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Extension of EnergyBox for LTE networks

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Abstract

With the steady increase in the use of mobile technologies, studying the energy consumption of mobile applications becomes more interesting. In this thesis, the energy consumption of such applications connected to Long Term Evolution (LTE) cellular networks is studied. Using physical measurements on a mobile device, this thesis aims at characterizing the energy consumption due to communication of a mobile device connected to an LTE network in order to extend EnergyBox. EnergyBox is a tool that estimates the communication energy of mobile devices using packet traces as input.

We perform systematic experiments which exercise the LTE network interface of a mobile device while measuring the consumed power. Using the resulting data and a literature review of the operation of the LTE interface an energy model for LTE is developed. The model is then implemented in EnergyBox. The evaluation of the model is performed by comparing the accuracy of the energy model to physical measurements using five different packet traces from different mobile applications. The results show that the model integrated in EnergyBox provides an average accuracy of between 90% and 100%.

Acknowledgements

The author would like to thank Ericsson AB for facilitating the measurement gathering phase.

Contents

1 Introduction

This bachelor thesis work was done at Linköping University at the Department of computer and Information Science at the Real-time systems laboratory (RTSLAB).

1.1 Motivation

The use of mobile devices and handhelds is increasing every day and the need to always stay connected is greater than it has ever been. With the recent technological advances, the use of Long Term Evolution (LTE) networks has increased at the same time as mobile devices become more powerful. Battery lifetime can therefore become a clear bottleneck. This makes natural the study and optimization of the energy consumption of mobile devices when connected to LTE networks. This thesis focuses on the communication energy the wireless interface when connected to LTE networks, and thus, the rest of the components of mobile devices are not considered.

Measuring energy consumption in mobile devices is useful at the development stage of applications as their energy consumption can be optimized to consume as little energy as possible. However, performing these measurements is a non-trivial task. It requires both extensive knowledge in terms of how to physically perform the measurements as well as additional measurement hardware and knowledge regarding the operation of the devices and the networks. In addition to this, performing physical measurements require a lot of time. This is far from ideal which has led to the development of simulation software that can make the process both easier and faster. EnergyBox [1] is such a software that simulates the energy consumption of a mobile device connected to 3G and WiFi networks. This thesis aims to characterize the LTE mechanisms that impact the energy consumption of the end user in order to extend EnergyBox. This will enable it to simulate the energy consumption of a handset when connected to an LTE network.

1.2 Problem Definition

In order to estimate the communication energy for mobile devices connected to LTE networks this thesis aims to:

- Extend EnergyBox to enable the simulation of communication energy of a handset when connected to an LTE network
- Instantiate the model for a specific real consumer network based on physical measurements
- Evaluate the LTE energy model against physical measurements

1.3 Methodology

The goal of this thesis is to create an LTE model that simulates the energy consumption for a packet trace due to the LTE interface. In order to achieve this goal a model based on a finite state machine is used. The model should be instantiable with parameters that may be taken from any network provider or phone. To achieve this, a literature study is done on the different mechanisms of the LTE standard as well as reported measurements and results from the literature in combination with experimental work.

The experimental work is in the form of tests where the behavior of the device is studied and the power consumption is measured in order to find the parameters needed to instantiate a model. Then, the model is implemented based on the measurements. Finally, the model is tested to evaluate its accuracy by comparing its results to physical measurements for different packet traces using different applications. The accuracy of the model for the specific network and phone used in the thesis should be as high as possible while staying within the workload limits of a bachelor thesis.

1.4 Related Works

The thesis is based on previous studies done by Vergara et al. [2] where the communication energy of handsets connected to mobile networks was measured and evaluated. These studies led to the development of EnergyBox [1], which this thesis aims to extend.

Huang et al. [3] have conducted studies regarding energy consumption of handsets in LTE networks. They use a tool for Android called 4GTest to study both the performance and model energy consumption of LTE networks in relation to 3G and WiFi as well as observing the effects of different configuration parameters. Their study points out that LTE networks are much more energy inefficient than both 3G and WiFi networks.

Siekkinen et al. [4] studied how energy may be saved in 3G and LTE networks for streaming applications. Their idea is to shape the traffic in bursts so that the device has time to transition to power-saving states between bursts. They also investigated the impact of certain network parameters and found that the use of Discontinuous Reception (DRX) is a very effective way of creating energy savings. DRX allows the wireless interface to enter sleep modes and is explained in the background section.

Several works [5, 6, 7] examine how effective the use of DRX modes is in LTE as well as how changing the DRX parameters affects the power consumption and performance. Mihov et al. [5] create an analytical model of the DRX mechanism in LTE and evaluate its performance in terms of power savings. They propose some guidelines for optimal configuration of these parameters. Finally they introduce a new performance measure for the DRX mechanism (relative power saving) which is intended to evaluate the exact power saving of using DRX in LTE. Fowler [6] also studies the use of DRX modes in LTE for power saving in combination with different Transmission Time Intervals (TTI). The work compares the cases of only using the short DRX mode and only using the long DRX, showing that using both the short and long DRX mode is optimal for low power consumption while not introducing high delay. Zhou et al. [7] performs a measurement study using adaptable DRX parameters which they evaluate using simulation experiments. They show that the use of LTE DRX achieves power savings at the cost of wake-up delay and that adjusting the parameters creates a trade-off of power savings versus performance in terms of wake-up delay.

Different works [8, 9] measure the communication energy of different technologies in mobile devices. Bernardo et al. [9] describe different methodologies to perform measurements, where one of those is used in this work. Balasubramanian et al. [8] also performed a measurement study regarding energy consumption in 3G, WiFi and GSM networks where they quantified the energy consumed by different actions the device can perform such as transmitting data or just being in a high-power state.

Compared to the previous approaches, this work creates a parametrised energy model of LTE which can be instantiated for different networks and devices. Using measurements we instantiate this model for a particular operator in Sweden (Tele2).

1.5 Thesis Structure

The thesis is structured as follows. Chapter 2 provides the background regarding EnergyBox and the factors impacting the energy consumption of a mobile device connected to LTE. Chapter 3 describes the measurements that were performed in order to create a model for LTE in EnergyBox. Chapter 4 describes how the model was evaluated and provides the results from the evaluation. Chapter 5 discusses the conclusions drawn from this thesis as well as future work.

2 Background

This chapter provides the needed theory and background information to understand the rest of this thesis. It describes the basics of EnergyBox as well as the main factors impacting the energy consumption of a mobile device when connected to an LTE network.

2.1 EnergyBox

EnergyBox [1] is a software tool written in Java used to simulate the energy consumption of mobile devices for both 3G and WiFi networks. It uses packet traces (synthetic or captured in devices) to estimate the energy consumed by the device. This is useful to characterize communication energy for applications which in turn can help better understand how to evaluate and optimize the applications.

For a given packet trace and configuration parameters such as how long the device will have to be inactive in order to switch to a low-power state, EnergyBox simulates the state transitions of the device. Then, using the values corresponding to the amount of power consumed by the device in the states, EnergyBox provides an estimation of how much energy was consumed for the input trace. Figure 1 provides an overview of the general idea behind EnergyBox.

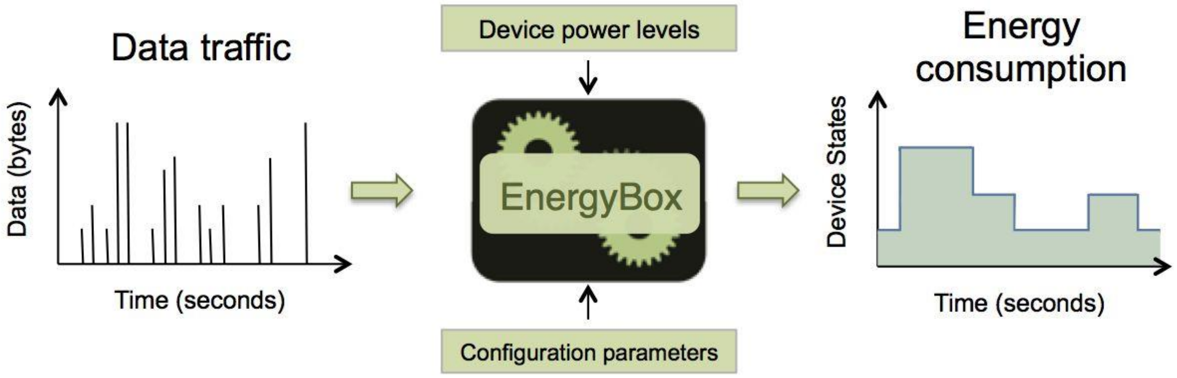


Figure 1. Overview of EnergyBox [1]

The models used in EnergyBox are finite state machines representing device states where each state corresponds to a specific power level. EnergyBox separates these device-specific power levels from other configuration parameters such as cellular network parameters. The output of running EnergyBox are the state transition graphs detailing the transitions between the different device states and power consumption levels over time as well as the total amount of energy consumed for the packet trace in Joules.

EnergyBox is convenient since it enables energy consumption simulations without having to perform any physical measurements, thus making the process easier and faster. However, there is currently no support for LTE networks and the tool requires extensions in order to enable communication energy simulations for LTE.

2.2 LTE Energy Consumption

In LTE, scheduling of data communication is determined by the network scheduling algorithms. These are controlled by the Mobility Management Entity (MME). The MME communicates with several base stations (NodeB) and services requests from the User Equipment (UE) to make sure that the UE receives the resources it requires from the base stations [10]. Figure 2 shows a simple overview of this.

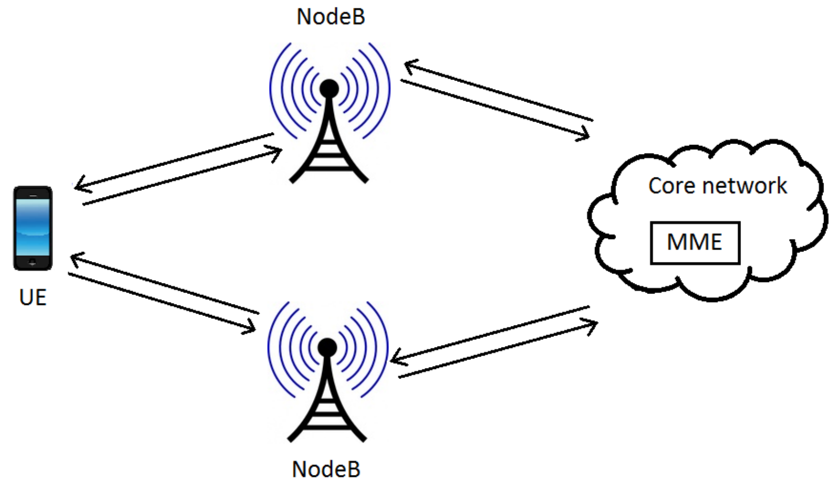


Figure 2. LTE Architecture overview

The energy consumption of a mobile device connected to an LTE network is mainly influenced by the Radio Resource Control (RRC) states. The RRC protocol defines different operation states that the UE can adopt and the transitions between the states. These states and transitions are shown in figure 3. There are two RRC states [3]: RRC_CONNECTED and RRC_IDLE. The UE is in the RRC_CONNECTED state when an RRC connection has been established with a node, otherwise the UE is in the RRC_IDLE state. This basic protocol helps to conserve energy when the device is not actively transmitting or receiving packets since the energy consumption in the RRC_IDLE state is very low [3].

The use of Discontinuous Reception (DRX) modes in the RRC_CONNECTED state is the main mechanism in order to make mobile communication more energy efficient in LTE. When a device has been transmitting or receiving data it stays in the RRC_CONNECTED state for a certain period of time after the transmission, waiting to enter the RRC_IDLE state. The energy consumed during this timeout is commonly referred to as tail energy.

When using DRX, the LTE state machine works as shown in Figure 3. When a device is actively sending or receiving packets it will stay in the Continuous Reception state. In this state, a DRX inactivity timer (t1) is used in order to control the switch to the DRX mode. This timer will be reset every time a packet is sent or received and upon expiration of the timer the device will enter the short DRX mode. There is also another timer (t3) started which will, upon timeout, make the device enter RRC_IDLE and release the allocated radio resource.

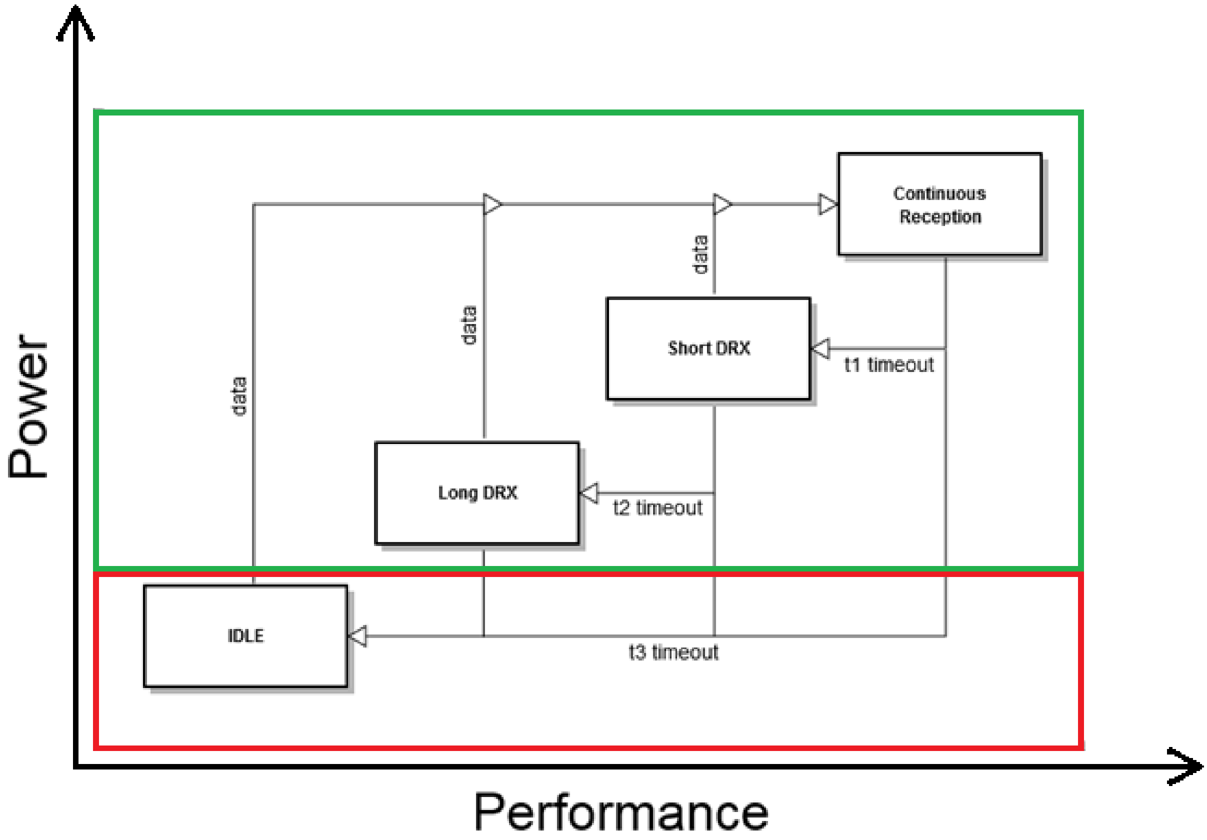


Figure 3. RRC network state transitions

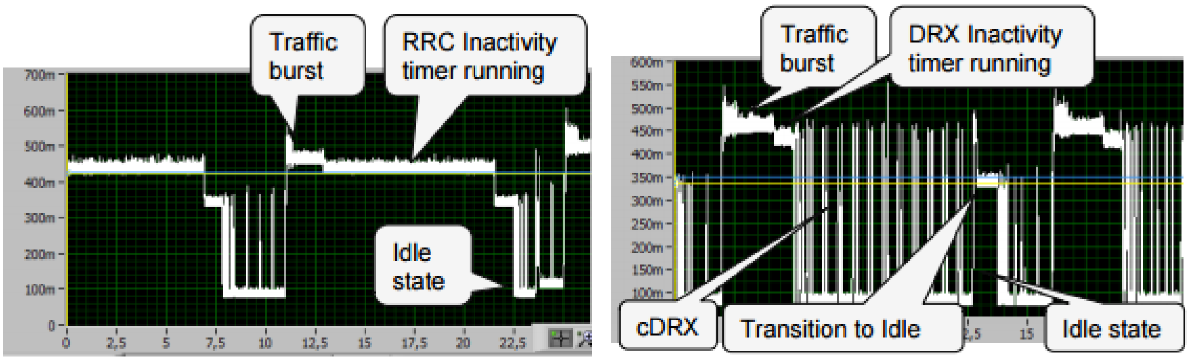
DRX modes work in cycles. A cycle is a predetermined period of time during which the device is sleeping and therefore conserving energy. DRX has two different cycle timers, a short cycle timer and a long one. The longer the device is inactive, the more energy is conserved, however this comes at the cost of performance as packet Round Trip Time (RTT) increases. A DRX inactivity timer (t2) is started upon entering short DRX as well in order to determine when to switch to long DRX mode. At the end of a cycle, if there is no data activity, the device will start a new cycle in which it sleeps. However, if there is activity it will enter the Continuous Reception state. If the Inactivity timer t2 expires, the device will enter long DRX mode which operates like the short DRX mode but with longer cycles leading to higher energy savings [5]. The duration of the cycle times can vary depending on the operator.

Work	Short DRX	Long DRX
Zhou et al. [7]	2s	10s
Mihov et al. [5]	2,5s	5s
Wigard et al. [11]	10ms	100ms
Fowler [6]	2s	10s

Table 1. DRX timers in the literature

2.3 DRX Timers in the Literature

Several different timers have been observed in the literature. Table 1 summarizes the observed DRX timers and the next section describes the observed behaviors. Siekkinen et al. [4] found that the use of DRX modes in LTE can drastically reduce the tail energy in the RRC_CONNECTED state. They performed measurements similar to those used in this thesis both with DRX enabled and disabled and found substantial energy savings with DRX enabled. They also found that the magnitude of these savings are highly dependent on the configuration parameters used. Figure 4 shows a measurement done by Siekkinen et al. [4] with DRX disabled and enabled. When the device is in DRX mode, one can clearly see how the power consumption is constantly fluctuating. This is because the device is continuously going from sleep mode to active in order to check for new activity.



(a) cDRX disabled (b) cDRX enabled

Figure 4. DRX disabled and enabled. The x-axis shows time in seconds and the y-axis power in mA. [4]

Previous measurements [3] show another example of the power levels of a mobile device connected to a particular LTE network as can be seen in Figure 5. At t1 the device enters the RRC_CONNECTED state in order to perform the requested transfer.

At t2 the transfer starts, the power consumed in this high-power state is fluctuating due to the data rate not being constant. At t3 the transfer is completed but the device stays in the high-power state until the timeout of the DRX inactivity timer which shows an example of tail energy. At t4 the device goes back into the RRC_IDLE state. The reason for DRX cycles not being accurately depicted is because of the limited sample rate used.

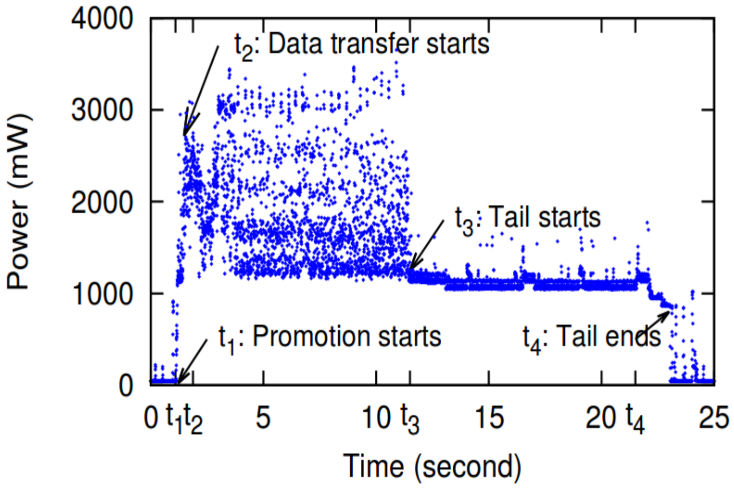


Figure 5. RRC State power levels [3]

An interesting aspect when modelling DRX behavior can be found in a work by Zhou et al [7] where they performed an analysis of the performance and use of so called adaptive or adjustable DRX parameters. In essence, the UE can, based on the properties of the transmission, adjust the DRX parameters in order to maximize power saving or improve performance. Some of these properties that may affect the DRX parameters are number of packets sent, inter-packet arrival time and the size of the packets. This behavior is important to examine since it may have an effect on the energy consumption of the mobile device.

3 LTE Model for EnergyBox

This chapter describes the approach to develop the LTE model based on physical measurements. It describes what measurements were performed, how they were performed as well as the testbed used. It also describes the model that was implemented in EnergyBox.

3.1 General Methodology

One of the most important aspects needed to extend EnergyBox is to figure out what parameters are required to perform energy simulations for a mobile device in an LTE network. The parameters are used as input when running EnergyBox in LTE mode in order to perform the evaluation. In order to find the parameters, systematic tests exercising the wireless interface of a mobile device in different ways are performed while collecting physical power measurements.

The general idea behind the approach to obtain the parameters is that the different states of the wireless interface can be clearly distinguished when observing a power trace due to the different power levels of the RRC states. By measuring the time between the last packet sent and the state transitions we can infer the timers of the RRC state machine. Performing systematic experiments varying the inter-packet transmission times as well as the packet sizes we can exercise the wireless interface to obtain the configuration parameters needed for the model.

The measurements that were used to find the parameters were similar to those used by Vergara et al. [2]. The mobile devices experience different performance in terms of Round Trip Time (RTT) depending on the state, since in DRX mode it will wait for a cycle to complete before transmitting or receiving, we can find how long the device must be inactive before switching mode. If we send two packets with a certain time (t) between them and the RTT is the same, we can assume that the device did not switch state. By increasing t and observing when the RTT changes for the second packet we can estimate the inactivity timers. This validation method can help to confirm that the conclusions drawn from observing the power traces are correct.

3.2 Measurement Setup

For our measurements, we use a rooted Samsung Galaxy S5 using a Tele2 SIM-card. When measuring the power consumption of the mobile phone, a common approach is to intercept the battery terminals. The terminals can be intercepted by placing copper tape or some other similar conductor between the battery terminals and the battery connectors. An external power supply was used to provide the phone with a stable voltage level (4 V). The reason for not using the battery to power the phone is because as the battery drains, the voltage level will drop and the current will increase, thus the amount of power consumed by the phone becomes dependent on the battery. This would cause fluctuations that would render the measurements useless.

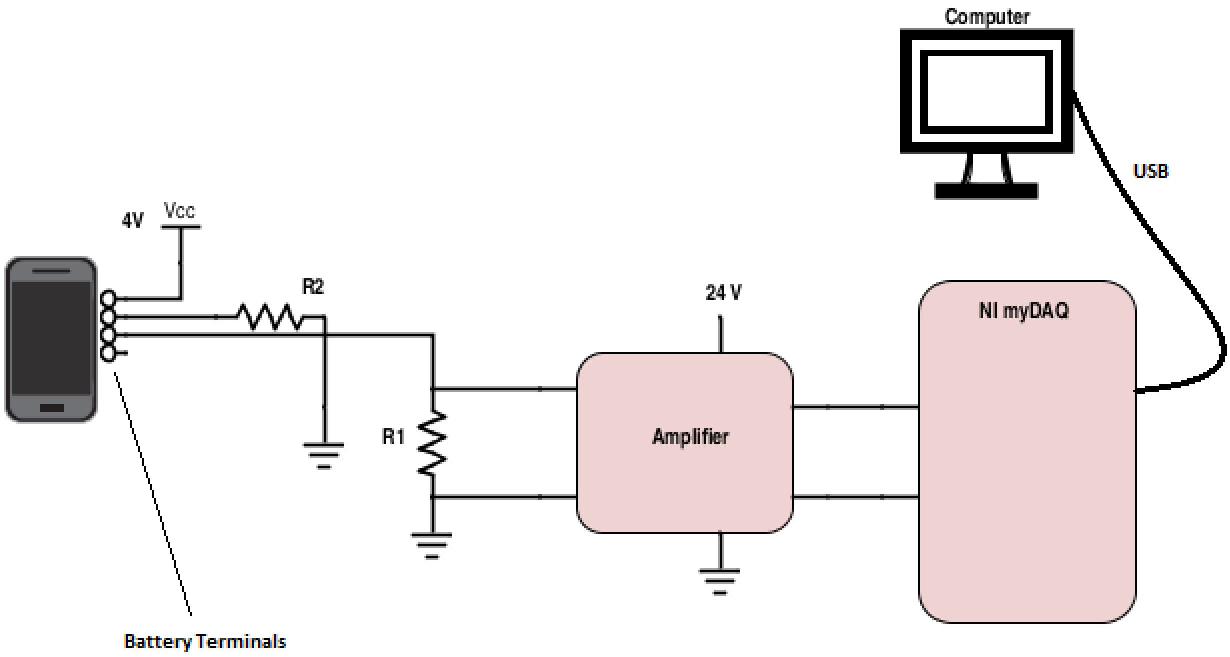


Figure 6. Physical Measurement Setup

Figure 6 shows the physical measurement setup used in the thesis. The plus terminal is connected to 4V and the minus terminal is connected via R1 to an amplifier (Phoenix Contact MINI MCR-SL-SHUNT-UI) with a maximum transmission error of 0.4%. R1 is a precision shunt resistor (0.1Ω). It is important that this resistor is not too small as that can negatively impact the accuracy of the measurements [8]. The amplified signal is then measured by the National Instruments myDAQ Data Acquisition unit and can then be viewed and processed using LabView in the computer. The fourth battery terminal function as a communication channel between the battery and the phone and it does not need to be given any particular voltage for the phone to function properly.

The measured signal is the amplified voltage drop over the precision shunt resistor. Since we are interested in measuring the power consumption rather than the voltage, we need to calibrate the signal. First we need to isolate the voltage over the resistor from that of the rest of the circuit, then scale the measured voltage down to account for the amplifier and finally simple application of Ohm's law will result in the power consumption of the phone ($P = V^2/R$).

Because the measurements are performed on a phone, not all of the consumed power is due to the wireless interface. For example, the CPU is constantly computing tasks which introduce uncertainty in the power trace. In order to isolate the power consumed by the wireless interface, the frequency of the CPU was locked to 1.19 GHz and a low-priority program is run to keep the CPU in a busy loop. This way, the power consumed by the CPU was almost constant and it is thereby easier isolate the power corresponding to the LTE interface. A firewall was also used to ensure that no undesired network traffic would interfere with the tests.

MatLab was used in order to process the gathered data and to perform calculations, chart diagrams as well as for model creation. In order to make the data easier to read and understand the signal was filtered using a moving average filter. A moving average is a calculation used to analyze data points by creating a series of averages of different subsets of the full data. In this case it allowed for getting a clear signal to chart in a diagram that is easier to interpret. Since we are interested in modelling energy during a period, averaging over time is a convenient method.

Figure 7 shows a filtered signal (red) on top of an unfiltered signal (blue). From simple traces like this one, we can extract the basic power levels for the observed states.

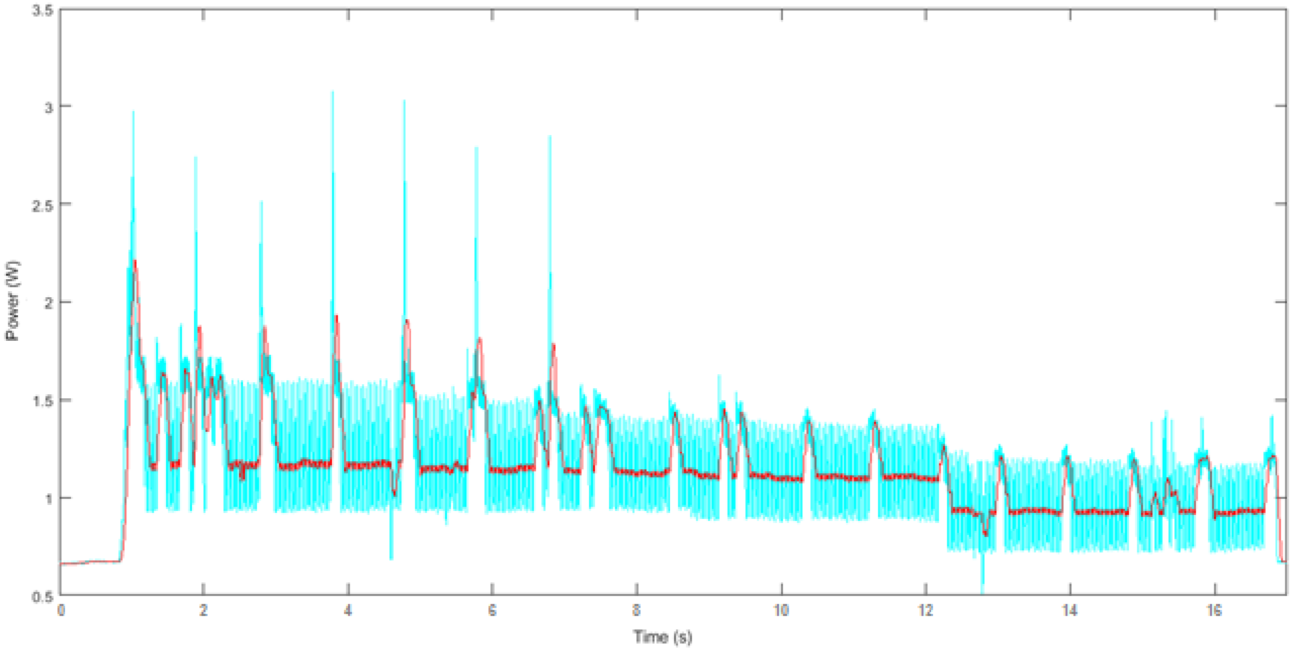


Figure 7. Filtered vs unfiltered signal

3.3 Inferring RRC State Machine Parameters

We perform systematic tests to infer the parameters for the model. These tests are based on the theoretical knowledge of how the LTE standard works and are performed by sending and receiving packets in a controlled manner. The resulting packet and power traces can then be studied in order to draw conclusions regarding the model and infer the parameters.

The LTE interface is exercised to trigger state transitions between different states, which should follow the theoretical state machine defined in the standard. We define different tests by varying the inter-packet interval (time) and the amount of packets sent (bytes). These two dimensions allow us to trigger the different state transitions. In the following subsections, methods for analyzing the state transitions and obtaining the following parameters for the model are presented: t3 inactivity timer, t2 long DRX inactivity timer and t1 DRX inactivity timer.

3.3.1 Observing State Transitions

This section presents some of the preliminary tests that were run to explore the behavior of the state machine used in the network.

According to the LTE network state machine shown in Figure 3 there are two DRX modes: short DRX and long DRX. In all the tests the UE starts from the RRC_IDLE state. This is done by not sending/receiving any data before the test starts and checking the power trace. By simply sending a single burst of data and waiting we should be able to first trigger the transition to the Continuous Reception state. Then, by sending small packets with long inter-packet intervals we should then be able to trigger the switch to the short DRX mode. After further inactivity, longer than t2, the device should enter the long DRX mode.

Figure 9 shows one of the several power traces collected when sending a large data burst, in this case 2.5 MB. From the trace we can see that right after the transmission there is a short period where the device is still active (between second X and Y). This is where the DRX inactivity timer is running. The demotion then happens to the Short DRX mode and about two seconds later to the Long DRX mode. After ten seconds of no activity, the device then returns to the idle state. This behavior is in line with the model described in Figure 3.

The following test was performed to analyze the Long DRX to Short DRX transition. We expect the device to switch from the Long DRX mode back to the Short DRX mode after having seen large activity. This test simply continuously sends small packets to make the device enter DRX mode and then begins a large transmission to force a promotion:

```
for i=1 to 4
    send a packet of 140 bytes
    wait 4 seconds
send a large data burst (7 MB)
```

Figure 8 shows the power trace from one of the runs of this test. As shown in the trace, the device did not switch back to the Short DRX mode even after the last burst. This leads to the conclusion that the device does not promote back to this state after being in the Long DRX mode. This is a clear difference from the LTE network state machine described by the standard in Figure 3. This was confirmed by repeating the tests with different inter-packet intervals and burst sizes ranging from a few kB to several MB.

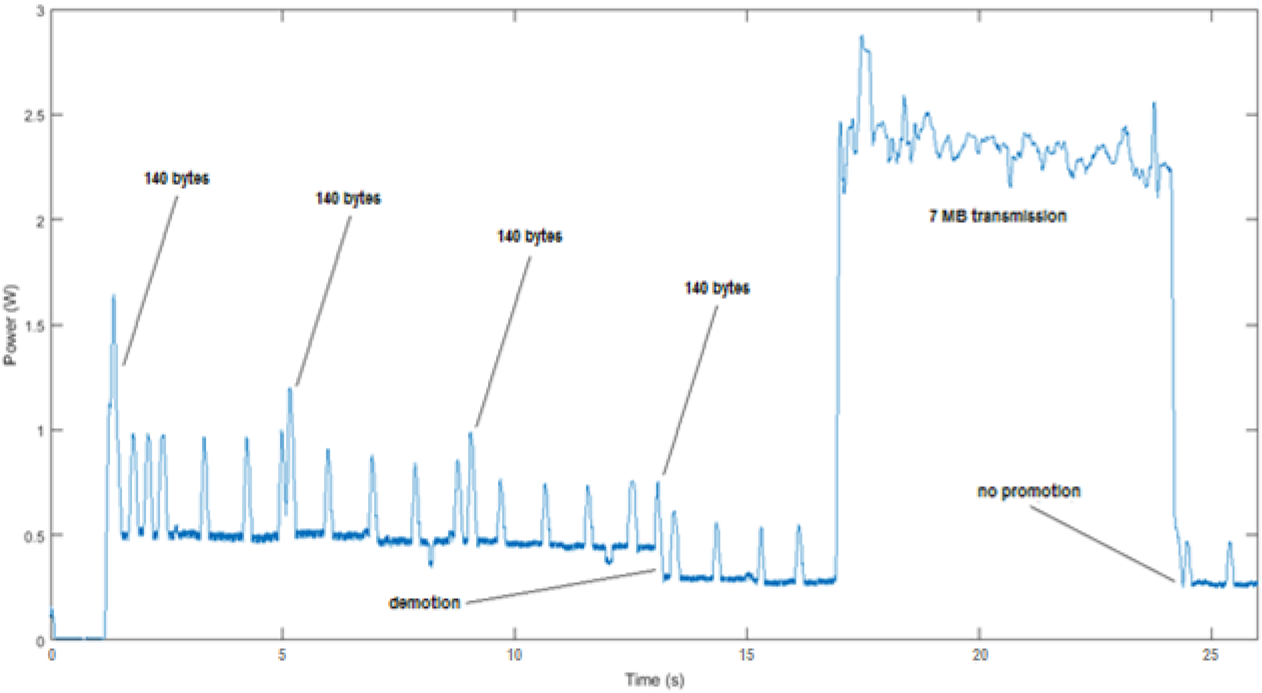


Figure 8. Analyzing the lack of transition from Long DRX to Short DRX

Figure 9 shows a measurement done in this thesis where a file of approximately 2.5 MB was downloaded, the experimental settings are described in Chapter 3. This looks in many ways similar to (b) in Figure 4 however there are some noticeable differences. First of all the network model studied in this thesis makes use of two different DRX modes whereas in the work by Siekkinen et al. [4] only one of them was used. As can be seen in Figure 9 though, the difference in energy consumption when the device is operating in these two different states is considerable.

Another factor that can impact the energy consumption during a transmission is data rates. Generally, the higher the data rate, the more energy consumed and since for LTE data rates are usually very high this becomes more noticeable here.

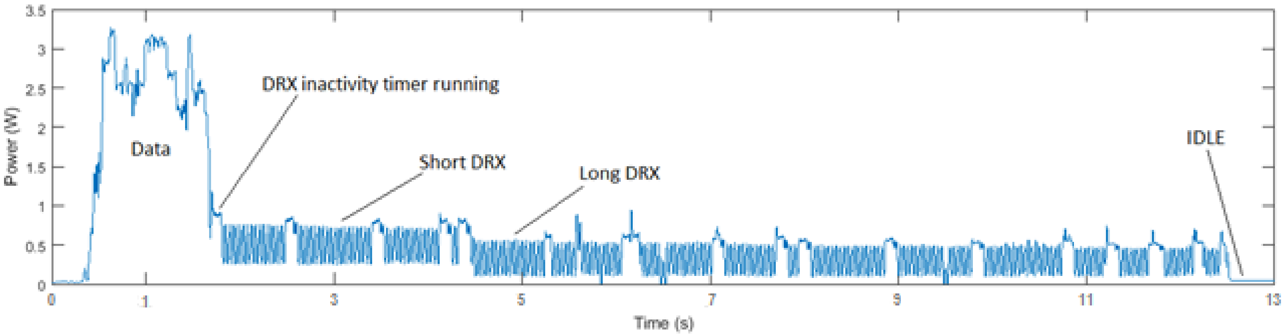


Figure 9. Data transmission showing the use of DRX modes

3.3.2 T3 Inactivity Timer

This inactivity timer is used to control the state transitions between the RRC_CONNECTED and RRC_IDLE states. The test to infer the inactivity timer is based on sending some data and waiting for a given time period. By increasing the inter-packet interval we expect a transition to the RRC_IDLE state when the inter-packet interval is greater than the inactivity timer. The following pseudo code describes the basics of the test.

```
for i=1 to 20
    send a packet of 1400 bytes
    wait i seconds
```

Figure 10 shows that when the inter-packet interval is more than 10 seconds, the UE moves to RRC_IDLE. From this we can deduce that the time the device needs to be inactive in order for it to transition to the RRC_IDLE state is more than ten seconds, but less than eleven. An additional test with smaller inter-packet intervals between 10 and 11 seconds lead to the conclusion that the inactivity timer is 10 seconds.

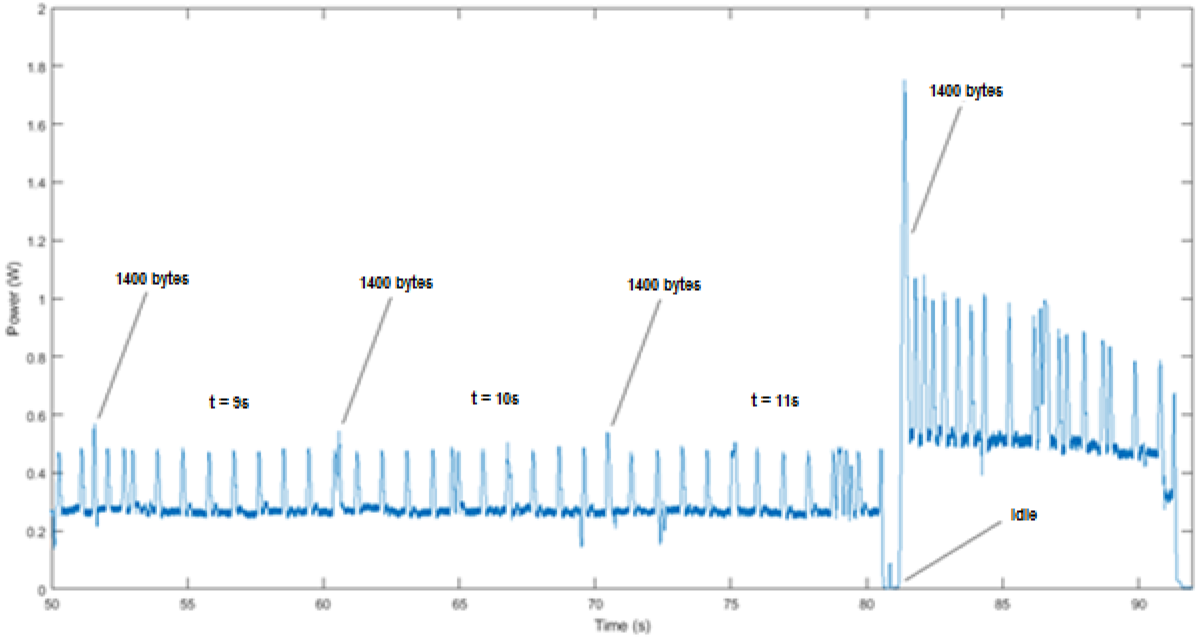


Figure 10. A fragment of the power trace to infer t3

3.3.3 T2 Long DRX Inactivity Timer

To infer this timer, a single burst of data was sent. The timer is then inferred by observing the power trace. However, after running this test with a few different burst sizes it became clear that the device was not consistent in when it demotes from the Short DRX mode to the Long DRX mode. As can be seen in Figure 9, the device performs this demotion after about two seconds of inactivity. In Figure 11 however, the demotion happens after around 7 seconds. This behavior was observed in all traces and was found to be connected to the amount of data that was transmitted.

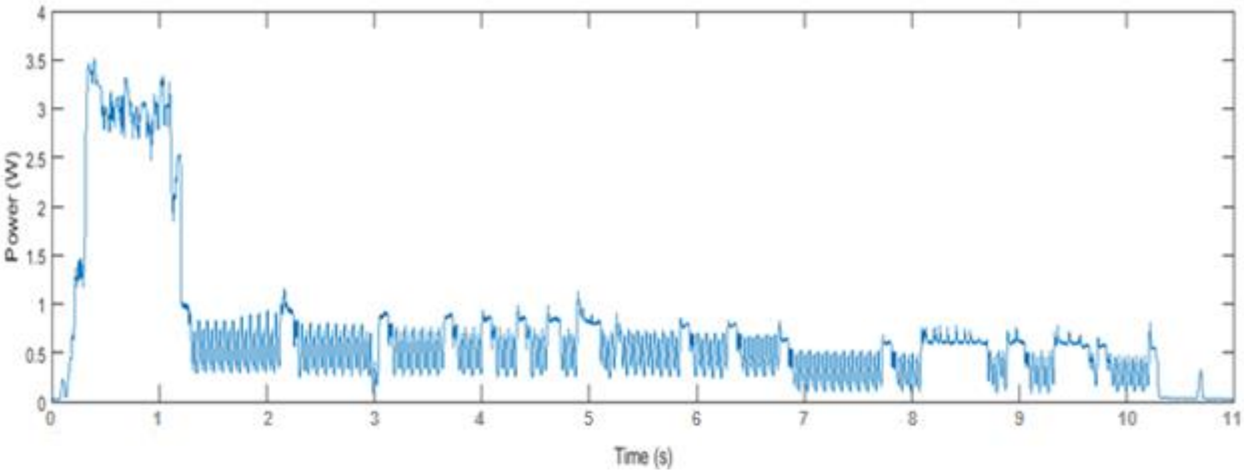


Figure 11. Transmission of 1MB

Figure 11 shows a transmission of 1MB. Comparing this power trace to the transmission of 2.5 MB shown in Figure 9, we can see that the demotion from Short DRX to Long DRX happens earlier when the amount of transmitted data is larger (Figure 9). It would seem that sending more data leads to the device demoting to the Long DRX mode earlier than when sending smaller amounts of data. This was confirmed to be the case in all traces that were run. The relation between how much data was sent and how much earlier the device demoted was not found to be linear. For example, the difference in sending 1kB or 100kB was much larger than going from 1001kB to 1100kB for example. Even for these somewhat small amounts of data, the inactivity timer was noticeably shorter, whereas for larger amount of data, the differences were relatively smaller.

The maximum time that it took for the device to transition to the long DRX mode was observed to be 13 seconds. By increasing the size of the data burst, the time to transition was observed to decrease until eventually, at a burst of around 10MB, the device skipped the short DRX mode altogether and went directly to long DRX. The relation between the size of the data and the change in time was, as previously stated, not linear. However it was implemented as such in EnergyBox as a simplifying solution.

Figure 12 shows a graph of this relation, in blue is the measured relation and in red is how we model it in EnergyBox. While we could not find any explanation for this behavior in the standard, we speculate that the idea may be that after sending a huge burst of data, you are less likely to send more and after having sent a small bit of data, more is likely to come.

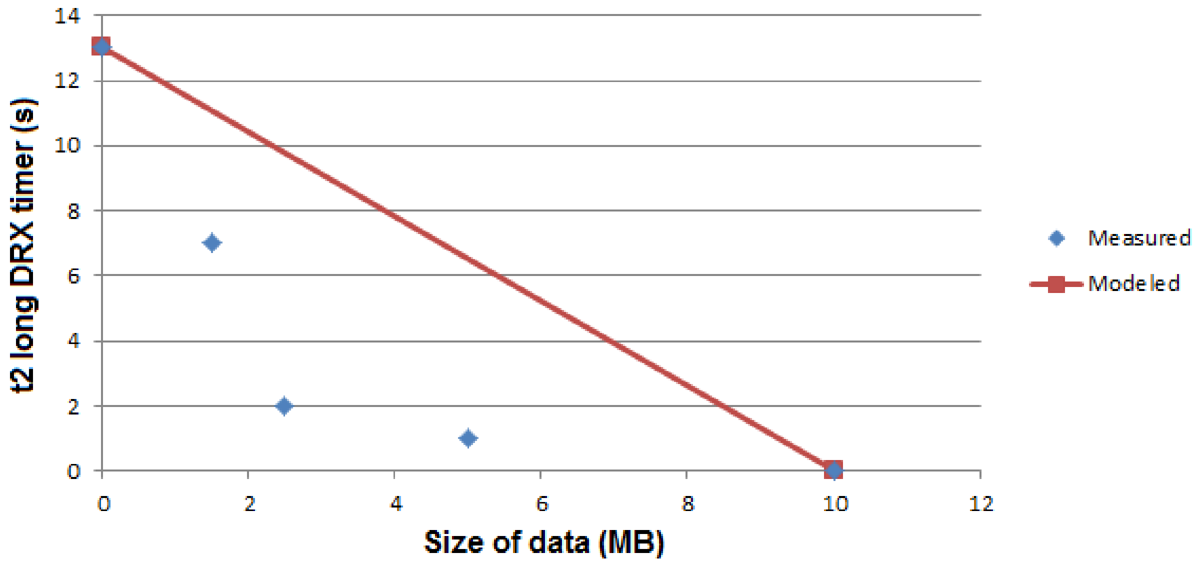


Figure 12. DRX timer and data size relation

3.3.4 T1 DRX Inactivity Timer

To measure the t1 inactivity timer we only need to send a burst of data. Then, by using MatLab and measuring the time from the transmission power spike and the transition to the DRX state in several traces this timer was found to be 100 milliseconds. The reason for not using the same method as in the test above is that this timer is much shorter and the Java sleep command used to wait between packets does not guarantee an exact sleep time in milliseconds.

3.4 Power Levels for the RRC States

In order to set the power level for each state two methods were considered. In the first, we keep the device in a given state for a period of time and measure the average power consumed in that state. In order to get this value as accurate as possible, this should be done over a number of different traces. In the second, we measure the power during the cycles when it is sleeping as well as when it is active and monitoring for new activity. While this method is more accurate, it is also more difficult and time consuming and would result in a model that is more complicated.

It was decided that simply considering the power in DRX as constant with the average of both the sleep cycles and when the device is active would provide accurate enough results while keeping the model simple. Therefore, the first method described was used to find the power consumption in all the states.

The power values for the different states were found to be as follows: Continuous Reception: 0.83 W, short DRX: 0.51 W, long DRX: 0.33 W.

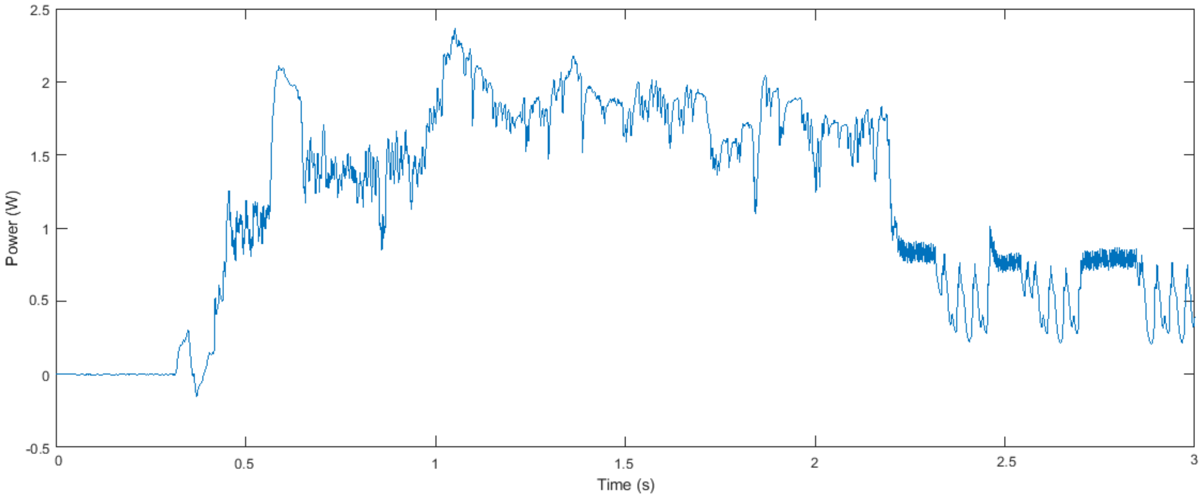
3.4.1 Data Rates

Another aspect to consider is the impact of data rates. For very high data rates, the amount of energy consumed will be considerably higher compared to the same trace with a lower rate. This has to be considered in the model for it to be accurate.

In order to find out how to model the impact of data rates in EnergyBox, first we perform several systematic experiments sending data at different rates. We fix the data rate by sending packets of different sizes and different inter-packet interval times. We fix the data rate by sending packets of 1000 bytes and setting the desired inter-packet interval (e.g., 1ms for 8Mb/s data rate). The data is transmitted while measuring the power trace. We select the following data rates: 1Mb/s, 4Mb/s, 8Mb/s and 16Mb/s.

We observed a considerable difference in terms of power consumption in the Continuous Reception state between transmitting and not transmitting data. However, no clear correlation was observed between the data rate and the average power level. Figure 13 shows a transmission at 4Mb/s on the left and one at 8Mb/s on the right. As can be seen in Figure 13, the power consumption varies greatly during the transmissions, making it hard to map a given data rate to a certain power consumption. Even calculating the average energy consumption for the transmissions led to varying consumption levels for the same data rates and a higher data rate was not always consuming more power. Similar results were found for other data rates as well.

This led to an implementation in EnergyBox where only one data rate was mapped to a hard coded energy consumption. In the EnergyBox model, the trace is divided into segments of 100 ms. In each of these segments, the amount of data sent is measured and if it does not reach a certain threshold, 1 KB, there is too little data being transmitted to warrant any added energy consumption. However, if the data rate is above the threshold, a constant energy consumption is added for this segment.



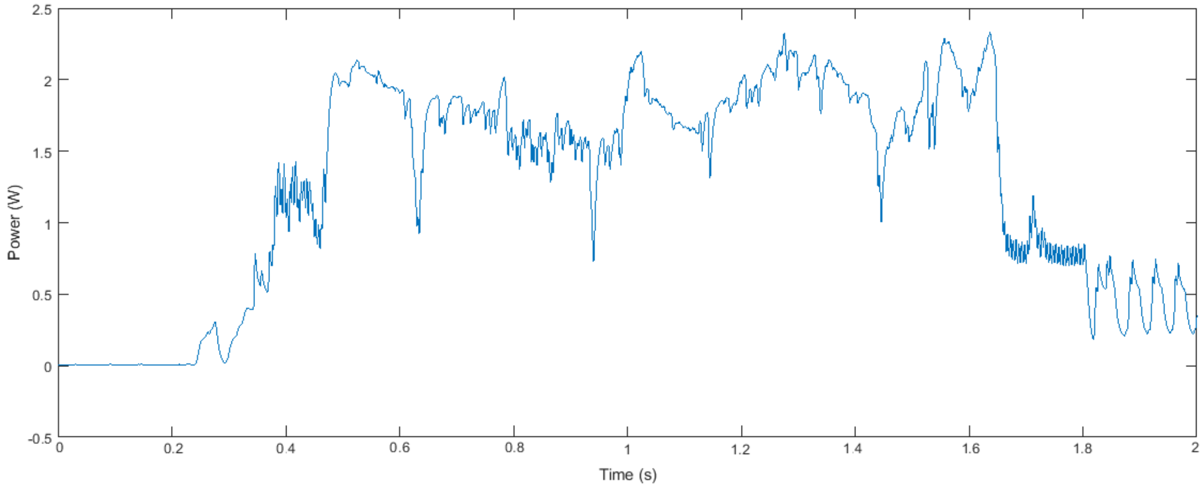


Figure 13. Power consumption when transmitting at 4Mb/s (top) and 8Mb/s (bottom)

3.5 LTE Model in EnergyBox

This section describes the model that was implemented as an extension to EnergyBox [13]. In order to accommodate the network model parameter values observed in the literature as well as our measurements we employ two types of network configuration files in EnergyBox.

To implement the LTE model in EnergyBox a couple of extensions to the code were needed as well as some modifications to existing files and classes. State machine model is implemented in the EngineLTE.java file which contains the EngineLTE class, an extension of the already existing Engine class. This class also performs the energy calculations using the calculatePower() function.

For creating the device and network objects containing all of the configuration parameters from the input files the PropertiesDeviceLTE and PropertiesLTE classes are used. These extend the Device and Network classes respectively. The output from EnergyBox for the LTE model is handled by the ResultsFormLTEController class which implements the already existing Initializable interface. The format of the output is defined by the ResultsFormLTE.fxml file. Minor changes were also needed to the EnergyBox and ConsoleBox classes in order to run the tool with the LTE extensions.

4 LTE Model Evaluation

This chapter presents the evaluation of the LTE model developed from our measurements compared to physical power measurements. We first describe our methodology and the metrics used and then present the results.

4.1 Evaluation Methodology

In order to confirm that the changes made to EnergyBox have had the desired result one can compare the simulation results of the developed model against the physical real measurements. Vergara et al. [1] propose to use energy accuracy as a metric to evaluate the accuracy of EnergyBox. Energy accuracy is calculated using a measured power trace from a physical device and represents the total energy that was consumed during the trace. EnergyBox is given an input packet trace and the configuration parameters for a given network and simulates the state transitions. Then, using the power levels for each of the states, EnergyBox can calculate the simulated power trace which is compared to the measured power trace.

We evaluate the accuracy of the LTE model against physical measurements. For a given packet trace we measure the power trace in the device which we use as a baseline. Then, the packet trace is fed into EnergyBox which outputs the total energy consumption. Energy accuracy represents the difference between the baseline and the simulated energy consumption.

4.2 Evaluation Traces

An important aspect to consider when measuring energy consumption for a mobile device is that different applications show different communication patterns, resulting in different energy consumption. One can consider for example a streaming media service that uses buffering to stream the content and therefore downloads a larger part of the media at the same time, giving it time later to enter an idle mode. Meanwhile, a similar service might stream all the content continuously, staying in the same high-power state all the time. In order to confirm the accuracy of the LTE model, different packet traces from real applications were employed.

Five different types of traces were used that all have different types of data pattern characteristics, as can be seen in Figure 14. The accuracy of EnergyBox may depend heavily on the types of traces used and therefore it is important that they have different characteristics in terms of inter-packet intervals and size of the data transferred. Figure 14 shows that the traces are sufficiently different that the results from the validation tests can be trusted.

The traces used to confirm the validity of EnergyBox are approximately five minutes long to ensure that the results are reliable. The Twitch trace is shorter since it involves a lot of data and too large pcap files created problems in the used version of

EnergyBox (this issue has been fixed in the current version). Five different types of applications are used namely: Whatsapp, Spotify, Vimeo, Twitch and the stock Samsung Web Browser. Whatsapp is an instant messaging service where users send text messages to each other that may or may not also contain images or videos. When testing this application, messages was be sent back and forth from a second phone to the phone where the measurements were made to simulate a conversation. Spotify is a music streaming service, this application was streaming music to the phone during the testing and songs were switched multiple times to simulate a more realistic usage. Vimeo is a video streaming service where users can upload and watch videos. During the testing of this application, a few different videos were streamed to the phone. Twitch is a live streaming service for games where users can broadcast live to thousands of people simultaneously. This is distinctly different from video streaming services as the content here is not a file of a certain size but rather continuous content for as long as the user watches. When testing this application, one stream was broadcasted to the phone in high quality. Web browsing was tested by simply browsing different websites for five minutes.

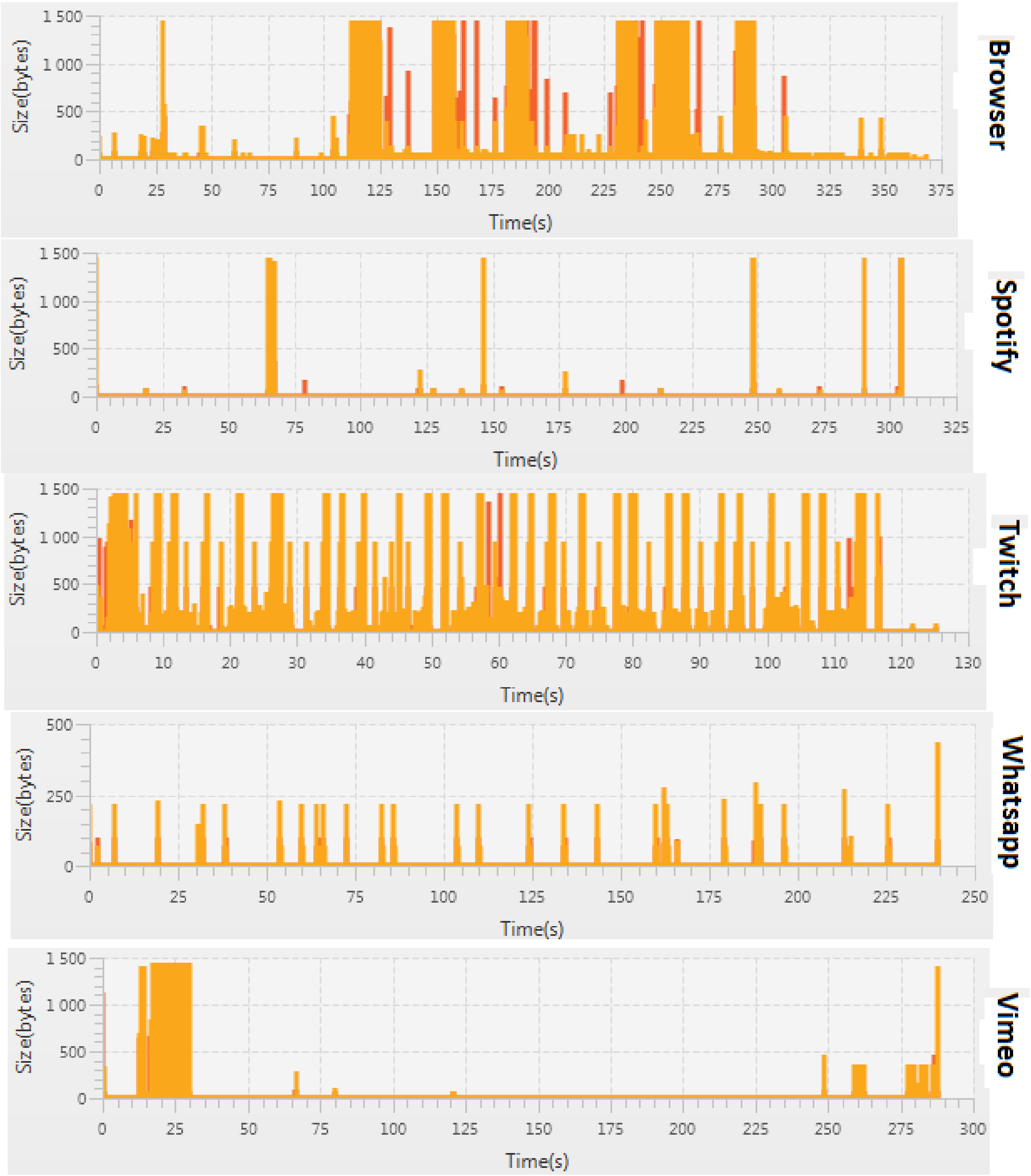


Figure 14. Packet distribution of validation traces, red is upload and orange is download

4.3 Energy Accuracy

This section presents the accuracy results of the LTE model compared to the physical measurements. Figure 15 shows the measured energy consumption for the different applications and the simulated energy by EnergyBox.

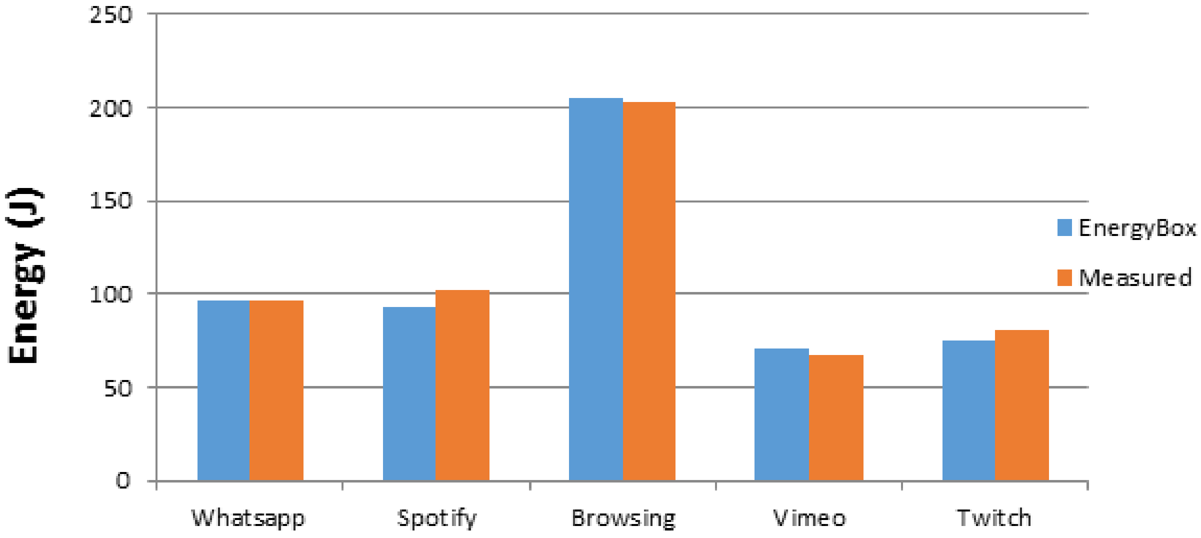


Figure 15. Energy Accuracy of EnergyBox for the LTE model

The average energy accuracy for the LTE model in EnergyBox is high, almost 96%. Figure 16 shows the relative energy accuracy from the different traces measured and gives a good overview of how accurate the different traces where to each other as well as makes it easier to compare differences. In all cases the accuracy is above 90% and in the case of Whatsapp and web browsing, the accuracy is 99% or more.

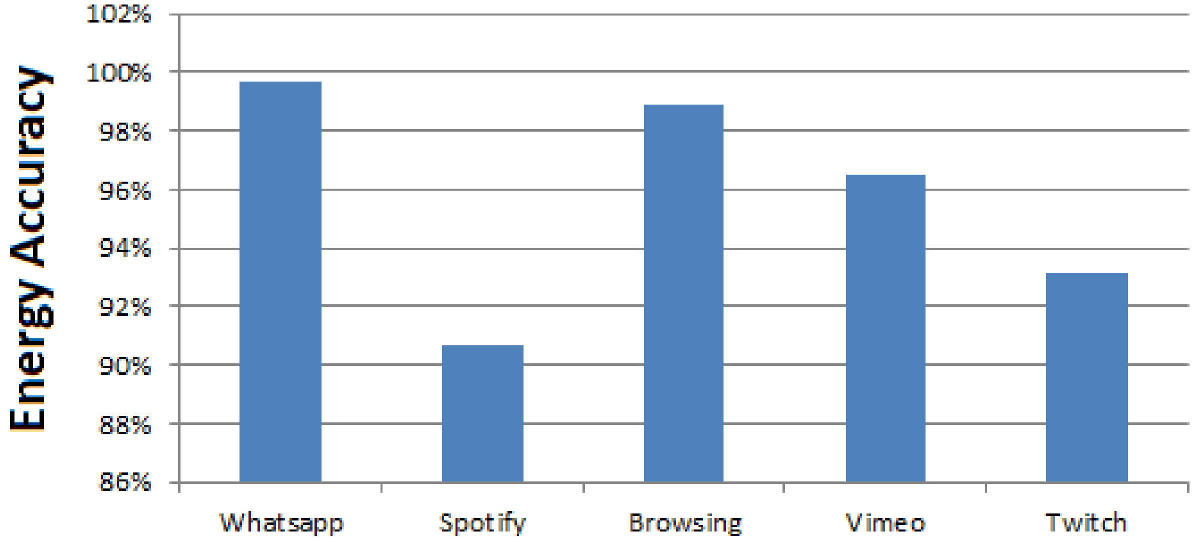


Figure 16. Energy Accuracy of EnergyBox

The inaccuracies that can be seen most prominently in the Spotify, Vimeo and Twitch simulations are a result of the energy model not being perfect in demoting from the short DRX mode to the long DRX mode when the transmissions are relatively large.

This was modelled as a linear relation while our measurements showed a non-linear nature.

Figure 17 shows a trace from Spotify modelled in EnergyBox on top of the actual power trace. EnergyBox demotes later than it should sometimes when dealing with larger transmission which causes slight inaccuracies. This is because the modelling was done based on some observations that, as mentioned, varied in some tests. Similarly, it may also demote slightly later than it should when transmissions are smaller however this flaw's effect on the overall accuracy is smaller.

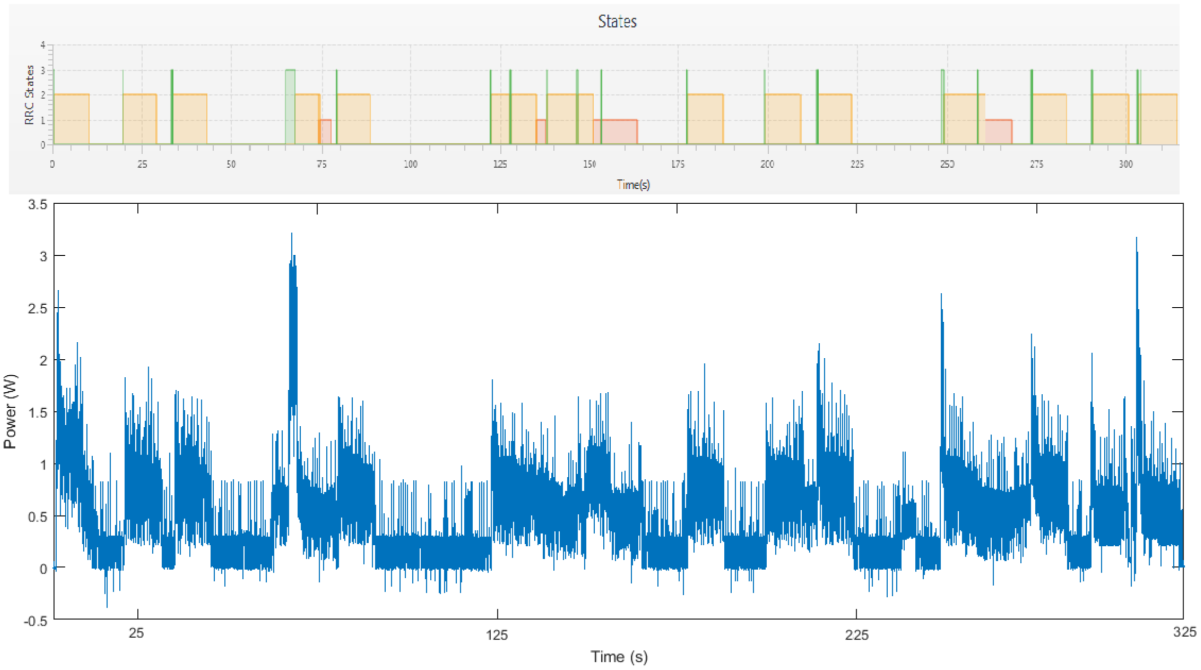


Figure 17. Spotify model and measured

5 Conclusions and Future Work

This chapter discusses the conclusions of this thesis as well as what future work can be done to extend the work done in this thesis.

5.1 Conclusions

The first step towards achieving energy-aware and energy-efficient solutions for mobile networks and applications is to understand where, how and why the energy is consumed. EnergyBox helps with this problem by allowing accurate simulations of energy consumption at the device end. The parameters specific to a device and network can be instantiated with different values that suit the users need.

In this thesis, the parameters and algorithms of an LTE network have been examined, characterized and then implemented in a model in EnergyBox. This was done by studying the behavior of the device while sending and receiving packets in a controlled manner. The model can be used to simulate the energy consumption of a handheld device connected to an LTE network. In order to validate that the model provides accurate results, the results have been compared to physical measurements done on a device. Five different types of applications which show diverse data patterns were used in the tests (Whatsapp, Spotify, Samsung Web browser, Vimeo and Twitch).

The LTE model implemented in EnergyBox in this thesis simulates the energy consumption of LTE networks with an accuracy between 90% and 100% across the traces. It is clear that the characteristics of the traces and data transmissions have an impact on how accurately EnergyBox can simulate the energy consumption. However, EnergyBox should still be an effective tool for examining how an application's network traffic affects the consumed energy of the device.

5.2 Future Work

For future work, the current LTE model for EnergyBox could be improved as well as extended in different ways. First of all, the way EnergyBox adjusts its parameter values depending on the transmitted data could be improved. Currently, the relation between the amount of data transmitted and the effect on the DRX timers is linear even though this behavior was found to be more similar to a logarithmic increase. If this behavior could be modelled close to how it works in reality, the accuracy of EnergyBox could improve.

The modelling of the power transmission when considering different data rates can significantly be improved. We adopted a simplified approach modelling it by adding an extra energy cost if the transmission data was larger than a threshold. Instead, we could model the data rate by mapping the instantaneous power and data rate of the measured power and packet trace. This would potentially provide more accurate results.

The received signal strength has an impact on the energy consumption and could be modelled in an extended version of EnergyBox. All the work presented in this report was done at the same place at the university where the signal strength did not vary significantly. A simple version of signal strengths is suggested where the model has a number of simple settings for signal strength such as good, normal or bad [14]. This could be done by simply increasing the power values of each state.

Finally, the current LTE model only has configuration files for the mobile device and network used in this thesis. More networks and devices can be measured and their parameters can be added as configuration files to instantiate the LTE model. Data from the literature can also be used to create additional configuration files.

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