Wireless Networks: An Easy *Cell*
PROBLEM B: Energy and the Cell Phone

Team #5265

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Abstract

The sheer number of cell phones worldwide has raised concerns about their energy usage, even though individual usage is typically very low (¡10 kWh/year). We first model the change in population and population density until 2050 with an emphasis on trends in the urbanization of America. The current cellular infrastructure and distribution of cell sites (based on actual site locations) in the US is developed. By relating infrastructure back to population density, the number and distribution of cell sites through 2050 is identified. The energy usage of individual cell phones is then calculated based on average usage patterns. The behavior of individuals during phone charging is found to play an important role, and greatly affects yearly power consumption. The power usage of phones consumes a large part of the overall idle energy consumption of electronic devices in the US. Finally, the total power usage of the US cellular network is calculated to year 2050. If poor phone usage remains, the system will require 400 MW, or 5.6 million barrels of oil per year. If ideal charging behavior is adopted, this number will fall to 200 MW, or 2.8 million barrels of oil per year.

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1 Introduction

As energy becomes a growing issue, we are evaluating our current infrastructure to locate inefficiencies in power consumption. The recent spike in cellular phone usage in the past decade is of growing interest due to concerns over increased energy consumption compared to land-line phone networks. In this report we investigate total energy consumption of cellular and land-line phone industries.

As mobile communication technology develops, there are inefficiencies in the way people use their mobile devices. By modeling subscriber growth and trends, we can get a clearer picture of the energy consequences of our mobile network.

By correlating the growth of mobile subscribers with changes in our mobile infrastructure, we can strategically develop our current communications network to meet energy efficient guidelines.

2 Approach

1. Collected and extrapolated housing, population, and population density statistics for the United States through the year 2050.

2. Determine the United States' total yearly energy consumption resulting from cellular phone infrastructure. Model takes into account changes in the U.S. population density, the number of subscribers, and the number of cell towers/power requirements necessary to meet consumer demands.

3. Determine the United States' total yearly energy consumption as a direct result of cellular phone use. Model takes into account typical cell phone battery and charger properties, phone manufacturer market share, U.S. population growth, increases in cell phone use, and the behavior of cell phone users.

4. Demonstrate considerable energy savings within the cell phone industry as a direct result of phone user behavior ("regular" behavior versus "ideal" behavior).

5. Compare the total yearly energy consumption of the cell phone industry (commercial and consumer energy expenses) against that of other technology industries (Television, Computing, Radio, etc.).

6. The total volume of oil (in barrels) needed to provide energy to the cellular phone industry on a yearly basis is determined. The analysis takes into account transient changes in the heat content of oil, the efficiency of converting heat to electricity, and the United States' use of oil in electricity production.

3 US Population Growth

Estimating the overall power consumption of the cellular network, a location based service, requires a detailed understanding of how the overall US population is distributed. Although detailed information for the current population total and number of households is available from US Census, predictions for power usage in the future required extrapolations.

3.1 Total Population

Growth of the overall US population is an important statistic and is well studied by the US Census Bureau [8]. Total population data and the relevant quadratic fit are shown in Figure 1.

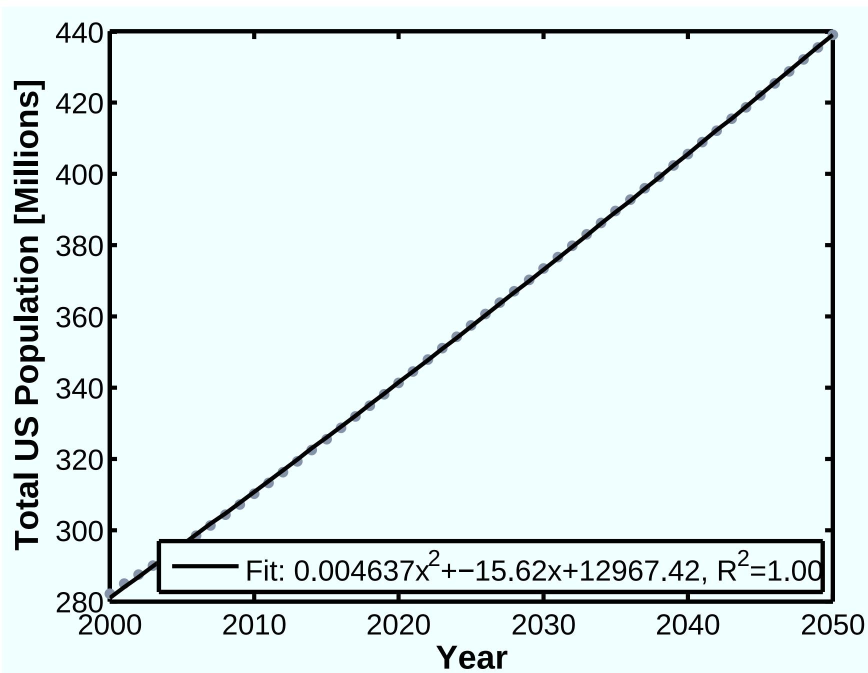
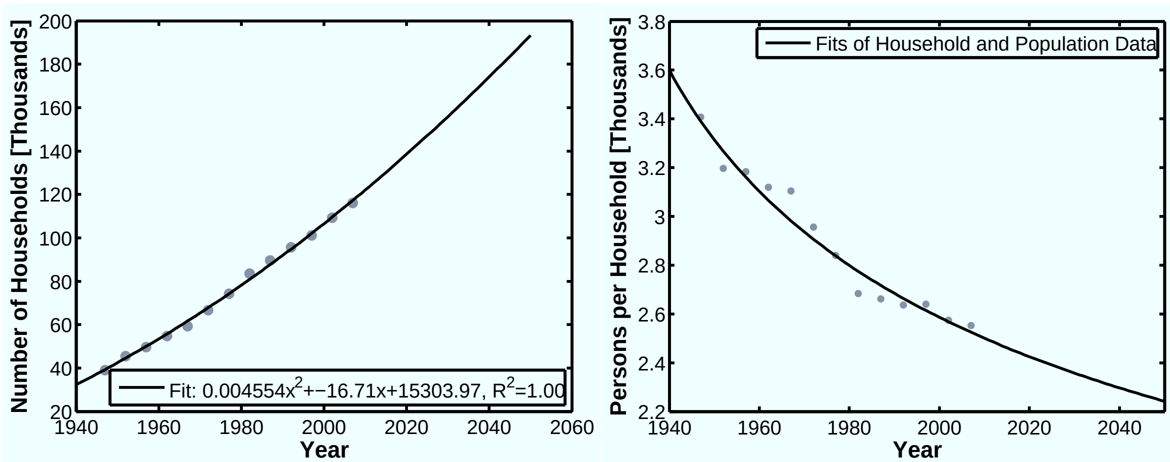


Figure 1: Predictions for the total US population as reported by the US Census Bureau. By 2011, when 95% of the population will own a cell phone, the total population will be 313 million. By 2050, the limits of our analysis in this report, the total population will be 439 million.

3.2 Number of Households

Landline services, which are delivered to homes and not individuals, requires knowledge of the changing number of households in the US. Simultaneously, the number of persons per household directly affects the tradeoffs between the two services. Historical data was obtained from the US Census [5] and is shown in Figure 2.



(a) (b)

Figure 2: Predictions for the number of US households obtained from the US Census Bureau. While the number of households is observed to be steadily increasing, it is not keeping pace with the rising US population. As fewer people live in each household, the benefits of collective communications (landlines) will increase.

3.3 Population Density Models

The population density across the US is a primary factor in the placement of cell sites and the relative power usage of both landline and cellular options. Regions that have very low population density may be better served by landlines than by cellular networks. At the same time, the population density distribution across the US will not remain constant as further urbanization occurs and previously rural regions catch up to more urbanized ones. The population density across the US are thus predicted over the time period relevant to the analysis in this paper (until 2050).

3.3.1 Assumptions

- Population density can be accurately modeled at the kilometer length (variations at smaller length scales, most noticeable in cities, will be unimportant).
- Population growth for a particular area is primarily linked to the current population density.
- Trends seen in urbanization from 1990 through 2008 will continue until 2050.

- Geographical distributions of population density are significantly symmetric around the center of latitude to neglect effects on latitude/longitude cell sizes.

3.3.2 Population Density Data

Maps of population density from 1990 to 2005 and predictions through 2015 were obtained from [2] and are shown for 2005 on a log scale in Figure 3.

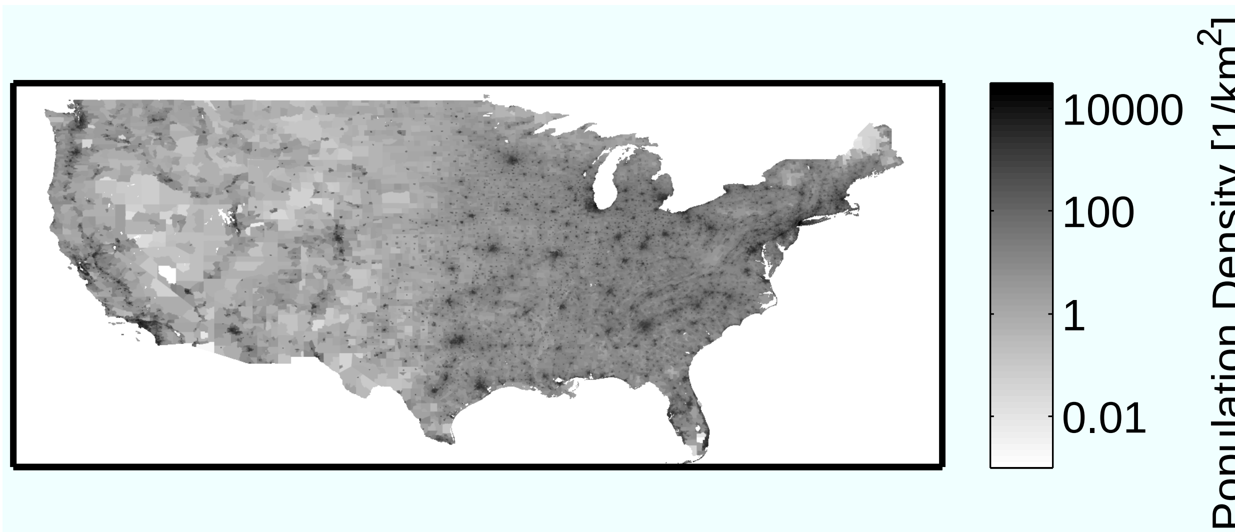


Figure 3: Population density for 2005 for $\sim$25km^2 segments across the continental US. As expected, the population is focused east of the Mississippi. Major cities are easily identifiable by peaks in density.

3.3.3 Observed Growth Rates

The changing distribution of population density was identified by comparing the predicted density distribution for 2015 against the distribution for 1990. The mean annualized growth rate was then calculated via the simple formula:

$$\%\text{Growth} = \left(\frac{\rho_{2015}}{\rho_{1990}}\right)^{\frac{1}{25}} - 1 \quad (1)$$

The US is grouped by binning data according to population data. For each range of population densities, the mean growth rate of the regions (and corresponding standard deviations) is obtained. These mean growth rates are then related to population densities as shown in Figure 4. Population is thus seen to be an excellent predictor of population growth rate, with the exception of regions with very low population density (less than one person per 100 km^2). This likely arises due to the behavior of developing rural regions with regions that are simply inhospitable (such as the Rocky Mountains). Regions that are historically extremely low in population density will likely never see population growth (1 person per 10000 km^2) and developing rural regions will only experience accelerated growth until they form stable communities or towns. Extremely large cities like New York City and Los Angeles will experience lower density growth than the rest of the country because they are already near their sustainable or established limits (few cities worldwide have managed population densities much higher than that of New York City).

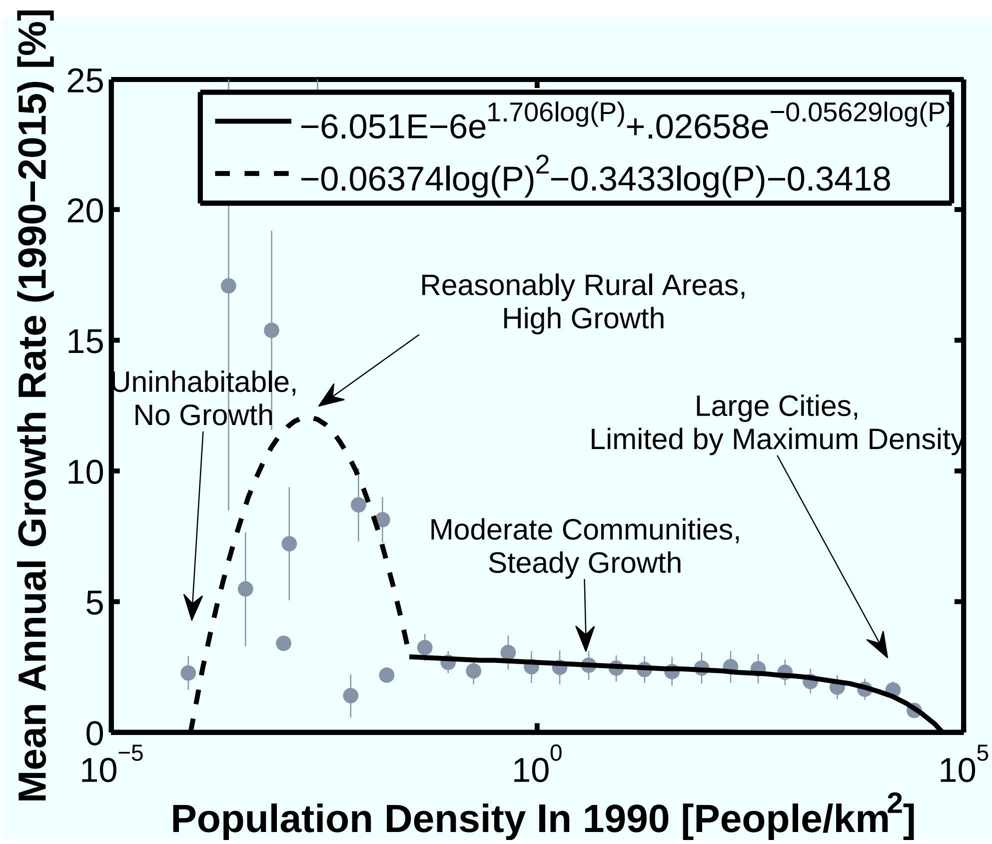


Figure 4: Relation of the mean annual growth rate for regions with local population densities. Several major effects are observed. Regions with extremely low population density are uninhabitable (such as the Rocky Mountains). Rural regions may (or may not) experience large growth as urbanization occurs. Stable communities, towns, and small cities experience reasonable steady growth, until limits on density are reached (in the case of huge metropolitan areas).

3.3.4 Predicted Distribution

The relationship developed in the previous section was used to predict density across the US until 2050. For each year, beginning with the 2015 predictions [2], the population density growth for each region is calculated using the fit shown in Figure 4. As the population of regions grow, the growth rate is continually adjusted. All results are scaled by the overall population growth statistics from Figure 1. The practical effect of this method is to slow density growth as populated regions increase in size. At the same time, rural regions which saw explosive growth from 1990 to 2015 will only continue growing rapidly until they reach a stable size. The population distribution thus becomes slightly more level. In order to show the impact of this population growth, the distribution of population densities in 2005 and 2050 are shown in Figure 5.

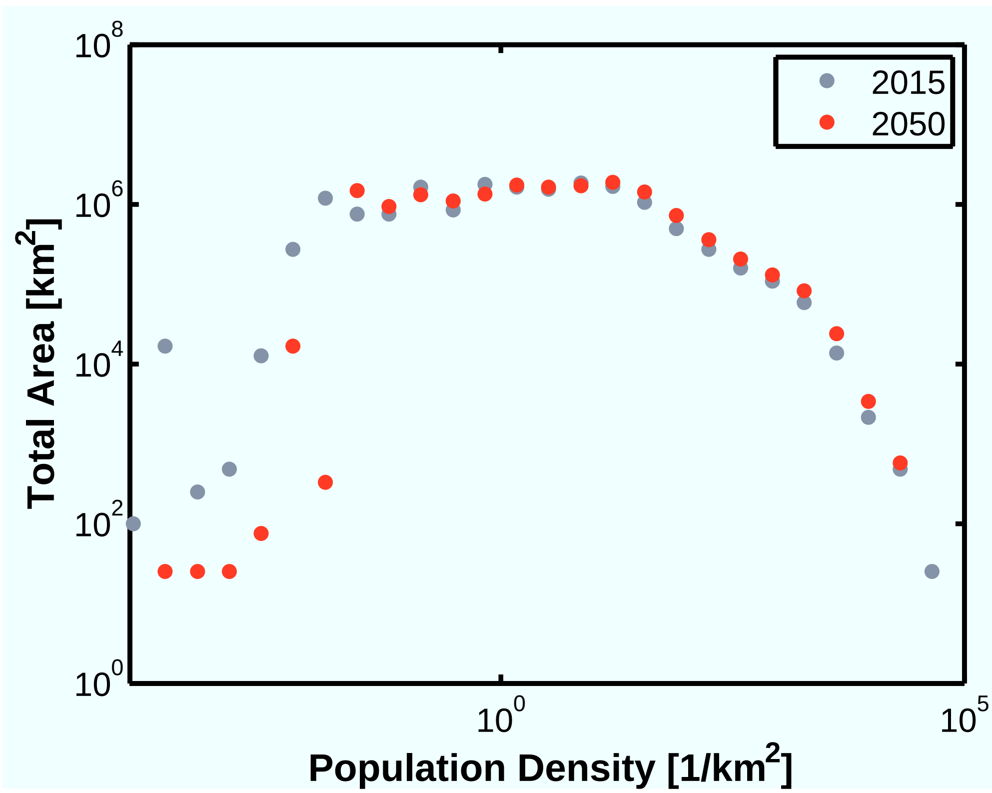


Figure 5: Comparison of the density distributions for 2015 (based on [2]) and 2050 (based on the methods growth methods presented). Much of the rural areas are seen to be developed into higher density regions. Areas with population density of about 1-10 km^{-2} are seen to differ little as competing growth of lower density regions offsets growth into higher density regions. A small increase in the number of areas with very high density is observed.

4 Current Cellular Network Model

4.1 Assumptions

- The FCC database contains all relevant and major cell sites in the US.

- Cell sites serve areas of homogeneous population density, characterized by the population density at the exact location of the site.
- All cell sites can communicate to 50km (approximately the limit of modern technologies).
- The strength of a cell tower is primarily dependent on the number of antennas (due to a lack of transmission power information).

4.2 Communication Standards

CDMA and GSM are the two primary standards for mobile phones in the United States. These primary standards require different antennas to transmit cellular communications, and therefore different cell sites exist for each standard. We estimate however that all mobile phones are covered one way or the other. In order to simplify our models, we assume that all mobile phones utilize one generic standard rather than multiple standards.

4.3 Network Model and Component Power Usage

Due to the huge variety of transmitters and strategies used in the US cell network today, constructing precise energy profiles is difficult. However, sources concerned with reducing the power usage of these networks provide data on the approximate usage of various pieces of the cellular network [3]. The simplified cellular network model and corresponding energy usage requirements are shown in Figure 6. Cellular phones connect directly to cell sites, which may or may not be mounted on antenna towers. Each antenna mounted on a tower was considered a separate cell site in later calculations. These towers can handle a range of calls at once (about 200-500 users, using 600-1000 W[3]) and pass the information along to Mobile Switching Stations (MSC's). Communication between MSC's and cell sites can be accomplished through fiber optic networks or microwave connections. Each MSC can handle approximately 1.5 million subscribers, and consumes about 200 kW. MSC's connect directly into the communications backbone of the country. Since the fiber optic network comprising the backbone will be necessary in any usage scenario (or in any pseudo-US), it was not considered in energy estimates.

4.4 Cell Site Registration Databases

Information about the current distribution of cell sites across the US was obtained by examining the FCC Universal Licensing System Databases [10]. All cellular radio transmitters located above 200m are required to be registered in the system, ensuring that a majority (but not all) cell sites are included. The database contained approximately 20,000 cell site locations comprising about 130,000 individual cell sites.

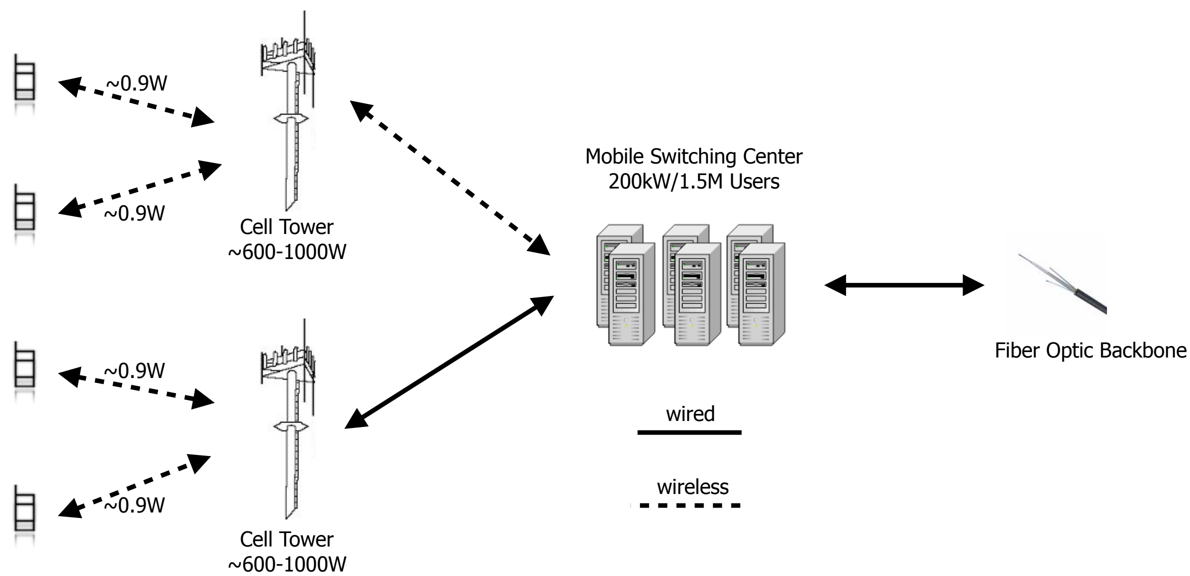


Figure 6: Simplified network model for infrastructure calculations. Each component (cell sites and MSC's) were assumed to be identical for all carriers and geographies.

4.5 Tower Location

The cell site location data obtained above was investigated by plotting against the population density map from above, as shown in Figure 7. Cell towers are seen to be positioned throughout the US. Interestingly, several seem to be positioned off of the coast in the Gulf of Mexico and in the Atlantic Ocean (either due to errors in registrations or for the use of ships and/or oil rigs). Since only towers above 200m are required to be registered in such a manner. Also interesting is the single tower at the center of Dallas (northern Texas), which contains 25 antennas and suggests a series of smaller sites spread throughout the city.

4.6 Antennas per Cell Site

Many cell sites in more urban areas use more antennas and higher transmission powers. Although some Effective Radial Power (ERP) data is included in the FCC database [10], many sites have no published information, and several had negative ERP's (impossible). In addition, many sites have similar transmission powers, likely due too FCC regulations. In order to quantify the power of each cell site, the number of antennas is used instead. The distribution of antennas is seen in Figure 8. While most sites have only a single antenna, had many several, and a few had as many as 9.

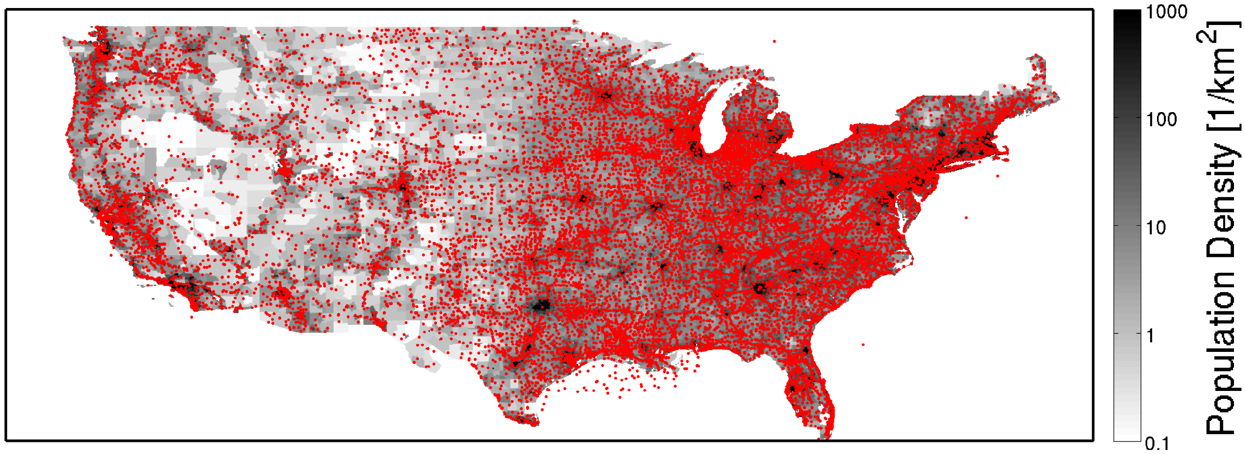


Figure 7: Distribution of towers around the US, as well as the population density as obtained from above.

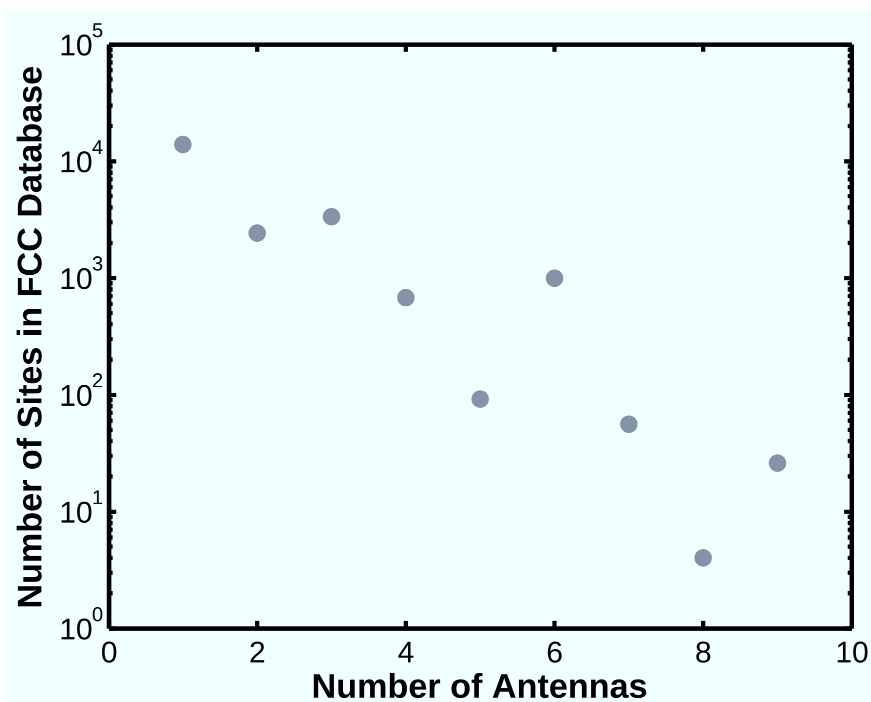


Figure 8: Distribution of the number of antennas per tower.

4.7 Tower-Antenna-Population Density Relations

In order to calculate how many cell sites are used on average in regions of varying population density, the site locations is used to interpolate densities from the maps of Section 3.3.2.

Binning this data to provide a distribution of population densities and dividing by the distribution of population densities across the US, the relationship between cell site and antenna densities and population density is identified as shown in Figure 9. The initial portion of the graph approximately shows a steady increase in the number of towers, with one antenna per tower. However, above 150 people/km^2, the number of towers levels off and the number of antennas per tower begins to rise to compensate for increased populations. As expected, these relation will contribute with the square of their radii.

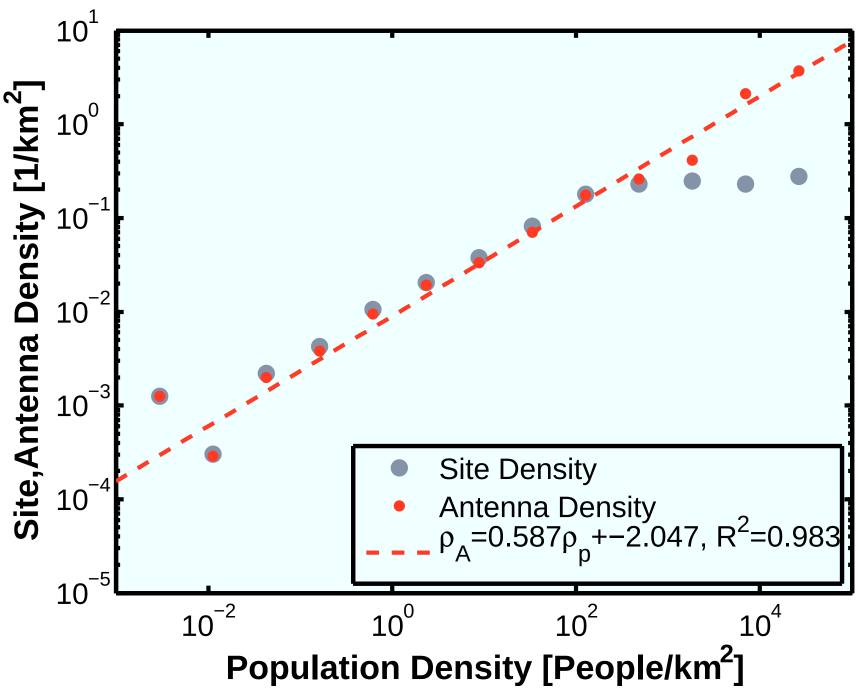


Figure 9: Relations between cell site and antenna density and the surrounding population density, formed by comparing the population density distribution around towers with the overall population density distribution. Below 150 people/km^2, there is a relatively constant increase in towers with respect to population. Above 150 people/km^2, the tower density is approximately constant, but the number of antennas per cell tower increases to compensate.

4.8 Coverage Overlap

The overlapping range of various cell sites was investigated by determining the number of nearby cell sites at a range of locations within the US. The method for this process is illustrated in Figure 10. For each cell in the population density grid (shown above), a trial list of all towers within a reasonable range was constructed (towers within 1 degree latitude, 3 degrees longitude or approximately 100-200 km in each direction). For each of these candidate towers, the great circle distance between the location (latitude δ_1, longitude

λ_1) and the tower (latitude δ_1, longitude λ_1) was calculated as follows [14]:

$$d = 6378[km] \cdot \cos^{-1}[\cos\delta_1 \cos\delta_2 \cos(\lambda_1 - \lambda_2) + \sin\delta_1 \sin\delta_2] \quad (2)$$

If the great circle distance is found to be less than the maximum range of the towers (approximately 50km), then the region is considered to be in the tower's plausible range. For each location, the number of cell sites within range is thus calculated, and is shown in Figure 11. While some cities have a large degree of overlap, others accomplish full connectivity by using many smaller rooftop sites or higher power antennas. Also noticeable is several regions in the Western US with no current conductivity.

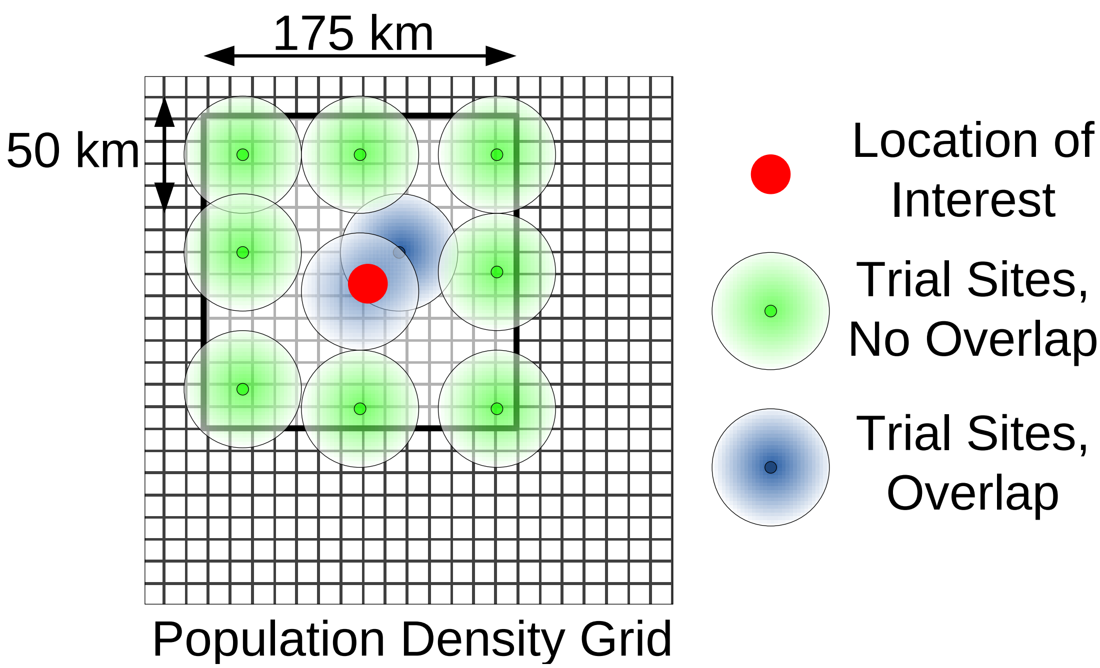


Figure 10: Illustration of algorithm to determine overlapping number of overlapping cell sites for a given latitude and longitude on the population density grid. The figure does not represent the eccentricities of the grid to due changing longitudinal lengths. This process was repeated for every latitude/longitude combination in the original grid.

5 Model for Cellular Phone Usage

5.1 Basic assumptions

Our investigations uncover three main components of electricity consumption regarding the direct use of cellular phones. Electricity is consumed not only by powering the cellular phone during talking and standby, but also by powering the charge-adapter with and without a

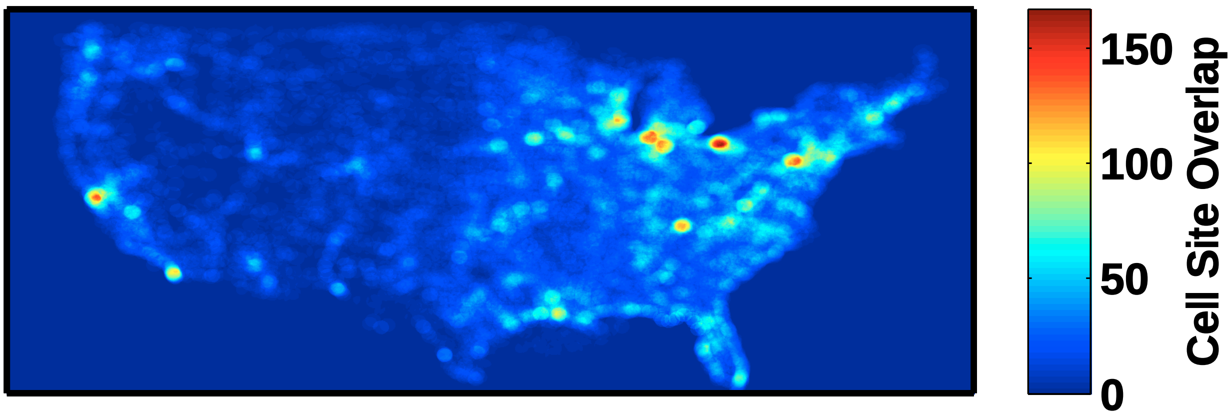


Figure 11: Results of overlap calculations for the known grid of cellsites as reported by the FCC. Most urban regions have higher overlap of cell towers to cope with an increased population load.

phone attached. Therefore, the cellular phone usage of an average person is modeled as a function of three different characteristics as follows: (1) at what remaining battery level (0 - 100 %) does the phone user decide to recharge his/her cell phone, (2) how long the cell phone remains connected to the charge after the battery is completely charged, and (3) whether or not the person unplugs the charge-adapter from the outlet upon completion of battery charging. The possible power consumption states of a phone adapter are displayed in Table 1.

Table 1: Different power consumption states of a cellular phone adapter

Adapter state	Consumption, W
Unplugged	0
Plugged in, no phone	0.5
Phone attached, not charging	0.9
Phone attached, charging	4.0

5.2 Cellular Phone Information and Usage Behavior

The following sections describe the collection and analysis of information and historical data for cellular phones and cellular phone users. This information is vital to the creation of a model for predicting the growth of energy consumption of the cellular phone industry.

5.2.1 Battery Capacity

Table 2 displays the average battery capacity, power consumption during talking, and standby power consumption for batteries of the top nine largest mobile phone manufacturers in the United States. Averages are determined using manufacturer information of over 150 popular cellular phones, approximately 15 phones per provider [7][1]. Power consumption is calculated using battery capacity and estimates of talk-time and standby-time for individual phones assuming each phone has a 3.7V lithium ion battery. Global averages for capacity, talk power consumption, and standby power consumption (found at bottom of table) are calculated as an average of values for individual manufacturers weighted using their present percent U.S. market share in 2008.

Table 2: Average values of capacity and energy consumption for popular U.S. cell phones

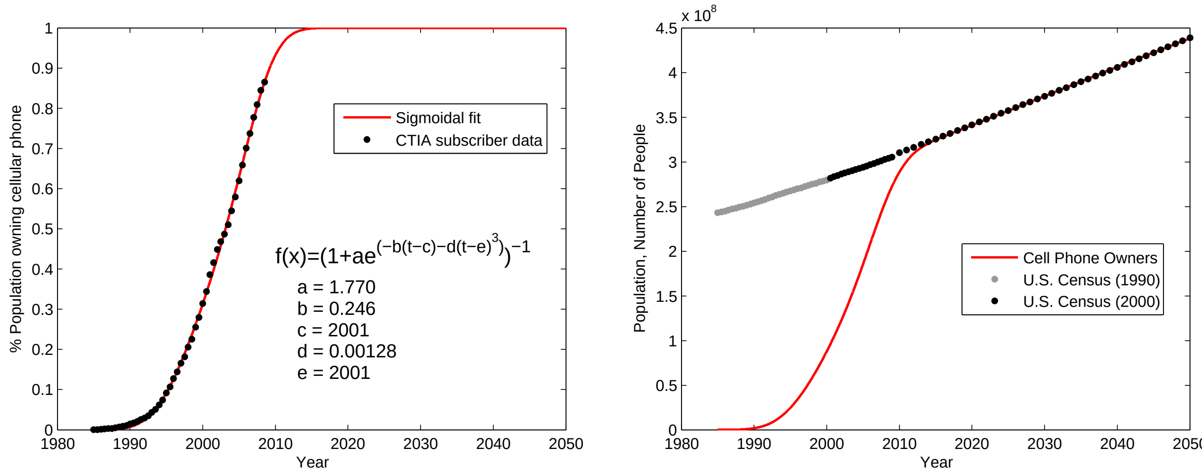
Rank	Manufacturer	Market Share, %	Battery Capacity, mAh	Talk-power, W	Standby-power, W
1	Samsung	22.0	980 ± 228	0.0138 ± 0.0051	0.875 ± 0.293
2	Motorola	21.6	826 ± 122	0.0108 ± 0.0023	0.655 ± 0.292
3	LG	20.7	890 ± 106	0.0116 ± 0.0036	0.923 ± 0.242
4	RIM	9.0	1216 ± 276	0.0145 ± 0.0060	1.065 ± 0.348
5	Nokia	8.5	1066 ± 192	0.0122 ± 0.0032	0.735 ± 0.334
6	Sony Ericsson	(7.0)	1015 ± 214	0.0085 ± 0.0039	0.431 ± 0.110
7	Kyocera	(5.0)	900 ± 0.00	0.0200 ± 0.0030	0.970 ± 0.080
8	Sanyo	(4.0)	810 ± 89.4	0.0161 ± 0.0037	0.908 ± 0.152
9	Palm	(2.2)	1500 ± 346	0.0167 ± 0.0042	1.402 ± 0.353
			960 ± 166	0.0127 ± 0.0039	0.829 ± 0.263

5.2.2 Number of Cell Phones Per Person

The average number of cell phones owned per a person is determined using historical population and mobile phone data and extrapolated to the year 2050 [8] [9]. Figure 12a displays the total number of cellular phone subscribers normalized by the population of the United States. The historical data is fit to a sigmoidal curve, assuming that the ratio will eventually reach a value of 1 cell phone per 1 U.S citizen (complete saturation). Figure 12b compares the yearly increase in U.S. population to that of cellular phone users. We see that by year 2015, the predicted number of cell phone owners has reached the total number of people in the United States and continues to grow with the population.

5.2.3 Average Talk-Time Per Person

The average talk time of an individual user between years 1991 and 2050 is determined in a similar fashion as the average number of cell phones per owner. Figure 13 displays the trends



(a) (b)

Figure 12: (a) Sigmoidal fit for the average number of cell phones per person in the United States (b) and predicted growth and saturation of cell phone owners in the United States.

in LAN line and cellular phone usage in terms of total minutes used per year between the years 1991 and 2007[6][9]. The data is extrapolated by normalizing with the population of the United States to determine the average minutes used per person per day. It is assumed that this average usage will eventually saturate to some value of minutes per person per day and a first order exponential growth function is employed to model this behavior. Figure 14 displays the predicted growth of cell phone usage assuming saturation at 15, 20, 25, and 30 minutes per person per day.

5.2.4 Recharge Probability and Duration

The battery level at which a person is likely to charge their phone was modeled as a Gaussian distribution based on cell phone behavior data collected by Zhong et al [12]. The data and fitted Gaussian distribution are found in Figure 15. It is observed that users tend to recharge their phone batteries between 25 and 75% of full capacity. A second Gaussian distribution is created with mean battery level of approximately 15-20% in order to compare with the fitted distribution and determine which scenario is more ideal (not shown).

The time it requires to charge a lithium ion battery is typically not linearly proportional to the remaining charge [**add citation**]. Therefore, it is assumed that the battery charge increases exponentially as a function of charge time, as depicted in Figure 16.

5.3 Calculation of Average Energy Consumption

The energy consumed by the average cell phone user over the course of a year is calculated employing the battery and usage behavior extrapolations discussed earlier. It is assumed

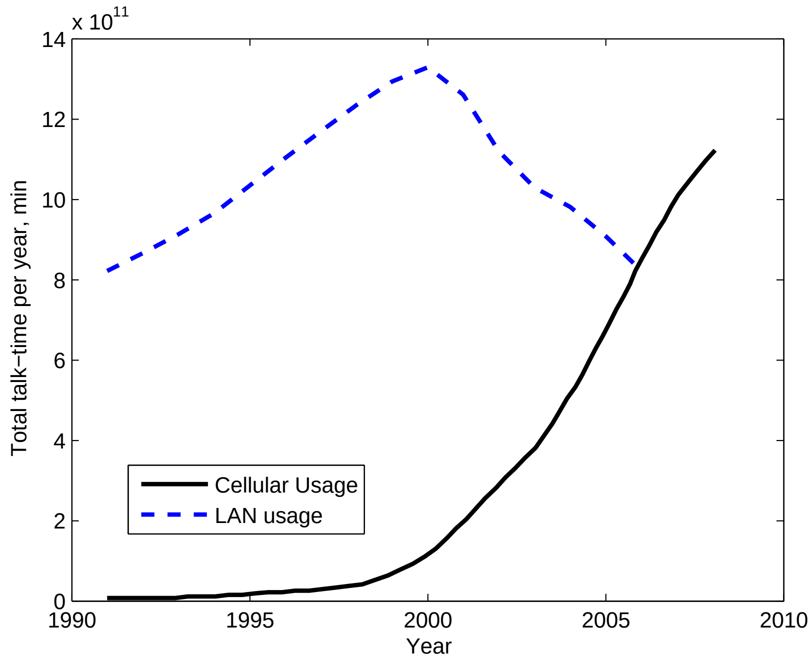


Figure 13: Historical behavior of Land-line and cellular phone usage in the United States.

that the full distribution of remaining battery charge (0 - 100%) can occur before charging is initiated. Therefore, given a remaining battery charge for an individual user, the total energy consumption can be calculated from battery capacity and different power states of a charge-adapter. The duration the adapter stays in a particular power state is determined by the frequency of charging (number of charge cycles per year) which is approximated by the power consumption during periods of cell phone talking and standby. Furthermore, the power consumption during talking/standby is weighted by the average number of minutes a person talks on the phone per day (see Figure 13). Finally, the average energy consumption across the entire population of cell phone users is determined using a weighted sum of energy at each remaining battery level and the probability distribution that charging starts at that battery level.

As mentioned earlier, three characteristics are defined for a given cell phone user, giving rise to a possible eight different types of users. For ours studies, it is assumed that there are only two types of cell phone users, (1) the "regular" user who charges his or her cell phone for 8 hrs at a time at the probability given by the fitted Gaussian distribution. The "regular" user also always leaves the charge-adapter plugged in, and (2) the "ideal" user who charges his or her cell phone for only the time it takes to reach 100% charge at the probability distribution centered at 15-20% battery levels. Additionally, the "ideal" user also never leaves the charge-adapter plugged in when not charging. All further comparisons are made between populations of "regular" and "ideal" users.

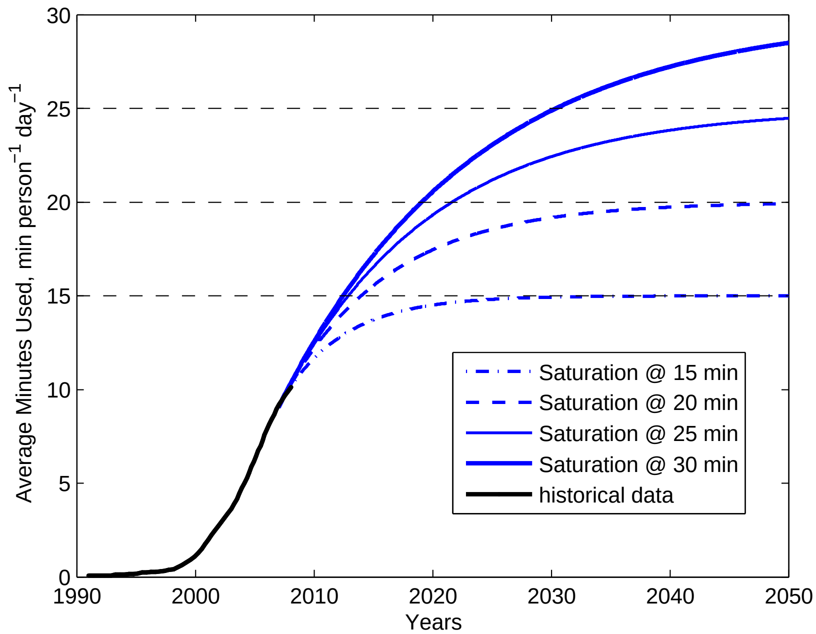


Figure 14: Predicted saturation behavior of average daily mobile cell phone usage.

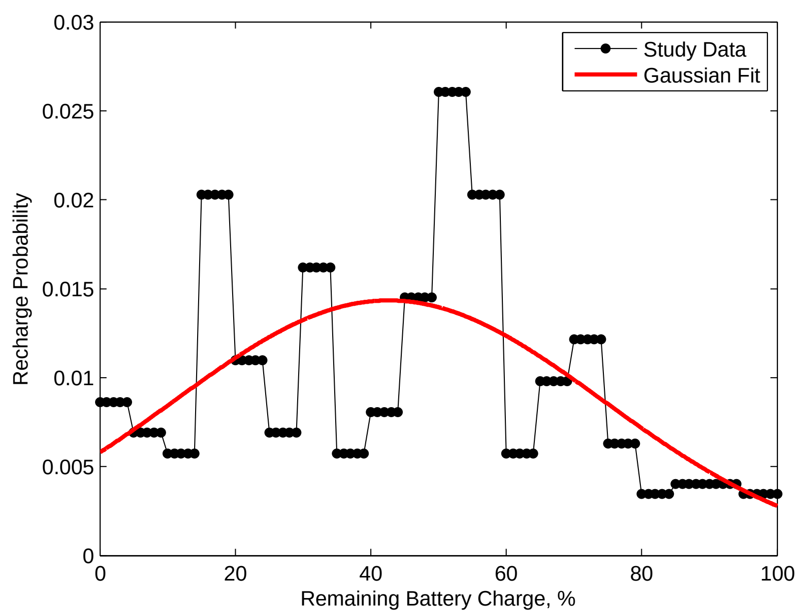


Figure 15: Fitted Gaussian distribution for recharge behavior of cell phone users.

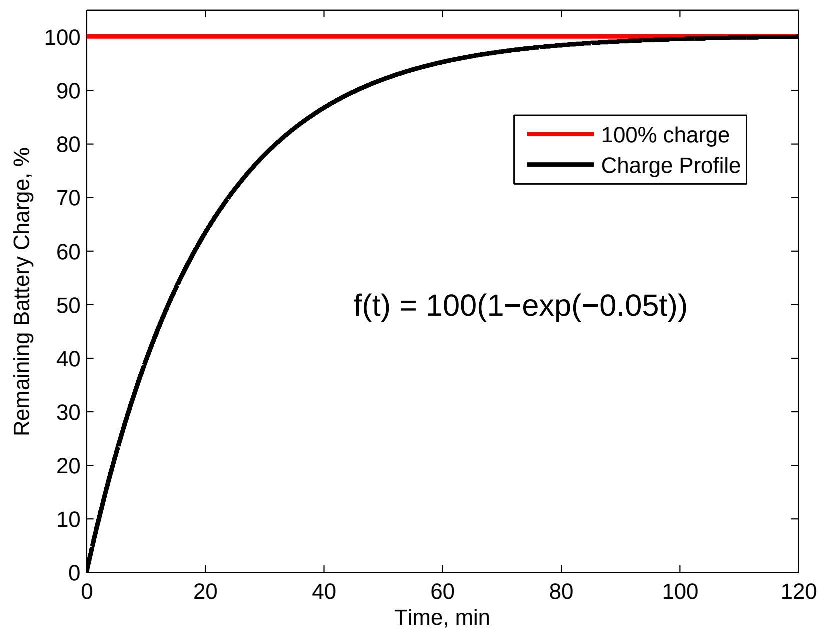


Figure 16: Typical charge profile for Lithium-ion battery.

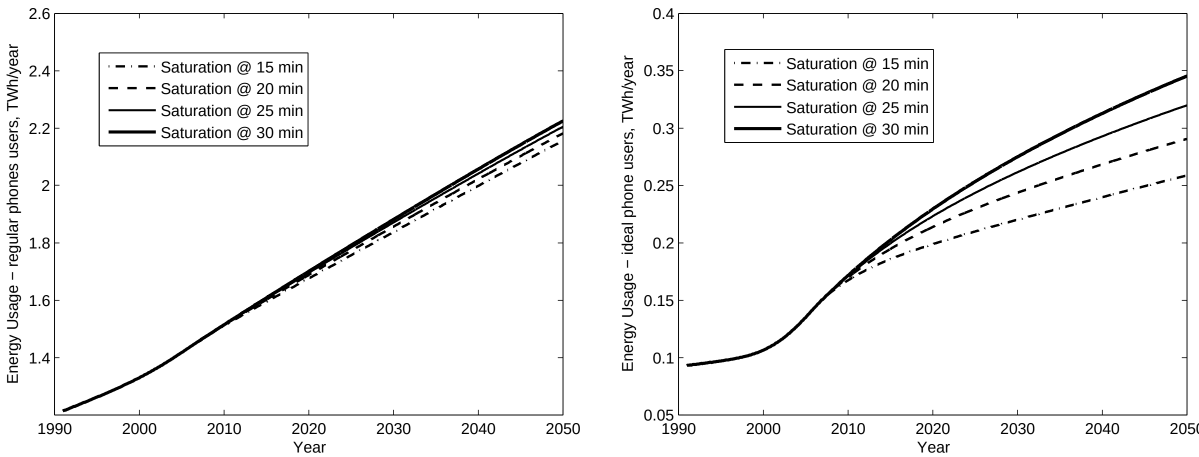
5.4 Energy Usage of Cellular Phones

The yearly energy consumed by cellular phone charging between the years 1991 and 2050 for the "regular" and "ideal" user (as defined earlier) is displayed in Figures 17a and 17b, respectively. It is observed that the yearly consumption of the ideal user is less than 1/5th of that of the regular user (80 - 90% energy savings in the year 2050 depending on usage). This drastic difference is primarily a consequence of unplugging the cell phone adapter from outlet after charge completion. As a result of the increased energy savings of the ideal behavior, we see an increased sensitivity to the cellular usage saturation at different values of minutes per person per day. These trends are more difficult to see with the regular behavior since the majority of energy consumption is caused by the charge-adapter.

6 Pseudo US Model

6.1 Assumptions

- A communication infrastructure is entirely non-existent
- A power grid already exists
- Each household must have television and internet service



(a) Regular User (b) Ideal User

Figure 17: Yearly energy consumption of regular and ideal user assuming different user saturation times (15, 20, 25, and 30 min person^{-1} day^{-1}).

- Each household has a phone, or a cell phone per person

6.2 Comparison of Fiber-optics to Wireless Networks

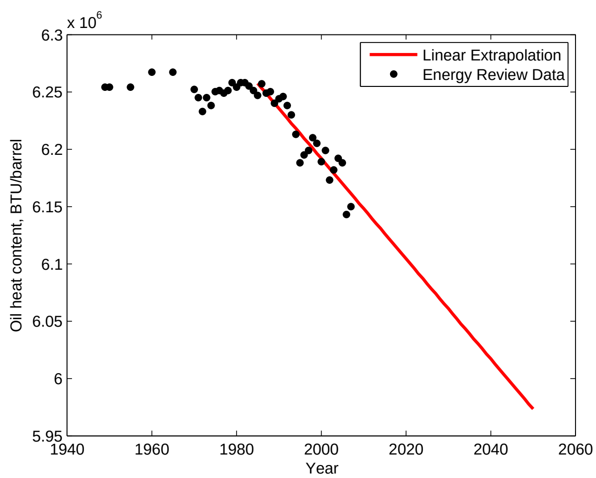
In order to identify an ideal communications system for the US, the energy usage per person for an entirely wireless network was compared to the cost of running a competitive fiber optic network. Since the choice of wireless versus fiber optic affects the energy usage of TV's, computers, and phones in a household, all three communication methods were considered. The estimated power usage for each system is summarized in Table 3. Based on current estimates for each electronic [11], a completely wireless approach could be energy competitive against a fiber optic solution, due to the energy inefficient link necessary in every household.

7 Energy to Oil Conversion

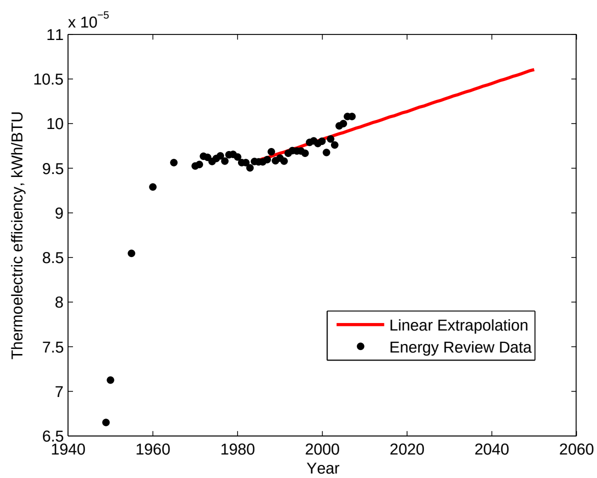
The amount of electrical energy available per barrel of oil is determined using historical data [4] [13]. Figure 18a shows the heat content per a barrel of oil from 1949 to 2007 with linear extrapolation out to 2050. It appears that the heat content is decreasing, possibly due to decreasing supply of energy-rich oil in the global market. The thermoelectric efficiency (i.e. the efficiency of converting heat created by burning fuel into electricity) is displayed in Figure 18b with extrapolation. Using the heat content and thermoelectric efficiency data, the total electricity produced per barrel of oil is obtained and displayed in Figure 19. From the extrapolation, it is found that one barrel of oil will produce approximately 628 kWh of electricity in year 2050.

Table 3: A comparison of the electricity needs per household for fiber optic and wireless approaches. Comparison for 2.5 members, one computer per member, one TV, and one phone per person.

Category	Fiber Optic Usage	Radio Usage
General	Fiber Optic Link (16W)	
TV		DTV Converter (5W)
Internet		2.5x WIMAX Card (1W)
		2.5x Transmission (0.75W)
Phone		2.5x Cell Phone (0.75W)
		2.5x Transmission (0.75W)
Total	16W	13W



(a) Heat Content



(b) Thermoelectric efficiency

Figure 18: Heat content and thermoelectric efficiency data and extrapolations

While it is a considerable amount oil needed to create a TWh or more of electricity, it is very unlikely that oil will be used to create this electricity. From Figure 20 we see at its peak use (1977), oil only accounted for approximately 17% of the electricity produced in the United States. Today oil accounts for less than 4% of the electricity and this value appears to be decreasing slowly.

8 Overall Charger Power Usage

The power consumption of electronics while not being used (including cell phones) is a major concern. In order to gauge the inefficiency of cell phones compared to other electronics,

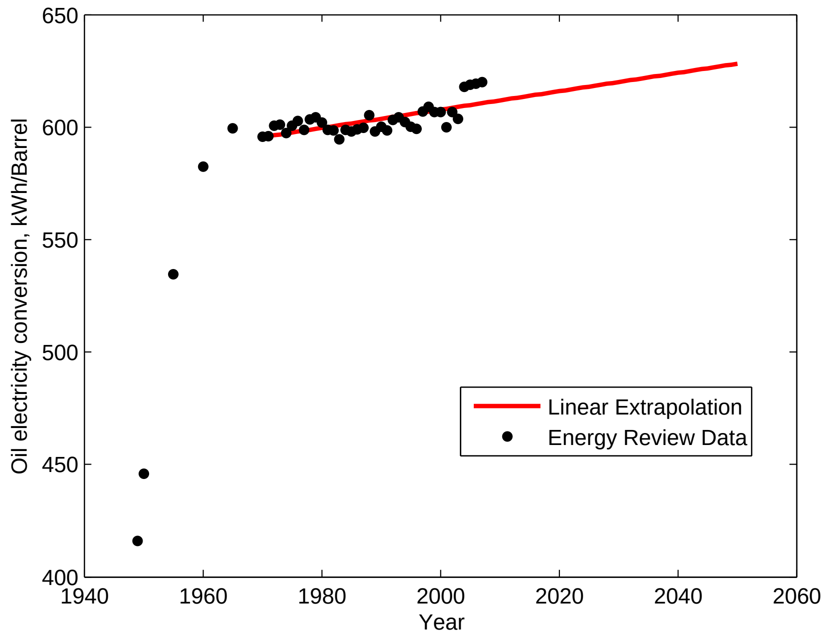


Figure 19: Total electrical energy produced per barrel of oil.

results in this analysis were compared with a comprehensive study completed in 1999 [11]. The distribution presented in that analysis is shown in Figure 21. Although the energy usage of cell phones chargers is significant (2TWhr/yr), it is only a small portion of the overall energy wasted by idle electronics (34TWhr/yr), or 54 million barrels per year using the conversions established above.

9 Cellular Network Growth Through 2050

9.1 Assumptions

- No new (radically disruptive) technologies will be introduced past 3G. Currently technology will improve until a minimum energy usage is achieved.
- Population density growth will follow similar trends to 2050.
- The number of towers necessary for a given population density will remain constant through 2050.

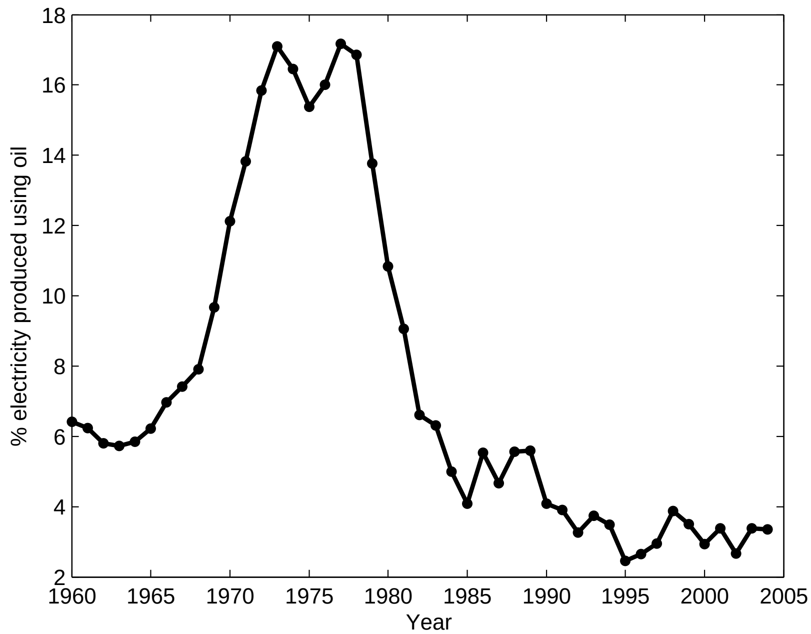


Figure 20: Trends in U.S. Electricity production from oil.

9.2 Technology Improvements

The power requirements of cellular networks have fallen drastically from their introduction in the 1980's as technology improved. Until 1950, similar reductions in power usage will be likely, either through improvements in the electronics of cell sites (computers and such) or more efficient communication strategies (antenna transmissions). In order to characterize this reduction in energy, information is used regarding the energy usage of past technologies [3], as shown in Figure 22. Technologies following the primary upgrade path (1G to 2G and beyond) are leveling out in their minimum energy usage. Although the introduction of 3G initially caused a large increase in power consumption, it seems to have a greater potential for reducing energy consumption. Since future such disruptive technologies cannot be accurately quantified, it is assumed that all future networks will be based on a variation of 3G architecture. The relevant efficiencies are shown for each decade in Table 4.

9.3 Infrastructure Improvements

As the population grows and the use of cell phones increases, more cell sites and related infrastructure will be necessary. To model the increasing number of towers, the tower density/population density relations of Section 4.7 is combined with the population density predictions of Section 3.3.4. The resulting increase in towers is seen in Figure 23. These predictions assume that tower capacity will not grow directly, but instead improve through

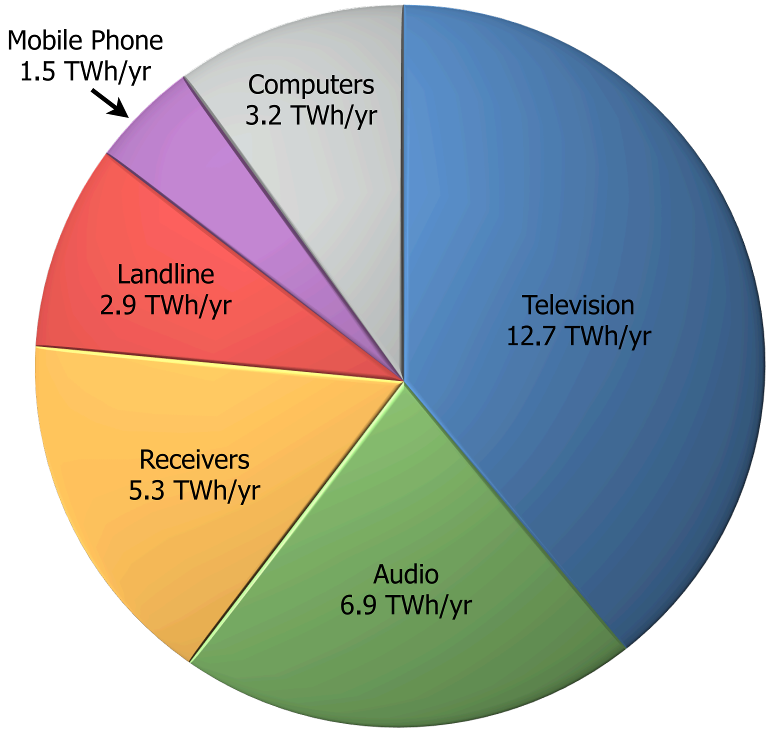


Figure 21: Usage of various electronics according to [11]. Cell phone energy usage was updated as per our model for 2008.

Table 4: Improvements in network technology efficiency from Figure 22

Year	Relative Power Usage
2005	1.0
2010	0.85
2020	0.66
2030	0.63
2040	0.62
2050	0.62

energy efficiency (shown in the next section).

9.4 Overall Energy Usage

The total energy usage of the US cellular network was calculated using the predicted increase in number of cell sites, observed trends in technology improvements, predicted usage patterns

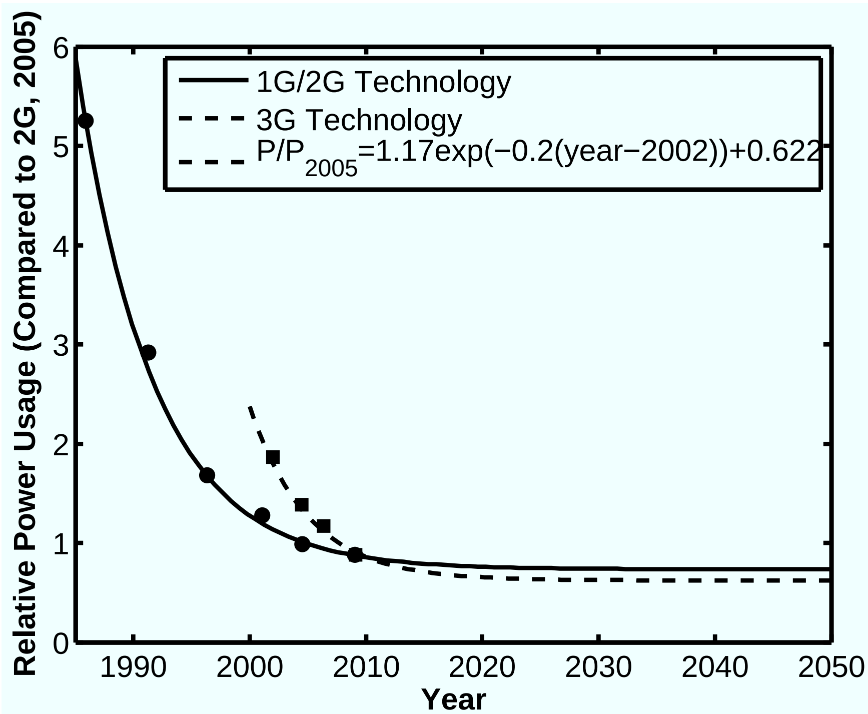


Figure 22: Characterization of technological improvements in cellular infrastructures on energy usage [3]. Information is presented for two different sets of technology, and corresponding exponential fits (of the form $a\exp(bx) + c$) are included to 2050.

for handsets, and energy usage statistics from recent years. Final predictions are shown for two usage scenarios in Figure 24. If chargers are used inefficiently power consumption will grow to approximately 400 MW, or 5.6 million barrels per year. However, if consumers choose to utilize their chargers efficiently, overally consumption by 2050 will be approximately 200 MW (2.8 million barrels per year).

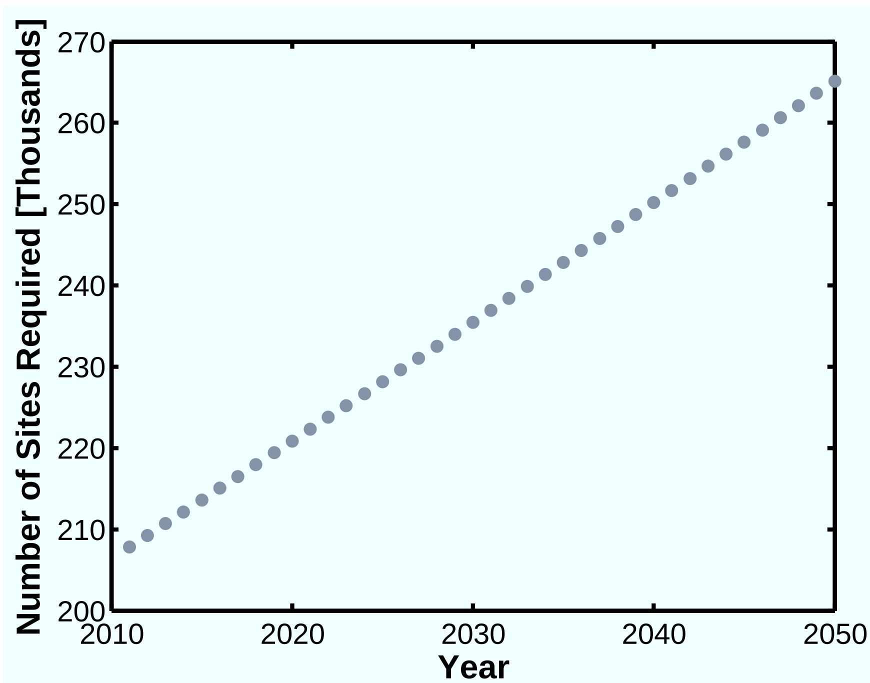
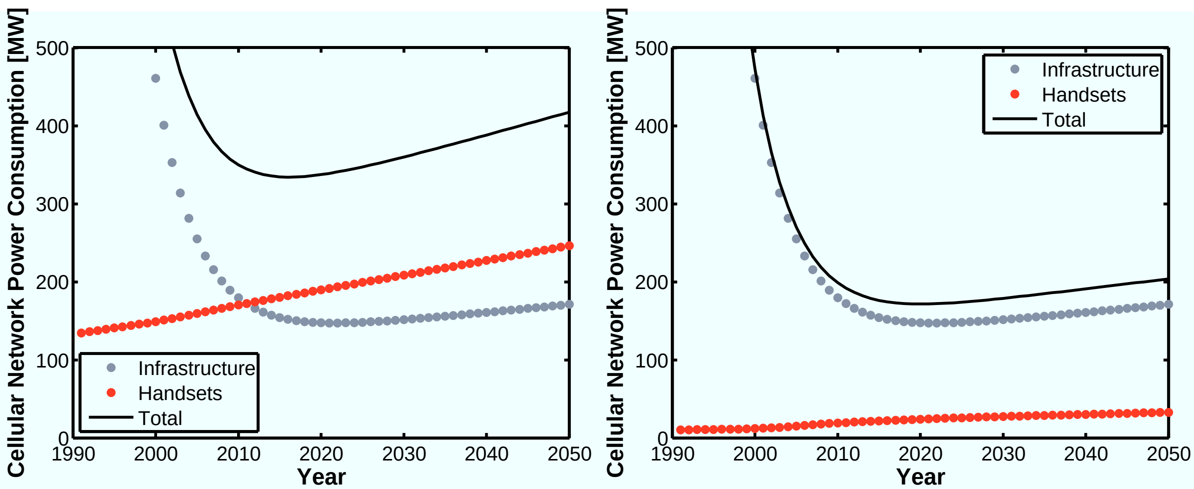


Figure 23: Predicted number of towers from 2007 to 2050 using the population density predictions and the observed distribution of cell towers in the US. Back calculations to 1990 are included (if similar technology and usage statistics were in place then). Created



(a) Inefficient charger usage

(b) Ideal charger usage

Figure 24: Predictions for the full energy usage of the US cell phone network for two different handset charge scenarios. If all people use the charger as efficiently as possible (a) overall usage will remain at approximately 200 MW. If current charge patterns are used, consumption will rise to 400 MW.

10 Conclusion

Our estimates of the power consumption of the US cellular network, based on models of normal cell phone usage and the current infrastructure, was applied to the various requirements for the problem solution as follows:

1. Requirement 1: Electricity utilization during a switch to a fully cellular communications network

   (a) Important population statistics of the US were derived (population, population density, and households) necessary for electricity .

   (b) We calculated the increase in demand for cell phones over the next few years based on increasing population and current usage trends.

   (c) The need for increased cellular infrastructure based on future was established.

   (d) The overall energy usage over the next several years was identified.

   Recent technology improvements will cause energy to decrease until 2015, after which increasing population will demand more power usage

2. Requirement 2: Estimate the optimal communications network for a country similar to the US

   (a) A fiber optic backbone will be necessary for any potential communications network.

   (b) The energy usage of radio based network (to houses) comprising voice, data, and TV service was found to draw less electricity than a fiber optic approach.

   A radio (cell/wifi/DTV) based approach to communications is optimal for a pseudo-US nation, as long as wireless communication can provide sufficient bandwidth (likely).

3. Requirement 3: Estimate the energy loss due to inefficient charging of cellphones

   (a) Several usage models were constructed, based on how many minutes per day a cell phone was used.

   (b) Charging strategies were based on probabilities (experimental) that an individual would charge a phone.

   (c) Energy consumption for regular and ideal users were then calculated.

   A regular citizen today wastes 4.8kWh/yr through inefficient charging strategies.

4. Requirement 4: Model energy wasted by various idle household electronics

   (a) Average energy consumption of a wide range of electronics was identified.

   (b) The more detailed cellular network usage was compared to that of other electronics

   A regular citizen today wastes 125kWh/yr through the use of various idle electronics.

5. Requirement 5: Model energy needs for phone service until 2050

   (a) The change in population density from the present until 2050 was predicted

   (b) Current tower density distributions (number of towers necessary to serve an area of particular population density) were calculated.

   (c) Number of new towers and infrastructure was calculated, as well as benefits from possible technological improvements.

   (d) Cellular handset usage statistics were estimated.

   If inefficient charging strategies are used, cellular networks in 2050 will require 400 MW of electricity (5.6 million barrels of oil per year). If more efficient chargers are introduced or is citizens change their habits, only 200 MW of power (2.8 million barrels of oil per year) will be required.

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