there is good consistency between the measurements.

The UL parameter results illustrate how the new UE2 have improved the power consumption approximately 35 percent, but also that the choice of PA greatly affects the overall power consumption and that it can eliminate the advantage obtained by switching to a newer transceiver.

The results furthermore show that network designers can aim for the highest UL data rate without affecting UE power consumption, but that transmit powers above 10 dBm must be avoided when possible.

### Downlink Characterization

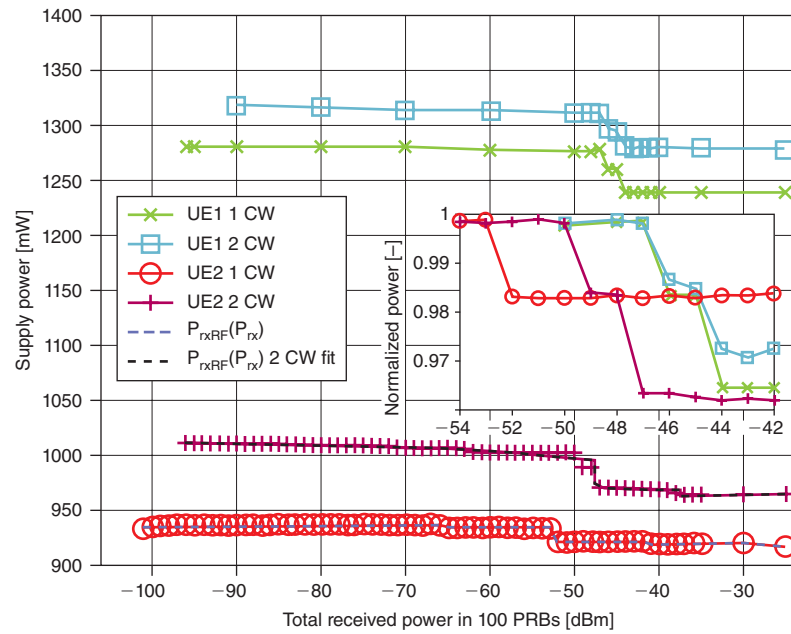
As opposed to the UL, the DL of LTE Release 8 allows for use of Multiple Input Multiple Output (MIMO) antenna configuration, more specifically 2x2. Actually all UEs are required to have two Rx antennas, and therefore Rx diversity can be expected to be applied for all single-stream receptions. Furthermore spatial multiplexing, using two streams, is applicable in favorable channel conditions. This can greatly improve the DL data rate, but since the examined UEs are category 3, the DL data rate is limited to 100 Mbit/s.<sup>[9]</sup>

Figure 7 shows the power consumption as a function of received power, based on TC 3, and as expected the improvement from UE1 to UE2 is at least 30 percent. Furthermore observe that UE2 applies a different gain adjustment scheme. The insert of Figure 7 highlights how the scheme adjusts the gain of the Low Noise Amplifier in multiple steps in order to ensure a good compromise between the amplifier's linearity and power consumption.

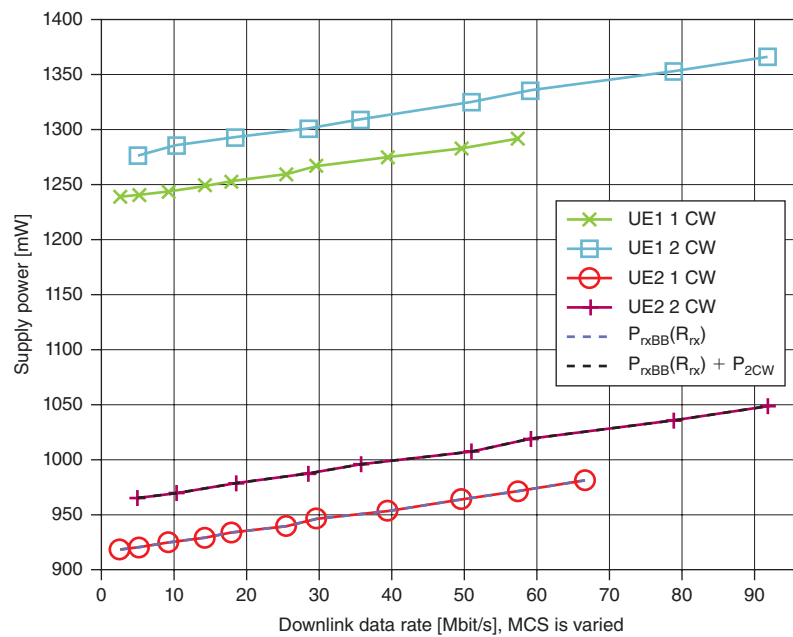
The result of TC 1, used to examine the DL data rate's effect on power consumption, is shown in Figure 8. The Turbo decoding complexity is known to scale linearly with DL data rate<sup>[10]</sup>, and this is clearly observable in the figure. The decoder power consumption does however not scale with the same proportion because increasing the data rate by a factor 10, for example from 5 to 50 Mbit/s, only increases the power consumption about 5 percent. This implies it is much more energy-efficient to run at high data rates. This is good for high data rate applications such as file transfers and high quality video streaming. Finally it is interesting to observe that the use of two CWs only add a constant offset to the power consumption.

Comparing the common point (DL MCS 0, DL PRB 100, Rx P -25 dBm) of Figure 7 and Figure 8, good consistency is again observed because the maximum difference is 1.4 mW.

The measurements on DL parameters showed the same 30–35 percent power consumption improvement as in UL, and that high data rates, similar to UL, results in the best EE.



**Figure 7:** Supply power consumption as a function of receive power  
(Source: Mads Lauridsen, Aalborg University, 2013)

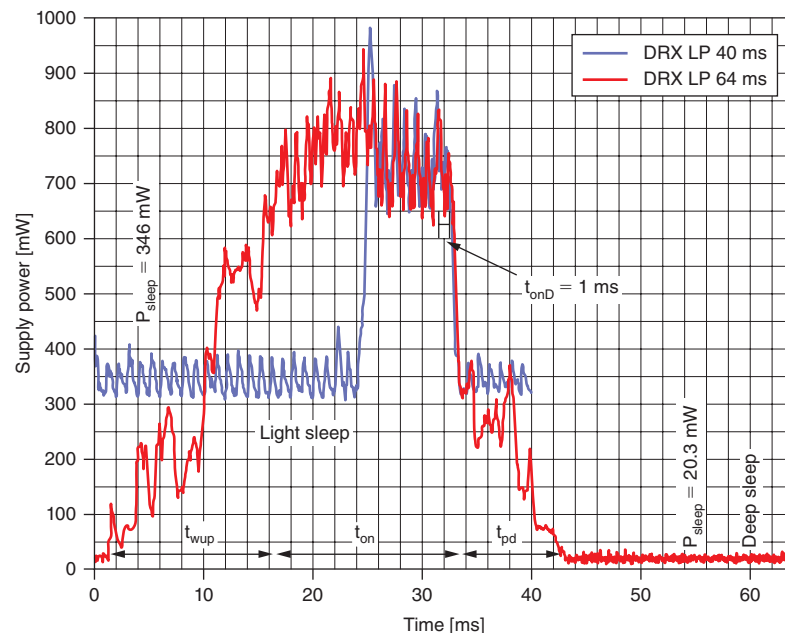


**Figure 8:** Supply power consumption as a function of DL data rate  
(Source: Mads Lauridsen, Aalborg University, 2013)

*“When LP is less than 32 ms the UE does not enter a sleep mode at all and therefore DRX Short Period was not examined.”*

### DRX Characterization

To examine DRX power consumption, the UEs were connected to the base station emulator and Connected Mode DRX was initiated. The DRX Long Period (LP) was varied from 32 ms to 256 ms, while the On Duration was set to 1 ms. When LP is less than 32 ms the UE does not enter a sleep mode at all and therefore DRX Short Period was not examined. Figure 9 shows two measurements on UE2 using DRX LP of 40 and 64 ms.



**Figure 9:** UE2 power consumption for DRX LPs 40 and 64 ms

(Source: Mads Lauridsen, Aalborg University, 2013)

Based on the DRX measurements, values for power consumption and duration of each phase have been derived. The results are given in Table 3

Device	$t_{LP}$	$P_{sleep}$	$t_{wup}$	$t_{pd}$	$t_{sync}$	$E_{wup/pd+sync}$
UE1	$\leq 40$ ms	570 mW	6 ms	9 ms	8 ms	19.2 mJ
UE2	$\leq 40$ ms	346 mW	0.7 ms	0.6 ms	6.7 ms	6.45 mJ
Improvements		39%	88%	93%	16%	66%
UE1	$\geq 80$ ms	29 mW	26 ms	21 ms	21 ms	41.4 mJ
UE2	$\geq 64$ ms	20 mW	16 ms	10 ms	16 ms	19.3 mJ
Improvements		31%	38%	52%	24%	53%

**Table 3:** Measured DRX parameters. On Duration is 1 ms

(Source: Mads Lauridsen, Aalborg University, 2013)

*“The ratio between power consumed in the active and sleep mode has improved to 39.9 for deep sleep...”*

The light and deep sleep power has improved 31–39 percent. This is as expected since similar improvements were noted in the previous sections. The ratio between power consumed in the active and sleep modes has however also improved from 1.8 to 2.2 and 35.6 to 39.9 for light and deep sleep respectively. This means the use of the sleep modes is even more effective.

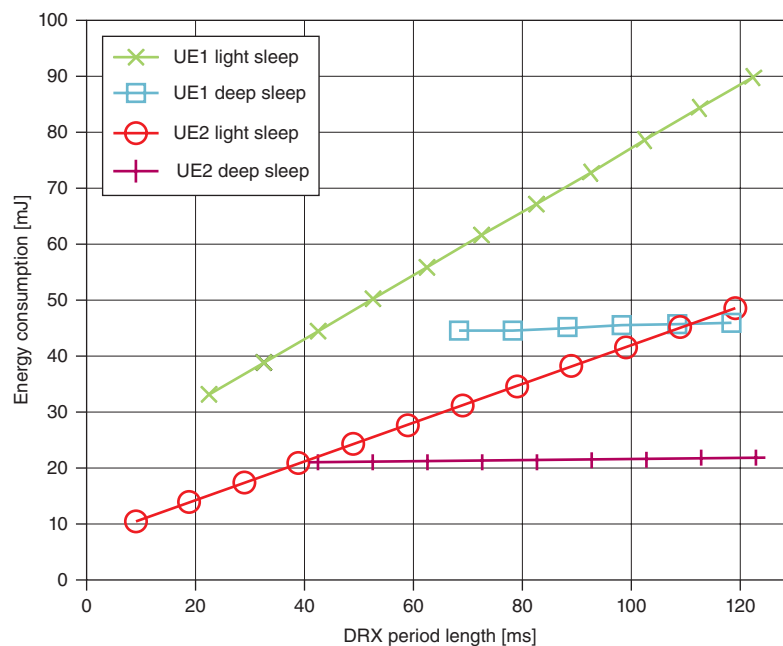
In addition the wakeup and power-down times have also become shorter in the new UE2. In particular, the mode change times for light sleep have improved about 90 percent, which means it is much more applicable for short sleep periods. Previously it was discussed<sup>[3]</sup> how Nokia's widely used LTE DRX power model<sup>[11]</sup> does not correspond well with reality because the active-to-sleep ratio was assumed to be 50 and the transition time 1 ms, but the current results at least indicate the UEs are approaching Nokia's estimates. The sub-millisecond transition time has now been achieved for light sleep, but in this case the active to sleep ratio is far from 50. Still the conclusion remains that DRX is a key method to improve smartphones' battery life.

The synchronization time has also improved, but not as substantially as the aforementioned times, and the reason is the inherent limitation given by LTE's synchronization structure, where the synchronization signals only appear every 5 ms. Examining the synchronization phase after exiting deep sleep, it seems like there is room for improvement, but it must also be noted that achieving proper AGC and a valid channel estimate becomes more difficult when the UE has been sleeping for longer, because the old settings and estimates will be outdated.

The 40 and 64 ms LPs were selected for Figure 9 because they represent the switching point where UE2 is applying either light or deep sleep. The light sleep is used when the LP is short or the On Duration is long, in either way eliminating the use of longer sleep periods. Furthermore the use of light sleep also represents the lowest energy consumption. This is illustrated in Figure 10, where the energy consumption as a function of DRX LP and sleep mode has

*“...DRX is a key method to improve smartphones' battery life.”*

*“...the inherent limitation given by LTE's synchronization structure, where the synchronization signals only appear every 5 ms.”*



**Figure 10:** Energy consumption when using DRX sleep modes as a function of DRX LP length

(Source: Mads Lauridsen, Aalborg University, 2013)

*“when developing an empirical model it is important to evaluate how easy it is to update with new measurements.”*

*“...the cellular subsystem contributes to 30–50 percent of the total power consumption depending on transmit power, screen brightness, and CPU load.”*

been calculated using Table 3. The figure clearly illustrates that deep sleep is more energy-efficient for  $LP \geq 64$  ms, hence the UE sleep settings are well chosen in terms of energy consumption.

### Model Parameterization

When developing an empirical model it is important to evaluate how easy it is to update with new measurements. In our work more specifically the required number of measurement points per TC needed to achieve a proper fit. We previously discussed it<sup>[3]</sup>, but now suggest the Tx BB is modeled using three points, since it is linear apart from the minor steps related to modulation scheme change. One point at each end of the data rate range is therefore sufficient, while a point in between is necessary as a sanity check. The Rx BB is also linear as a function of DL data rate and therefore three points should be sufficient. The Rx RF always includes UE-specific gain adjustments, which affect the power consumption, and therefore 5–6 points will be required to detect and model the steps of this piecewise linear function. The Tx RF exhibits a linear relation up to 0 dBm, thus the first part can be modeled using three points. For higher transmit powers, one measurement point per dB increase in transmit power is suggested. The reason for this accurate modeling is that the PA is the dominant power consumer.

Based on the above discussion it is clear how the functional blocks of the model in Figure 1 must be fitted to the measured data presented in the earlier subsections on uplink and downlink characterization. Each fit, representing one function in Equation 2, is based on adjusting a polynomial to the measured data by minimizing the least square error. The function of transmit power is divided into three piecewise linear sections due to its nonlinear behavior, while the function of UL data rate is a constant. The function of receive power is also divided into two sections due to the observed gain adjustment steps. The DL data rate function is a first order linear polynomial.

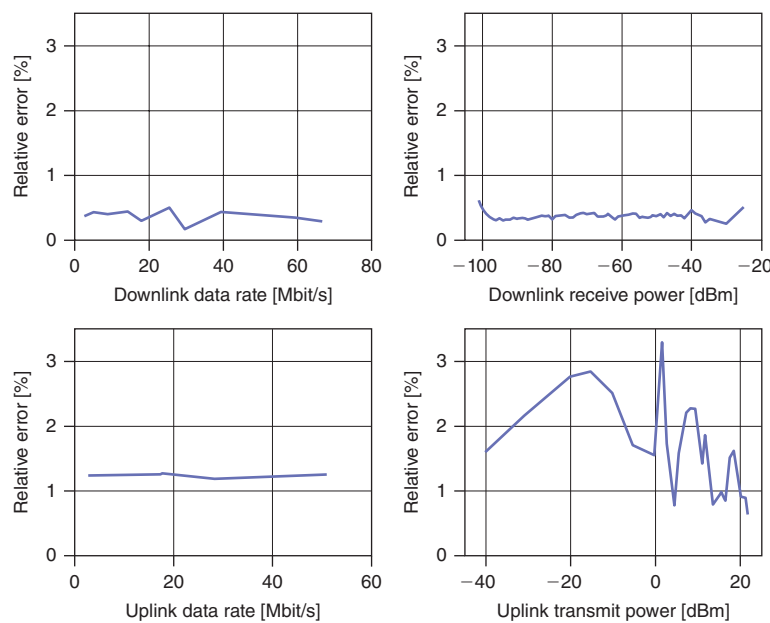
As mentioned earlier, the TCs in Table 1 are designed to have a common point, and the mean value of the four TCs in this point is 908 mW. By comparing this point with the 0 PRB point of TC 2 and 4, the cellular subsystem ON power, the active reception, and transmission power consumption were calculated. These values were then subtracted from the previously determined polynomials such that they can be applied in Equation 2 without contributing multiple times. The estimated polynomials are given in Table 4 and can be directly applied in Equation 2.

For information on how the UE cellular subsystem compares with the power consumption of screen, central processing unit (CPU), and graphics processing unit (GPU), refer to our previous measurements.<sup>[3]</sup> We concluded that the cellular subsystem contributes to 30–50 percent of the total power consumption depending on transmit power, screen brightness, and CPU load.

The accuracy of the model fit is examined by comparing each of the measurement results with the model’s estimated value. The relative error for each test point in each TC is illustrated in Figure 11. The maximum relative error is 3.3 percent hence a good fit has been achieved.

Part	Polynomial	Comment
$P_{TxRF}$	$0.78 \times S_{Tx} + 23.6$	$S_{Tx} \leq 0.2$ dBm
$P_{TxRF}$	$17.0 \times S_{Tx} + 45.4$	$0.2 \text{ dBm} < S_{Tx} \leq 11.4$ dBm
$P_{TxRF}$	$5.90 \times S_{Tx}^2 - 118 \times S_{Tx} + 1195$	$11.4 \text{ dBm} < S_{Tx}$
$P_{TxBB}$	0.62	
$P_{RxRF}$	$-0.04 \times S_{Rx} + 24.8$	$S_{Tx} \leq -52.5$ dBm
$P_{RxRF}$	$-0.11 \times S_{Rx} + 7.86$	$S_{Tx} > -52.5$ dBm
$P_{RxBB}$	$0.97 \times R_{Rx} + 8.16$	
ON	853, 29.9, 25.1	Cellular subsystem, Tx, Rx active

**Table 4:** Polynomial fits in mW for the UE2-based model  
(Source: Mads Lauridsen, Aalborg University, 2013)



**Figure 11:** Relative error between estimated and measured power  
(Source: Mads Lauridsen, Aalborg University, 2013)

## Energy Efficiency Evolution

The measurements, presented in the previous sections, clearly showed the power consumption of LTE UEs have improved with each new chipset generation. The question is how the improvement compares with other modern RATs. We use the metric EE defined as the number of joules required to transfer one bit. In most articles the instantaneous power consumption is given as a function of data rate, but this is equal to EE:

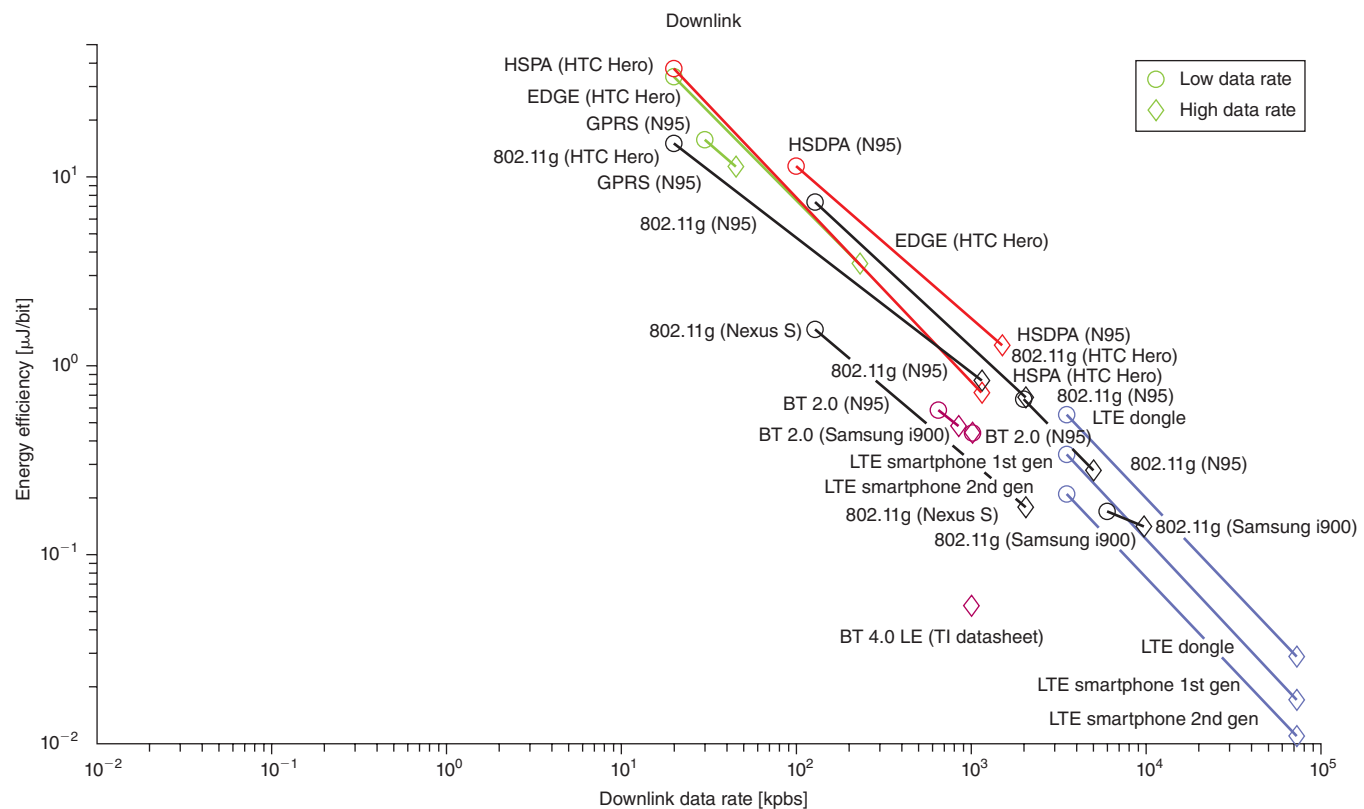
$$P [W] / R [\text{bit/s}] > W \times s/\text{bit} = J/\text{bit}$$

*“The measurements clearly showed the power consumption of LTE UEs have improved with each new chipset generation.”*

*“The downlink energy efficiency has improved with each RAT generation, as a result of improvements in CMOS node and devices in general, but also due to changes in the technologies used in the RATs ...”*

Our study is based on a review of power consumption measurements reported in recent literature; EDGE, HSPA, and Wi-Fi\* 802.11g (Wi-Fi) has been reported for an HTC Hero by Wang and Manner<sup>[12]</sup>, Friedman et al.<sup>[13]</sup> analyzed Bluetooth\* (BT) 2.0 and Wi-Fi power consumption in a Samsung i900\*, while Perruci et al.<sup>[14]</sup> covered BT 2.0, GPRS, HSDPA, and Wi-Fi using a Nokia N95. Xiao et al.<sup>[15]</sup> examined Wi-Fi using both a Nokia N95\* and a Nexus S\*. Our measurements on LTE dongles<sup>[6]</sup> and smartphones<sup>[3]</sup> are also included. In addition Texas Instruments have reported the power consumption of their standalone Bluetooth 4.0 Low Energy (BT LE)\* chip.<sup>[16]</sup> Finally System-on-Chip measurements on BT LE and ZigBee are reported for UL by Siekkinen et al.<sup>[17]</sup> The latter two studies obviously differ because they only cover the RAT chip and not a fully functional phone.

The DL EE is shown in Figure 12 for the examined devices. Usually the power consumption is reported as a function of increasing data rate, and therefore Figure 12 includes the dependency on both low and high data rates.



**Figure 12:** Downlink energy efficiency for modern RATs  
(Source: Mads Lauridsen, Aalborg University, 2013)

The DL EE has generally improved with each RAT generation, as a result of improvements in complementary metal–oxide–semiconductor (CMOS) node and devices in general, but also due to changes in the technologies used in the RATs, such as switching from CDMA to OFDMA.<sup>[18]</sup>



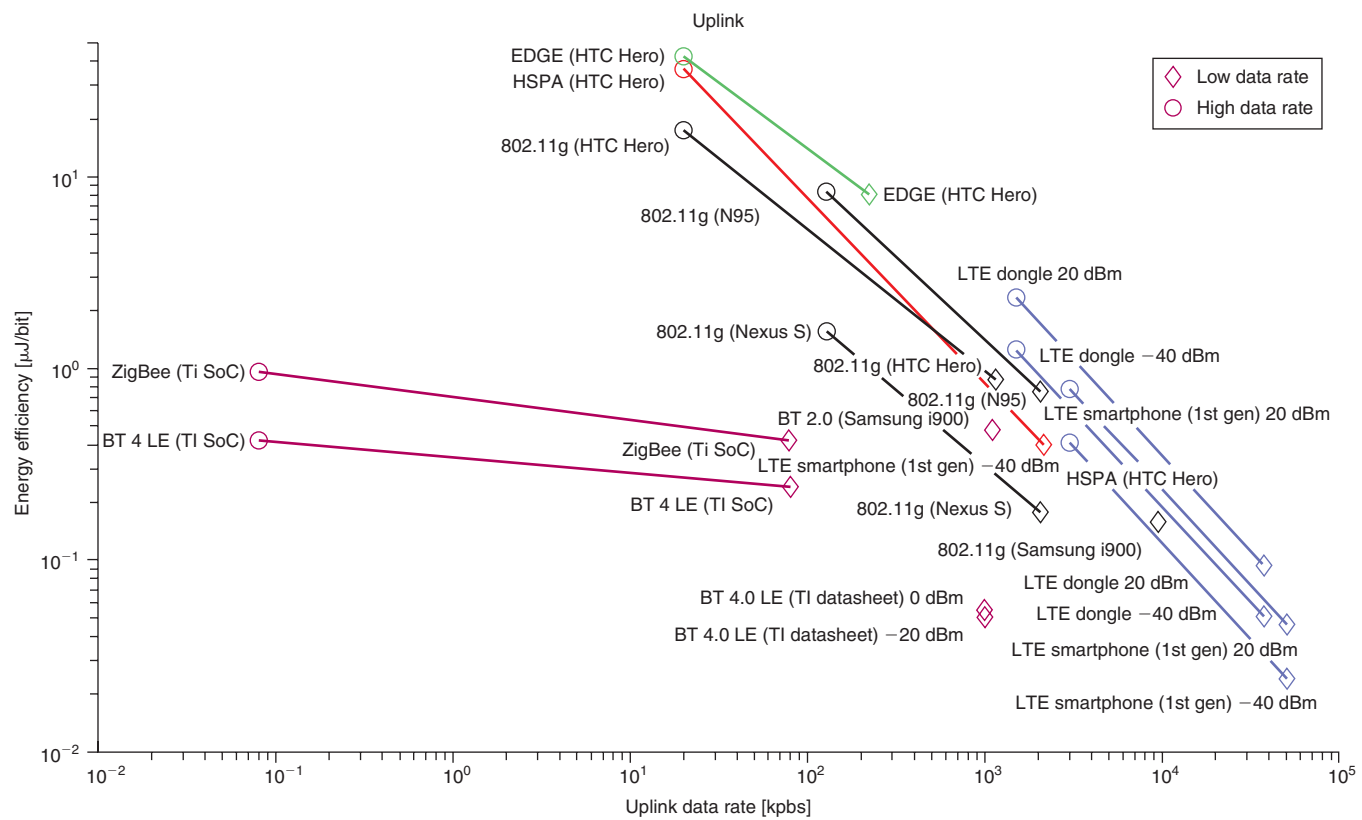
LTE achieves both the highest data rates and the best EE, while Wi-Fi is number two in both categories. One interesting observation is that the slope between the low and high data rate points is similar for all technologies.

If the target is Machine Type Communications (MTC), with low data rate, none of the systems seem optimal, because the EE rapidly decreases as the data rate is lowered. Currently the 3rd Generation Partnership Project (3GPP)<sup>[19]</sup> is running a study on MTC for LTE, which includes reducing the bandwidth and peak data rates, together with a single RF chain and lower transmit power to make LTE cost competitive and energy efficient.

Comparing the EE for UL transmission is more complicated because the transmit power and the general range of the system plays an important role.

The result of the literature review is shown in Figure 13. As in Figure 12, low and high data rates are reported, when available, and additionally the transmit power of the device is included.

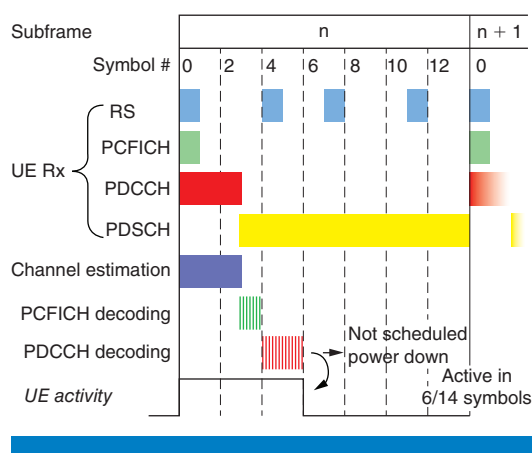
*“If the target is Machine Type Communications, with low data rate, none of the systems seem optimal, because the energy efficiency rapidly decreases as the data rate is lowered.”*



**Figure 13: Uplink energy efficiency for modern RATs**  
(Source: Mads Lauridsen, Aalborg University, 2013)

Again LTE proves to be the most energy-efficient RAT at high data rates, both for low and high transmit powers. The LE version of BT, based on TI's datasheet<sup>[16]</sup>, is almost as efficient at a data rate approximately two orders of magnitude lower. This means it is very useful for MTC, but one could

*“...LTE has proven to be the currently most energy-effective RAT for transferring data...”*



**Figure 14: Micro sleep in LTE Release 8**  
(Source: Lauridsen et al. 2012<sup>[20]</sup>)

have expected the BT LE to be even more efficient because it was developed specifically for low power purposes. The limiting factor is the low data rate, which prevents the EE from improving significantly. The chip implementations of BT and ZigBee<sup>[17]</sup> are a little less efficient, but at data rates below 100 kbps, no other RAT can compare with them in terms of EE. The authors<sup>[17]</sup> furthermore mention BT can be made even more efficient using another protocol stack.

It is important to note that the “communication range” of the RATs differs a lot. The mobile communication systems, such as HSPA and LTE, can have a range of several kilometers, whereas Wi-Fi and BT are limited to 10–100 m. This affects their applicability in certain MTC scenarios, and therefore the 3GPP work on LTE for MTC<sup>[19]</sup> is important.

To conclude, LTE has proven to be the currently most energy-effective RAT for transferring data, and based on our new measurement and the observed trend it is not expected to change. It is for further study to evaluate how tail energy<sup>[4]</sup>, which covers the energy consumed after the actual data transmission is completed and is due to network and RAT dependent timeouts, affect each RAT.

## Energy Efficiency Improvements

The device maturity may not be enough to guarantee user satisfaction with regards to the battery life and therefore researchers are investigating methods that do not affect the current LTE standard, but decrease the power consumption. In the following subsections we discuss the micro sleep concept and how CA may affect the battery life.

### Micro Sleep

One issue in LTE is that the UE is forced to receive and buffer the Physical Downlink Data Channel (PDSCH) while it is decoding the Physical Control Format Indicator Channel (PCFICH) and Physical Downlink Control Channel (PDCCH), which carry scheduling information about PDSCH.<sup>[9]</sup> This occurs every subframe and if the UE is not scheduled it will be receiving and buffering PDSCH for no purpose.

To deal with this issue the Fast Control Channel Decoding<sup>[20]</sup> concept has been proposed. The idea is to perform a fast decoding of the control channels, stop buffering the PDSCH if the UE is not scheduled, and then power down specific RF and BB components. The UE has to wake up and receive the next subframe, meaning the sleep period is no longer than 7–9 symbols (0.47–0.60 ms) hence the label “micro sleep.” The concept is illustrated in Figure 14. The cost is that the UE will not receive the Reference Signals (RS) in the latter part of the subframe. In literature<sup>[20]</sup> this has been described as an SNR loss, which was simulated to result in a throughput degradation of 1–4 percent. On the other hand potential energy savings of 5–25 percent were reported and therefore the concept was deemed valuable.

Further advantages of the micro sleep concept include the fact that it can complement DRX, and it fits all types of traffic scenarios as opposed to DRX, which require a periodic pattern to be effective. In addition there is no increase in control message overhead as in DRX where configuration parameters are transferred. Finally the network scheduler will not be affected, because the concept is applied autonomously and individually by each UE.

Comparing the assumptions in the micro sleep literature<sup>[20]</sup> with current smartphones' DRX capabilities, as presented in the section "DRX Characterization," it is clear that the instantaneous power consumption cannot be lowered as much as initially expected. The reason is the wakeup and power-down times caused by powering ON and OFF of UE components, which was measured to be 0.6–0.7 ms. Table 3 does however show great improvements in wakeup and power-down times from UE1 to UE2 and therefore UE manufacturers may be able to apply the micro sleep concept in future LTE generations.

Unfortunately the introduction of the Enhanced PDCCH (EPDCCH) in LTE Release 11 has precluded the use of micro sleep. The reason is that the E-PDCCH is spread across the whole subframe time-wise, as illustrated in Figure 15, in order to obtain a frequency diversity gain by only using selected resource blocks in the frequency domain.

In a recent proposal<sup>[21]</sup> for a next generation RAT, the control and data channel position has however been reordered such that the control data is a whole frame ahead of the data as illustrated in Figure 16. This allows for efficient pipelining and micro sleep.

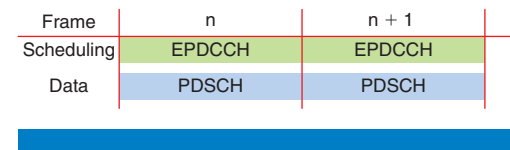
### Carrier Aggregation

Carrier Aggregation is included in LTE Release 10 to improve user throughput and coverage. The standardization of CA entails a more complicated transceiver design, because the UE needs to be able to receive at least two (up to five) carriers simultaneously each up to 20 MHz wide. The additional hardware can potentially lead to increased UE power consumption, hence the search for even higher data rates may worsen the users' battery life.

To examine this issue we proposed a narrow and a wideband UE power model<sup>[22]</sup> and calculated the energy consumption in a heterogeneous network (HetNet) scenario using macro and small cells. The narrowband model applies two RF front ends and two analog-to-digital converters (ADCs), while the wideband model applies a single RF front end and ADC, but with double bandwidth capability.

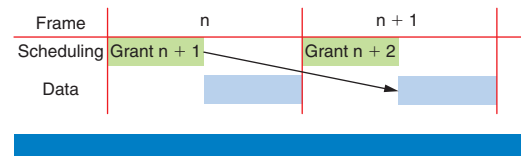
The users were set to receive a file either via single carrier LTE Release 8 or using two carriers. The narrowband CA UE was estimated to consume 20 percent more power on average as compared to the Release 8 UE, but as illustrated in the simulation results in Figure 17, the energy consumption is approximately the same for both UEs. The reason is that with CA the

*"Further advantages of the micro sleep concept include the fact that it can complement DRX, and it fits all types of traffic scenarios as opposed to DRX..."*



**Figure 15:** Control and data channel position in LTE Release 10

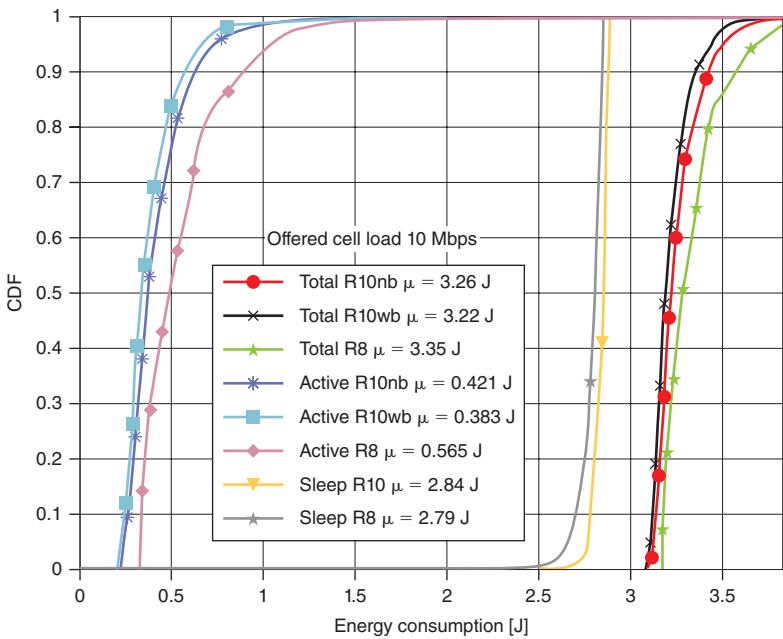
(Source: Lauridsen et al. 2014<sup>[18]</sup>)



**Figure 16:** Control and data channel position in a 5G concept<sup>[21]</sup>

(Source: Lauridsen et al. 2014<sup>[18]</sup>)

*"Carrier Aggregation is included in LTE Release 10 to improve user throughput and coverage, but entails a more complicated transceiver design..."*



**Figure 17:** Carrier Aggregation energy consumption in a HetNet scenario (Source: Lauridsen et al. 2013<sup>[22]</sup>)

*“If the throughput does not increase at least 20 percent, Carrier Aggregation will lead to decreasing energy efficiency.”*

throughput increased more than 50 percent in the simulated scenario, and therefore the UE can receive the file faster with little penalty on the power consumption of the Rx BB as illustrated in Figure 8. Then the UE can enter a low power sleep mode and achieve high EE. If the throughput does not increase at least 20 percent<sup>[22]</sup>, CA will lead to decreasing EE.

When the work was performed there was no knowledge about how fast the transition to sleep mode could be made, but the measurements in the section “DRX Characterization” have made it clear that shifting to DRX sleep mode takes a considerable amount of time. Therefore CA will mainly be effective for very large file transfers, where the time difference between CA and Release 8 UEs, including the transition time, is large. Otherwise the penalty on the user may be heavy due to the increased instantaneous power consumption.

As mentioned, the work<sup>[22]</sup> was based on a theoretical extension of the existing power model<sup>[6]</sup>, but recently a vendor has launched a CA device<sup>[23]</sup>, which could help clarify if the assumptions were correct.

**Conclusion**

In this work an empirical smartphone power model was presented. The model covers the cellular LTE subsystem and is based on measurements on the newest generation of LTE smartphones. By comparing with our previous measurements on older LTE generations, power consumption improvements of approximately 35 percent were noted and attributed to device maturity. The LTE Discontinuous Reception feature was also examined and the results

*“The model covers the cellular LTE subsystem and is based on measurements on the newest generation of LTE smartphones.”*

show the deep sleep power is now as low as 1/40 of the active mode power. Furthermore the new smartphone is able to enter and exit the sleep modes at least 30 percent faster, which makes DRX more applicable in a real network and enhances the possibility for use of micro sleep.

The cellular subsystem model is intended for use in system level simulations to evaluate how specific network settings affect user equipment power consumption. The measurements show that the power consumption is dominated by the subsystem being ON, consuming about 0.9 W, and also very affected by transmit powers above 10 dBm, consuming an additional 0.6–1.5 W. The power consumption is almost independent of uplink and downlink data rates, and therefore the combination of high data rates and long sleep periods must be the target of an energy-efficient network setup.

The work also surveys the energy efficiency, in terms of number of joules required to transfer one bit, of multiple radio access technologies. For high data rates, LTE is superior to older technologies such as EDGE, HSPA, and 802.11g Wi-Fi.

Finally it was evaluated that Carrier Aggregation, which is a prominent new LTE feature, will affect the energy efficiency positively if the throughput can be increased 20 percent as compared to conventional single-carrier LTE UEs.

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