LTE UE Power Consumption Model

For System Level Energy and Performance Optimization

Jensen, Anders Riis; Lauridsen, Mads; Mogensen, Preben; Sørensen, Troels Bundgaard; Jensen, Per

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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 the level of detail is not sufficient 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 in [10], such as the Adjacent Channel Leakage Ratio (ACLR), and the envelope tracking concept [12].

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...
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 (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, \( P_{\text{idle}} \), and connected mode, \( P_{\text{con}} \), 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 different techniques as described in section II. This

### TABLE II

<table>
<thead>
<tr>
<th>Part</th>
<th>( P_{\text{idle}} )</th>
<th>( P_{\text{con}} )</th>
<th>( P_{\text{Rx}} )</th>
<th>( P_{\text{Tx}} )</th>
<th>( P_{\text{Rx+Tx}} )</th>
<th>( P_{\text{2CW}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode</td>
<td>( m_{\text{idle}} )</td>
<td>( m_{\text{con}} )</td>
<td>( m_{\text{Rx}} )</td>
<td>( m_{\text{Tx}} )</td>
<td>( m_{\text{Rx+Tx}} )</td>
<td>( m_{\text{2CW}} )</td>
</tr>
<tr>
<td>Value</td>
<td>0.50</td>
<td>1.53</td>
<td>0.42</td>
<td>0.55</td>
<td>0.16</td>
<td>0.07</td>
</tr>
</tbody>
</table>
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

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

(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 \(-30 \text{dBm} \leq S_{Tx} \leq 10 \text{dBm} \) and Tx RF2 accounts for \(10 \text{dBm} < S_{Tx} \leq 23 \text{dBm} \).

Because each model has been based on a measurement with one varying parameter there is an overlap in predicted power, when e.g. \( P_{\text{B-B}} \) and \( P_{\text{RF}} \) 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 \( P_{\text{Tx}} \) was then defined as:

\[ P_{\text{Tx}} = [P_{\text{RF}}(5 \text{dBm}) + P_{\text{B-B}}(\text{MCS3})] / 2 - P_{\text{con}} \quad \text{[W]} \]  

(3)

The polynomials are scaled to result in \( \approx 0 \) Watt in the common point. By using modified \( p_0 \)'s as \( p_{0\text{mod}} = p_0 - P_{\text{con}} \) this is obtained. In this way the polynomial models comply with equation (1) when they are added together with \( P_{\text{Tx}} \) and \( P_{\text{con}} \). 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.

The polynomial fits’ residuals are given in table III. The residuals for Tx RF1 and especially Tx RF2 are larger since 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 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 III

<table>
<thead>
<tr>
<th>Part</th>
<th>Variable</th>
<th>( p_0 )</th>
<th>( p_{0\text{mod}} )</th>
<th>( p_1 )</th>
<th>Residual ( e )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rx BB</td>
<td>( R_{\text{Rx}} ) [Mbps]</td>
<td>1923</td>
<td>-26.6</td>
<td>2.89</td>
<td>0.08</td>
</tr>
<tr>
<td>Tx BB</td>
<td>( R_{\text{Tx}} ) [Mbps]</td>
<td>2110</td>
<td>34.5</td>
<td>0.87</td>
<td>0.01</td>
</tr>
<tr>
<td>Rx RF</td>
<td>( S_{\text{Rx}} ) [dBm]</td>
<td>1889</td>
<td>-60.7</td>
<td>-1.11</td>
<td>0.06</td>
</tr>
<tr>
<td>Tx RF1</td>
<td>( S_{\text{Tx}} ) [dBm]</td>
<td>2004</td>
<td>-71.3</td>
<td>5.50</td>
<td>0.60</td>
</tr>
<tr>
<td>Tx RF2</td>
<td>( S_{\text{Tx}} ) [dBm]</td>
<td>1132</td>
<td>-943</td>
<td>117</td>
<td>6.87</td>
</tr>
</tbody>
</table>

### TABLE IV

<table>
<thead>
<tr>
<th>( P_{\text{Rx}} )</th>
<th>DL MCS</th>
<th>( P_{\text{model}} )</th>
<th>( P_{\text{meas}} )</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>-40 dBm</td>
<td>5</td>
<td>1.93 W</td>
<td>1.94 W</td>
<td>-0.5 %</td>
</tr>
<tr>
<td>20</td>
<td>1.96 W</td>
<td>1.98 W</td>
<td>0.8 %</td>
<td></td>
</tr>
<tr>
<td>-80 dBm</td>
<td>5</td>
<td>1.98 W</td>
<td>1.98 W</td>
<td>-0.3 %</td>
</tr>
<tr>
<td>20</td>
<td>2.02 W</td>
<td>2.04 W</td>
<td>-1.0 %</td>
<td></td>
</tr>
</tbody>
</table>

### TABLE V

<table>
<thead>
<tr>
<th>UL PRB</th>
<th>( P_{\text{Tx}} )</th>
<th>UL MCS</th>
<th>( P_{\text{model}} )</th>
<th>( P_{\text{meas}} )</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>2.93 W</td>
<td>3.00 W</td>
<td>-2.3 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 dBm</td>
<td>2.94 W</td>
<td>3.00 W</td>
<td>-2.0 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-10 dBm</td>
<td>1.99 W</td>
<td>1.92 W</td>
<td>-3.1 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>2.93 W</td>
<td>3.03 W</td>
<td>-3.4 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 dBm</td>
<td>2.95 W</td>
<td>3.03 W</td>
<td>-3.0 %</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\( S_{\text{max}} = 5 \, \text{[W]} \)
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 ±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 effect.

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.

### ACKNOWLEDGEMENT

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