M2M Communications over LTE - Evaluating Energy Consumption Models

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***Abstract*— Long Term Evolution (LTE) communications systems are increasingly being used for remote applications where a battery life of 10 to 15 years can be specified. To ensure these demands can be met, accurate modelling of power consumption is required. Existing models which decompose LTE power consumption focus on laboratory-only measurements and use continuous transmission scenarios. The work presented shows that whilst these are valid for the continuous case, they are not relevant for Machine to Machine (M2M) activity on a live network. Under these conditions, packet size is likely to be small in relation to protocol and system overheads, resulting in a dramatically increased and hard to model consumption of power. In addition, network measurement and optimisation transmissions in supposedly low power idle periods threaten to further confound the issue.**

***Index Terms*— Machine-to-machine communications, 4G Mobile communication, Power measurement.**

I. Introduction

The number of connected devices is predicted to increase exponentially over the next few years. Of particular interest is the use of machine to machine (M2M) communications. M2M communications can cover a vast array of data types and transmission durations, however of particular interest to this paper is the case of wireless sensor networks, which are likely to be remote and battery powered. Consumers have been demanding battery lives of at least ten years, which puts intense demand on modem efficiency. In addition to this, it is important to form an idea of what kind of battery life we can expect for a given application.

Previous work surrounding modelling of uplink and downlink LTE power consumption between user equipment (UE) and base station (eNB) tends to focus on long term measurements, proportional to activity in the baseband and RF blocks of the transmit and recieve chains [1], [2]. These models are valid for systems transmitting or receiving large amounts of data continuously. Where packet size is small in comparison with overheads, such as a sensor node reports, transmitted as infrequently as daily or less often, these models become less valid.

More realistic work looking at periodic updates has been done in [3], however this still lacks network measurements and assumes no transmissions occur in discontinuous reception (DRX) modes. DRX and the optimisation of its parameters for low power have been well examined in [4] but would benefit from being combined with verification on a live network to incorporate more of the effects of LTE signalling.

II. Theory

LTE lends itself to a wide variety of uses due to the highly adaptive nature of the transmission and reception data rate and power output. The amount of data transmitted in one transport block of duration 1ms, varies from 2 to 6378 bytes depending on the modulation and coding scheme used and the amount of bandwidth allocated to the UE. In realistic terms, a minimum resource block allocation would increase this lower limit to 19 bytes.

This project focusses on M2M scenarios where data packet size is likely to be comparable to associated overheads. The total amount of energy consumed in these transmissions is a function of two main factors, the amount of RF transmission power needed to effectively communicate with the base station, and the duration over which this takes place.

Figure 1 expands on factors affecting power consumption. The quality of the RF channel including signal to noise ratio (SNR) dictates a metric called channel quality information (CQI). CQI then be used by the eNB to set the required transmission power the UE must use, and the MCS supported. MCS in turn can be combined with the bandwidth allocated to give transport block size (TBS), the amount of data that can be transmitted in a 1ms subframe. In order to further explain this model, we can split into two sub processes; Power and duration.

A. Power

A thorough analysis of LTE transceiver performance is given in [1], summarised in Equation 1. This models transceiver power consumption as the sum of power

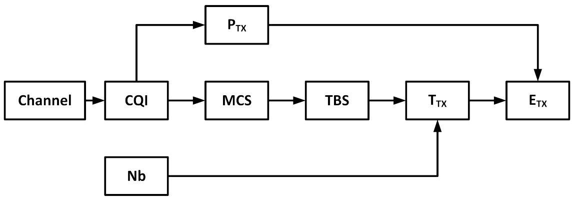

Fig. 1. Factors affecting TX energy consumption

consumed by baseband transmit and receive processes (P_{TxBB}&P_{RxBB}) and RF transmit and receive processes (P_{TxRF}&P_{RxRF}).

$$P_{tot} = m_{idle} \cdot P_{idle} + \bar{m_{idle}} \cdot \{P_{con} + m_{Tx} \cdot m_{Rx} \cdot P_{Rx+Tx} + m_{Rx} \cdot [P_{Rx} + P_{RxRF}(S_{Rx}) + P_{RxBB}(R_{Rx}) + m_{2CW} \cdot P_{2CW}] \quad m_{Tx} \cdot [P_{Tx} + P_{TXRF}(S_{Tx}) + P_{TXBB}(R_{Tx})]\} \tag{1}$$

Similar modelling processes have shown that total power consumption on the transmit side in based almost entirely on the RF output power, with the TX data rate having very little effect, due to the large energy consumption of the power amplifier. The RF power level isself is well described in [5] and [6], shown in equation 2. This shows UE power level is set by the eNB, dependent on reference power P_0 and path loss (PL) as expected, but additionally resource block allocation (M), with offsets for MCS (Λ_{TF}) and closed loop operation (f). [7]

$$P_{Tx} = min\left(P_{max}, P_0 + 10log_{10}(M) + \alpha \cdot PL + \Lambda_{TF} + f\right) \tag{2}$$

B. Duration

In a basic sense, transmission duration can be calculated as packet size, divided by transport block size, which would be valid for the continuous transmission case. The only parameter that would be required for a model would be a derivation of MCS as a function of SNR; with higher MCS's (higher order modulation and less forward error correction) being used over more stable channels.

Modelling the likelihood of a particular MCS being prescribed can be particularly challenging, as this is usually done with proprietary algorithms in the eNB. These algorithms are most likely aimed at maximising metrics such as throughput or latency.

One of the biggest differences with machine type communications is the duration. If uplink data can fit into a single subframe, the amount of time and energy spent transmitting the request for resources will be approximately the same duration again. In addition to this, there are many other LTE system overheads that can throw off a data based power consumption model.

C. Idle Time

Once the UE has sucessfully transmitted data, there is a sequence of power states the devices passes through before true idle mode, the state diagram in Figure 2 illustrates this.

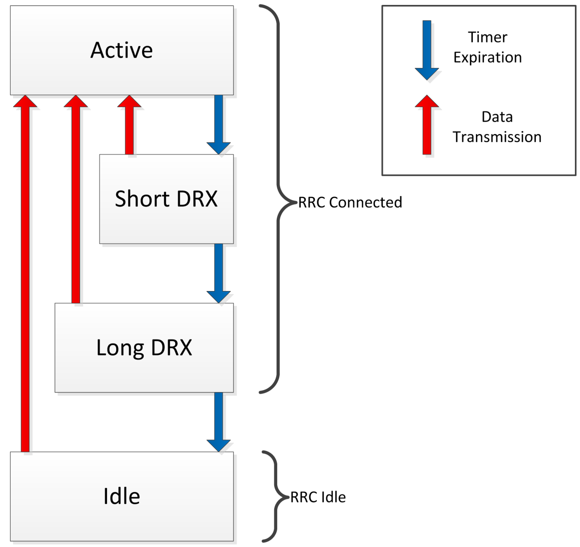

Fig. 2. UE Power States

Once transmission has occurred in the active state, an inactivity timer begins, when this has expired, the device enters 'Short DRX' mode, where resources are no longer assigned, and reception of control information from the eNB is periodic rather than continuous, in order to reduce energy consumption. Similarly, a short cycle timer is initiated, upon expiry the UE enters the 'Long DRX' state, which simply increases the length of the period between waking to receive messages.

Once the system inactivity timer has expired, the UE enters the 'RRC Idle' state, where is is no longer connected to the network, but continues to be able to receive paging data in a DRX scheme.

The idea behind this scheme is that power consumption reduces as we move from the top of the diagram to the bottom, but the latency for a new transmission increases. Ideally this state machine should make for an easily characterisable system, however this has not been found to be the case in network measurements.

III. Measurement Set-up, Results and Discussion

A. Measurement Set-up

The equipment used for measurement is shown in figure 3. Current consumption is achieved using a simple series resistor fed through a low noise instrumentation amplifier into an ADC, which also measures supply voltage, combined to give DC power consumption. RF output power is measured using a 20dB directional coupler fed into an envelope detector, then through a pre digitisation low pass filter, and finally an ADC before being logged.

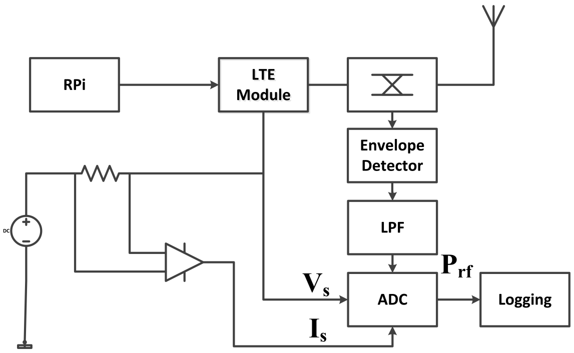

Fig. 3. Block diagram of measurement hardware

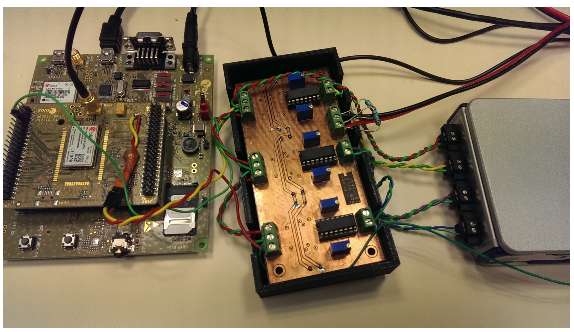

Fig. 4. Photograph of measurement hardware

Initial experiments consisted of using an appropriate source to generate UDP packets, appropriately fire-walled in order to block any system level communications interfering with measurements. The waveforms for supply voltage, supply current, and RF output power were recorded for the duration of the transceiver active process. UPD packet size was varied between 2^3 and 2^{15} bytes of data.

The first scenario was recorded in a lab based scenario with a base station emulator. This gave baseline performance comparable with prior work. A second experiment was carried out on a live LTE network in order to asses the effects of additional protocol overheads in a real environment.

B. Results

To begin with, a comparison can be drawn between the power profile of the ideal transmission using the base station emulator, and the real world equivalent using an actual network. Figure 5 is the ideal scenario; Two peaks can be observed in the RF envelope, corresponding to the process of requesting resources from the base station for the first peak, and transmitting the UDP packet for the second peak. Increases in DC power consumption in between the two peaks correspond with the reception and decoding of resource grants and acknowledgements from the base station. It is important to note that this entire process takes no longer that 20ms.

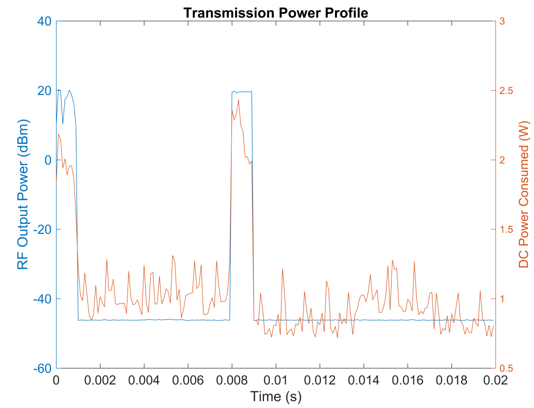

Fig. 5. Power profile - Lab setup

Figure 6 shows an equivalent transmission on a standard LTE network, DC power consumption has been omitted for clarity. The most important thing to note is the large increase in activity in the RF transmitter; a duration of 10.5 seconds in comparison to the 20ms of the ideal case. As mentioned in the subsection on measurement set-up, appropriate firewalling is used to ensure no extraneous transmission from the UDP source, so all activity beyond transmission of the UDP data is a result of communication between the UE and eNB / network.

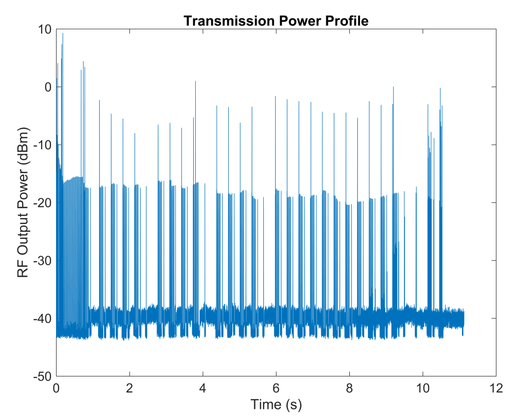

Fig. 6. Power profile - External network

In order to ensure that is is not an infrequent occurrence, Figure 7 shows the distribution of the time spent transmitting for all packet sizes from 8 to 32768 bytes over 10 iterations of each set. It can be seen that the RF activity time is independent of UDP packet size. The likelihood here is that the transmission time is determined by the RRC activity timer. Once the UDP transfer has been completed, additional network traffic is transmitted until the timer expires and the UE enters the RRC idle state.

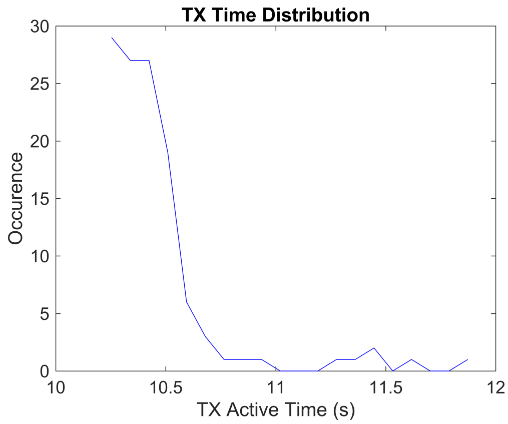

Fig. 7. Distribution of time spent transmitting

To gain a better idea of the processes contributing to this additional energy consumption, it is helpful to compare the the ideal emulated case with the real deployment. Figure 8 shows energy consumption and transmission in proportion to the amount of data transmitted. It can be seen that there is a strong correlation between packet size and both RF energy transmitted, and DC energy consumed. The flat portion at the beginning of each data series corresponds to where the transport block size is less that one subframe, thus a complete transmission consists of a request for resources, followed by a transmission of data, and since we are have not entirely filled a transport block over these values, transmission time is set at the lower bound of 1 subframe (1ms) and the energy consumption is consistent with this. Using higher modulation schemes will increase potential transport block size, and thus the range of UDP packet size over which transmission energy consumption is invariant. This also means that measurement of the length of this invariant section can help to ascertain the allocated MCS from the eNB.

Figure 9 shows the same measurements, averaged over 10 iterations on a real network deployment. It can be seen that the plot of RF energy versus packet size follows a similar trend to the lab scenario. This is particularly interesting as is suggests that despite the dramatic increase in perceived transmitter activity, and consistent length of this activity, the amount of actual energy transmitted increases proportional to packet size. It can be ascertained that the additional transmissions are short in duration or low in power in comparison with the core packet transmission. Considering the plot of energy consumed overall, this appears to be relatively uncorrelated with packet size; from which we can deduce that while extended duration does not result in a large amount of extra energy being transmitted, the energy consumed by all of the modem processes being active is significant, and results in a distribution of power consumption uncorrelated with packet transmission size.

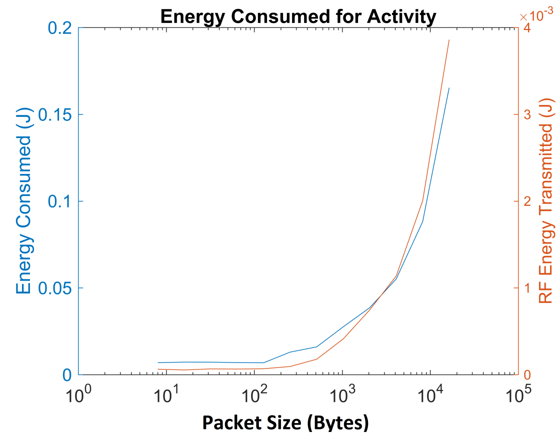

Fig. 8. Energy used per transmission - Lab setup

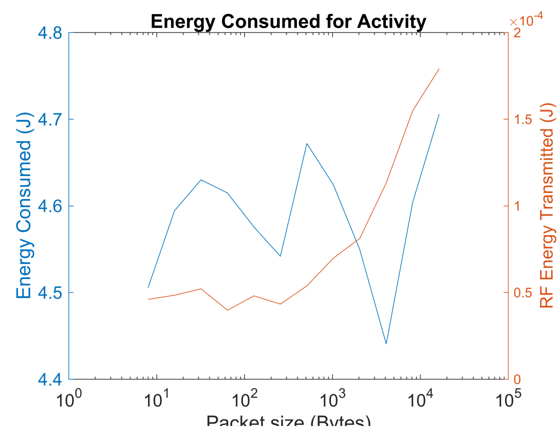

Fig. 9. Energy Used per Transmission - Network setup

Verification can be obtained from Figure 10 that shows the additional periods of transmission are both at a significantly lower power, which can be observed in Figure 6, and are also likely to have a low duty cycle in terms of RF active power. It is possible that the additional information transmitted is done so at a lower MCS, is order to take advantage of a lower P_{Tx} , intended to save energy.

IV. Conclusion

Using a comparison of experimental results from an emulated lab based LTE network and a real-world deployment, it can be seen there are large differences in system energy consumption whilst transmitting UDP packets of various sizes. The main discrepancy is the addition of a large amount of network communication between the UE and eNB, likely to be related to networks optimisation parameters such as self organising networks and automatic neighbour relations [8], in addition the multitude of

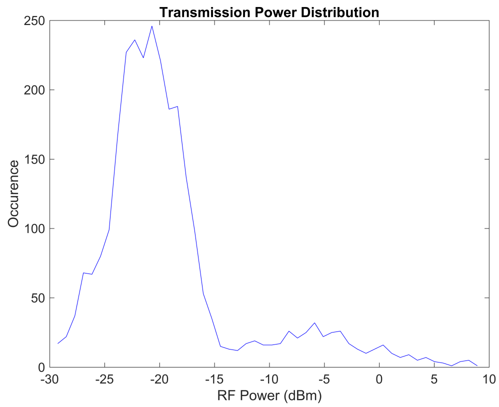

Fig. 10. TX Power Distribution - External network

possible measurements the UE can be required to make, specified in [9].

Despite the fact that the level and duty cycle of these additional transmissions are low, the effect of the transceiver being active over a much larger interval adds considerably to the overall power consumption of the device. This occurs to such an extent that over the range of UDP packet sizes transmitted, the DC power consumption of the transceiver cannot be accurately modelled in relation to transmission size, but may perhaps be better defined by peak transmission power, and a distribution of power consumption associated with this.

Acknowledgment

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