

# Breathe to Stay Cool: Adjusting Cell Sizes to Reduce Energy Consumption

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## ABSTRACT

Reducing the energy consumption of a wireless cellular network is an important and urgent problem. This paper studies the effect of cell sizes on the energy consumed by the network, assuming base station technologies of today and the future. Making cell sizes too small or too large can significantly increase energy consumption. We show that the optimal cell size from an energy perspective depends on a number of factors, including base station technology, data rates, and traffic demands. Given that traffic varies significantly during a day, dynamically adjusting cell sizes can help reduce energy consumption. We propose a practical, 2-level scheme that adjusts cell sizes between two fixed values, and show an energy saving of up to 40%. The paper also proposes some self-organizing techniques to allow this dynamic cell size adjustment.

## Categories and Subject Descriptors

C.2.1 [Network Architecture and Design]: Wireless communication; C.2.3 [Network Operations]: Network Management

## General Terms

Design, Management, Performance

## Keywords

Energy Efficiency, Wireless Network Design, Cellular Network Planning

## 1. INTRODUCTION

Energy consumption has become a serious concern for the telecommunications industry world wide. Both wireless and wireline operators are attempting to streamline their energy usage for environmental as well as economic reasons. The economic impact of energy is particularly dire in emerging markets. For example, in India energy costs for large operators amount to several hundred million dollars annually

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and are close to half of their overall operating expenses [32]. The main reasons for the high energy-related expenses include the lack of access to a reliable grid supply and high ambient temperatures requiring significant cooling. Some sites don't have access to any electric grid at all, and are operated entirely on diesel-powered generators. At most other sites, diesel generators are routinely run as back-up for several hours during the day. They not only lead to high emissions, but suffer from the high cost of diesel fuel and maintenance, as well as diesel pilferage.

In this paper, we focus on optimizing the energy consumption of wireless cellular networks. Optimizing capacity, coverage and their trade-off has been well studied in the design of cellular networks. At the planning stage, urban cell sizes are typically limited by capacity constraints while rural cell sizes are determined by the uplink power budget of the mobile. Power-efficient small cells such as femtocells are becoming popular in very small areas (especially indoors) where capacity or coverage require boosting [10]. However, there has been little study of what cell sizes are the most power efficient in a wider, macrocellular setting. This paper shows that several factors affect the energy consumption of a cellular network. Therefore, energy usage must be carefully accounted for not only during static planning, but also dynamically as the cell's traffic varies.

Intuitively, since receive power falls rapidly with distance from the base station,<sup>1</sup> the smaller the cell size, the lower should be the total power consumption of the access network. However, there are several unavoidable energy costs involved in simply keeping a base station active with full coverage but minimal capacity. For example, the circuitry, the paging channel, the backhaul and the power amplifier all consume power. Figure 1a shows the variation of power consumption of a commercial base station with capacity, while Figure 1b shows the power consumption of another base station while varying the output power (and hence coverage). Even at low coverage and capacity levels, the power consumed by a base station today is non trivial. Therefore, it is not clear what cell size is the most energy efficient. Further, turning off entire base stations will give more energy savings than simply reducing capacity by turning off carriers at times of low load.

This paper aims to find the "sweet spot" for cell sizes in terms of energy consumption<sup>2</sup>. We find that different cell sizes are most energy efficient for different loads. Since traf-

<sup>1</sup>Typical path loss exponents are greater than 3 [1], while cell sizes grow as square of the cell radius.

<sup>2</sup>Other expenses such as hardware, rent, maintenance, back-

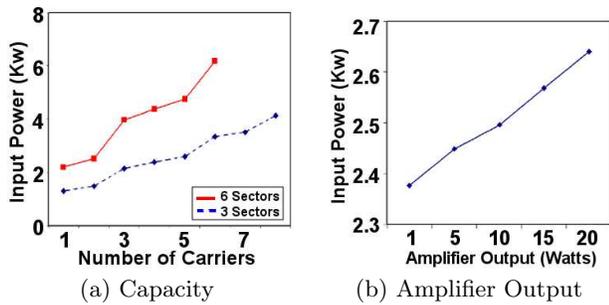


Figure 1: Power variation of commercial BS with (a) capacity (represented as number of voice carriers) and (b) amplifier output power. Each CDMA2000 1x voice carrier is a 1.25MHz FDD channel that can support 33-45 voice calls. (a) is from specifications and (b) is from experiments with a commercial 3x3 BS (3 sectors, 3 carriers each).

fic demands change significantly over the day [8], no single cell size will always be most power efficient. We show that by constantly and arbitrarily (at fine granularity) varying cell sizes with traffic demands, the energy consumption can be reduced by up to 46%. Clearly, arbitrarily varying cell sizes while maintaining coverage may not be practical since base stations can only be installed in certain fixed locations. Therefore, we introduce a multi-layer cellular architecture that automatically detects traffic demands at different locations and selects the best cell size from a few alternatives. Limited cell boundary adjustments or “cell breathing” automatically takes place in today’s CDMA networks; a highly loaded cell shrinks due to interference and mobiles get handed off to neighbouring cells. In our scheme, we stress the importance of completely turning off some cells. Thus all the cells are turned on and operate at a small cell size when high capacity is required. At times of low loads, the lower-layer cells turn themselves off and the higher-layer cells expand to take over their coverage area. Automatic management of such a dynamic architecture becomes a key requirement and we suggest some techniques towards this goal. We show that a simple 2-layer architecture that is compatible with current cellular standards can save up to 40% power compared to a traditional static cellular network.

## 2. RELATED WORK

The large and rapidly growing number of base stations consume the most energy [12] in such a cellular network. Several recent efforts by researchers and vendors have reduced the energy-related costs of individual base stations, such as using more energy-efficient components (especially power amplifiers), better cooling, turning down resource usage at idle times, or applying alternative energy sources [4, 5, 9, 18, 31]. However, limited attention has been given to designing or optimizing the overall network architecture to make it more energy-efficient, either statically or dynamically. Our network-level optimization approach is entirely complementary to such efforts for making individual base stations more energy efficient.

Energy efficiency of a network has been very well studied in the ad-hoc networking and sensor networking world, haul, etc. will need to be factored in when conducting a complete cost analysis.

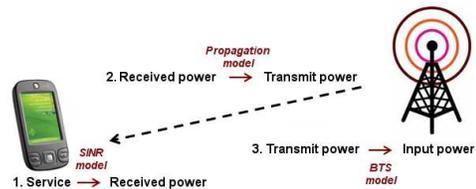


Figure 2: Methodology for computing base station’s power consumption for a given user service.

where inexpensive, battery-powered wireless devices need to prolong their lifetime with minimal expenditure of energy<sup>3</sup>. In contrast, the capacity and coverage constraints imposed upon cellular networks are entirely different. Nevertheless, cellular technologies can benefit by learning from some of the self-organizing, self-managing techniques explored in ad-hoc networks. Our work to self-configure the network dynamically for energy efficiency fits well under the 3GPP LTE theme on self-organizing networks [3, 10, 25].

Cell breathing, that is, adjusting local cell boundaries has been studied for load balancing [28]. Hierarchical cellular networks have been proposed with the aim of increasing capacity using smaller cells while avoiding high hand-off rates [33], or to integrate multiple wireless technologies [19]. Multi-hop wireless networks that relay data to one mobile through another mobile for improved coverage and capacity have also been proposed [17, 20], including schemes to save the mobile’s energy consumption [30]. However, as far as we know, this is the first paper to propose multi-layer networks to reduce the total energy consumption of the cellular network.

## 3. ENERGY EFFICIENT CELL SIZE

In this section we model the total power consumption of a cellular network and study its dependence on the cell size and traffic load.

### 3.1 Power Consumption of a Cell

We first model the power consumption of a single cell, based on the cell size, type of service, terrain, active user population and the base station’s fixed power consumption. The major components of this model are illustrated in Figure 2.

#### 3.1.1 SINR Model

Table 1 lists parameter values of GSM [27], UMTS [22] and WiMAX [2] services. We use the Shannon-Hartley theorem [29] to calculate the *SINR* from the bit rate and channel bandwidth, accounting for the energy efficiency [6] of the encoding scheme. The total interference and noise level from thermal noise level [16, 23], noise figure of the device [15] and the maximum allowed adjacent channel interference margin for that service [14] are also computed. The product of *SINR* and combined interference and noise level is the received signal required at the user. For GSM, we simply assume the receiver sensitivity of  $-104$  dbm defined in the standard [27] to be the received signal.

#### 3.1.2 Signal Propagation Model

Given the receive power required at the user, we compute the power that must be transmitted by the base station (BS)

<sup>3</sup>References are too many to include here.

	GSM900	UMTS FDD	WiMAX
Downlink Freq.	935 MHz	2110 MHz	2300 MHz
Channel b/w	200 kHz	5 MHz	10 MHz
GBR per user	13 kbps	384 kbps	5 Mbps
Channel Code	LPC	Turbo	Turbo, LDPC

Area of cell of radius $d$	hexagonal: $(3\sqrt{3}/2) * d^2$
Urban pathloss model	COST 231 Walfisch-Ikegami [1]
Urban fading values	Rayleigh [26] 9dB (0 for WiMAX) Shadow[21] 5dB, Indoor prop. 10dB
BS power model	Antenna feeder loss 3dB, Tx gain 10db, Power amplifier efficiency $\sim 50\%$

Table 1: Urban modeling parameters.

antenna. Similar to downlink budget calculation [7, 24], we consider path-loss due to free-space loss and terrain details, multipath-fading and shadowing with values in Table 1. The signal received at user after adjusting upwards for all these losses is the transmit power required at the BS. The total BS transmit power is then obtained by multiplying it with the active user population under that BS.

### 3.1.3 Base Station Power Model

From the total transmitted power obtained in the above section, we compute backwards the total input power to the BS power amplifier, accounting for power loss in the power-amplifier and in the antenna feeder cable (see Table 1). We have modeled several commercially available amplifiers [11] as well as a futuristic power amplifier with 70% efficiency. The BS also has a fixed power consumption due to the circuitry, backhaul, control channel etc. Hence, the total power consumption of the base station  $P_{BS}$  is the addition of these fixed and variable components.

## 3.2 Network Power Consumption

We now relate the network's total energy usage with the cell size  $d$ . Let us assume the access network is over an area  $A$  with a homogeneous cell size. Also, there are  $N_u$  active users at a particular instance of time distributed among cells. The total number of cells in the network ( $N_c$ ) can be calculated as per Table 1. The cell size  $d$  and number of users per cell will determine power consumption  $P_{BS}$  of each BS and the total network power consumption will be  $P_{total} = P_{BS} * N_c$ . It can also be expressed as

$$P_{total} = \frac{A \cdot c_1}{d^2} + c_2 \cdot N_u \cdot d^e \quad (1)$$

Here constants  $c_1$  and  $c_2$  depend on various parameters used in the model and  $e$  is the associated path-loss exponent. The first term, due to the BS fixed power, dominates for small  $d$  while the second term due to path loss dominates for large  $d$ . We can now determine the optimal cell size in terms of power for the entire network. Moreover, we can vary other parameters like type of service, user population, base station's fixed power consumption and study the variation in optimal cell size in each case.

### 3.2.1 Effect of Base Station's Fixed Power

In this section we study how the BS fixed power consumption affects the optimal cell size of an access network for a fixed service and user population. It is evident that a higher fixed power consumption will bring down the number of cells in order to keep the total energy minimum. This will result in a bigger optimal cell size as the total area is fixed. The plots in Figure 3 illustrates this behavior for the three cellular services. The fixed power consumption of a single BS

here is varied discretely from 10W to 600W. Today's base stations incur at least a few hundred watts due to their power amplifier to simply stay on and provide coverage. Therefore the 10W curve is intended to quantify the energy gains from designing base stations in the future that will consume extremely low power at idle times.

Figure 3a shows the variation of optimal cell size with fixed power consumption for GSM voice service (13 kbps data rate) in an urban area of 100 sq km and with 20000 active users. The optimal cell size varies from 440 meters to 920 meters, depending on the fixed power consumption. Figures 3b and 3c shows the same for UMTS and WiMAX data services with 4000 and 2000 active users, respectively. In this case, the optimal cell sizes are smaller but show the same trend.

The above two plots strengthen the fact that the effect of the BS fixed power consumption is a significant parameter in determining the optimal cell size (power shown here on a log scale). For an urban setting, the cell sizes shown here may be further limited by capacity constraints.

### 3.2.2 Effect of Active User Population

We now proceed to show the effect of user population on the optimal cell size. A higher user population implies higher transmit power from the base station. Clearly, reducing the cell size results in fewer users per BS, as well as reduced path loss. This behavior is illustrated in the plots of Figure 4, assuming an urban area of 100 sq km. Figure 4a shows different optimal cell sizes for GSM voice service with different user population. In this case we have assumed 100W of fixed power consumption per BS. A user population of 1000 results in an optimal cell size of 1060 meters whereas, 50000 users brings down the optimal cell size to 560 meters. A similar behavior can be observed in Figures 4b and 4c for UMTS and WiMAX data, with smaller cells being more power efficient at higher load.

The plots in Figure 4 clearly shows that there cannot be a fixed optimal cell size for the network and the current network design methods, which specify static cell sizes, will always cause an inflated power consumption as the parameters like user population vary over time. Therefore, a new network design strategy is needed in order to keep the power consumption minimum.

## 4. A MULTI-LAYER CELLULAR ARCHITECTURE

In the last section we have seen that there is no fixed cell size that optimizes the overall energy consumption of a cellular network. Smaller cells are more efficient for supporting higher capacity but due to the fixed power consumption, they become less energy efficient when the demand is low.

The demand for capacity as well as user demography itself varies over the time-span as small as one day [8]. A typical scenario is that the demand is high during day time, peaks in the evening and then becomes low at night. To optimize energy consumption under such situation, we need a cellular architecture whose cell size can adapt to current demand.

For example, consider the seven BS's named A–G in Figure 5a serving an area. Let us assume an even distribution of 700 active users in the area, during peak hour. The cell sizes are designed to support this peak load. Now, suppose that during off-peak hours, there are only 70 users in the

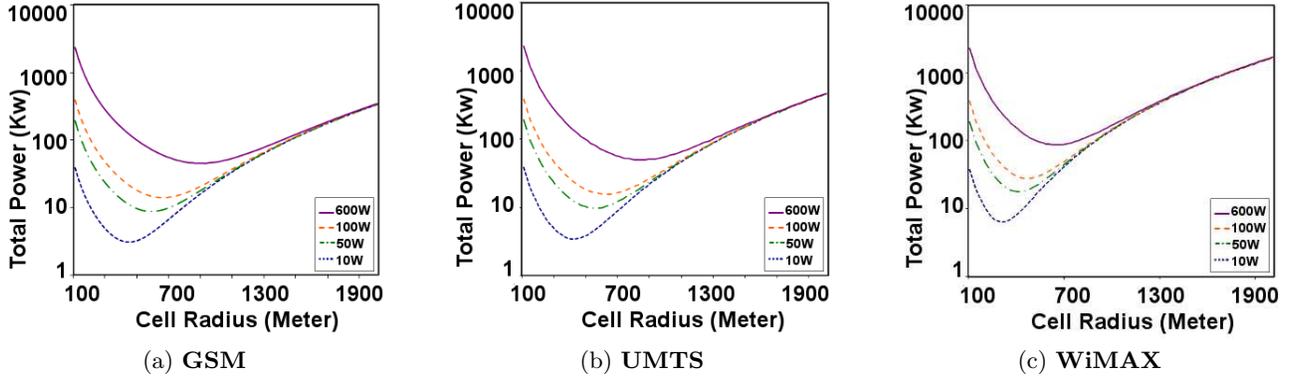


Figure 3: Network energy consumption as a function of cell radius, given a 100 sq Km area with a fixed user population. Different curves represent different values of the fixed BS power consumption.

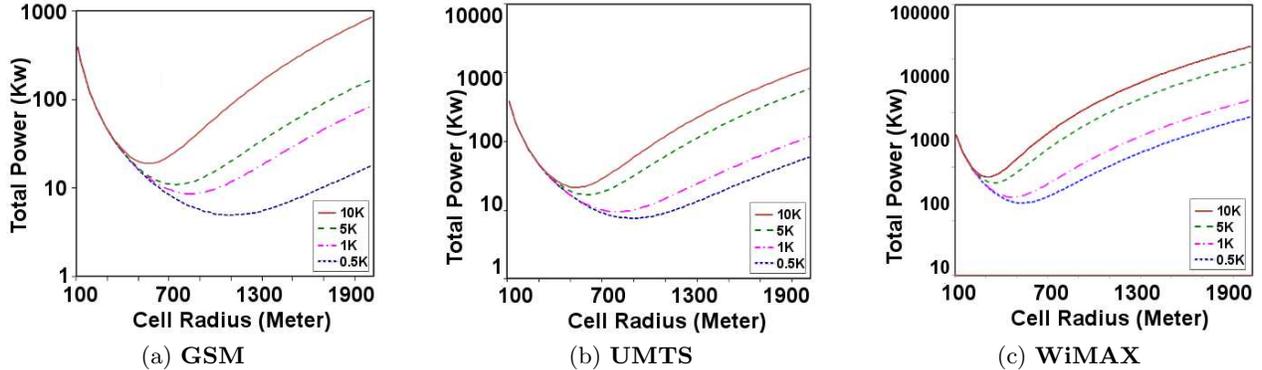


Figure 4: Energy consumption of the network as a function of cell radius, assuming a 100W fixed BS power and a 100 sq km area. Different curves represent different values of active user population in the network.

area and only 10 users under BS  $F$ . These 10 users can either be served by the central BS  $D$  using higher power or can be served by BS  $F$ . From the energy perspective, if the incremental power for BS  $D$  to serve these 10 users is less than that of keeping BS  $F$  on and serving these users, BS  $F$  should be turned off and the users should be served by BS  $D$ . Here, in Figure 5b, the cell under BS  $D$  is denoted as an *umbrella cell*, while the other cells are called *subsidiary cells*. The corresponding BS's are denoted as *umbrella BS* and *subsidiary BS* respectively. Note that, if a subsidiary BS is on, the umbrella BS can turn down its transmit power in that sector (thereby reducing coverage in that direction) to save energy. In Figures 5c and 5d cell  $D$  is the subsidiary cell with multiple umbrella cells. Subsidiary cells can be implemented in multiple ways.

**Micro Cell.** Conventional base stations with independent backhaul links to the network core can be used to implement subsidiary cells. They can be provisioned with more energy-efficient hardware compared to the umbrella cell as they serve smaller areas. Each cell here is managed independently by the radio access network.

**Relay.** Combination of a regular macro cell as umbrella cell and relays as subsidiary cells can be another option. Relays use the air interface channels from the umbrella cell for backhaul and they need not be managed by the network core. But the disadvantage is that the air interface channels have to be properly coordinated among the users served by the umbrella cell and the relays.

**Remote Radio Head.** Subsidiary cells can be implemented using remote radio heads [31]. Here a fiber carries the analog signal from the umbrella BS to the remote radio head, which is co-located with the power amplifier.

#### 4.1 Dynamic Self-Organization of the Layers

To cope with the dynamic nature of load variation with time, it would be more efficient to organize the network of umbrella and subsidiary cells in a region based on current capacity demand of that region. Each BS must be able to determine the demand in its cell, and thereby influence the decision of either acting as a subsidiary cell or turning itself off, so that the umbrella cell can serve the area. Essentially, the cellular architecture should self-organize to reduce the total power consumption. Self-organizing network (SON) concepts have been introduced in the 3GPP standard (3GPP TS 32.521). Their purpose has been to automate the provisioning and management of a network with a large number of nodes. We extend the SON concept to the optimization of energy consumption of a network. The *self-organization* can be achieved in multiple ways.

**Timed sleep mode:** In this scheme, each subsidiary BS wakes up after a pre-defined time interval and monitors the demand in its coverage area. Only if the demand is high enough, such that it is more energy efficient to serve the area from the subsidiary BS than the umbrella BS, it keeps itself on and take over the users in its coverage area. If the

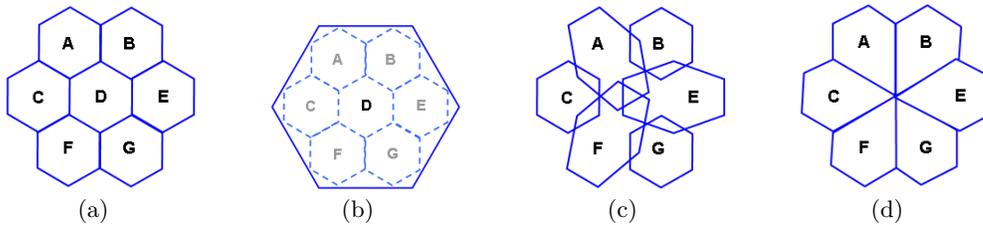


Figure 5: (a) Original, high-traffic cell configuration, and some possible low-traffic configurations: (b) Cell D covers for its subsidiary neighbors; or cell D is the subsidiary and (c) some, or (d) all of its neighbors take over its coverage.

demand drops below a predefined threshold, the subsidiary BS goes into sleep mode.

**User location prediction:** Here, the current location, direction of motion and speed of a user is detected by monitoring the signal strength from that user at multiple umbrella BS's [13]. Depending on these, the future location of that user is predicted. If an umbrella BS predicts a high enough number of users in the coverage area of a subsidiary cell, it sends a signal to the subsidiary cell to wake up and resume service.

**Reverse channel sensing:** In this scheme, the subsidiary BS's stay on in a very low-power mode (with only Rx and control channel), monitoring the reverse link noise (between users and umbrella BS) to estimate the number of users in its coverage area. An estimate beyond a threshold, triggers the beacon on, so that users in its coverage area start sensing the cell and consequently handed over to it. The umbrella cell can help in this scheme by providing current user information to the subsidiary cells around it.

## 4.2 Energy efficiency of a two layer cellular network

To show that current *worst-case-capacity* based cell sizes are not optimum in terms of energy consumption, we simulate the energy consumption of the network using an hourly traffic model based from urban measurements (see Figure 6a).

Parameters	GSM	UMTS	WiMAX
Area	100 Sq Km		
Population	20000	4000	2000
Cell Capacity	270 kbps	8 Mbps	10 Mbps
Fixed Radius	480 meters	300 meters	200 meters
Dynamic Radii	480 and 920 meters	300 and 700 meters	200 and 480 meters
Optimal Saving	36%	53%	54%
Dynamic Saving	29%	39%	40%

Table 2: Traffic Model Simulation

Figure 6 plots the hourly power consumption over a day incurred by three different schemes for GSM, UMTS and WiMAX services using parameters from Tables 1 and 2. The "Fixed" scheme selects a fixed cell radius which minimizes total power consumption while satisfying capacity constraints. The "Optimal" scheme shows the ideal scenario, where the cell radius changes to be the optimal in terms of energy at every hour. This scheme saves the most power (see Table 2) and is an upper-bound for any cell breathing scheme we employ. Finally, the more practical "Dynamic" scheme shows the power consumption of our proposed two-layer architecture. This scheme chooses two radii that minimize total power consumption over the day and switches between these

two radii depending on the traffic at every hour. Table 2 lists these fixed and dynamic radii. At times of peak load, cell sizes in all three schemes are equal and limited by capacity, and hence consume the same power. Our two-layer architecture achieves a power savings of up to 40% over the entire day. Practical radio planning considerations, described in the next section, may limit these savings to some extent.

## 5. PRACTICAL CHALLENGES

A number of challenges need to be overcome before cellular networks can dynamically reconfigure themselves to save energy.

- **Radio frequency planning.** Cells in today's cellular networks are rarely of uniform shape and size; a non-uniform physical environment (such as location of roads, buildings, hills and other clutter) and traffic demands lead to highly non-uniform cells. Further, the techniques for dynamically increasing coverage of an existing urban cell, such as increasing pilot power or reducing electrical antenna tilt, depend on the air interface standard and base station equipment being utilized. These techniques and other factors such as the physical environment, the uplink power budget, and capacity constraints may limit the extent to which coverage can be extended. Urban cells that are added purely to enhance capacity are more likely candidates for being turned off at low traffic times. Therefore, a careful study is needed at the planning stage to determine which base stations can be safely turned off, and what adjustments are needed from one or more neighboring base stations to ensure complete coverage. The pre-computed adjustments can then be executed dynamically based on load. In the simplest instantiation, two cellular configurations can be pre-computed based on peak and off-peak traffic demands, and the network can be switched between the two at appropriate times of the day.
- **Determination of switching points.** In the simplest case, the switch between "high-traffic" and "low-traffic" configurations could take place at a predetermined time daily. Alternatively, a traffic threshold at a local or network level could be set to determine when to turn off individual cells or switch between alternative network configurations.
- **Operations support.** The operations support system (OSS) needs to reconfigure the network and its parameters frequently, and manage turning on and off cell sites without affecting the rest of the network. For example, the OSS must distinguish between cells put to sleep and actual outages.

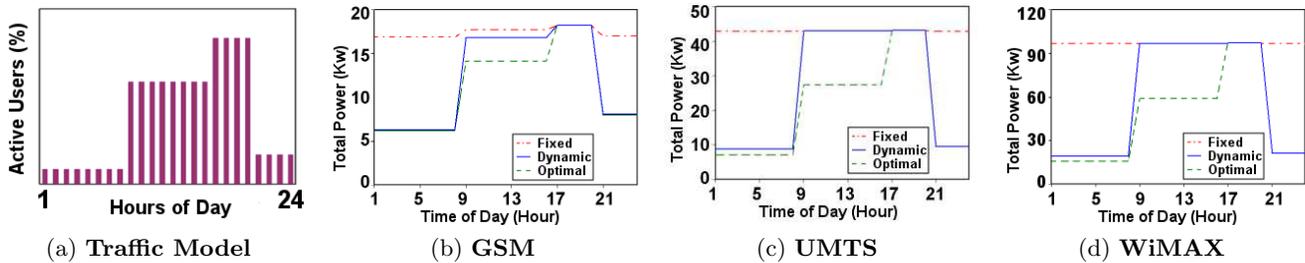


Figure 6: Urban traffic model, and energy consumption of the network over a 24 hour period. Here peak hours are 4-8pm.

## 6. CONCLUSIONS

We have shown that the most energy efficient cell size depends on several factors, including traffic load. Automatically adjusting the cell sizes and turning off cells entirely at low traffic times will be energy efficient. Our simulations show significant gains from switching between just two cell sizes in a urban scenario. Network architectures should in general be designed to adjust dynamically and automatically to save energy.

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