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Empirical LTE Smartphone Power Model with DRX Operation for System Level Simulations

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***Abstract*—An LTE smartphone power model is presented to enable academia and industry to evaluate users' battery life on system level. The model is based on empirical measurements on a smartphone using a second generation LTE chipset, and the model includes functions of receive and transmit data rates and power levels. The first comprehensive Discontinuous Reception (DRX) power consumption measurements are reported together with cell bandwidth, screen and CPU power consumption.**

The transmit power level and to some extent the receive data rate constitute the overall power consumption, while DRX proves to be a very efficient method to prolong the battery life.

I. Introduction

Today smartphone users experience limited battery lifetime, and the trend is not expected to improve in the future. This is due to an increasing gap between smartphone battery capacity and the energy required to power a smartphone, [1], [2], using complex telecommunication standards, such as the UTRAN Long Term Evolution (LTE) standard [3]. This is a major issue because User Equipment (UE) battery life is key to achieve high user satisfaction [4]. The UE energy consumption depends on the mobile network setup and therefore a comprehensive smartphone power consumption model is needed, when system level designers adjust key network parameters.

In previous work smartphone power consumption was examined by running an application on the phone, which logs battery discharge [5] or, by measuring the power drain using external monitoring equipment [2], [6]. All measurements were made in a live network entailing the authors could not control and record network settings. However, network trace analysis was applied to estimate some parameters in [7].

In this work we apply network emulators to perform conducted tests and measure the power consumption using a battery dummy. This entails full control and easy logging of network parameters missing in the previous work. Furthermore, there is no power footprint when using external monitoring equipment as opposed to the logging application.

The general approach to smartphone modelling is to apply submodels covering the screen, network modem, CPU and other components. In [2], [5] the screen power consumption as a function of general and pixel brightness, and the CPU power consumption as a function of utilization, and in [5] also as a function of clock frequency, is examined. Each study briefly examines WiFi but completely disregard the cellular modem. In this work we show a smartphone's LTE modem is a major power consumer, hence it is important to model and optimize.

In [6], [7] measurements on LTE modems are presented, but the power consumption is only reported as a function of receive and transmit data rates. This is problematic because the power amplifier (PA), as shown in this article, is the LTE modem part which consumes the most power, when transmitting at maximum output power. The PA also exhibits the largest power variation and therefore constitutes big potential energy savings. In addition, [6] claims that switching to a low power idle state will not reduce the power consumption significantly. In this study we present what we believe is the first comprehensive Discontinuous Reception (DRX) power consumption measurements. The results clearly show that DRX is an important method to prolong UE battery life. In [7] DRX power consumption is measured, but they report the DRX power consumption to be 1.1 W, where we measure 0.03 W. Furthermore, they do not evaluate how the DRX power consumption depends on the main DRX parameters On Duration and Long Period [8]. The only existing detailed DRX model was proposed by Nokia [9], but based on arbitrarily selected values, which we show do not match well with current LTE modems. We therefore believe our model can be used on system level to get a more accurate and realistic view of DRX's applicability. The work in [10] covers the basic LTE parameters, but also has its limitations: the UE is a USB dongle, which is a non-power optimized device, and also uses a first generation LTE chipset, for which neither the impact of DRX nor that of cell bandwidth (BW) were captured.

First we present the power model design, then we discuss our measurement setup and results, which mainly focus on the LTE modem. Next, we fit the model to the measurements and validate it. Finally, we discuss the limitations and present a conclusion and outlook for future work.

II. Design of the Smartphone Power Model

In this section, the smartphone power model is designed. It is based on [10] but updated to include cell BW and DRX in addition to the functions of Transmit (Tx) and Receive (Rx) power levels (S) and data rates (R) as shown in fig. 1.

The modem power consumption P_{modem} is defined as

$$P_{\text{modem}} = m_{\text{idle}} \cdot P_{\text{idle}} + m_{\text{DRX}} \cdot P_{\text{DRX}} + m_{\text{act}} \cdot P_{\text{act}} \quad [\text{W}] \quad (1)$$

where m are Boolean variables used to activate certain UE modes. The power consumption variables P are functions of relevant input parameters as defined in the following section.

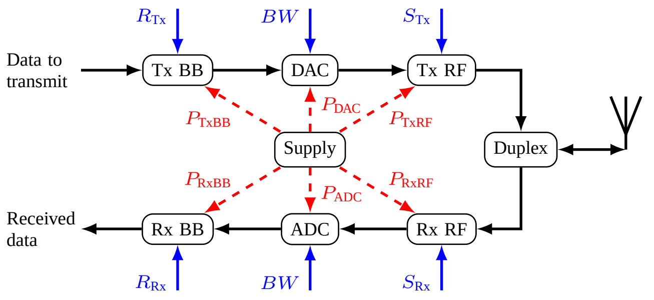

Fig. 1. LTE smartphone modem power model. Red dashed lines indicate power consumption and blue solid lines are input parameters.

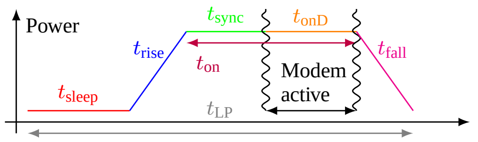

Fig. 2. DRX timing parameters.

The active power consumption model includes transmit and receive Base Band (BB), Radio Frequency (RF), and BW power consumption as shown in fig. 1. Each component has an input parameter defining the power consumption:

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

The RRC_idle mode power consumption depends on the length of the paging cycle t_{pc}, because the modem will power on once each period to check if it is paged by the network.

$$P_{idle}(t_{pc}) = (t_{iA} \cdot P_{iA} + (t_{pc} - t_{iA}) \cdot P_{iS}) / t_{pc} \text{ [W]} \quad (3)$$

where iS and iA indicate the sleep and active parts of the paging cycle. By measuring the two power parameters P_{iS}, P_{iA} and the active time t_{iA} the average idle power is estimated. The DRX power model is a function of DRX Long Period t_{LP} and On Duration t_{onD}, [8]. The parameters are defined in the sketch of a DRX period fig. 2. The DRX sleep power P_{DRX} is defined to be the average of the power consumed during the sleep t_{sleep}, rise t_{rise} and fall t_{fall} stages and the part of the active period t_{on}, where frequency synchronization t_{sync} is acquired:

$$t_{on}(t_{LP}) = t_{sync}(t_{LP}) + t_{onD} \quad \text{[s]} \quad (4)$$

As explained in sec. III the P_{DRX}, t_{rise}, t_{fall}, and t_{sync} depend on whether $t_{LP} \leq 40$ ms. The sleep time is

$$t_{sleep} = t_{LP} - t_{rise}(t_{LP}) - t_{fall}(t_{LP}) - t_{on}(t_{LP}) \quad \text{[s]} \quad (5)$$

hence the average DRX sleep power is

$$P_{DRX}(t_{LP}, t_{OnD}) = \frac{t_{sleep} \cdot P_{sleep} + E_{R/F+sync}(t_{LP})}{t_{LP} - t_{onD}} \quad \text{[W]} \quad (6)$$

where $E_{R/F+sync}$ is the energy consumed during t_{rise}, t_{fall}, and t_{sync} stages. The P_{DRX} does not include the power consumed in t_{onD}, this value should be calculated using P_{act} in eq. (2). Average power consumption values are used because the model is made for system level simulations were average parameters are often used instead of Transmission Time Interval (TTI) level values. If TTI time traces are used P_{act} is still applicable, but the average values of P_{idle} and P_{DRX} are not.

TABLE I
DEVICE UNDER TEST (DUT) MAIN PHYSICAL CHARACTERISTICS.

	UE1	**UE2**	**UE3**
Android OS version	2.3.6	4.0.4	4.0.4
Launch date	May ’12	June ’12	Nov ’12
Modem & CPU CMOS node	45 nm	28 nm	28 nm
RF transceiver CMOS node	65 nm	65 nm	65 nm
RF transceiver	Part #A	Part #B	Part #B
Band 4 PA	Part #C	Part #C	Part #D
LTE bands	4,17	4,17	2,4,5,17

TABLE II
MEASUREMENT TEST PLAN. CELL BANDWITH 20 MHZ, CARRIER FREQUENCY 2145 MHZ. DOWNLINK TESTS MADE FOR 1 & 2 CW.

Test case		**DL parameters**			**UL 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]

III. CONDUCTED SMARTPHONE MEASUREMENTS

To obtain realistic values for the smartphone power model measurements were carried out on 3 LTE smartphones. UE2 was selected as the basis for the model. All measurements are performed in a conducted test environment, each UE being placed in a Faraday cage to ensure adequate shielding from the surrounding laboratory basestations. UEs are connected to an Anritsu 8820C eNodeB emulator, according to GSMA TS09 battery life test guidelines, using a dummy battery. UEs are supplied with a linear, low noise DC power supply, and the UE instantaneous power consumption is recorded over at least 30 seconds per test point. The UE average power consumption is then post processed. The power measurement accuracy of the test setup, including repeatability of the collected data is estimated at ±10mW. UEs are modern, Android based touch-screen smartphones whose relevant hardware characteristics can be found in tab. I. RF cable insertion losses are calibrated for each UE for both uplink (UL) and downlink (DL) carrier frequencies. Measurements are performed in band 4 (AWS band) on DL carrier frequency 2145 MHz. The strategy to derive the UE power consumption model is based upon [10], i.e. estimate Rx BB, Rx RF, Tx BB, and Tx Rf contributions by varying one variable, shown in brackets, at a time in respective test cases (TC) in tab. II. For the sake of simplicity, only the results collected in 20MHz cell BW are presented. Measurements collected for 15 and 10 MHz cell BW are used to validate the derived UE power consumption model accuracy.

Out of the numerous baseband receiver tasks, for a given cell BW, Turbo decoding activity scales in a linear fashion

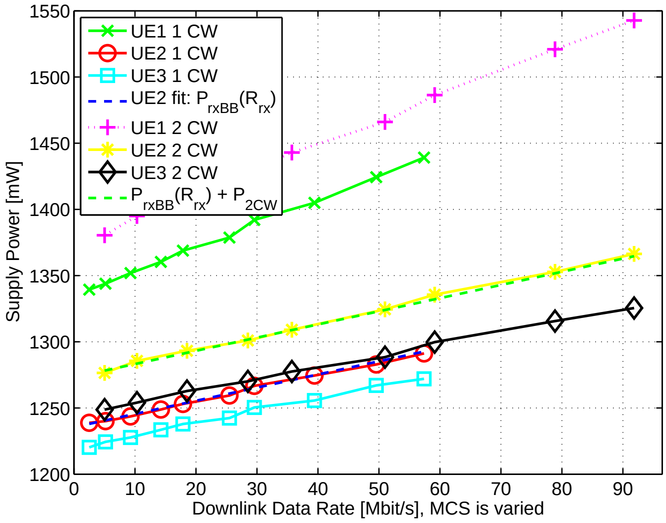

Fig. 3. Receive BB, test case 1.

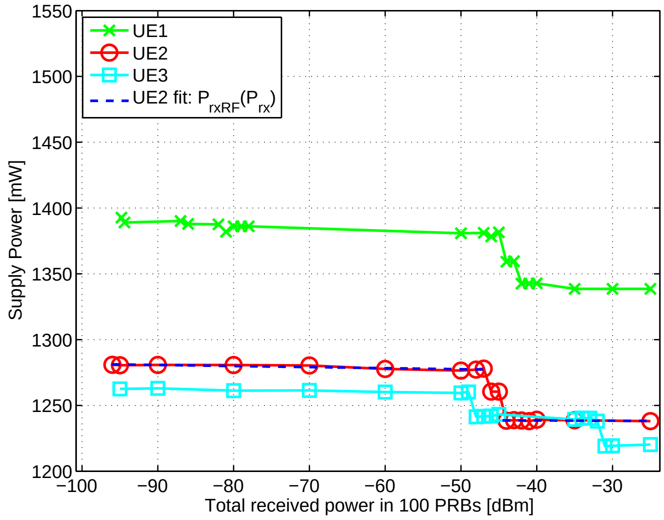

Fig. 4. Receive RF, test case 3.

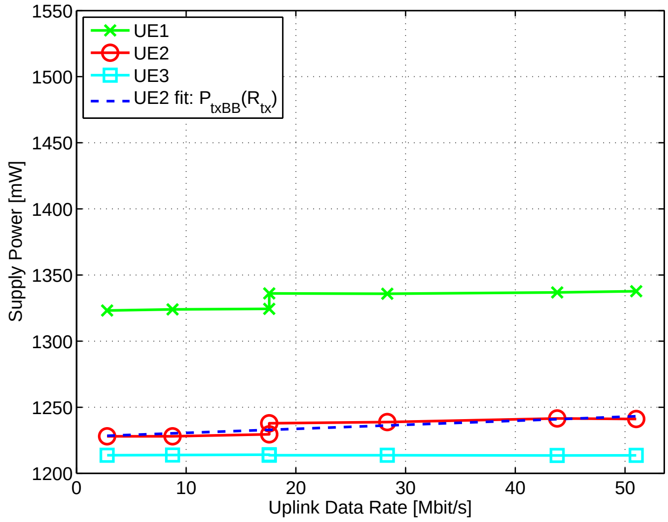

Fig. 5. Transmit BB, test case 4 & 5.

with the DL data rate [11, Ch.14]. Fig. 3 clearly illustrates the linear power consumption increase vs. DL data rate: TC1 stresses the turbo decoder by varying the PDSCH MCS, while TC2 operates at constant MCS and increases DL data rate by varying the allocated DL PRB. The TC2 result is omitted since it has a trend similar to TC1. In both TCs, the Tx contribution is minimised by using a low R_{Tx} and transmitting at minimum power S_{Tx}. Using 2 code words (CW) adds a constant offset.

Fig. 4 shows that the Rx RF chain power consumption increases as the DL carrier power is decreased, with either one or two sudden power consumption steps. The gain steps are believed to be caused by Low Noise Amplifier (LNA) gain control. Modern RF CMOS transceivers [12] implement discrete gain steps in the LNA to deliver the best compromise between linearity and power consumption. The LNA may be implemented with two (UE1 & UE2) or three gain (UE3) modes. The gain step may entail a sudden phase jump, which, if toggled frequently by the Automatic Gain Control loop, may degrade the BB demodulation performance. One mitigation technique often used consists in applying hysteresis on the LNA gain step control. This was observed by decreasing and increasing the received power during the measurements, but is not shown here for the sake of simplicity, and since hysteresis won't dramatically impact the UE power consumption model.

Fig. 5 shows the Tx BB power consumption vs. the UL data rate. The Tx BB power consumption is nearly independent of the PUSCH data rate, hence a constant value can be added to the model. Power consumption steps can be seen in UE1 (12mW) and UE2 (10mW) when UL modulation toggles from QPSK to 16QAM. It is believed that these are due to PA bias settings to deliver the best compromise between Adjacent Channel Leakage Ratio (ACLR) and power consumption performance under the higher Peak-to-Average Power Ratio (PAPR) of the 16QAM modulation scheme. The Rx chain power consumption is minimised by selecting a low DL data rate and maximum DL RF input power. In [6], [7] the power per Mbps is reported to be higher for transmission than reception, but fig. 3 & 5 clearly show this is not the case.

Fig. 6 shows modem power consumption is dominated by the PA when $S_{\mathrm{Tx}} > 10$ dBm. The ACLR power consumption trade-off is handled differently between UEs: the PA of UE1 & UE2 uses 2 gain modes, while UE3 PA uses 3 gain modes. The ACLR performance is out of the scope of this study.

While UE2 and UE3 only differ by their PA and front-end architecture, UE1 & UE2 use the same PA and differ by the BB CMOS process and front-end architecture, tab. I. Inspection of the PCB layout indicates a lower component count and PCB area for UE1 than UE2, but it is believed that the PA to antenna port insertion losses are within a fraction of a dB from one another. It is therefore assumed that UE1 & UE2 power consumption difference is dominated by CMOS process shrink. At transistor level, CMOS 28 nm can save between 35 to 40 % power vs. CMOS 45nm [13]. From a system performance perspective, our measurements show a moderate

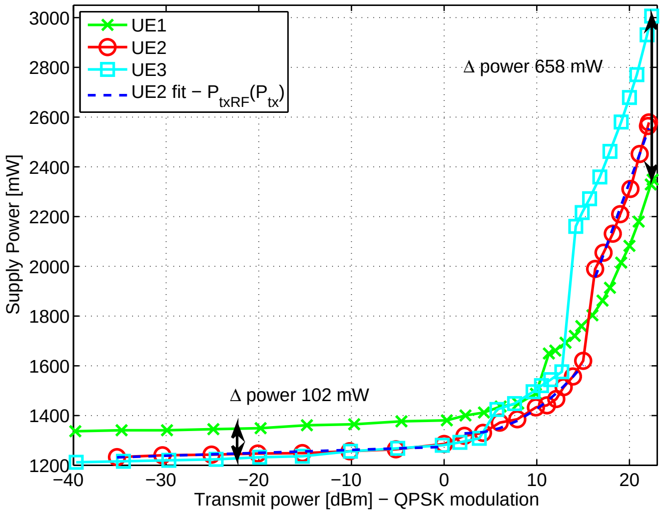

Fig. 6. Transmit RF, QPSK modulation, test case 6.

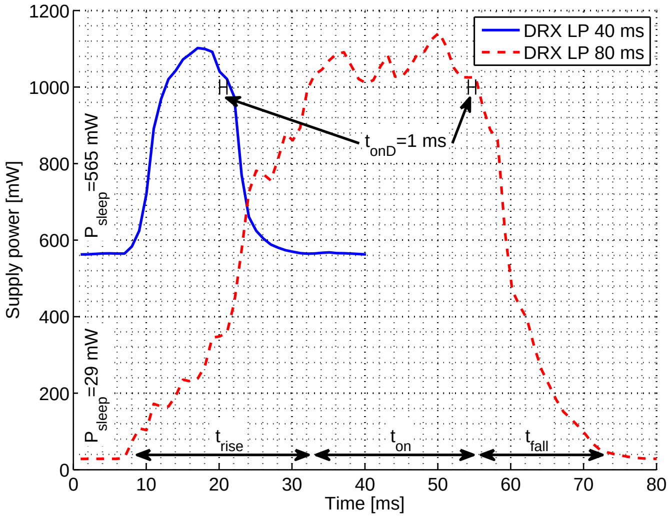

Fig. 7. DRX for long periods 40 & 80 ms.

7 to 11 % savings at low and high data rates respectively.

A. Connected Mode DRX

Connected mode DRX measurements were made for long period t_{LP} of 32-2048 ms, and one result is shown in fig. 7. The UE was not scheduled during t_{onD} to prevent triggering of the Inactivity Timer. When $t_{\text{LP}} \leq 40$ ms the UE powers down fast to a 0.57 W light sleep mode. When $t_{\text{LP}} \geq 80$ the UE enters a deep sleep mode consuming only 29 mW, which is close to the modem being powered off. The reason is that the UE can disable BB & RF including the Local Oscillator, and instead utilize a low precision oscillator to maintain time synchronization. When the modem awakes it takes longer to reboot, and in addition it needs an LTE frame (10 ms) to achieve proper frequency synchronization. This is done by receiving Synchronization and Reference Signals. Hence when t_{LP} $\geq$80 ms both t_{rise} and t_{fall} are increased, but also t_{on} due to the re-synchronization.

TABLE III
MEASURED DRX PARAMETERS. BASED ON t_{OND} OF 1 AND 6 MS.

t_{LP}	P_{sleep}	t_{rise}	t_{fall}	t_{sync}	$E_{\text{R/F+sync}}$
$\leq$40 ms	570 mW	6 ms	9 ms	8 ms	19.2 mJ
$\geq$80 ms	29 mW	26 ms	21 ms	21 ms	41.4 mJ

TABLE IV
AVERAGE POWER DIFFERENCE COMPARED TO 20 MHZ CELL BW.

Cell BW	Rx BB	Rx RF	Tx BB	Tx RF	Global
10 MHz	146 mW	151 mW	137 mW	148 mW	145 mW
15 MHz	40 mW	45 mW	44 mW	42 mW	43 mW

The measurements were performed for t_{onD} of 1-200 ms, and obviously a long t_{onD} prevents the UE from reaching the deep sleep mode. If the t_{onD} is selected properly the time and power values are however independent of the t_{onD}, and the results are given in tab. III.

When $t_{\text{LP}} = 64$ the UE will almost reach the deep sleep mode if $t_{\text{onD}} = 1$ ms, while for longer t_{onD} it only utilizes the light sleep mode. Measurements on other LTE UEs have shown similar power consumption trends, but the rise, fall and on times are varying among the UEs and depending on t_{LP} and t_{onD}. When t_{LP} $\leq$20 ms the UE does not sleep at all and therefore measurements with DRX Short Period were not performed.

B. Cell Bandwidth Dependency

To determine the power consumption dependency on cell BW, TC 1, 3, 5, and 6 in tab. II were repeated for cell BWs of 10 and 15 MHz. Next each measurement point of the TCs, made using 10 and 15 MHz, was compared with the measurement point of the corresponding 20 MHz TC, and the average power difference per TC was determined. The results are given in tab. IV. The global average is used as a basis for the cell BW dependency in the power model.

C. Other Smartphone Components

The screen power consumption was measured, when the UE was in flight mode and using both a static and an example of a live tiles background. The result is shown in fig. 8, and the power consumption as a function of screen brightness is almost linear. Turning the screen on costs ~0.5 W and if the screen is set to full brightness another 0.35 W is consumed.

To examine the relative contribution from the major power consuming components in a smartphone, measurements were also made to evaluate the CPU and GPU. They were loaded 100 % by using the Android app StabilityTest v.2.7, and the combined result is shown in fig. 9. When all components are fully loaded, which is highly unrealistic, the LTE modem consumes about half of the total power. A scenario where the modem and CPU+GPU is less loaded is more realistic and in that case the screen, which in the full load scenario only accounts for 20 %, will become more dominant. The figure however indicates that it is important to continue working on the LTE modem, especially the transmit PA.

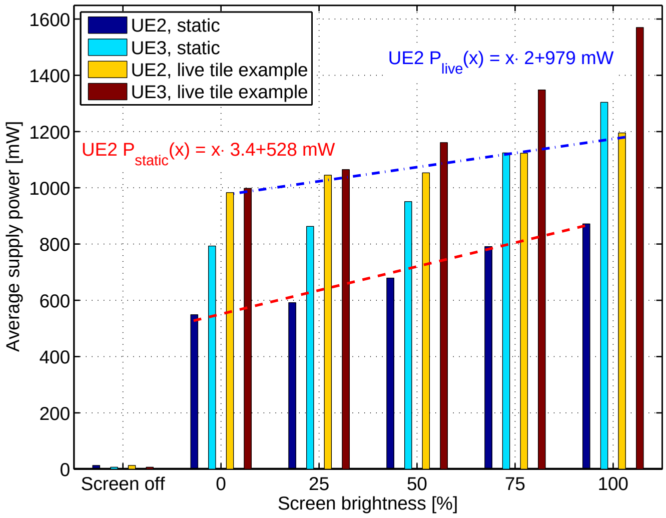

Fig. 8. Screen power consumption, UE in flight mode.

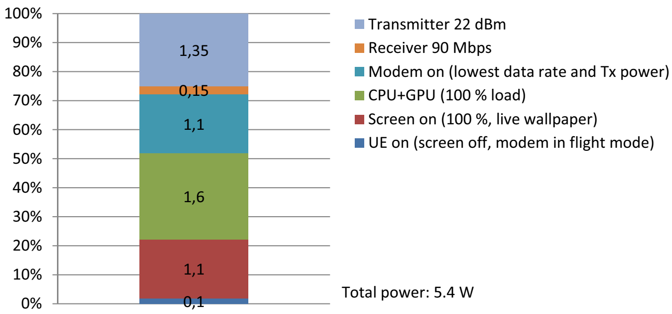

Fig. 9. UE2 smartphone power consumption. Components are fully loaded.

TABLE V
IDLE AND BASIC MODEL PARAMETERS.

P_{con}	t_{iA}	P_{iA}	P_{iS}	P_{Tx}	P_{Rx}
1169 mW	35 ms	290 mW	102 mW	28 mW	38 mW

WiFi was out of scope in this study, but in [14] measurements on a smartphone with a widely used WiFi chipset are presented. The receive power consumption is reported to never exceed 750 mW even for as high data rate as 49 Mbps, hence WiFi power consumption is not a major contributor.

IV. The Smartphone Power Consumption Model

In this section the model in sec. II is fitted to the data from sec. III. The target is to capture the trend of the smartphone modem and not implementation specific techniques.

The RRC_idle mode power consumption was measured using t_{pc} =320 ms, and the derived parameters are given in tab. V.

Based on the measurement results polynomial fits are made for each of the 4 functions in eq. (2) by minimizing the least square error. The Rx BB is modelled as a 1st order linear fit with an offset P_{2CW} if 2 CWs are used. The Rx RF function is divided into two 1st order fits due to the observed gain adjustments. The Tx BB is modelled as a constant due to the minor dependency on data rate. The Tx RF is divided into three fits to model the PA behaviour. The parameters are given in

TABLE VI
POLYNOMIAL FITS. POWERS ARE IN MW.

Part	Function	Comments
P_{RxBB}	$1.00 \cdot R_{\text{Rx}} - 3.51$	$P_{\text{2CW}} = 37.8$
P_{RxRF}	$-0.08 \cdot S_{\text{Rx}} + 34.5$	$S_{\text{Rx}} \leq -45.5$ dBm
P_{RxRF}	$-0.02 \cdot S_{\text{Rx}} - 1.23$	$S_{\text{Rx}} > -45.5$ dBm
P_{TxBB}	5.93	
P_{TxRF}	$1.18 \cdot S_{\text{Rx}} + 43.5$	$S_{\text{Tx}} \leq 1.1$ dBm
P_{TxRF}	$1.77 \cdot S_{\text{Rx}}^2 - 8.96 \cdot S_{\text{Rx}} + 109$	$1.1 < S_{\text{Tx}} \leq 15.6$ dBm
P_{TxRF}	$103 \cdot S_{\text{Rx}} - 962$	$S_{\text{Tx}} > 15.6$ dBm
P_{B}	0 mW=20 MHz, -43 mW=15 MHz, -145 mW=10 MHz	

tab. VI. The measurements in tab. II were made with only one varying parameter e.g. S_{Rx}, but the other Rx parameter R_{Rx} still contribute to the total power consumption when the model is used. Therefore a common receive point (MCS0, 100 PRB, -25 dBm) was identified and the average value subtracted from the y-intercept point of the Rx fits. A similar approach was used on the transmitter. Finally P_{Tx}=28 mW and P_{Rx}=38 mW were estimated by comparing the first and second test points of TC 2 and 4 i.e. the UE being allocated either 0 PRBs or transferring with the lowest data rate.

An empirical verification of the modem power model was made by comparing the measured power consumption of TCs 1, 3, 5, and 6 of tab. II for cell BWs of 10, 15, and 20 MHz with the power predicted by the model, which applies the average values and polynomial fits of tab. VI. The relative error between the measurements and the predicted power for each of the 3 cell BWs and 4 TCs is presented in fig. 10. They show an average error of 1.0 % and a maximum error of 5.5 %, which we believe is sufficient for reasonable assessment of UE power consumption. The DRX and idle parameters have not been verified by additional measurements.

V. Discussion

The presented model is based on UE2, but as the included results on UE1 and UE3 show the power consumption trends are similar for the 3 smartphones. It is however important to remember that the model is meant for system level simulations and not examination of individual UE components.

An important limitation is that the measurements are conducted hence circumventing the UE's antennas. Due to lossy antennas the power consumption may differ in real life, but Over-The-Air measurements are complicated and expensive.

Comparing our DRX measurements with Nokia's estimated numbers [9], which have been used extensively in 3GPP and academia, it is interesting to note that Nokia estimated the sleep power to be 1/50 of the "active with no data reception"-state. Our measurements show the ratio is 1/1.8 to 1/35 depending on whether the light or deep sleep mode is used respectively. Furthermore, [9] estimate the UE can transition from sleep mode to being active within 1 ms. Our measurements show this transition takes considerably longer (up to 21 ms for $t_{\text{LP}} \geq 80$ ms). This entails the benefits of DRX have been overestimated in previous work, but on the other hand our measurements also confirm that DRX sleep is key to achieve long battery life.

The comparison with screen and CPU+GPU clearly showed

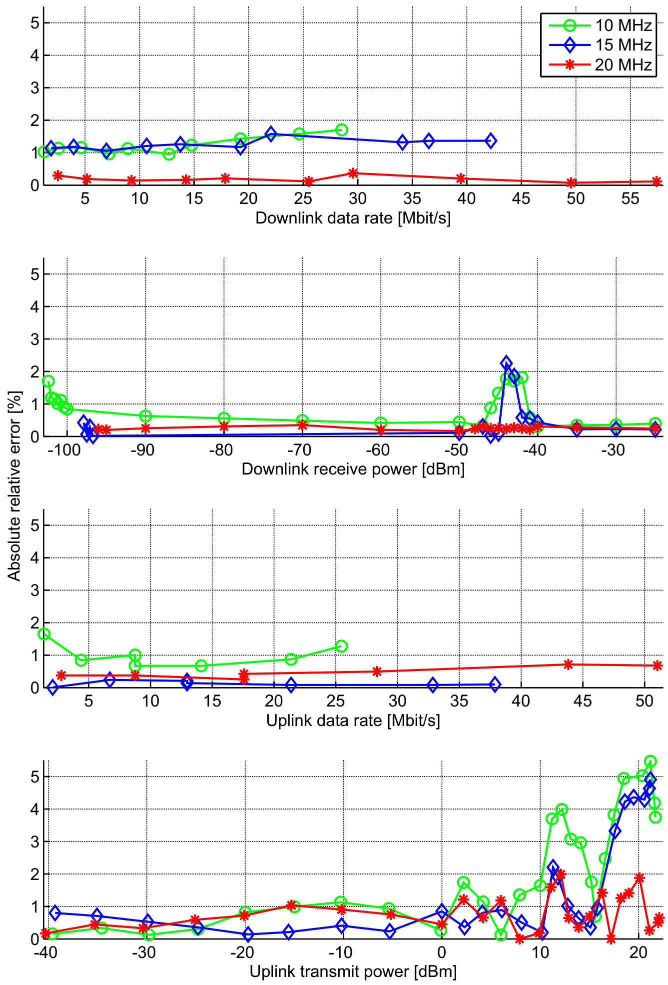

Fig. 10. Model validation using test case 1,3,5,6 in 10,15,20 MHz BW.

the LTE modem is a major contributor to the total power consumption, which makes the presented model relevant for future work. Especially because the modem can actively be affected by mobile network operators by adjusting data rates and power levels via scheduling and power control.

An interesting topic for future work is an assessment of the minimum number of measurement points per TC needed to achieve the level of accuracy, which we have obtained with our model. If only a few measurement points are needed the test time can be kept short, hence the model can easily be updated using new generations of phones. Based on the measurements in this study and [10] it is obvious that the power consumption is almost linearly dependent on downlink data rate, and therefore the receive BB power consumption trend can be captured with as little as 3 measurement points. The receive RF exhibits UE specific power consumption steps and therefore 5-6 points will be needed. The transmit BB power consumption is linear besides minor steps, when the modulation scheme is changed. Since it is known when the modulation scheme changes 4-5 measurement points will be sufficient. The transmit RF is the most power consuming component, and also the one which requires the most detailed analysis, because it is very non-linear for transmit powers above 0 dBm. Finally the DRX measurements require quite a few points to determine the behaviour and number of sleep modes used.

VI. Conclusion

In this work an LTE smartphone power model was presented. The model can be applied by academia and industry in system level simulations to determine UE energy consumption. This can be an important aid, when selecting one set of network parameters or another. The model is based on empirical measurements on an LTE smartphone, and includes comprehensive LTE Connected Discontinuous Reception (DRX) measurements and also a detailed examination of second generation LTE chipsets. The measurements show that DRX can help achieve longer battery life because the deep sleep mode power consumption is less than 1/35 of the active mode power consumption.

Furthermore, a discussion of the chipset evolution is presented. As expected the power consumption has decreased due to the more efficient transistor technology in 2nd generation chipsets. Future work can include measurements on LTE Carrier Aggregation and other vendors' chipsets.

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