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***Abstract*—In this work a novel LTE user equipment (UE) power consumption model is presented. It was developed for LTE system level optimization, because it is important to understand how network settings like scheduling of resources and transmit power control affect the UE's battery life.**

The proposed model is based on a review of the major power consuming parts in an LTE UE radio modem. The model includes functions of UL and DL power and data rate. Measurements on a commercial LTE USB dongle were used to assign realistic power consumption values to each model parameter. Verification measurements on the dongle show that the model results in an average error of 2.6 %.

The measurements show that UL transmit power and DL data rate determines the overall power consumption, while UL data rate and DL receive power have smaller impact.

I. Introduction

The gap between available and required energy in battery supplied wireless user equipment (UE) is increasing year by year [1]. The 3GPP LTE standard therefore includes energy saving methods like discontinuous reception. Unfortunately the available methods cannot fill the gap, and therefore new methods are investigated to further reduce the energy consumption. They focus on both optimizing network settings [2] and improving the UE [3], but one critical problem is that valid and comprehensive UE power consumption models are not publicly available. A model is much needed to evaluate the potential of new energy saving methods on system level.

For 3GPP, Nokia has presented a power model [4], but it only depends on the Radio Resource Configuration (RRC) mode, and not data rate and power levels. Another model was presented in [5], and it describes the Power Amplifier (PA) in details, but uses a static power for the receiver and is based on WCDMA UEs. Carroll et al. analysed the consumption of a smartphone in [6], but the level of detail is not sufficient for optimization on system level. In [7] Li et al. presented a detailed model, but it only covers the Radio Frequency (RF) parts, and e.g. the PA-model is out-dated. The chip manufacturers have detailed models based on development platforms [8], but they are confidential. The recent launch of LTE networks has made first generation LTE UEs publicly available, hence an empirical model can be established.

In this work a litterature survey was performed to develop a UE power consumption model. It was fitted to measurements made on a commercial LTE USB dongle using linear regression. The target was a sparse model, which is robust and

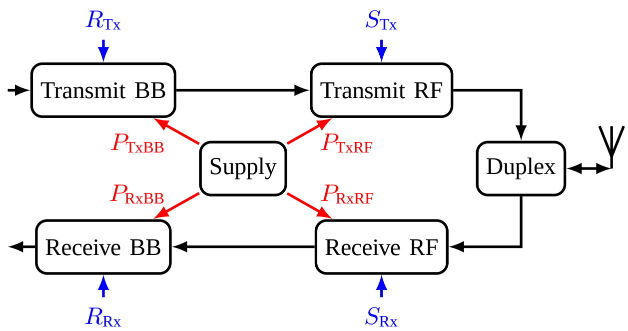

Fig. 1. LTE UE physical layer

transferable as suggested in [8]. The model can be applied in system level optimization, e.g. to examine how network settings affect the UEs as in [2], but the model is not intended for optimization on UE component level. The reason is that the model reflects the power consumption trends and not implementation specific behaviour. The model is novel because it describes an LTE UE radio modem and is dynamic in the sense that it depends on power levels and data rates.

First we present a survey of power consumption in the LTE physical layer and define a model in section II. Then we present measurement results in section III, fit the suggested model to the measurements in section IV, and finally we verify and discuss the model in sections V and VI.

II. UE Model Design

In this section the UE's power consuming physical layer components are examined one by one. The purpose is to determine how the components affect the total power consumption. Figure 1 shows the LTE physical layer components and the UE model parameters. The envisioned UE model shall depend on receive (Rx) and transmit (Tx) power levels, uplink (UL) and downlink (DL) data rate, and RRC mode. In the following sections the parts in figure 1 are examined to determine if and how they depend on the aforementioned parameters.

A. Transmit Baseband

In the LTE Tx baseband (BB) the main task is to turbo encode user data with Forward Error Correction codes. Turbo encoding relies on convolutional encoding and generates a bitstream with code rate 1/3. The Turbo encoding complexity scales linearly with the amount of data to encode which is set by the Transport Block Size (TBS) i.e. the UL data rate, but is independent of the UL Tx power [9].

B. Transmit RF

In general the RF will not depend on the UL data rate, but when the modulation format is changed the Peak-to-Average Power Ratio (PAPR) is affected. This entails the PA will adjust its performance to comply with the Tx emission requirements in [10], such as the Adjacent Channel Leakage Ratio (ACLR), and this may affect the power consumption.
The Tx RF will obviously depend on the UL Tx power. A single PA only has one output power level where it achieves its maximum energy efficiency, and therefore researchers develop methods to increase the efficiency at other output power levels. These include the use of multiple PAs [11], supply voltage and bias switching [5], and the envelope tracking concept [12]. The Power Added Efficiency is expected to be stepwise increasing with output power as each of the methods are utilized.

C. Receive RF

The Rx RF power consumption is expected to be independent of the DL data rate, but it will depend on the DL Rx power level. The reason is that the RF contains Gain Controls and Low Noise Amplifiers, which are used to obtain a certain signal level at the ADC. If the DL Rx power level is high the gain in the aforementioned circuits can be reduced, and they may be powered off, to reduce the power consumption [13].

D. Receive Baseband

The majority of the BB processing tasks' complexity, e.g. channel estimation and equalization, is independent of the DL data rate. To decode the received user data the UE applies turbo decoding, which is an iterative algorithm and the most computational complex task in the digital BB. To support the high data rates of LTE a highly parallelized turbo decoder architecture is required, [14]. The complexity and thus the power consumption scale linearly with DL data rate [15].

E. UE Power Consumption Model

Based on the review of the four physical layer parts, the model is defined as follows:

$$\begin{aligned} P_{\text{tot}} =& m_{\text{idle}} \cdot P_{\text{idle}} + \overline{m_{\text{idle}}} \cdot \{ P_{\text{con}} + m_{\text{Tx}} \cdot m_{\text{Rx}} \cdot P_{\text{Rx+tx}} + \\ & m_{\text{Rx}} \cdot [P_{\text{Rx}} + P_{\text{RxRF}}(S_{\text{Rx}}) + P_{\text{RxBB}}(R_{\text{Rx}}) + m_{\text{2CW}} \cdot P_{\text{2CW}}] \\ & m_{\text{Tx}} \cdot [P_{\text{Tx}} + P_{\text{TxRF}}(S_{\text{Tx}}) + P_{\text{TxBB}}(R_{\text{Tx}})] \} \quad [\text{W}] \end{aligned} \tag{1}$$

where P is the power consumption. The subscript *tot* defines the total consumption, *idle* and *con* the consumption in RRC idle and connected mode, *rxRF* and *txRF* the consumption of the RF part in the Rx and Tx chains respectively, *rxBB* and *txBB* the consumption of the BB parts, and *2CW* is related to increased consumption when using two code words (CW) in DL. The parameters P_{Rx}, P_{Tx}, and $P_{\text{Rx+Tx}}$ are included to model the base power the Rx and Tx chains consume when active. The logical variable m is the mode, which can be RRC idle, transmitting, receiving, and indicate the use of 2 CW. The Rx and Tx power levels are designated by S, and R is the Rx and Tx data rate.

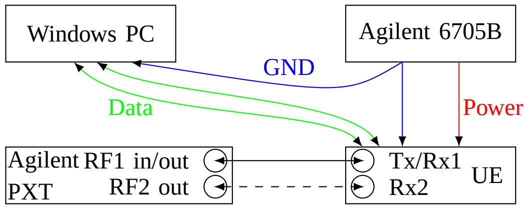

Fig. 2. Measurement setup.

TABLE I
MEASUREMENT PARAMETERS. THE CHANNEL BANDWIDTH WAS 20 MHZ, AND THE LINK WAS LOADED USING FIXED MAC TEST. P IS IN DBM.

Measu-rement	**DL MCS**	**DL PRB**	P_{Rx}	**UL MCS**	**UL PRB**	P_{Tx}
Rx BB	*[0, 28]*	100	-60	3	75	-20
Rx RF	0	100	*[-80, -20]*	3	75	-20
Tx BB	5	100	-57	*[0, 28]*	50	5
Tx RF	5	100	-57	3	100	*[-30, 23]*

III. LTE UE MEASUREMENTS

In order to assign meaningful values to the proposed power consumption model the authors performed measurements on a commercial LTE USB dongle. The reason for measuring on a dongle is that it do not include peripherals such as display, general purpose processor, and other radios (wifi, fm, bluetooth). This is a benefit since the focus is on the LTE UE radio itself. The downside is that the measurements include the power the USB driver consumes.

The UE was supplied using the Agilent 6705B DC Measurement Power Supply, which was set up to comply with the USB standard (5 V, 1 A). The supply sampled the current consumption every 1 ms for 30 s. The measurements were performed as conducted interference free tests using the Agilent PXT E6621A Wireless Communication Tester, which emulated a band 7 LTE base station. Measurements were made for SISO and DL 2x2 MIMO as shown in figure 2.

Based on the setup, current consumption measurements were performed and related to the proposed model in equation (1) by varying one variable at a time. This is illustrated in table I where italic fonts indicate the varied parameter in each measurement. The current consumption as a function of DL data rate was examined by keeping the DL Rx power level constant and adjusting the Modulation and Coding Scheme (MCS) index, and the results are shown in figure 3. The MCS index was mapped to TBS using [16]. The mapping also depends on the number of allocated PRBs and the link direction. Next the MCS was fixed and the DL Rx power varied to examine current as a function of the DL Rx power, see figure 4. Similar measurements were made in UL and the results are given in figure 5 and 6. The measurement parameters are given in table I. Note that the measurements in DL were repeated for a 2x2 MIMO setup using 2 CW. The connected mode current, P_{con}, was measured in RRC_connected mode without scheduled traffic and the idle mode current, P_{idle}, was measured in RRC_idle mode with paging messages monitored every 320 ms. Finally a DL Rx sensitivity test was made, and it showed the UE always utilizes both receive antennas.

The PXT's Fixed MAC padding test was used to generate

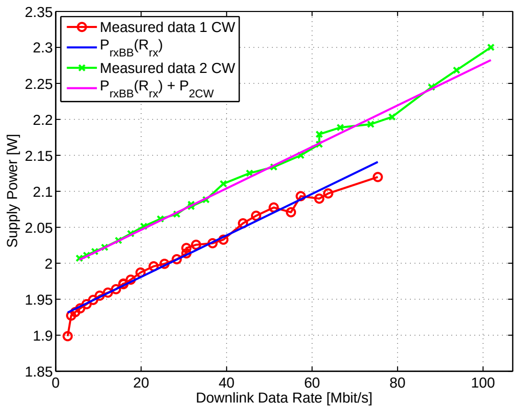

Fig. 3. Receive BB.

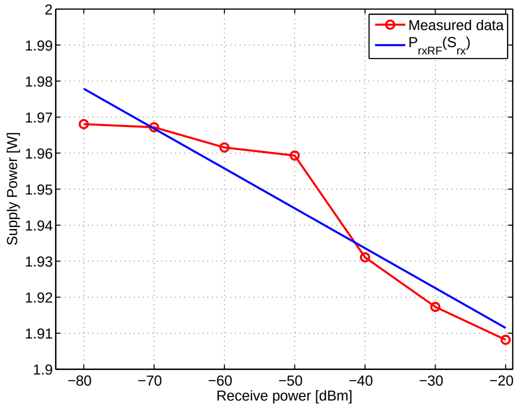

Fig. 4. Receive RF.

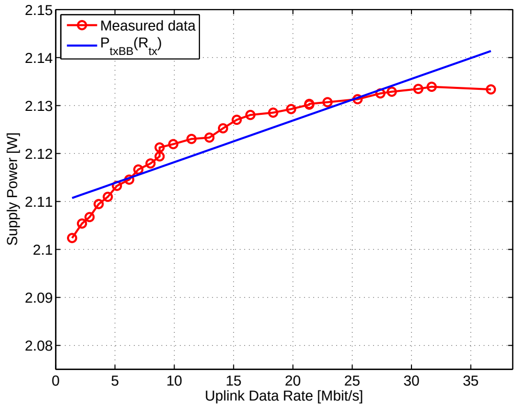

Fig. 5. Transmit BB.

data on either PUSCH or PDSCH. The test exploits that the MAC layer has to multiplex the logical channels to a MAC Protocol Data Unit (one unit per transport block) [17]. In order to fill the transport block the MAC layer pads the multiplexed data with random data, and when a padded transport block is received the padding will be discarded and the remaining data if any, forwarded to the logical channels. When the Fixed MAC padding test is initiated by the PXT it will pad the DL stream, fully loading the assigned PRBs. If there is no other applications running the only payload on the DL channel is padded data, hence the UE will only send ACK/NACKs from layers below the MAC.

As mentioned in section II the varying PAPR were expected to affect the current consumption. To examine this a measurement was made where the UE was transmitting QPSK signals

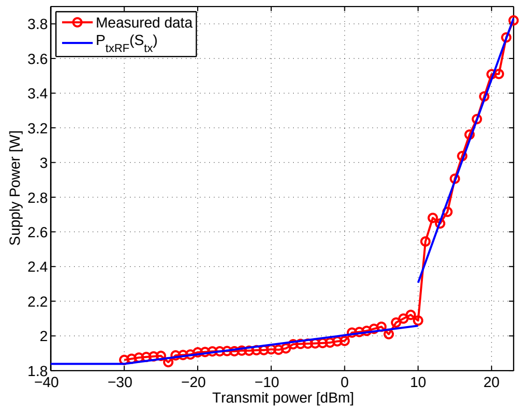

Fig. 6. Transmit RF.

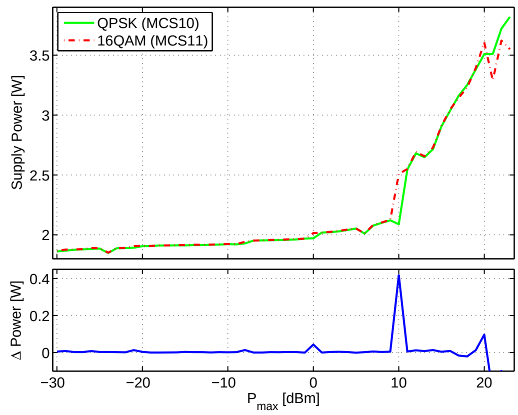

Fig. 7. UL Tx power measurement for UL QPSK & 16QAM. The lower plot shows the current difference between the two lines in the upper plot.

TABLE II
CONSTANT MODEL PARAMETERS IN WATT.

Part	P_{idle}	P_{con}	P_{Rx}	P_{Tx}	$P_{\text{Rx+Tx}}$	P_{2CW}
Mode	m_{idle}	$\overline{m_{\text{idle}}}$	m_{Rx}	m_{Tx}	$m_{\text{Tx}} \cdot m_{\text{Rx}}$	m_{2CW}
Value	0.50	1.53	0.42	0.55	0.16	0.07

(MCS10) and 16QAM (MCS11), and the current consumption as a function of UL Tx power was measured. Figure 7 show that the modulation format do not affect the current consumption except for UL Tx powers 0 and 10 dBm, where the 16QAM signal forces the UE to adjust a little earlier than the QPSK signal. This adjustment is implementation specific and therefore not modelled.

IV. MODEL FITTING

The model for each power function in equation (1), is derived either as a constant or a polynomial fit. It is desired that each function reflects the general power consumption trend and not unique implementation specific solutions.

The idle, P_{idle}, and connected mode, P_{con}, are the average powers in each RRC mode and given in table II. The connected mode power is measured without user data in UL and DL.

The complexity, hence the power consumption, of BB processing in UL and DL are highly linear dependent on data rate, and therefore they are modeled as first order polynomials.

The receiver and transmitter RF architecture can be based on several diffent techniques as described in section II. This

TABLE III
POLYNOMIAL MODEL PARAMETERS IN MILLIWATT.

Part	Variable	p_0	$p_{0\text{-mod}}$	p_1	Residual e
Rx BB	R_{Rx} [Mbit/s]	1923	-26.6	2.89	0.08
Tx BB	R_{Tx} [Mbit/s]	2110	34.5	0.87	0.01
Rx RF	S_{Rx} [dBm]	1889	-60.7	-1.11	0.06
Tx RF1	S_{Tx} [dBm]	2004	-71.3	5.50	0.60
Tx RF2	S_{Tx} [dBm]	1132	-943	117	6.87

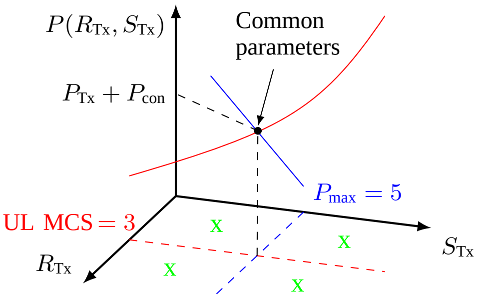

Fig. 8. Example of common parameters for the transmitter.

makes it difficult to predict a suitable model and therefore the model selection for transmitter RF and receiver RF rely on curve-fitting. The polynomial values of the models are found by minimizing the least square error given as

$$e = \frac{1}{N} \sum_{n=0}^{N} (p_0 + p_1 x_n - Y_n)^2 \quad [\text{W}^2] \tag{2}$$

where e is the residual error, Y_n is the measured power, N is the number of measurements, p are polynomial values and x is the input variable. The polynomials and the corresponding residuals are given in table III. Note that Tx RF is composed of two lines, where Tx RF1 is valid for $-30\,\text{dBm} \leq S_{\text{Tx}} \leq 10\,\text{dBm}$ and Tx RF2 accounts for $10\,\text{dBm} < S_{\text{Tx}} \leq 23\,\text{dBm}$.

Because each model has been based on a measurement with one varying parameter there is an overlap in predicted power, when e.g. P_{TxBB} and P_{TxRF} are combined, because they both include the power the UE consumes when actively transmitting. The measurements were made such that the BB and RF functions share one common set of parameters (same MCS index and power level) as illustrated in figure 8. The blue line illustrates the power consumption as a function of the UL data rate for a fixed UL Tx power (figure 5), and the red curve illustrates the power consumption as a function of the UL Tx power for a fixed UL data rate (figure 6). The power P_{Tx} was then defined as:

$$P_{\text{Tx}} = \left[P_{\text{TxRF}}(5\,\text{dBm}) + P_{\text{TxBB}}(\text{MCS3})\right]/2 - P_{\text{con}} \quad [\text{W}] \tag{3}$$

The polynomials are scaled to result in ≈ 0 Watt in the common point. By using modified p_0's as $p_{0\text{-mod}} = p_0 - P_{\text{Tx}} - P_{\text{con}}$ this is obtained. In this way the polynomial models comply with equation (1) when they are added together with P_{Tx} and P_{con}. A similar approach was used on the receiver models, and the results are given in table II and III. The offset $P_{\text{Rx+Tx}}$ was based on measurement where both Rx and Tx were active.

V. VERIFICATION

To verify the model two methods are applied. First the fits in figures 3-6 are evaluated individually by examining the residuals. Next the model is examined empirically, i.e. the power consumption of the transmitter and receiver is compared with verification measurements. These measurements are made for power and data rate pairs, which were not used when fitting the models. This approach is shown in figure 8 where the green crosses indicate the settings of the verification measurements on the transmitter. An identical approach is used for verification of the receiver model.

TABLE IV
VERIFICATION, DOWNLINK.

P_{Rx}	DL MCS	P_{model}	P_{meas}	Error
-40 dBm	5	1.93 W	1.94 W	-0.5 %
	12	1.96 W	1.98 W	0.8 %
	20	2.02 W	2.04 W	-1.0 %
-80 dBm	5	1.98 W	1.98 W	-0.3 %
	12	2.01 W	2.02 W	-0.7 %
	20	2.06 W	2.09 W	-1.3 %

TABLE V
VERIFICATION, UPLINK.

UL PRB	P_{Tx}	UL MCS	P_{model}	P_{meas}	Error
50	-10 dBm	0	1.98 W	1.92 W	3.5 %
		12	1.99 W	1.91 W	4.1 %
	15 dBm	0	2.93 W	3.00 W	-2.3 %
		12	2.94 W	3.00 W	-2.0 %
100	-10 dBm	0	1.99 W	1.92 W	3.1 %
		12	2.00 W	1.92 W	3.9 %
	15 dBm	0	2.93 W	3.03 W	-3.4 %
		12	2.95 W	3.03 W	-3.0 %

The polynomial fits' residuals are given in table III. The residuals for Tx RF1 and especially Tx RF2 are larger since the two functions span a larger power consumption range than the other BB and RF functions. The range for Tx RF2 is e.g. 2.1 W to 3.8 W as shown in figure 6. Based on the residuals it is concluded that good and valid fits have been obtained.

The results of the comparison between the model and the verification measurements are given for DL in table IV, UL in table V, and for the combination of UL and DL in VI. The average error for the DL verification is 0.8 % hence a good fit has been achieved. The verification of the UL model resulted in an average error of 3.2 %. The UL model is a bit more inaccurate because the Tx RF model is the most power consuming part, hence an error in it's fit will affect the overall result more. The average error for the combined verification is 2.6 % and the maximum error is 6.0 %.

VI. DISCUSSION

The goal with the described work was to develop a UE power consumption model for system level optimization. Because the model is based on measurements on one dongle and focused on major power consumption trends it cannot be used to optimize power consumption in individual UE components. The presented model only covers the LTE radio modem, but if a user wishes to get a complete overview of UE power consumption it is important to include statistics for the display, general purpose processor, and other radios.

TABLE VI
VERIFICATION, UPLINK AND DOWNLINK.

P_{Rx}	**DL MCS**	P_{Tx}	**UL MCS**	P_{model}	P_{meas}	**Error**
-40 dBm	0	15 dBm	3	2.99 W	3.10 W	-3.4 %
			12	3.01 W	3.09 W	-2.9 %
		-20 dBm	3	2.00 W	1.98 W	0.6 %
			12	2.01 W	1.99 W	1.0 %
	12	15 dBm	3	3.04 W	3.19 W	-4.9 %
			12	3.06 W	3.19 W	-4.5 %
		-20 dBm	3	2.04 W	2.05 W	0.1 %
			12	2.06 W	2.04 W	0.6 %
-57 dBm	0	15 dBm	3	3.01 W	3.17 W	-5.4 %
			12	3.03 W	3.17 W	-4.9 %
		-20 dBm	3	2.01 W	2.02 W	-0.3 %
			12	2.03 W	2.02 W	0.2 %
	12	15 dBm	3	3.06 W	3.25 W	-6.0 %
			12	3.07 W	3.25 W	-5.8 %
		-20 dBm	3	2.06 W	2.08 W	-0.7 %
			12	2.08 W	2.08 W	-0.2 %

A critical limitation is that the power consumption in each of the blocks in figure 1 cannot be separated because of the integrated circuit design. This entails that when a DL parameter is examined, contributions from UL, e.g. transmission of ACK/NACK, will also be included and vice versa.

During the measurements we experienced that the absolute power level depends on which USB port the UE is connected to. This does not affect the relative trend, but entails that the absolute values vary about $\pm 10\,\%$. Furthermore the implementation architecture, choice of components, and component tolerance will be different for every UE model. The most important is however the trend and not the absolute value.

It is important to note the measured UE is of the first LTE generation. This means the UE may not be as optimized and adaptive as future UEs from a power consumption point of view. One important feature the UE is missing is the Discontinuous Reception mode [17], consequently this is not included in the model.

VII. CONCLUSION

A LTE user equipment power consumption model was presented. The model is designed to assist in system level simulations, e.g. optimization of network parameters, by providing knowledge of how the settings affect the user equipment (UE). This is important because the network set up is critical for the UE power consumption.

The model is based on a review of how radio frequency and baseband power consumption depends on signal power levels and data rates. The model was fitted to measurements performed on a commercial LTE USB dongle. The measurements show uplink transmit power and downlink data rate greatly affect the power consumption, while uplink data rate and downlink receive power has little affect.

Verification measurements on the LTE USB dongle show that the proposed model results in an average error of 2.6 % and a maximum error of 6 %.

In future work we expect to modify the proposed model to include multiple power amplifiers in order to examine LTE Advanced proposals such as carrier aggregation, and multiple transceiver chains to examine MIMO. Furthermore the model shall be updated to model the next generation of LTE UEs, which are expected to be more energy optimized.

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