A Measurement-Based Model of Energy Consumption in Femtocells

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***Abstract*—We report detailed measurements of the electrical energy consumption of a commercial 3G femtocell basestation. We propose a simple analytic model that accurately fits our measured data and which can be used to predict energy consumption as a function of the offered load and datagram size.**

I. Introduction

In this paper we report detailed measurements of the electrical energy consumption of a commercial 3G femtocell basestation. To the best of our knowledge these are the first such power consumptionmeasurements presented in the open literature. We also present a simple analytic model that accurately fits our measured data and which can be used to predict energy consumption as a function of the offered load and datagram size.

Femtocells are a key component of next generation hierarchical cellular networks. They are small cells, with typically less than 50m coverage radius, that allow traffic to be offloaded from an existing macrocell and so provide an economic way to increase network capacity. Use of small cells yields a significant reduction in the radio energy required to achieve a target data rate or, alternatively, allows higher data rates to be achieved. However, use of large numbers of femtocells (>250,000 femtocells are reported to already be deployed in the UK alone) raises questions about the corresponding electrical energy consumption footprint. It is the latter which we address here.

While there exists a large literature relating to energy consumption in cellular networks, this is almost entirely focussed on either (i) macro-cell basestation energy consumption (*e.g.* see [2] and references therein) or (ii) handset energy consumption. One notable exception is the recent work by Auer *et al* [1] which integrates detailed component models to obtain models for overall energy consumption in both large and small cell basestations. However, this work focusses on prediction of energy consumption in future LTE basestations, and does not present any empirical measurements of basestation energy consumption. Recent work on energy minimisation in femtocell networks formulates this task as an optmisation problem, but assumes the availability of an appropriate model of electrical energy consumption *e.g.* see [3] and references therein.

The rest of the paper is organised as follows. In Section II we describe our measurement setup. In Section III we present representative measurements of electrical power consumption under a range of operating conditions. In Section IV we derive a simple predictive model that fits our measured data well, and in Section V we demonstrate the use of the model to predict the energy consumption of voice and data applications.

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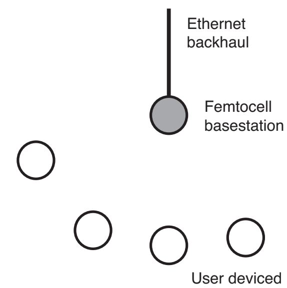


Fig. 1: Network topology.

II. Experimental Setup

A. Network setup

The test environment is composed of a single femto–cell and up to four end–user devices, see Figure 1.

The femtocell basestation is an Alcatel–Lucent device (model 9361 Home Cell V2-V). The femtocell acts as a standard 3G basestation and uses a SIM card which is active on the cellular network and that has been registered for use with the femtocell. The femtocell basestation is equipped with an Ethernet port that must be connected to a suitable broadband connection to provide backhaul access to the network operator. In our experiments the femtocell is connected to the campus network. During bootstrap the femtocell establishes an encrypted VPN connection to the network operator which is used to carry all the traffic to/from end–user devices in the cell. This traffic may include voice/video calls and data transfer sessions. The femtocell supports up to four simultaneous end–user devices.

End-user devices studied included one mobile broadband modem and three mobile phones. The mobile broadband modem used during the measurements is a Huawei K3770. This device supports HSUPA/HSDPA/UMTS standards on the 2100MHz/900MHz bands and the GSM/GPRS/EDGE standards on the 850/900/1800/1900MHz bands. The device is rated for 2Mbps HSUPA and 7.2Mbps HSDPA date service. Mobile phones were Samsung model Galaxy S2.

B. Measuring electrical energy consumption

We used a custom Energino instrument to measure the electrical energy consumption of the femtocell basestation. Energino is a plugload meter designed to monitor the energy consumption of DC devices. It consists of an hardware and a software components both based on the Arduino platform. A management backend written in Python is used to congure Energinos operating parameters, *e.g.* sampling rate and resolution, to turn the monitored device on/off, and to gather the energy consumption statistics. Energino supports sampling rates up to 10KHz and measures electrical power with an accuracy of approximately 1mW. See [4], [5] for further details. In our experiments the Energino instrument is located between the electrical power plug of the basestation and the wall socket, and so measures the power consumption of the complete basestation.

C. Traffic generation

Several types of traffic were generated on the end-user devices, including 3G voice calls, SMS, MMS, 3G data (youtube, browsing) and CBR and VBR UDP data traffic. UDP data traffic was generated using iperf, with traffic transmitted from the end-user device to a public machine.

III. Measurements

In the following sections we present representative measurements of energy consumption when the basestation is idle (powered on but with no end-user devices associated to the cell), as the offered load is varied and as the datagram size used is varied.

A. Basestation idle

Figure 2 shows measured electrical power consumption vs time when the basestation is idle. It can be seen that the power consumption consists of a baseline value of around 7.77W (with some variability around this mean value), periodic spikes (with period 10s) and a number of less regular spikes. From inspection of tcpdump traces on the wired backhaul link, we find that the spikes in power are correlated with communication on this link and so appear to be related to network management functions.

B. Energy consumption vs offered load

Figure 3 presents measurements of the mean power consumption of the femtocell basestation when a single end-user device is associated that is transmitted UDP data traffic. Results are shown of power consumption as the offered load is varied. Figure 3(a) shows measurements when the UDP datagram size is 1536B, while Figure 3(b) shows measurementst when the UDP datagram size is 128B. Also indicated are the 2σ confidence intervals.

It can be seen that the power consumption increases with offered load before reaching a plateau. For a given offered load, the power consumption is uniformly higher for the small datagrams than for the large datagrams, *e.g.* at 0.5Mbps the mean power consumption is 8.07W with 1536B datagrams and

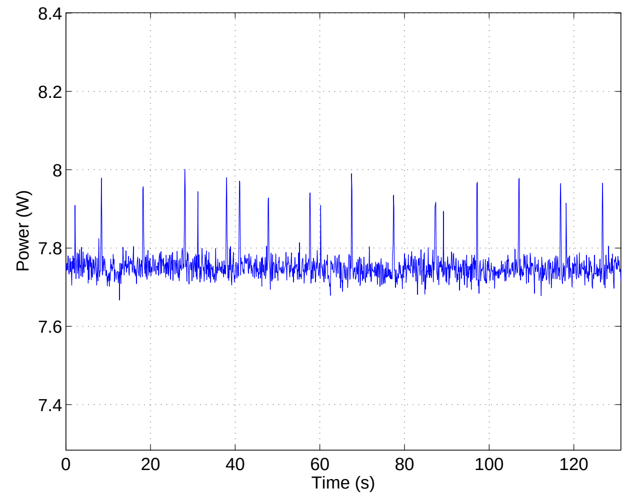
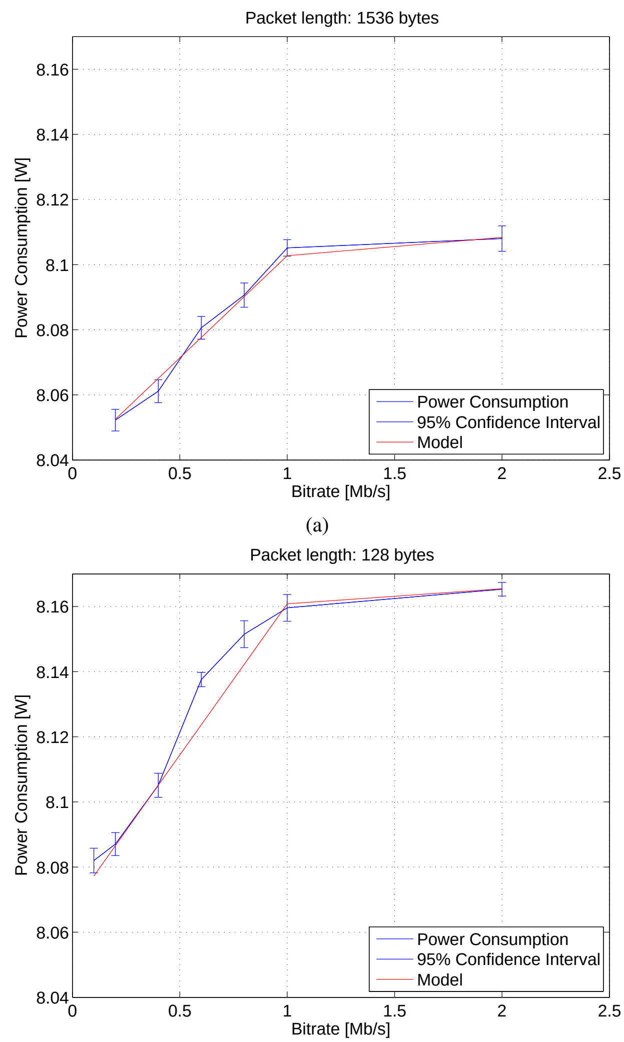


Fig. 2: Measured power consumption of the femtocell basestation when idle (no end-user devices associated).



(a)

(b)

Fig. 3: Average power consumption at the Femtocall as a function of the bitrate size for a constant datagram length. Packet loss was lower that 5% for bitrates equal to or lower than 1 Mbps. The femtocell is acting as receiver.

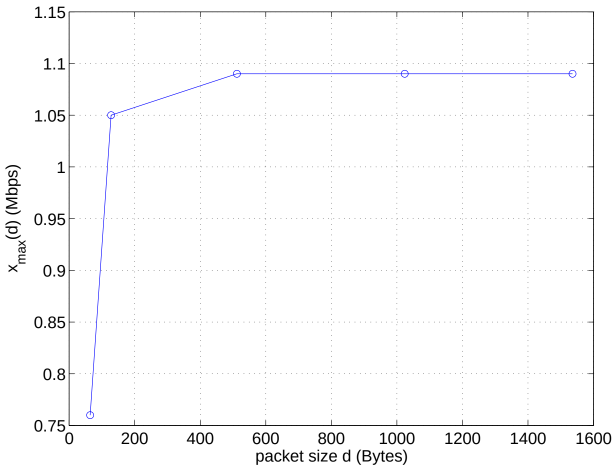


Fig. 4: Measured maximum network throughput vs datagram size.

8.12W with 128B datagrams. The rate of increase with offered load is also somewhat higher with smaller datagrams.

The plateau in power consumption correlated with the offered load reaching the network capacity. With 1536B datagrams the maximum network throughput is observed to be 1.09Mbps – at offered loads above this level, significant packet loss is observed and the net goodput remains constant at 1.09Mbps. With 128B datagrams, the maximum network throughput is observed to be 1.05Mbps. Measured values for other datagram sizes are shown in Figure 4. It can be seen that the maximum throughput increases monotonically with datagram size, and is significantly reduced at the smallest datagram size of 64B. This is as expected, since fixed network overheads (framing, ARQ and control overheads *etc*) are amortised across more data bits as the datagram size is increased.

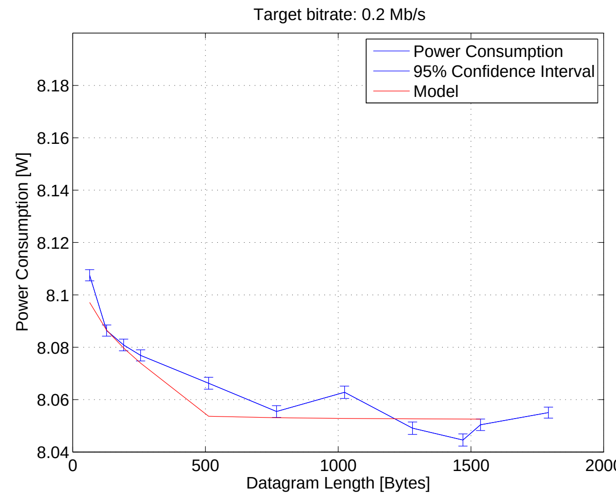
C. Energy consumption vs datagram size

Figure 5 plots measurements of power usage vs UDP datagram size. Figure 5(a) shows data when the offered load is 0.2Mbps and Figure 5(b) shows the corresponding data when the offered load is 1Mbps. Also indicated are the 2σ confidence intervals. It can be seen that the power consumption tends to decrease as the datagram size is increased. As the datagram size is increased, the number of datagrams sent per second decreases when the offered load in Mbps is held fixed. Per datagram overheads (framing, ARQ, *etc*) are therefore reduced and presumably this is the source of the reduction in power consumption. Observe that the power consumption appears to rise again for datagrams above about 1470B. We believe that this is due to fragmentation of these larger datagrams – from separate downlink tcpdump measurements, we estimate the wireless link MTU to be 1368B.

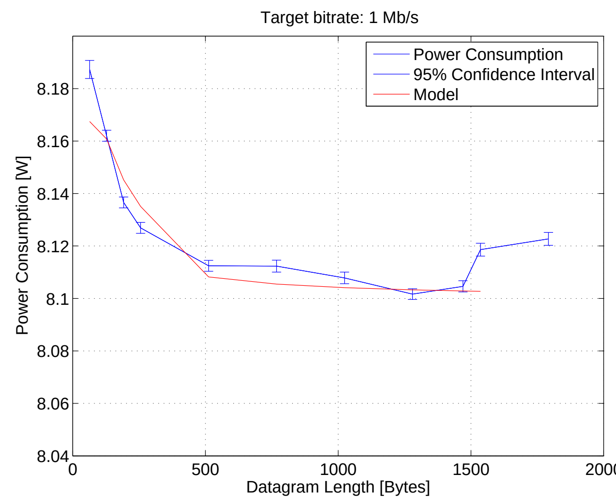
IV. Energy Model

Based on the preceding measurements, we propose the following simple model of femtocell basestation energy consumption,

$$P = \alpha(d)sat(x,d) + \beta(d)\delta(x) + \gamma \tag{1}$$



(a) 0.2Mbps



(b) 1Mbps

Fig. 5: Average power consumption at the Femtocall as a function of the datagram size for a constant traffic generation rate of 1Mb/s. Packet loss is lower that 2% for all measurements, except for the one with datagram length set to 64 bytes where packet loss is 26%. The femtocell is acting as receiver.

where P is the basestation power consumption in Watts, x is the offered load in Mbps, d is the datagram size in bytes and

$$sat(x,d) = \begin{cases} x & 0 \le x \le x_{max}(d) \\ 0 & x \le 0 \\ x_{max}(d) & x > x_{max}(d) \end{cases} \tag{2}$$

$$\delta(x) = \begin{cases} 1 & x > 0 \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

In this model, $sat(\cdot)$ captures the observed plateau (see Figure 3) in power consumption once the offered load exceeds the network capacity. $\alpha(d)$ captures the fact that the rate of increase in power consumption with offered load is observed to depend on datagram size (again, see Figure 3). $\beta(d)$ captures the dependence of power consumption on datagram length when the offered load is held fixed (see Figure 5). γ captures the baseline power consumption when the femtocell is idle (no

Parameter	Value
α_0	0.06 W/Mbps
α_1	70 B
γ	7.77 W

TABLE I: Energy model parameter values

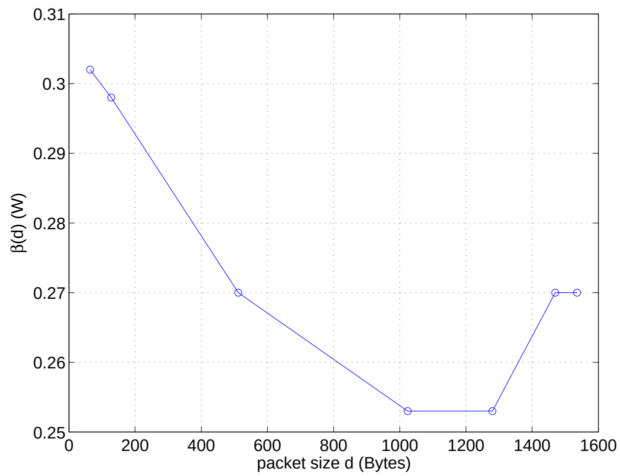


Fig. 6: Energy model $\beta(d)$ values.

end-user clients associated).

From Figure 2 we can estimate γ to be 7.77W. Figure 4 gives the measured values for x_{max}. When the dependence of $\alpha(d)$ on datagram size is primarily due to the contribution of fixed overheads per datagram (framing *etc*, as already noted), we can select

$$\alpha(d) = \alpha_0(1 + \frac{\alpha_1}{d}) \tag{4}$$

where α_0, α_1 are parameters. α_1 can be thought of as the per datagram overhead, specified in bytes, while α_0 is a factor converting between units of bytes and energy.

Using this choice of structure for $\alpha(d)$, we find that with the parameter values given in Table I and the $\beta(d)$ values shown in Figure 6 this simple model provides a good fit to our measurements across the full range of operating conditions considered. For example, the model energy consumption predictions are indicated by the red lines in Figures 3 and 5. Similar predictive accuracy is obtained for other datagram sizes and offered loads.

Observe that structure of the proposed model is simple yet intuitively reasonable. γ and x_{max} can be directly measured. The function $\alpha(d)$ varies in accordance with fixed overheads. From Figure 6 it can be seen that $\beta(d)$ decreases with increasing datagram size until a datagram size of around 1300B is reached and then increases again. This increase is consistent with the onset of fragmentation commented upon previously.

V. Energy usage of voice and data applications

As a first application of the model (1) we consider predicting the energy usage of two applications, namely: voice and and FTP. Note that the model is derived from energy measurements with uplink UDP transmissions whereas these applications all involve a mix of downlink and uplink transmissions while the FTP application uses TCP rather than UDP. Hence, they provide quite a harsh test of the model.

No. of calls	Measured Power (W)	Model Predicted Power (W)
1	8.055	8.073
2	8.050	8.079
3	8.075	8.086

TABLE II: Power consumption vs number of active voice calls.

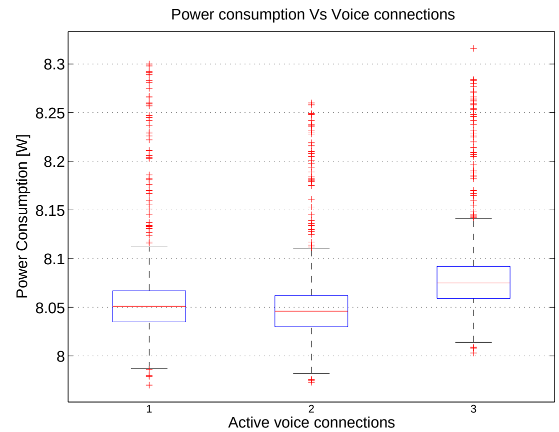


Fig. 7: Measured femtocell basestation power consumption vs. an increasing number of voice calls. Note that the femtocell only supports up to 4 active user terminals at any given moment.

A. Voice

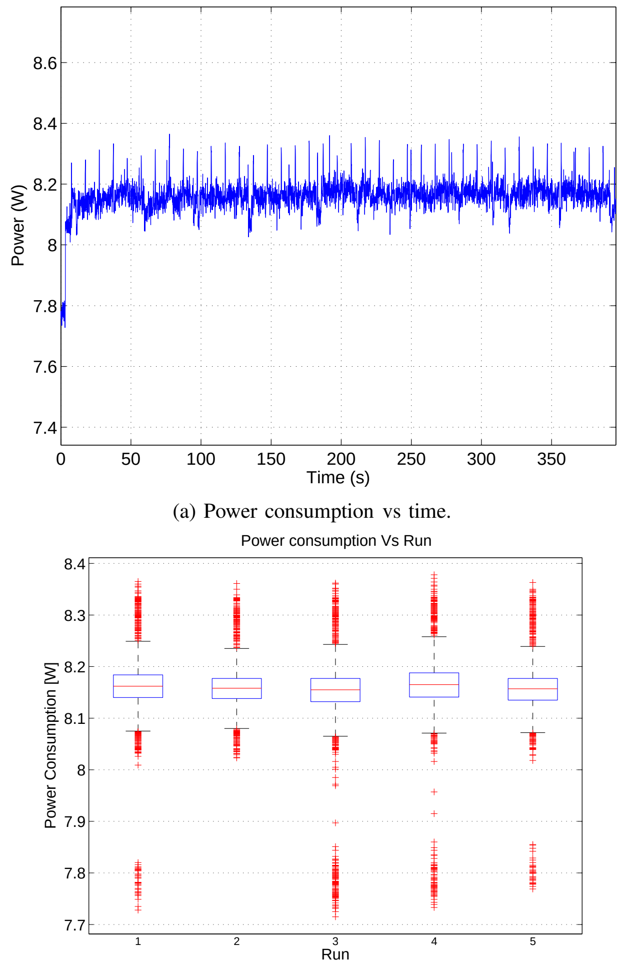
Figure 7 plots the measured power consumption vs the number of active voice calls. The data is presented in box and whiskers form – the central mark is the median and the edges of the box are the 25th and 75th percentile values.

Using a datagram size of 128B (from tcpdump measurements) and an offered load of 64Kbps per call, the mean power consumption predicted by model (1) is shown in Table II together with the mean measured power (from Figure 7).

It can be seen that the model predictions for power consumption is slightly too high, by 10-30mW. Note that the prediction using (1) assumes that downlink transmissions behave the same as uplink transmissions from an energy consumption point of view (since the model is derived from uplink transmissions). This is certainly inaccurate since it neglects the fact that radio energy must be expended by the basestation when making downlink transmissions. Since the user device was located within a few metres of the basestation in our tests and we believe that the basestation uses transmit power control, the transmit power should be relatively small and is likely to explain much of the observed power difference.

B. FTP Download

Figure 8 plots measurements of the femtocell basestation electrical power consumption during an FTP download (the download is of an large file from a linux mirror site). Figure 8(a) shows a measured time history of power usage while



(a) Power consumption vs time.

(b) Power consumption Vs. FTP runs

Fig. 8: Power consumption during an FTP download.

Figure 8(b) summarises the results of 5 downloads in a box and whiskers plot.

Using a datagram size of 1368B (from tcpdump measurements) and an offered load on the downlink of 1Mbps (close to the network capacity), the mean power consumption predicted by model (1) is 8.094W. This compares with a mean value of 8.16 W in the measurements shown in Figure 8. The difference between these measured and predicted power usages is 66mW.

As noted above, the prediction using (1) neglects the fact that radio energy must be expended by the basestation when making downlink transmissions. While in the case of a voice call the downlink is active only for a fraction of the time, during our FTP downloads the downlink is active for the majority of the time. Hence, we can expect the radio power consumption to somewhat higher than in the case of voice calls, and this is consistent with the observed difference of 66mW with FTP vs 10-30mW with voice.

VI. Conclusions

In this paper we report detailed measurements of the electrical energy consumption of a commercial 3G femtocell basestation. To the best of our knowledge these are the first such power consumptionmeasurements presented in the open literature. We propose a simple analytic model that accurately fits our measured data and which can be used to predict energy consumption as a function of the offered load and datagram size. We demonstrate the use of this model to predict the energy consumption of voice and data applications. We are currently using the model to formulate femtocell energy minimisation as an optimisation task and will report on these results in due course.

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