ACCOUNTING OF ENERGY CONSUMPTION FROM WI-FI INTERFACE IN PORTABLE DEVICES

A Thesis by

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IN PORTABLE DEVICES

The following faculty members have examined the final copy of this thesis/dissertation for form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science with a major in Electrical Engineering.

Vinod Namboodiri, Committee Chair

Abu Asaduzzaman, Committee Member

Brian Driessen, Committee Member

DEDICATION

To my parents

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Sincere thanks go to my research advisor, Dr. Vinod Namboodiri, for his timely, important, and appropriate advice throughout my research work. It was a pleasure working with and learning from him. I thank Dr. Ravi Pendse for encouraging this research and for his contribution in the successful completion of my master's degree program. I also thank committee members Dr Abu Asaduzzaman and Dr Brian Driessen for their important advice. I am very grateful for the opportunity provided by Wichita State and for feeling at home here.

I thank my parents and my brother for their love and continued support. The values that they instilled in me helped me complete my master's degree program with confidence. I am grateful to Lord Sai Baba for his grace and motherly love. I am also grateful to my friends for always supporting me.

ABSTRACT

Various reports about greenhouse emissions over the past decade have raised the global consciousness regarding worldwide energy consumption in various arenas. The time has come to adopt energy-efficient methods in all areas, including computing devices. The need for energy efficiency in portable computing and communication devices is great, first due to the fact that because their usage has been increasing exponentially and, second, because little has been done in this field, with performance still being tracked as the focal point of development. One of the major features of any portable device is the wireless communication interface (typically a Wi-Fi card), with many applications being based on the Internet. A major concern with portable devices is maintaining a battery charge for long periods of time. All major applications like the voice over Internet protocol (VOIP), file transfer protocol (FTP), and video conferencing deplete a large amount of energy from portable devices. Thus, accounting for the energy consumption of the Wi-Fi card is very important, both to improve the battery lifetimes of these devices in the future and to reduce the amount of energy consumed from the power grid to charge these batteries.

In this thesis, the energy consumption of the Wi-Fi interface in portable devices, such as laptops and smartphones, was calculated for various applications. Energy consumption was measured experimentally and then scaled to account for the large number of devices in use. The carbon footprint was calculated and the offset required was determined. Considering the explosive growth in the number of portable devices in use, projections on energy consumption over the next few years were made.

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LIST OF ABBREVATIONS

CCK	Complimentary Code Keying
CPU	Central Processing Unit
CSMA/CA	Collision Sense Multiple/Collision Detection
CTIA	Cellular Telecommunication Industry Association
DSSS	Direct Sequence Spread Spectrum
EC-MAC	Energy Conserving-Medium Access Control
EIA	Energy Information Administration
FHSS	Frequency Hopping Spread Spectrum
FSM	Frame Synchronization Message
FTP	File Transfer Protocol
IDC	International Data Cooperation
IP	Internet Protocol
LAN	Local Area Network
LCD	Liquid Crystal Display
MAC	Media Access Control
OFDM	Orthogonal Frequency Division Multiplexing
PBCC	Packet Binary Convolution Code
PBS	Priority-Based Bulk Scheduling
PSTN	Public Switched Telephone Network
QOS	Quality of Service
RF	Radio Frequency
TCP	Transmission Control Protocol

LIST OF ABBREVATIONS (continued)

VOIP	Voice Over Internet Protocol
WAN	Wide Area Network
WLAN	Wireless Local Area Network
WNIC	Wireless Network Interface Card

CHAPTER 1

INTRODUCTION

The advent of the Internet has revolutionized the field of computing. The computing sector has observed extraordinary growth in the past two decades. Mass production and lower prices have further fueled the increase. Lately, there has been a shift of resources and interest in the direction of portable devices, due to their small form factor**.** For the first time in the past few decades that the computing sector has been developing**,** laptop sales have exceeded desktop sales, with 38.6 million units being sold compared to 35.5 million desktops in 2008 [1], thus signifying the popularity of portable devices.

Much awareness and research have focused on the phenomenon of energy efficiency as the result of environmental issues caused by greenhouse gases released from the use of fossil fuels. Although several new technologies, like wind energy and solar energy, are environmentally friendly, their usage is still minimal; dependence on fossil fuels is still very high. In the push for general portable computing devices, it is only natural to think of their energy efficiency. Since Internet access is one of the major reasons for utilizing portable devices, the study of energy consumption of the Wi-Fi card is very important.

1.1 Thesis Organization

To date, no studies have documented the impact of the Wi-Fi wireless card, in terms of both energy and the environment, including an analysis of its energy consumption from the power grid and an understanding of the impact. In this thesis, an experimental study was done to calculate the energy consumption of a Wi-Fi card. Chapter 3 provides detailed experimental calculations for applications like the file transfer protocol (FTP), video, and voice over Internet protocol (VOIP). Energy consumption of the Wi-Fi interface was calculated in two ways: first with battery statistics available through the Linux terminal, and then by evaluating the battery discharge at various battery states. The performance of each application was compared, and the performance of the overall system was estimated.

A comparison of Wi-Fi energy consumption with per capita energy consumption energy consumption in the United States would provide insight on what fraction of energy consumption is contributed by the Wi-Fi interface. Environmental impact is another factor that should be considered with high energy usage, as the ecological balance is affected and greenhouse gas emissions increase in the atmosphere. Chapter 4 discusses this issue.

Projections are important in any research in order to know the trends of each field. Chapter 5 includes projections for the Wi-Fi energy-consumption pattern, greenhouse emissions, and various other parameters.

Smartphone usage has increased over the past decade (currently about 50 million smartphone users). Approximately 75% (37 million) of users actively use the Wi-Fi interface [2]. The energy consumption for smartphones and the environmental impact due to energy consumption is discussed in Chapter 6. Chapter 7 provides projections for smartphone energy consumption. Recommendations and future work are discussed in Chapter 8.

1.2 Contribution

Contributions of this work are as follows:

- Energy consumption due to usage of the Wi-Fi card for various applications was measured experimentally and calculated as 14.7 watt-hour (Wh) per day.
- Energy consumption was calculated for the Wi-Fi interface for all laptops in the United States as .85 terrawatt-hour (TWh). Projections for the year 2014 show estimates of 2.5 TWh.

- Energy consumption of the Wi-Fi card for all phones in the U.S. was found to be .17 TWh. Projections for the year 2011 are estimated to be .5 TWh.
- Environmental impact due to usage of the Wi-Fi card was described. Currently, CO_2 emissions from Wi-Fi cards for all laptops total 1.15 billion pounds. Projections of CO_2 emissions from Wi-Fi cards for the year 2014 are estimated to be 3.37 billion pounds. Currently, CO_2 emissions from Wi-Fi card usage for all smartphones is 23.3 million pounds. CO_2 emissions from smartphones for the year 2011 are projected to be 72 million pounds.
- Offset was calculated for the Wi-Fi card for both smartphones and laptops.

CHAPTER 2

LITERATURE REVIEW

Many studies have contributed to the energy-consumption pattern in the computing sector. Data center energy consumption is one area where there has been considerable investigation. One such study is the Report to Congress on Server and Data Center Energy Efficiency Public Law 109-431 [3], for the Energy Star Program by the U.S. Environmental Protection Agency. Although many studies have concentrated on energy consumption of desktops computers, servers, and data centers, very little has been done in the field of portable computing devices. Somavat et al. [4] accounted for energy consumption of computing devices including portable devices. They found that a typical data center consumes about four megawatts (MW) of power per day. In 2006, the estimated power consumption by server and data center was around 61 million megawatt-hours (MWh), and by their projections, this figure would further increase to about 100 million MWh in the year 2011, an annual increase of about 12.7% per year. Also, according to their study, the total number of personal computing devices by the year 2009 was estimated to be 1,300 million, which includes all portable devices.

Also according to Somavat et al., energy consumption for the year 2009 was estimated to be 44.2 million MWh for mobile devices, 44.6 million MWh for laptops, 163 million MWh for desktops, 168 million MWh for data centers, and 29 million MWh for mobile infrastructures. It was calculated that computing devices consumed about 3% of total electricity consumption. For a typical smartphone, a central processing unit (CPU) consumes about 35% of battery power, followed by Wi-Fi at 25%, global system for mobile communications (GSM) radio about 25%, Bluetooth open wireless technology about 7%, and the backlight for communications about 3%

[4]. Battery drain due to the Wi-Fi card depends upon the applications used; hence, the tracking of energy consumption due to applications is quite important.

2.1 Wireless Communication and Related Energy Research

Wireless technology was first adopted in 1997. Referred to as standard 802.11, it provided three physical layer specifications at 2.4 gigahertz (GHz): 1–2 megabits per second (Mbps) of frequency hopping spread spectrum (FHSS), infrared, and 1–2 Mbps of direct sequence spread spectrum (DSSS) . The technology further evolved in the year 1999, when standard 802.11b improved the data rate above 10 Mbps. This new standard was compatible with standard 802.11. It used complimentary code keying (CCK) to attain a higher data rate of 11 Mbps and packet binary convolution code (PBCC) to provide superior performance in the range of 5.5 to 11 Mbps. This standard provided a coding gain of three decibels (db).

Another version developed from standard 802.11 was standard 802.11a, operating at a frequency band of 5.2 GHz and achieving a data rate of up to 54 Mbps. The orthogonal frequency division multiplexing (OFDM) multicarrier modulation technique was used in this standard. Since 802.11a operates in a 5.2 GHz spectrum, it is not interoperable with other standards. To resolve this interoperability issue of standard 802.11a and lower the data-rate issue of standard 802.11b, standard 802.11g was developed. Standard 802.11g provides a data-rate speed of 54 Mbps in a 2.4 GHz spectrum and provides interoperability with all standards.

The Wi-Fi card consumes a significant amount of energy in a wireless network that is active. Not only is there a need to minimize the power consumption in portable devices, there is also a need for energy conservation in order to extend the lifetime of the battery, in both the short term, by extending the lifetime per recharge cycle, and in the long term, for improving the total lifetime of the battery.

2.2 Wireless Network Architecture

There are two types of wireless network architecture: infrastructure and ad hoc. An infrastructure network is often an extension of a wired network, the backbone of which is the hierarchy of local-area and wide-area wired networks. The backbone is connected to a unique node called the base station, which is a usual workstation but with custom wireless adapter cards. The backbone coordinates access to transmission channels for users within the coverage range. Wireless access in an infrastructure network occurs in the last hop between the base station and the mobile hosts, where they share wireless channel bandwidth. In contrast to infrastructure networks, an ad hoc network is a multi-hop wireless system where a group of users maintains the network connectivity. It has on-demand network architecture without any physical connectivity. Ad hoc networks do not have any infrastructure support and are random and unpredictable, i.e., nodes need to exchange topology information periodically to update topology table. Ad hoc networks are more suitable when temporary connectivity is needed. Figure 2.1 shows the infrastructure network and Figure 2.2 shows the ad hoc network.

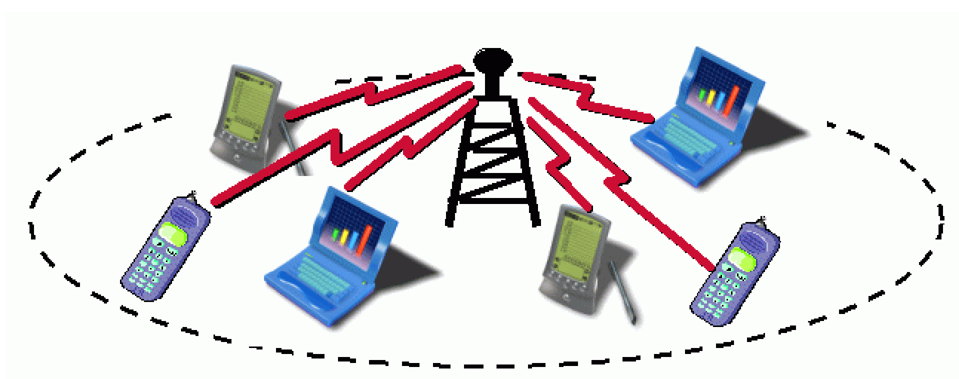

Figure 2.1 Infrastructure network

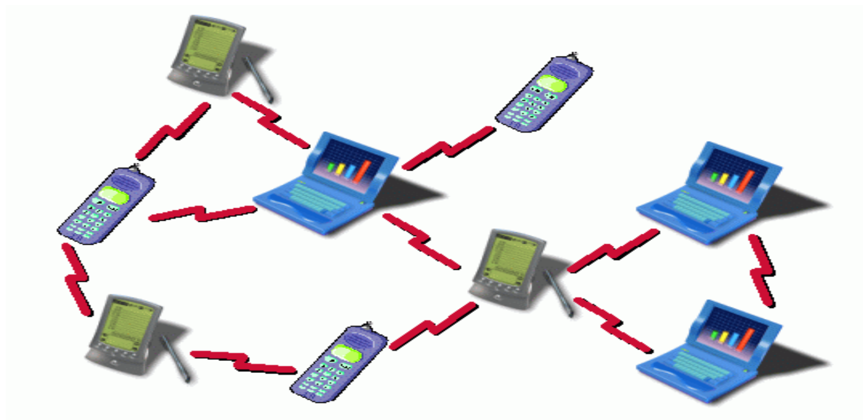

Figure 2.2 Ad hoc network

The wireless protocol stack has the following layers: physical, data link, network, transport, operating system/middleware, and application. The *physical layer* contains radio frequency (RF) circuits, channel coding, and modulation systems. Considerable attention has focused on an energy-efficient design for this layer.

The *data link layer* is responsible for establishing a secure and reliable logical link over the wireless link, which is typically unreliable. Hence, this layer is responsible for encryption/decryption, link-error control, and packet retransmission. Media access control (MAC), the sublayer of the data link layer, is responsible for allocation of the frequency time for devices sharing a wireless channel in the area. The MAC protocol, an IEEE standard 802.11 [5] for wireless local area networks (LANs), is a multiple-access technique based on collision sense multiple access/collision avoidance (CSMA/CA). This protocol is defined as follows: A mobile node senses the transmission medium for activity. If the channel is free, then the mobile node takes over the channel and transmits all data; otherwise, the node enters a back-off state when the channel is busy. The time period that the mobile node stays in the back-off state is called the contention window and consists of a predetermined number of transmission slots. The node senses the available contention slots and then selects a slot randomly from those available. The mobile node again enters a back-off state if it detects some other transmission through the channel. If the channel is free, then the channel identification is captured and packets are transmitted. To conserve energy in this technique, the mobile node intending to sleep informs the base station about its decision, and the base station buffers the packets that are destined to the sleeping node. The base station sends beacons that contain information about the buffered packets, and when the mobile node wakes up, it responds to the beacons and packets are transmitted. This approach conserves energy but results in additional delays, which are not acceptable in the wireless world. Also, the quality of service (QOS) is affected.

The central design theme of the energy conserving-medium access control (EC-MAC) protocol [6] is energy efficiency, in contrast to IEEE standard 802.11. In EC-MAC at the beginning of each frame, the base station is sent a frame synchronization message (FSM), which contains synchronization information and an uplink transmission order for the succeeding reservation phase. The registered node and status of established queues, according to the order of transmission received in the FSM, is communicated during each phase. Collisions are avoided, thus allowing the base station to send a "clear order reservation" transmission. Energy consumption is reduced in this technique due to the use of a centralized scheduler; hence, collisions over the wireless channel are avoided, and in turn, the number of retransmissions is reduced. Due to communication schedulers, mobile receivers are not needed to monitor the transmission channel.

The *network layer* routes packets and transfers packets between the link layer and the transport layer, and also controls congestion control. Since all traffic in an infrastructure network is routed through a base station, energy-efficient routing does not apply to infrastructure networks relative to the network layer.

For applications running on network endpoints, the *transport layer* provides reliable data delivery service. The most common and popularly used transport layer protocol is the transmission control protocol (TCP). Over a wireless link, performance of the TCP degrades drastically due to natural wireless link properties. Throughput is reduced, and delays are very high because of retransmissions and a commonly invoked congestion-control mechanism, which causes confusing wireless link errors and loss due to handoff as channel congestion. Lately, a few schemes have attempted to reduce retransmission: (a) split-connection protocols, (b) link-layer protocols, and (c) end-to-end protocols. A spilt-connection wireless link is hidden from a wired link by a termination TCP session at the base station. To accomplish this, the TCP connection is split between source and destination, with two different connections at the base node, which results in an on-connection between the base station, the wired network, and other connections between the mobile nodes and the base station. Two examples of split-connection protocols are the migratory TCP (M-TCP) and the indirect TCP (I-TCP).

In a wireless system, the *application layer* is responsible for partitioning tasks between the fixed and mobile hosts, video and audio source encoding/decoding, and adaptation of content in a mobile environment. Considerable importance is given to energy efficiency at the application layer. Energy efficiency at the application layer can be maintained as follows: Load partitioning is a technique that selectively partitions applications between the base station and the mobile node, since there are several bandwidths and power constraints. Power-intensive applications are handled by the base station, and other mobile nodes display and acquire multimedia data.

Proxies can also be used to manage energy at the application and also at the mobile nodes. This *middleware layer* adapts the application to changes in bandwidth and battery power, for example, a low-bandwidth environment video that can be suppressed, permitting only audio. Multimedia applications consume considerable battery power. Reduction of the effective bit rate of video transmissions permits a lightweight video encoding and decoding technique, which can be used to reduce power consumption.

Furthermore, for portable devices, energy consumption at the operating system level can be reduced by designing an operating system whereby the CPU operates at a lower speed by decreasing the supply voltage, according to the quadratic relationship that exists between power and voltage. Reducing the supply voltage by half would decrease power consumption by a quarter. Throughput can be maintained by reducing the circuit speed with techniques like pipelining and parallelism.

Dynamic power management is also a solution to energy issues in portable devices. Here, different power states are provided, each power state having different properties. The workload-driven policy is one such policy, wherein the device moves to power down a mode, to sleep or standby mode, for a certain amount of time when the device is idle. Based on the previous history of the device, idle time can be predicted. Another such policy is the consumption-driven policy, where the maximum battery lifetime is the main concern; a constant battery-discharge profile over time is more favorable in this condition.

A context-driven policy for power management considers environmental variables, like temperature inside the phone, remaining battery capacity, ambient light, etc., to control the power. Since this policy may affect the performance or quality of service for the user, other policies must be enabled or disabled by users depending upon their requirements. In a service-driven policy, power management is achieved by the service parameters of the system, such as data stream and applications. Applications that monitor the energy supply and demand can modify behavior to conserve energy. A service-driven policy can detect low bandwidth, high cost, low battery, voice quality, and frame rate, and can change the power consumption accordingly. A proper balance of the above policies would drastically affect a device's power consumption.

For video processing applications, the conservation of power over a long period of time has focused on a low-power circuit design. Previous suggestions to conserve power have been to use flash memories and reduce the supply voltage, including variable clock-speed processors. Agarwal et al. [6] proposed the reduction of energy consumption by decreasing the number of bits transmitted over the wireless link. Here, video-quality degradation must be kept minimal. There are various schemes for video encoding. The Joint Photographic Experts Group (JPEG) standard for still images can also be used for video by considering each frame as a still image. The scheme for coding the JPEG is similar to that of the Moving Picture Experts Group (MPEG), whereby the video coding from JPEG is popularly called MJPEG. MPEG-1 and MPEG-2 are two other video-encoding mechanisms. MPEG-2 has certain advanced features like scalability, compatibility, error resilience, and interlaced video manipulation.

The main components in a portable unit that supports video processing are the video encoder, video decoder, and Wi-Fi card. The wireless encoder programs the normal video stream into a compressed stream and sends it to the Wi-Fi card; then, the video decoder converts the compressed video to an uncompressed video. According to Agarwal et al. [6], a daemon program is run in the background of the portable device and constantly monitors its battery level. When the power level of the battery is up to the threshold limit, no changes are made to the bits in the video stream. When the battery power level drops, the daemon requests a reduction in the number of bits transmitted over the wireless medium. The reduction in number of bits transferred depends upon the power level of the device. In their study, Agarwal et al. defined battery-power level as being one of the following levels: almost full, half-full, low-power, and nearly empty. A reduction factor “r” was associated with each level, whereby the application would reduce the bit rate. If the application transmitted n bits/second when the battery was almost full, then the application would transfer at rate (1-r) n bits/second.

2.3 Wi-Fi Research

The power consumption of Wi-Fi, as referred to in section 2.1, accounts for the majority of power consumption in portable devices. Moving the Wi-Fi into a sleep state when the device is idle can effectively reduce the power consumption, but in order to support continuous streaming applications, current techniques cannot put the Wi-Fi in a sleep state because of the severe delay requirement, i.e., Wi-Fi takes some time to wake up from the sleep state [7]. The switch-over time from an active state to a sleep state and back again is on the order of a few tens of milliseconds. Due to the translation delay in states, existing schemes should not be applied to applications since the inter-packet arrival time may be too small, and the device cannot power-off the Wi-Fi without violating the delay requirement. Since almost all portable devices are powered by battery, the rate at which battery performance increases is very slow. Due to this limitation, communication protocols can be designed carefully to perform all services, while minimizing overall power consumption. Zhu and Cao [8] proposed a technique called priority-based bulk scheduling (PBS), where a proxy is added to the end of the device. The proxy buffers sufficient data from the server and allows Wi-Fi to sleep until the buffered data runs out. In PBS, the scheduler keeps track of buffered data for every flow. The flow with sufficient buffered data would be poised until buffered data is over, and the flow with insufficient buffer would be served based on priority. By using this technique, Wi-Fi can sleep enough to counterbalance the impact of the state-transition delay.

As mentioned in the previous paragraph, power consumption of portable devices can be reduced by deploying certain energy-aware protocols. One such protocol, Cell2Notify, was proposed by Agarwal et al. [9] for conserving energy while making VOIP calls. VOIP enables voice communication over Internet protocol (IP)-based networks, such as wide area network (WAN), LAN, and the Internet. Protocols associated with VOIP digitize voice in packets and send them using regular IP routing. VOIP, unlike the public switched telephone network (PSTN), does not require a dedicated infrastructure, thus making it much cheaper. Cell2Notify attempts to reduce the energy consumption of Wi-Fi when no VOIP call is active. The Wi-Fi is again activated once the VOIP call is received or established.

In recent years, there has been considerable focus on improvising device properties, but little has been done to provide methods in software and hardware to scale down devices to the least of different functionalities. Mayo and Ranganathan [10] suggested techniques for scaling down the energy consumption by evolving certain changes in device functionality. The scaling down of energy was tested on three components: display, Wi-Fi card, and processor.

Energy consumed by the display was scaled down by leveraging the fact that users normally use only a fraction of the screen area; hence, the display screen can selectively control pixel intensity to match the power consumed by the display with portions significant to the user. For Wi-Fi, it was observed that the energy consumed in the idle mode was dominated by the energy spent in listening to beacons that are periodically issued to guarantee a timely response. Generally the listen interval is set to 100 milliseconds (ms) in default configurations, but the mean time between messages received by users is many minutes. Based on this observation, Mayo and Ranganathan [10] implemented a wireless system that could adapt its listening interval to application response times. The energy consumption of this processor could be scaled down by using multi-core architecture. It was observed that by implementing the above-suggested techniques, the energy consumption could be scaled down by a factor of 2 to 10, compared to existing methods and designs.

2.4 Novelty of Contribution

Most previous studies conducted in the field of computing have concentrated on devices such as desktop computers and data center equipment. The Wi-Fi card is a very important component of any portable computing device, and the energy efficiency of Wi-Fi operation is also important since the entire world is using the Internet to access various applications. This thesis takes a novel approach to accounting for the energy consumption of the Wi-Fi card.

CHAPTER 3

WIRELESS INTERFACE ENERGY CONSUMPTION IN LAPTOPS

Wi-Fi energy consumption for various applications was calculated using a setup that included an IBM ThinkPad laptop as a portable device and the Linux operating system, since it provides users higher flexibility in analyzing the energy-consumption pattern. The energy consumption of various Wi-Fi card applications was calculated and will be discussed later in this chapter. The energy consumption of a typical laptop due to Wi-Fi will also be shown later in this chapter. The aim of these experiments was to understand the power consumption of the Wi-Fi in relation to the power consumption of a whole system.

Section 3.1 describes the specifications of the system and the applications considered for measurement. Section 3.2 shows how the energy-consumption measurements were taken. In section 3.3, the energy consumption of each application, a single laptop, Wi-Fi use, and all laptops in the United States is calculated.

3.1 Experimental Methodology

3.1.1 System Specifications

Table 3.1 shows the system specifications of the device under consideration.

TABLE 3.1

SYSTEM SPECIFICATIONS

Component	Specification
Processor	Intel® Core ™2 Duo 2.4 GHz
Memory	2 GB
Hard Drive	160 GB
Optical Drive	DVD RW
Wireless Networking	Intel 4965AGN (802.11 a/b/g/n Wi-Fi), Blue Tooth 2.0
Screen	14.1” 1024 x 768

TABLE 3.1 (continued)

Component	Specification
Processor	Intel® Core ™2 Duo 2.4 GHz
Memory	2 GB
Hard Drive	160 GB
Optical Drive	DVD RW
Wireless Networking	Intel 4965AGN (802.11 a/b/g/n Wi-Fi), Blue Tooth 2.0
Screen	14.1" 1024 x 768

The operating system used for testing was a Linux 9.10 [11 because the Linux command prompt can be used for accessing information and cannot be extracted by any other operating system. For this study, it was especially useful because the battery state, battery capacity, and power consumption parameters were easily accessible through the command line. Also, the Wi-Fi card states could be changed using the terminal program. In addition, Linux was quite useful for writing intricate batch tasks and scripts.

3.1.2 Applications Considered for Measurement

FTP, VOIP, video streaming, soft browsing, and idle were considered for measurement because these applications cover almost all operating states of a Wi-Fi.

- **FTP:** This application was tested for effectiveness of reading by downloading a 700 MB file multiple times from 100% battery capacity to 25% battery capacity.
- **VOIP**: This application was tested using Skype space [12]. Various other software applications, like Google talk, Messenger, and Meebo, were tried, but these applications were not compatible to the Linux operating system. Hence, Skype was used because one of its releases (Skype 2.1 Beta 2) was compatible with Linux.
- **Video Streaming:** For measuring the energy of this application, video was streamed over the Internet from 100% battery capacity until it reached 30%.

3.2 Energy Measurement Methodology

Energy for the wireless local area network (WLAN) was measured in two ways: the first at various instants through the Linux terminal, as shown in the screen shot in Figure 3.1, and the second by accessing battery statistics. The current state of the battery is either charging or discharging. It can be seen in Figure 3.1 that the state of the battery is in a discharging state. The current rate is the energy consumed at one particular instant of time. This screen shot shows that the present rate is 15,960 mW.

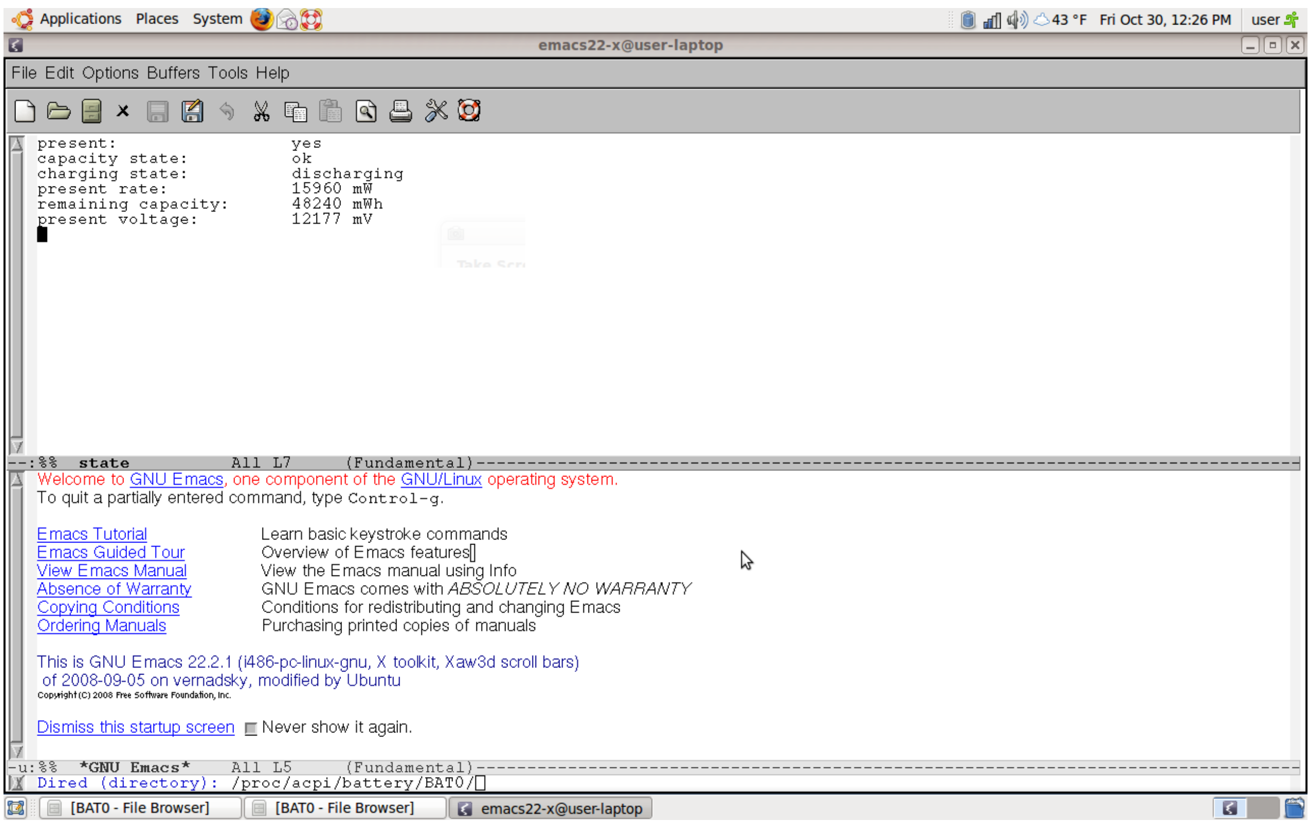

Figure 3.1 Battery statistics

Remaining capacity is the capacity of the device to be functional. The screen shot in Figure 3.1 shows that the battery capacity is 48,240 mWh. When the battery is fully charged, the capacity of the battery would be 51,700 mWh. The charge rate in this scenario means the discharge rate, since all readings were taken when the AC power was unplugged. The discharge rate is the rate at which chemical energy is converted into electrical energy. From Figure 3.1, it can be seen that the charge rate of the battery at that particular instant was about 17.3 W. This parameter was required to check the charge rate at different battery capacities. Also, it was observed that the discharge rate was higher when the battery capacity was low.

Figure 3.2 shows the battery discharge versus time since startup. It can be seen that the discharge rate from about 95% to 50% battery capacity was three hours, and from 50% to 20% battery capacity was about one hour. That is, when the battery capacity is higher, the discharge rate is slower, whereas when the battery capacity is lower, the discharge rate is faster. This contrast in performance can be attributed to the battery characteristic.

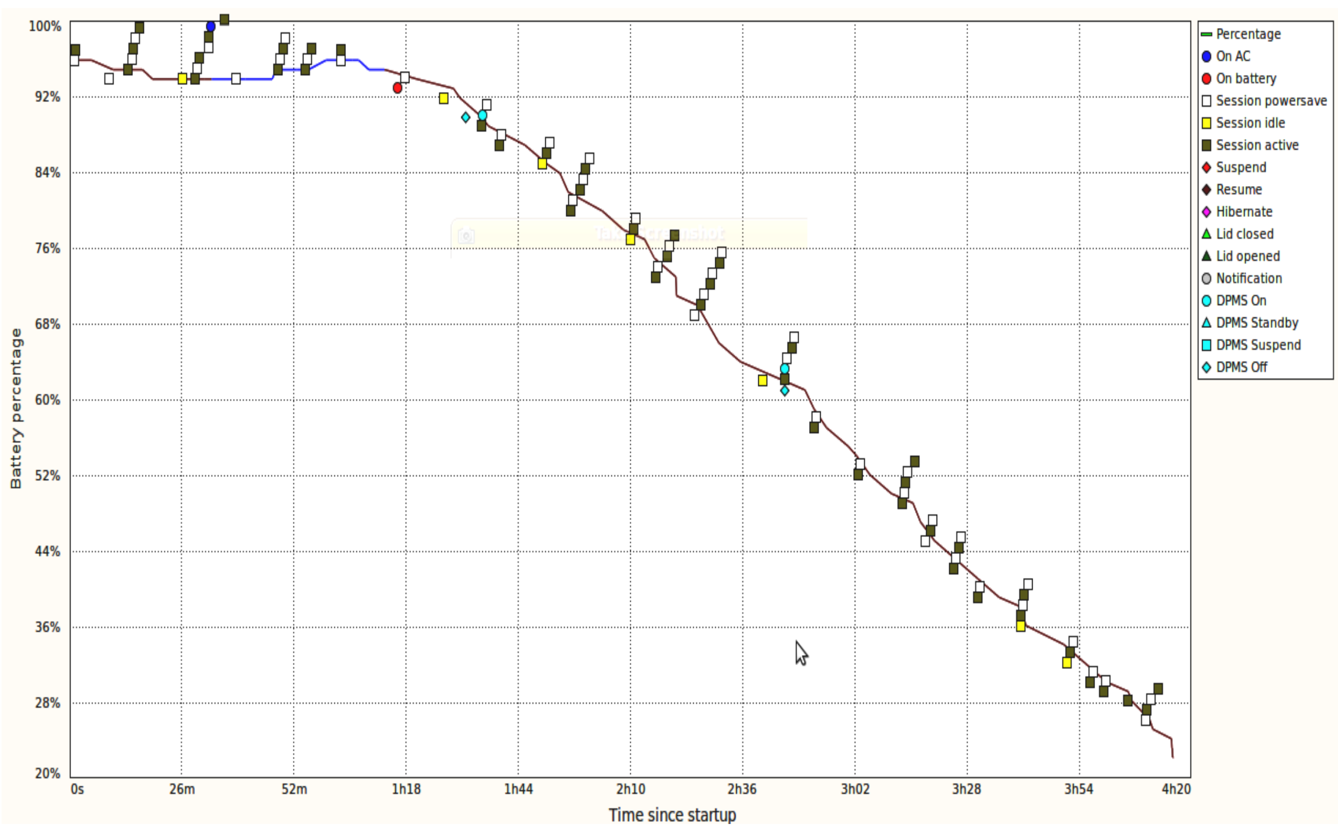

Figure 3.2 Battery discharge versus time since startup

Figure 3.3 shows battery device information for a particular battery capacity as well as for various other parameters like current charge rate, current capacity, and design charge.

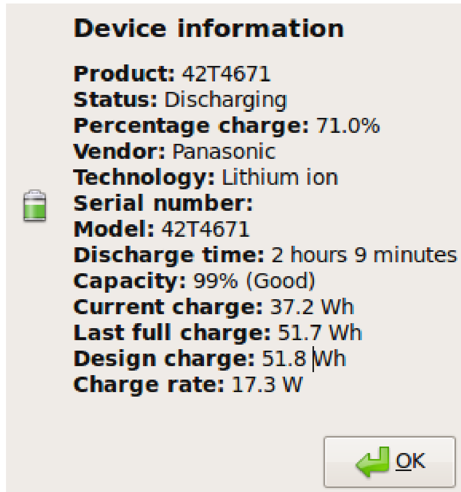

Figure 3.3 Battery device information

3.3 Energy Measurement Results

The energy consumption of the wireless network interface card (WNIC) card was measured for certain major applications such as FTP, VOIP, and video streaming. Figure 3.4 shows the averaged power consumption of each application at various instants from 100% to 30% battery capacity. It was found that the VOIP application consumed the maximum power of about 20.68 Wh, followed by video-streaming of 20.62 Wh, and then the FTP application. Table 3.2 shows the power consumed by each application.

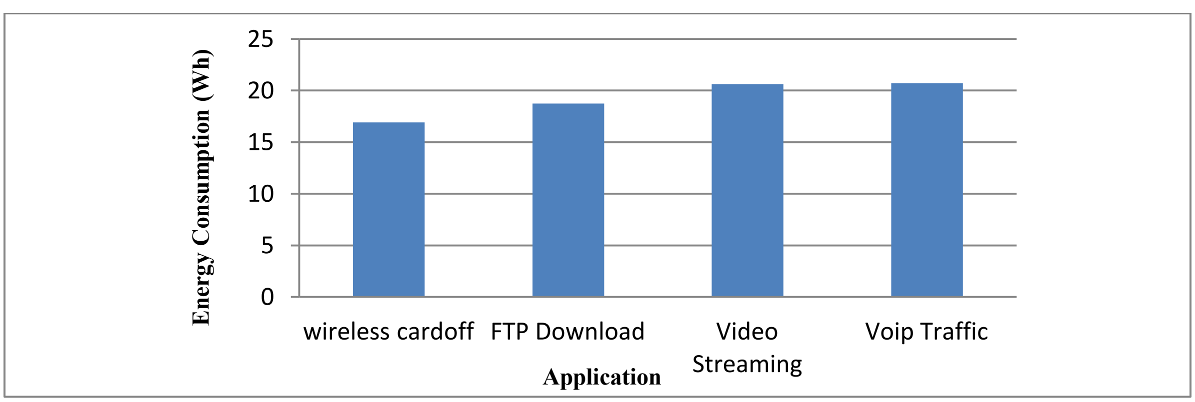

Figure 3.4 Instantaneous energy consumption of each application

TABLE 3.2

POWER CONSUMED BY DEVICE WHEN EACH APPLICATION IS RUNNING

Application	Power Consumed (W)
Wireless Card Off	17.3
FTP Download	18.732
Video Streaming	20.62
VOIP	20.6

Figure 3.5 shows that the charge rate of the battery depends on the battery capacity, where the higher the battery capacity, the lower the charge rate.

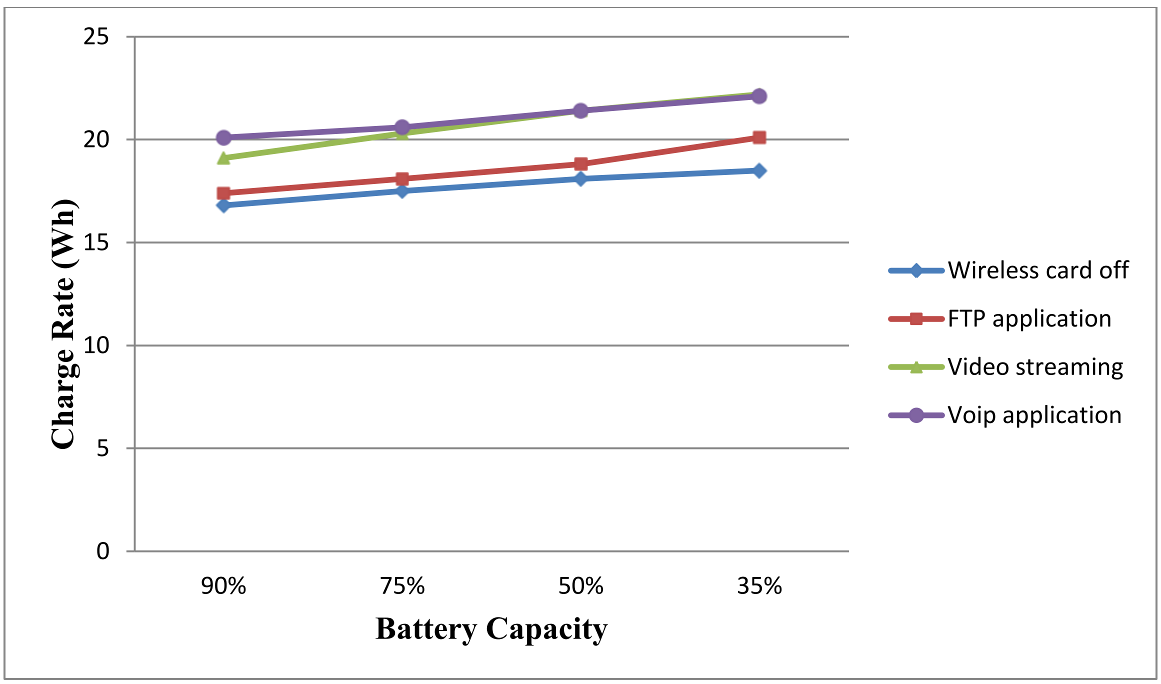

Figure 3.5 Charge rate for each application versus battery capacity

3.3.1 Accounting for Energy Consumption of Single Laptop

Accounting for the energy consumption of a Wi-Fi card would make it useful to know its fraction of the world's energy consumption. Laptops form the major portion of portable devices, and they consume more power because they support various applications, high-memory storage capacity, and size. The energy consumed by laptops is discussed first, and then the figures for energy consumed as the result of Wi-Fi card usage are provided.

According to a survey in 1999, the daily mean usage of laptop was 3.2 hours by children between the ages of 10 and 17 years [13]. Also, according to a computing survey at Harvard University in 2009–10 [14], most people said that they used laptops roughly eight hours a day. With the abundance of wireless technology, laptop usage roughly doubled in this ten-year span. To account for the energy consumption, it is assumed that a laptop is used eight hours per day. For 40% of the time, or about three hours, laptops are in either an idle state or a light-browsing state. The most actively used applications are VOIP and video, so it is assumed that these two applications are used about 25% of the total time, or about two hours each. The remaining 10% of the time is used for FTP applications, since file downloads and file transfers are not that frequent. As referred to in section 3.4, the energy consumed for a Wi-Fi card in the idle state is 17.3 Wh, an FTP application is 18.7 Wh, video streaming is 20.62 Wh, and VOIP application is 20.68 Wh. The energy consumed while light browsing is close to idle. Table 3.3 shows the energy consumed daily for each application.

TABLE 3.3

ENERGY CONSUMPTION OF DEVICE FOR EACH APPLICATION

Application	**Energy Consumption (Wh)**
Wireless Idle State	51.9
FTP	18.7
Video Streaming	41.24
VOIP	41.36

The figures in Table 3.3 were used for estimating the overall energy consumption of all laptops. The energy consumption of various vendor laptops was calculated to check if the energy consumption of the laptop in consideration (IBM ThinkPad) was realistic for estimating the overall energy consumption. In order to determine the energy consumption of laptops of other vendors, operations like video streaming and browsing were performed, and the energy consumption was measured using a kill-a-watt meter. This meter provides a reading of the instantaneous power consumption of any device plugged into it. Table 3.4 shows the energy consumption pattern for various vendors' laptops.

TABLE 3.4

ENERGY CONSUMPTION OF LAPTOPS FROM VARIOUS VENDORS

Model	**Specification**	**Energy Consumption with WNIC Off (Wh)**	**Energy Consumption Idling with WNIC On (Wh)**	**Energy Consumption with Streaming Video through WNIC (Wh)**
HP Pavilion dv4t	4 GB RAM, 2 GHz Processor	30	31	32
Dell Inspiron 1525	3 GB RAM, 2 GHz Processor	21	24	36
Compaq Presario C300	2 GB RAM, 2 GHz Processor	28	30	34
Dell Inspiron 1440	4 GB RAM, 2.2 GHz Processor	18	19	24
Aspire 4730Z	2 GB RAM, 2 GHz Processor	27	29	31

From Table 3.4, it can be seen that the energy consumption of laptops from various vendors is on the higher side when compared to the energy consumption of the IBM ThinkPad. Hence, using those figures found for the energy consumption of the IBM ThinkPad laptop for estimating overall consumption would be ideal.

3.3.2 Energy Consumption Due to Wi-Fi Card Usage

The energy consumption of a Wi-Fi card can be calculated from the laptop energy consumption. As referred to in the previous section, energy consumed in the wireless off state was 17.3 Wh and for the file transfer protocol state was 18.7 Wh. Hence, the difference between the two states was the energy consumed for the FTP application, or 1.3 Wh. The energy consumed for video streaming was 20.62 Wh and, after deducting it from the wireless off state, this was 3.32 Wh. Similarly, VOIP application energy consumption was 3.38 Wh. If each application was used according to section 3.3.1, then the energy consumed would be 14.7 Wh.

3.3.3 Aggregate Energy Consumption from Wi-Fi Card for All Laptops in United States

To account for the energy consumption of all laptops, first, the number of laptops must be taken into consideration. Cheaper prices of laptops over the past few years have fueled their sales. Due to their compactness, laptops have become so popular that in 2008, their sales of 38.6 million units surpassed the sales of desktop computers, which was 35.5 million [1].

According to a government census report [15] published in 2001, the number of laptops sold in 1998 was 2.66 million. Since laptop sales increased by 6% in 1999 [16], the number of laptops sold that year would have been 2.75 million. Similarly, if the growth was 13.6% in 2000 [17], then the number of laptops sold in 2000 would have been 3.138 million. According to a *USA Today* report, the number of laptops doubled in the market from 2000 to 2004. A report of the International Data Cooperation (IDC) indicated that the number of laptops sold was 30 million in 2007, 35.5 million in 2008, and 41.1 million in 2009 [18]. Summing up these figures, the number of laptops in the U.S. would account for around 160 million. Figure 3.6 shows an accounting of laptops in various years between 2000 and 2009.

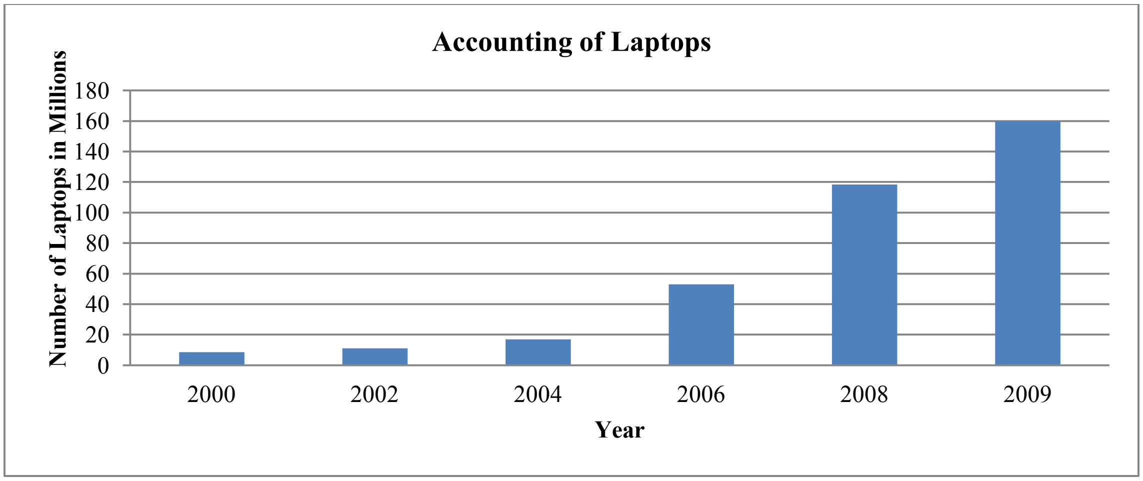

Figure 3.6 Accounting of laptops between 2000 and 2009

As calculated in section 3.3.2, the energy consumed as the result of Wi-Fi card usage was 1.3 Wh for FTP applications, 3.32 Wh for video, and 3.38 Wh for VOIP. Therefore, if each application is used for two hours per day, the energy consumed would be 16 Wh. As calculated in this section, the number of laptops in the U.S. is estimated to be around 160 million. Therefore, energy consumption per day from all laptops in the U.S. would be 2,352 MWh.

CHAPTER 4

WI-FI CARD ENERGY COMSUMPTION IN BROADER PERSPECTIVE

Chapter 3 provided a discussion of the results of Wi-Fi card energy consumption for various applications, and the total energy consumption for all applications combined was calculated. Chapter 4 shows the various calculations of Wi-Fi card energy consumption as a fraction of per capita energy and total energy consumption in the U.S. Also, the environmental impact of Wi-Fi card energy consumption is discussed, and the offset required to balance CO_2 emissions is calculated. The results of this study, which was done on the Wi-Fi of a laptop, are found in Chapter 5, and Chapter 6 covers the energy consumption of Wi-Fi for a smartphone.

4.1 Wi-Fi Card Energy Consumption as Fraction of Per Capita Energy Consumption

Per capita energy consumption is the energy consumption per individual and, in certain cases, per household. A comparison of energy consumption of Wi-Fi to the per capita energy consumption would provide a broader perspective on the share of Wi-Fi energy consumption in totality. A comparison would also help to evaluate the seriousness of the impact.

According to a survey conducted by the U.S. Energy Information Administration (EIA), the average monthly energy consumption per household is 920 kWh. As calculated in section 3.3.1, the energy consumption of a Wi-Fi card per day is 14.7 Wh. Therefore, the monthly consumption would be 441 Wh, or .44 kWh. Section 3.3.3 showed that the number of laptops in the U.S. is 160 million, and from a census report, it was projected that in 2009, the number of laptops in U.S. households was 113 million [20]. From these figures, it can be estimated that on average, there is at least one laptop per household. The per household energy consumption from the Wi-Fi card is at least 441 Wh, which may seem insignificant in light of the average monthly energy consumption of 920 kWh, but 441 Wh is the energy consumption from the Wi-Fi card alone, and does not consider the total energy consumption of the laptop's other components. Energy consumption from the Wi-Fi card is about 0.5% of a household's energy consumption.

4.2 Wi-Fi Card Energy Consumption as Fraction of U.S. Energy Consumption

The United States is a leader in manufacturing and transportation, two sectors where energy consumption is at a maximum. A quarter of the world's energy is consumed in the U.S. Comparing the energy consumption of the Wi-Fi card to the overall energy consumption would give an idea of the Wi-Fi energy conservation that is needed.

According to the EIA report, the net generation of electricity by all sectors in 2009 was 3,600,739 MWh, which is approximately 3,600 TWh [20]. As calculated in section 3.3.2, the energy consumption from Wi-Fi card usage is 14.7 Wh per day. It was also estimated that the number of laptops is 160 million; hence, the energy consumption due to Wi-Fi card usage for all laptops would be 858,480 MWh, or approximately 1 TWh. This may seem insignificant in comparison to the total energy consumption (i.e., around 3,600 TWh), but 1 TWh is a large figure and the energy consumption of the Wi-Fi card alone, not for other components like the liquid crystal display (LCD), 3D card, and hard disk. Figure 4.1 shows an accounting of the Wi-Fi card's energy consumption.

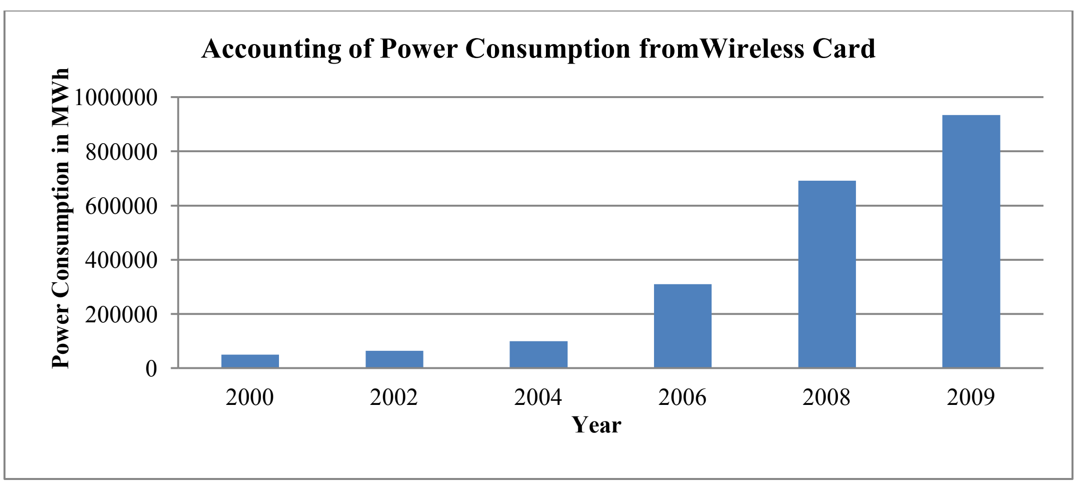

Figure 4.1 Accounting of wireless card energy consumption

4.3 Energy Consumption per Application

The experimental calculations in section 3.7 show that the energy consumed is about 1.3 Wh for the FTP application, 3.32 Wh for video, and 3.38 Wh for VOIP. The energy consumed by both the video and VOIP applications is about three times the energy consumed for the FTP application. In the real world, if a portable device is used for light browsing and the FTP, there would be a major difference in the energy-consumption pattern. The battery would die out three times faster running VOIP and video applications, compared to running the FTP or light browsing; hence, it is important to know the energy consumption pattern for each application.

4.3.1 Energy Consumption per Application as Fraction of Per Capita Energy Consumption

Knowing the energy consumption of each wireless application component would provide insight on the impact of each. As calculated in section 3.3.2, energy consumption of the FTP is 1.3 Wh. If the FTP application is used for one hour, then the energy consumption of the FTP would be 1.3 Wh. Since the number of laptops in United States was estimated to be 160 million, the monthly energy consumption of the FTP application would be 6.2 GWh. Also, the average energy consumption per household is 920 kWh per month. The census report projected that the number of U.S. households in 2009 was 113 million. Therefore, from these figures, it can be seen that on average, there is at least one laptop per household. Hence, the energy consumption of FTP applications for every household is 80.6 Wh per month. Similarly, the energy consumption from the video-streaming application, which is used for approximately two hours per day, is about 3.32 Wh per hour. Hence, the energy consumption of the video application would be 6.64 Wh per day. Also, since the numbers of laptops in the U.S. was calculated to be 160 million, the monthly energy consumption would account for 32.934 GWh. Energy consumption of the video application per household would be 199 Wh per month. Similarly, energy consumption of the VOIP application per household would be 209.56 Wh per month. Also, the energy consumption of all laptops using the VOIP application would account for 33.5 GWh per month.

4.3.2 Energy Consumption per Application for One Year

It was calculated in section 4.3.1 that the monthly energy consumption of an FTP application for all laptops is 6.2 GWh; therefore, the energy consumption would be 74.4 GWh per year. Energy consumption of the video application accounted for 32.93 GWh, or 395.16 GWh per year. Similarly, energy consumption of VOIP applications accounted for 33.5 GWh per month, or 402.16 GWh per year.

4.4 Environmental Impact

To understand the environmental impact on the atmosphere from Wi-Fi cards, it is important to analyze the CO_2 released from each source initially and then calculate the CO_2 released into atmosphere as the result of Wi-Fi card usage. In the United States, 51% of electricity is generated from coal, and for every kilowatt of electricity generated from this source, 2.117 pounds of CO_2 are released into the atmosphere [21]. Approximately 15.2% of electricity in the U.S. is generated from natural gas, and for every kilowatt of electricity produced from this source, 1.314 pounds of CO_2 is released. Approximately 3.2% of electricity in the U.S. is generated from petroleum, and for every kilowatt of electricity produced from this source, 1.314 pounds of CO_2 is released. Other sources like biomass, hydroelectricity, renewable sources (sun, wind, geothermal), and nuclear fuel together account for about 30.6% of electricity generation; the CO_2 released for every kilowatt of electricity generated from these fuels is about 1.378 pounds. Averaging all sources then, the U.S. national average of CO_2 emissions per kilowatt of electricity generated is 1.350 pounds. Table 4.1 shows the CO_2 emissions by energy source.

TABLE 4.1

POUNDS OF CO_2 RELEASED FOR EVERY KILLOWATT OF ENERGY SOURCE

Source	CO_2 Emissions (pounds)
Coal	2.117
Petroleum	1.918
Natural Gas	1.314
Other Fuels	1.378
Average	1.350

4.4.1 CO_2 Emissions from Wi-Fi Card Usage for One Day

As calculated in section 3.3.2, the energy consumed by Wi-Fi card usage for a single laptop is 14.7 Wh. Laptops number 160 million, as estimated in section 3.3.3, and their energy consumption for one day would be 2,560 MWh. The amount of CO_2 emitted for a kilowatt of electricity generation is 1.350 pounds, which is the average of all sources such as coal, petroleum, and natural gas, as referred to in section 4.4. Therefore, the amount of CO_2 emitted from 2,352 MWh of electricity consumed by Wi-Fi cards would account for 3,175 thousand pounds per day.

4.4.2 CO_2 Emissions from Each Wi-Fi Application for One Year

As calculated in section 4.3.2, the energy consumption from FTP application usage for a year is 74.4 GWh. The CO_2 emitted for a kilowatt of electricity generation is 1.350 pounds, which is the average of all sources like coal, petroleum, and natural gas, as referred to in section 4.4. Therefore, the amount of CO_2 emitted from 74.4 GWh of electricity used by the FTP application usage would amount to 100 million pounds. Energy consumption from video application usage on a Wi-Fi card for a year is 395.16 GWh; therefore, CO_2 emissions from this application would be 513 million pounds. Energy consumption from VOIP application usage on a Wi-Fi card for a year is 402 GWh; therefore, CO_2 emissions from this application usage would be 523 million pounds.

4.4.3 CO_2 Emissions from Wi-Fi Card Usage for One Year

The energy consumed from using a Wi-Fi card is 858,480 MWh or 1TWh, as accounted for in section 4.2. The CO_2 emitted for 1 kW of electricity generation is 1.350 pounds, which is the average of all sources like coal, petroleum, and natural gas, as referred to in section 4.4. Therefore, the amount of CO_2 emitted from a Wi-Fi card using 858,480 MWh of electricity would be 1,158 million pounds. According to the EIA report [22], CO_2 emissions in the U.S. in 2004 accounted for 1,042 million metric tons; in 2005, CO_2 emissions accounted for 1,060 million metric tons; in 2006, this number was 1,043 million metric tons; and in 2007, this number was 1087.4 million metric tons. From the above data and that from other previous years, it can be projected that the carbon emissions for the year 2009 would have been approximately 1,130 million metric tons, or approximately 2,491 billion pounds. The 1,158 million pounds of CO_2 generated as the result of Wi-Fi card usage would be approximately .1% of the total carbon emissions in the U.S. Although .1% might seem like a small number, it is important to keep in mind that the U.S. consumes almost 25% of the world's energy. Figure 4.2 shows the CO_2 emissions from Wi-Fi card usage between 2000 and 2009.

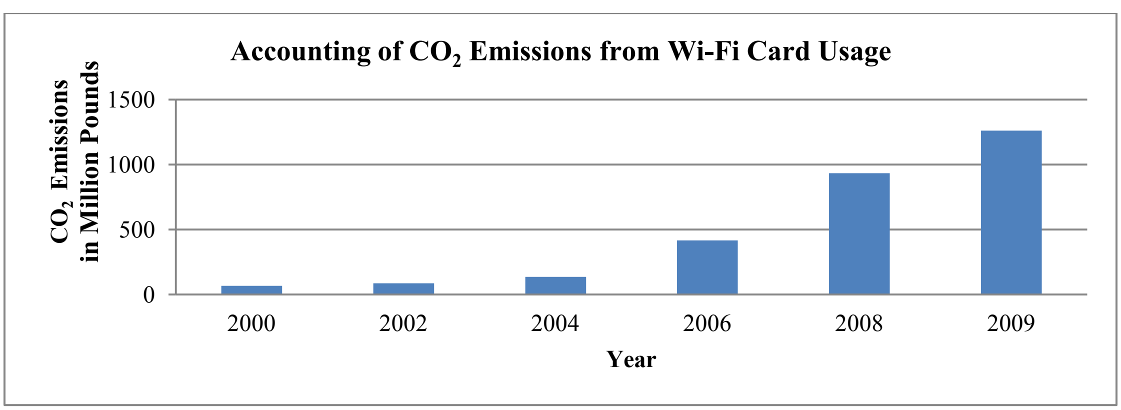

Figure 4.2 CO_2 emissions from Wi-Fi card usage

4.4.4 Comparison of CO_2 Emissions from Each Wi-Fi Application to CO_2 Emissions from Vehicles

A comparison of CO_2 emissions from Wi-Fi usage with CO_2 emissions from vehicular use would provide a broader picture of the impact of CO_2 emission on Wi-Fi. A comparative study would also help in analyzing the impact of Wi-Fi usage on the atmosphere. The average passenger vehicle is driven 12,000 miles per year, according to a report from the U.S. Environmental Protection Agency [23], and the resultant CO_2 generated is approximately 5.48 metric tons, which is approximately 12,077.92 pounds. As calculated in section 4.4.2, CO_2 emissions in the United States from using the Wi-Fi card's FTP application is 100 million pounds, which is equivalent to the CO_2 emissions of approximately 8,500 passenger vehicles. The CO_2 generated from the Wi-Fi's video application is 513 million pounds, which is equivalent to the amount of CO_2 emitted from approximately 42,474 passenger vehicles. The CO_2 generated from the Wi-Fi's VOIP application usage is 523 million pounds, which is equivalent to CO_2 emissions from approximately 43,305 passenger vehicles.

4.4.5 Comparison of CO_2 Emissions from Wi-Fi Card Usage to CO_2 Emissions from Vehicles

As mentioned in section 4.4.4, the average passenger vehicle is driven 12,000 miles per year as per the report of U.S. Environmental Protection Agency [23], and CO_2 generated is approximately 5.48 metric ton that is around 12,077.92 pounds. As calculated from the information in section 4.4.4, CO_2 emissions as the result of wireless usage in the U.S. is 1,261 million pounds, including idle time and soft browsing, which is equivalent to the CO_2 emissions of approximately 95,877 passenger vehicles. This is a very high figure, although the number of passenger vehicles is in the hundreds of millions.

4.5 Offset Requirement

4.5.1 Number of Trees Required to Offset Impact of CO_2 Generated from Wi-Fi Card Usage

As mentioned in section 4.4.3, the CO_2 emissions from Wi-Fi card usage are approximately 1,261 million pounds, which is approximately .1% of the total CO_2 emissions in the United States. These emissions can cause adverse effects like ozone depletion; hazardous effects on human health, such as asphyxiation, frostbite, and kidney damage; and a decline in global harvest of grains and pulses. The number of trees required to offset the effect of CO_2 emissions from Wi-Fi card usage would be 441,941, a figure calculated using the carbon-offset calculator [24]. Even though the use of passenger vehicles, air travel, and technological devices is increasing, offsetting the effect of those CO_2 emissions with trees is not possible because deforestation is also increasing. More energy efficient technology should be developed to resolve this issue.

4.5.2 Number of Trees Required to Offset Impact of CO_2 Generated from Each Wi-Fi Application

As mentioned in section 4.4.2, CO_2 emissions from the Wi-Fi card's FTP application is approximately 206.55 million pounds. That is, the number of trees required to offset the effect of CO_2 emitted from using the FTP application on the Wi-Fi card would be 240,625, a number calculated with the carbon offset calculator [24]. Similarly numbers of trees required to offset the effect of CO2 emitted from video and VOIP application is 597630 and 609280 respectively. Since the use of passenger vehicles, air travel, and technological devices is increasing, so is deforestation; therefore, offsetting the effect of CO_2 emissions by trees is not possible. More energy efficient technology should be developed to resolve this issue.

CHAPTER 5

PROJECTIONS OF ENERGY CONSUMPTION IN LAPTOPS

Research that includes future projections is useful for providing the future scope of the field. Projecting the number of wireless users is important in order to know the future impact on energy consumption and, in particularly, to know what share of energy consumption is the responsibility of wireless devices compared to overall energy consumption. In this chapter, the number of laptops in the near future as well as their energy consumption is projected. Projections of CO_2 emissions and an offset are also calculated.

5.1 Projections of Number of Laptops

As estimated in section 3.3.3, by the year 2009, the number of laptops in the United States was 160 million. According to the IDC survey, the sale of laptops was projected to be 47.5 million in 2010, 54.1 million in 2011, and 61.1 million in 2012 [18]. Based on these projections, it is estimated that the number of laptops would be 68.4 million in 2013 and 75.5 million in 2014. Therefore, the total number of laptops in the U.S. by 2014 would be approximately 466 million. The increase in laptop sales is also fueled by lower prices and portable features. Figure 5.1 shows projections of the number of laptops between 2009 and 2014.

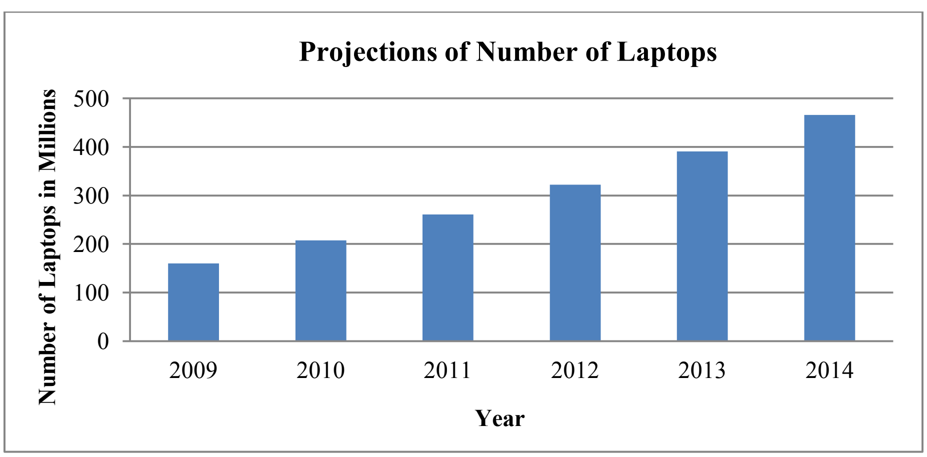

Figure 5.1 Projections of number of laptops between 2009 and 2014

5.2 Projections of Energy Consumption

5.2.1 Projections of Energy Consumption from Wi-Fi Card Usage

As described in section 3.3.2, energy consumption of the Wi-Fi card was calculated to be 14.7 Wh per day. According to the projections calculated in section 5.1, the number of laptops by the year 2014 would be around 466 million. Energy consumption from Wi-Fi card usage for all laptops would be 2,500,323 MWh, which is 2.5 TWh. According to the EIA report, the total energy consumption was 4,064 TWh for the year 2006, 3,810 TWh for 2007, 4,121 TWh for 2008, and 3,944 TWh for 2009. As discussed in section 4.2, from these figures and other previous statistics, the estimated energy consumption in 2014 would be approximately 4,218 TWh. Wi-Fi card usage would be around .1% of the total energy consumption. Figure 5.2 shows a comparison of energy consumption projections in 2006 2009, and 2014.

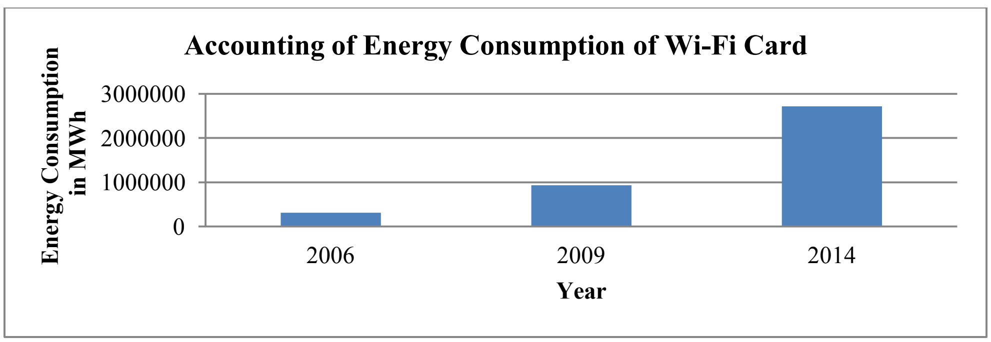

Figure 5.2 Projections of energy consumption of Wi-Fi card

5.2.2 Projections of Energy Consumption from Each Wi-Fi Application

As described in Section 4.3.2, energy consumption from the FTP application on a Wi-Fi card was calculated to be 1.3 Wh per day. As described in section 5.2.1, the number of laptops by the year 2014 is expected to be approximately 233 million. Therefore, the energy consumption of all laptop Wi-Fi card usage would be .2 TWh. Energy consumption from the video application per day would account for 6.64 Wh, and with approximately 466 million laptops in the U.S. by 2014, the energy consumption for video applications would be 1.12 TWh.

Similarly, energy consumption of VOIP application usage is 7.6 Wh per day; hence, the projected energy consumption would be 1.21 TWh in 2014.

5.3 Projections of CO_2 Emissions

5.3.1 Projections of CO_2 Emissions from Wi-Fi Card Usage

As mentioned in section 4.4, approximately 51% of the electricity in the United States is generated from coal. For every kilowatt of electricity generated from coal, 2.117 pounds of CO_2 is released into the atmosphere. Natural gas generates 15.2% of the electricity, and for every kilowatt of electricity produced by this source, 1.314 pounds of CO_2 is released. Petroleum generates 3.2% of electricity in the U.S., and for every kilowatt of electricity produced from this source, 1.314 pounds of CO_2 is released. Other sources, such as biomass, hydroelectricity, renewable sources (sun, wind, geothermal), and nuclear fuel, together account for about 30.6% of electricity generation. The amount of CO_2 emitted for every kilowatt of generation of electricity from the combustion of these fuels is about 1.378 pounds. Averaging all sources, the national mean of CO_2 emissions for one kilowatt of electricity generated is 1.350 pounds. As mentioned in section 5.2.2, for Wi-Fi card usage in 2014, the projected energy consumption would be approximately 2.5 TWh, and CO_2 emissions would be 3.37 billion pounds. Figure 5.3 shows the projections of CO_2 emissions from the Wi-Fi card.

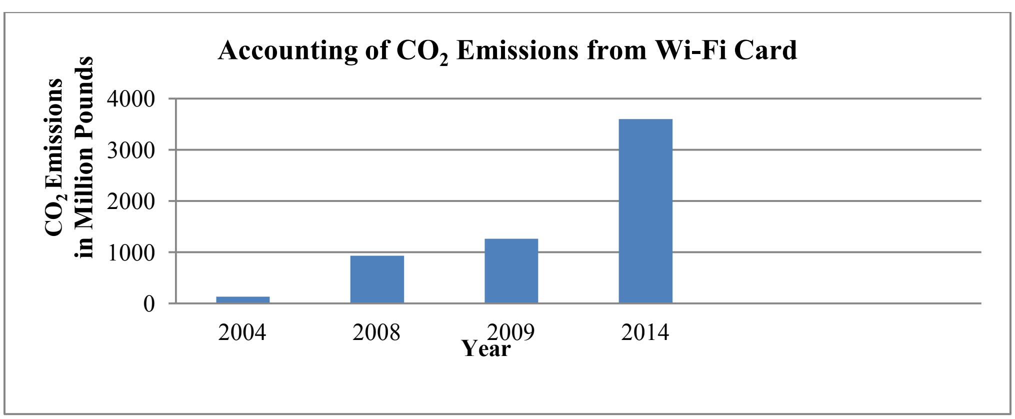

Figure 5.3 Projections of CO_2 emissions from Wi-Fi card

5.3.2 Projections of CO_2 Emissions from Each Wi-Fi Application

The U.S. national average of CO_2 emissions from all sources for one kilowatt of electricity generated is 1.350 pounds. As referred to in section 5.2.2, for the year 2014, the projected energy consumption from FTP application usage was about 0.2 TWh, and the CO_2 emissions was 540 million pounds. The 2014 energy consumption from video application usage was projected to be 1.12 TWh, with corresponding CO_2 emissions at 0.755 billion pounds. The 2014 projected energy consumption for VOIP application was 1.21 TWh, with CO_2 emissions at 1.63 billion pounds.

5.4 Offset Requirement

From section 5.3, CO_2 emissions in 2014 was projected to be 3.37 billion pounds. CO_2 emissions can cause some adverse effects like ozone depletion; hazardous effects on human health such as asphyxiation, frostbite, and kidney damage; and decline in the global harvest of grains and pulses. The number of trees required to offset the effect of CO_2 emitted as the result of Wi-Fi card usage would be 130,175, using the carbon offset calculator [22].

CHAPTER 6

WIRELESS INTERFACE ENERGY CONSUMPTION IN SMARTPHONES

The usage of smartphones is increasing exponentially. Since all major features of a smartphone require Internet access, accounting for the energy consumption of a smartphone Wi-Fi card is very important. In this chapter, the number of smartphones and their energy consumption is discussed. The environmental impact and offset required are also calculated.

6.1 Accounting for Number of Smartphones

. According to a National Purchase Diary (NPD) market research survey, smartphones accounted for approximately 28% of sales of handsets in the second quarter of 2009, a massive 47% increase from a similar period the previous year [25]. According to the Allied Business Intelligence (ABI) market research firm, 74% of users having Wi-Fi capability on their phones use Wi-Fi for connectivity. In 2009, Wi-Fi chipset shipments reached 100 million. According to a forecast, in 2011, the number of Wi-Fi chipsets for smartphones is expected to be 1 billion [26].

From these statistics, it can be concluded that the number of smartphone users utilizing Wi-Fi capability is 37 million.

6.2 Accounting for Energy Consumption of Smartphones from Wi-Fi Card Usage

The energy consumption of the average smartphone when all radios are turned off is around 0.015 Wh, and when sending and receiving data over a Wi-Fi channel, this consumption is around 1.3 Wh [26]. Deducting the energy consumption when all radios are turned off from the 1.3 Wh when radios are sending and receiving data would provide the energy consumption of the Wi-Fi card alone. Thus, the energy consumption of Wi-Fi card usage alone is approximately 1.28 Wh. It was mentioned in section 6.1 that the number of smartphones actively using wireless capability is approximately 37 million; therefore, the energy consumption for all smartphones using Wi-Fi actively for a day is 47.36 MWh, and the total energy consumption for a year would be approximately 17,286 MWh.

6.2.1 Wi-Fi Card Energy Consumption as Fraction of Per Capita Energy Consumption

According to the survey conducted by the Energy Information Administration, the average monthly energy consumption per household is 920 kWh, as mentioned in section 4.1. From section 6.2, the energy consumption of a Wi-Fi card per day is 1.28 Wh. Therefore, the monthly consumption would be 38.4 Wh, which is 0.038 kWh. In section 6.1, it was also mentioned that the number of smartphones in the United States is 50 million, and from the census report, it was projected that the number of U.S. households in 2009 was 113 million [19]. From these figures, it can be observed that, on average, there is at least one smartphone for every two households. Therefore, the energy consumption from a Wi-Fi card for every two households is at least 38.4 Wh. This amount may seem insignificant before the average monthly energy consumption of 920 kWh is taken into consideration however, it is important to keep in mind that 38.4 Wh is power consumption from the Wi-Fi card only.

6.2.2 Wi-Fi Card Energy Consumption as Fraction of Overall U.S. Energy Consumption

According to the EIA report, the net generation of electricity by all sectors in the year 2009 was 3,600,739 thousand MWh, which is around 3,600 TWh, as mentioned in section 4.1. From section 6.2, the energy consumption of smartphone Wi-Fi card usage is 1.28 Wh per day, and with 50 million smartphones, 37 million of which are actively using the Wi-Fi card, the total energy consumption from smartphone Wi-Fi card usage would be 17,286 MWh. This energy consumption may seem insignificant compared to the total energy consumption, but 17,286

MWh is still a large number, and the smartphone is a handheld device, the usage of which will increase enormously in the future.

6.3 Environmental Impact

This section focuses on the environmental impact from energy consumption of a smartphone Wi-Fi card. As referred to in section 4.4, in order to understand the environmental impact of a Wi-Fi card on the atmosphere, it is important to analyze the CO_2 emissions released from each source initially and then calculate the CO_2 released into atmosphere as the result of Wi-Fi card usage. From section 4.4, 51% of electricity in the United States is generated from coal, and for every kilowatt of electricity generated from this source, 2.117 pounds of CO_2 is released into the atmosphere. Natural gas accounts for 15.2% of the electricity generated in the U.S., and every kilowatt of electricity generated from this source produces 1.314 pounds of CO_2. Petroleum makes up 3.2% of electricity generated in the U.S., and for every kilowatt of electricity produced from this source, 1.314 pounds of CO_2 is released. Other sources, such as biomass, hydroelectricity, renewable sources (sun, wind, geothermal), and nuclear fuel together, account for about 30.6% of electricity generation sources, and the amount of CO_2 released for every kilowatt of electricity generated from these sources is approximately 1.378 pounds. All sources averaged, the U.S. national average of CO_2 emission for one kilowatt of electricity generated is 1.350 pounds.

6.3.1 CO_2 Emissions from Smartphone Wi-Fi Card Usage for One Day

As mentioned in section 6.2, the energy consumed by a single smartphone Wi-Fi card for a day is 1.28 Wh. Smartphones that are actively using a Wi-Fi card number 37 million, as mentioned in section 6.1. The energy consumed for a day would be 47.36 MWh. The CO_2 emitted for a kilowatt of electricity generation is 1.350 pounds, which is the average of all sources like coal, petroleum, and natural gas, as mentioned in section 4.4. Hence, the amount of CO_2 emitted as the result of 47.36 MWh of electricity used by a smartphone Wi-Fi card would be 63,936 pounds.

6.3.2 CO_2 Emissions from Smartphone Wi-Fi Card Usage for One Year

The energy consumed in 2009 as the result of smartphone Wi-Fi card usage was 17,286 MWh, as mentioned in section 6.2.1. The CO_2 emitted for a kilowatt of electricity generation is 1.350 pounds, which is the average of all sources like coal, petroleum, and natural gas, as referred to in section 4.4. Therefore, the amount of CO_2 emitted as the result of 17,286 MWh of electricity used to operate a smartphone Wi-Fi card would be 23.3 million pounds. According to the EIA report [22], CO_2 emissions in the U.S. were 1,042 million metric tons in 2004, 1,060 million metric tons in 2005, 1,043 million metric tons in 2006, and 1,087.4 million metric tons in 2007. From this data, and the data from other previous years, it can be projected that the carbon emissions for 2009 would have been approximately 1,130 million metric tons, or about 2,491 billion pounds. The 23.3 million pounds of CO_2 generated from Wi-Fi card usage would have been around 0.01% of the total carbon emissions in the United States.

6.3.3 Comparison of Wi-Fi Card CO_2 Emissions to Vehicular Emissions

The average passenger vehicle is driven 12,000 miles per year, according to the U.S. Environmental Protection Agency [23], and as a result, approximately 5.48 metric tons of CO_2 generated, or about 12,077.92 pounds. As mentioned in section 6.3.2, CO_2 emissions from smartphone Wi-Fi card usage in the U.S. is 23.3 million pounds, which is equivalent to the CO_2 emitted from approximately 1,904 passenger vehicles.

6.4 Offset Requirement

As discussed in section 6.3.2, the CO_2 emissions from Wi-Fi card usage are around 23.3 million pounds, or about 0.01% of the total CO_2 emissions in the U.S. These emissions can cause adverse effects like ozone depletion; hazardous effects on human health, such as asphyxiation, frostbite, and kidney damage; and a decline in the global harvest of grains and pulses. Approximately 8,900 trees would be required to offset the effect of CO_2 emitted as the result of smartphone Wi-Fi card usage. This was calculated using the carbon offset calculator [24]. Not only is the use of passenger vehicles, air travel, and technological devices increasing, but deforestation is also increasing; therefore, any offsetting of CO_2 emissions by trees is not possible. More energy-efficient technology needs to be developed to resolve this issue.

CHAPTER 7

PROJECTIONS FOR ENERGY CONSUMPTION IN SMARTPHONE

In Chapter 6, the energy consumption of smartphones was calculated, as well as the environmental impact and offset. This chapter projects the energy consumption of smartphones due to Wi-Fi usage. Also, the projections of CO_2 emissions and offset are calculated.

7.1 Projections of Number of Smartphones

According to *RedEye Chicago*, a free daily newspaper, 8% of Americans used smartphones in 2007 [27]. Since the U.S. population at that time was around 300 million [28], the number of smartphones users in 2007 was 22 million. As discussed in section 6.1, the number of smartphones by the end of 2009 was 50 million. Also, according to a Nielsen Company estimate, around 80 million new smartphones connections will be added by the end of 2011, thus making the total number of smartphone users by that time to be approximately 150 million. It is projected that the number of smartphones in the year 2014 will be 270 million. Figure 7.1 shows a projected accounting of the number of smartphones.

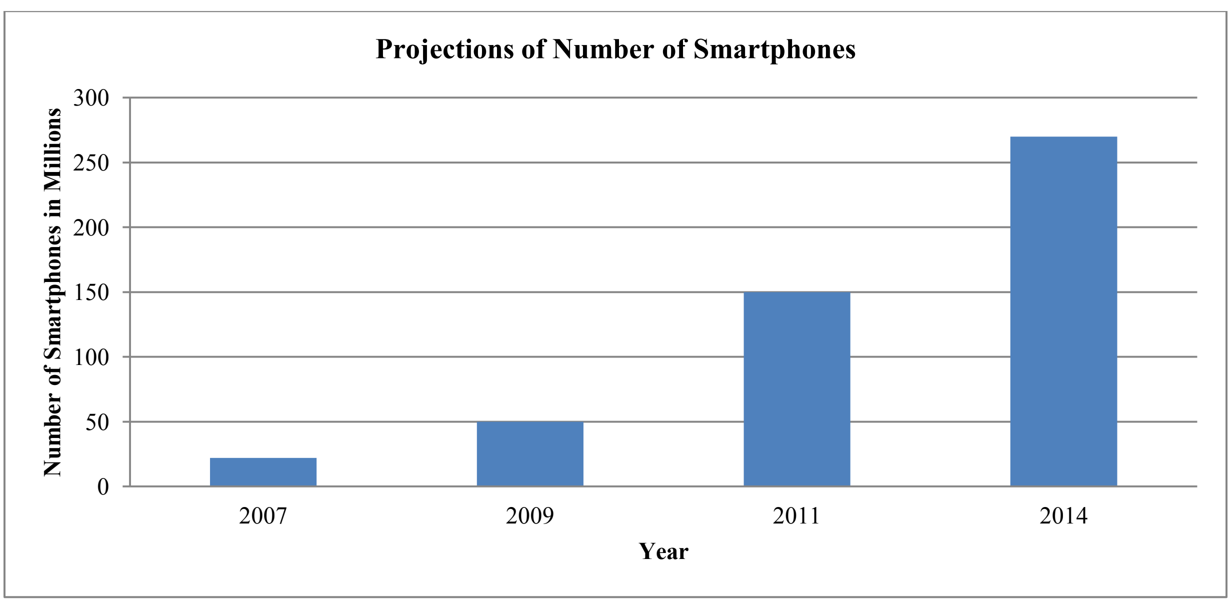

Figure 7.1 Projections of number of smartphones between 2007 and 2014

7.2 Projections of Energy Consumption of Smartphone Wi-Fi Card Usage

As described in section 6.2, energy consumption of the smartphone Wi-Fi card was calculated to be 1.28 W per day. From section 7.1, the number of smartphones by the year 2014 is projected to be around 270 million. Also, as referred to in section 6.1, 77% of smartphone users actively use wireless capability. From this information, the number of smartphones actively using wireless capability in 2014 would be around 207 million, and the energy consumption from the smartphone Wi-Fi card usage would be 96,710 MWh. Similarly, the number of smartphones users in 2007 was 22 million, as mentioned in section 6.1. The number of smartphone users that actively used the wireless capability in that year would have been 16.94 million, and the energy consumption from smartphone usage would have been 7,914 MWh. Also from section 6.2.2, in 2009, energy consumption due to smartphone usage was 17,286 MWh. Figure 7.2 shows the energy consumption of smartphone Wi-Fi cards.

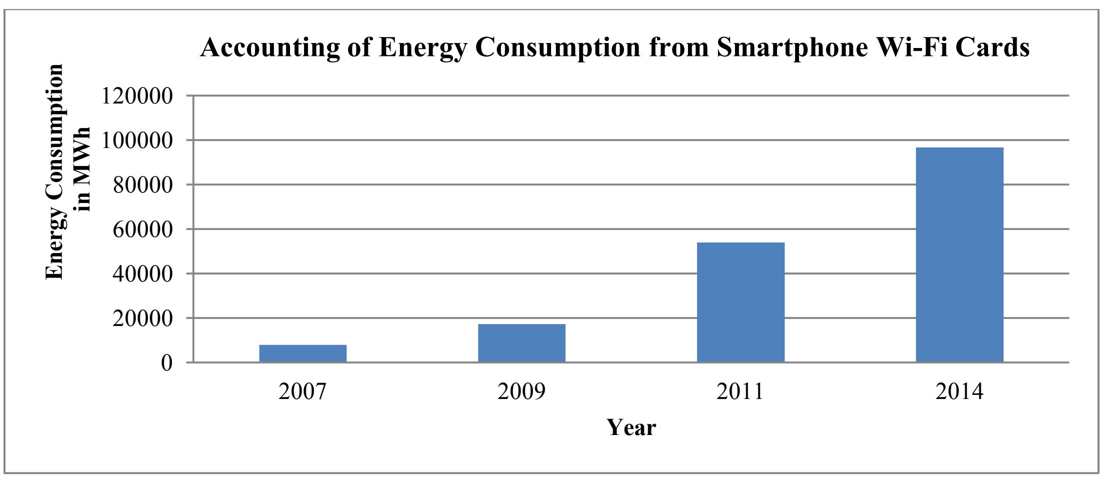

Figure 7.2 Projections of energy consumption from smartphone Wi-Fi cards

7.3 Projections of CO_2 Emissions

As referred to in section 4.4, in the United States, 51% of electricity is generated from coal, and for every kilowatt of electricity generated from that source, 2.117 pounds of CO_2 is released into the atmosphere. The percentage of electricity generated from natural gas is 15.2%, and for every kilowatt of electricity produced from that source, 1.314 pounds of CO_2 is released. The percentage of electricity generated from petroleum is 3.2%, and for every kilowatt of electricity produced from that source, 1.314 pounds of CO_2 is released. Other sources like biomass, hydroelectricity, renewable sources (sun, wind, geothermal), and nuclear fuel together account for about 30.6% of electricity generation, and the CO_2 released for every kilowatt of electricity generated from these fuels is about 1.378 pounds of CO_2. When all sources are averaged, the national mean of CO_2 emissions for one kilowatt of electricity generated is 1.350 pounds. As referred to in section 7.2, for the year 2014, the projected energy consumption as the result of smartphone Wi-Fi card usage would be about 96,710 MWh, and the CO_2 emissions would be 130 million pounds. Figure 7.3 shows the projections of CO_2 emissions from smartphone Wi-Fi card usage.

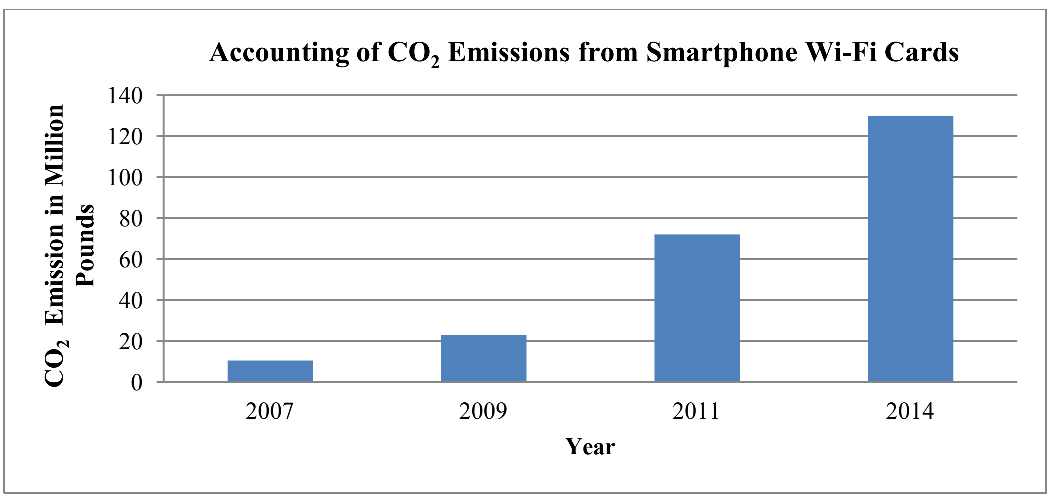

Figure 7.3 Projections of CO_2 emissions from smartphone Wi-Fi cards between 2007 and 2014

CHAPTER 8

CONCLUSIONS

The major issue involving Wi-Fi usage is its considerable energy consumption. Conserving energy is very important in the case of portable devices because a greater battery lifetime would mean a significant increase in time before having to recharge the device. The energy consumed from various Wi-Fi applications, around 3 watts per hour, may seem insignificant from a layman's perspective. But it must be remembered that millions of portable devices are being used, and their usage patterns vary from a few hours to several hours each day. In turn, the high dependence on technology for all tasks has increased the number of hours for which portable devices are used. Also, the exponential increase in the use of portable devices, like smartphones and laptops, indicates that this trend will continue.

The energy consumption of laptop Wi-Fi was calculated to be around 1 TWh in 2009 and projected to be 2.7 TWh by 2014; this is an approximately 170% increase in energy consumption in four years. Similarly, the energy consumption of smartphones was calculated to be 17.2 GWh in 2009 and projected to be 53.961 GWh in 2014, an approximately 300% increase in four years. The CO_2 emissions from usage of these applications would increase at the same rate. In developing economies like China, India, and Brazil, these numbers in the near future could be much higher due to a technological upsurge and higher disposable incomes in these countries. These figures are quite alarming, and energy efficiency is the only answer to these issues.

As referred to in section 4.4.3, 2009 energy consumption from Wi-Fi card usage was .85 TWh, and from section 6.2, energy consumption from smartphone Wi-Fi card usage was .17 TWh. Therefore, in 2009, the energy consumption from total Wi-Fi card usage was about 1 TWh. From the Ubuntu paper [11], energy consumption of all portable devices in the world is 9

TWh (46.2 million MWh from smartphones, and 44.6 million MWh from laptops). Therefore, Wi-Fi card usage in the United States is about 9% of the total energy consumption of all portable devices in the world. Figure 8.1 shows these statistics.

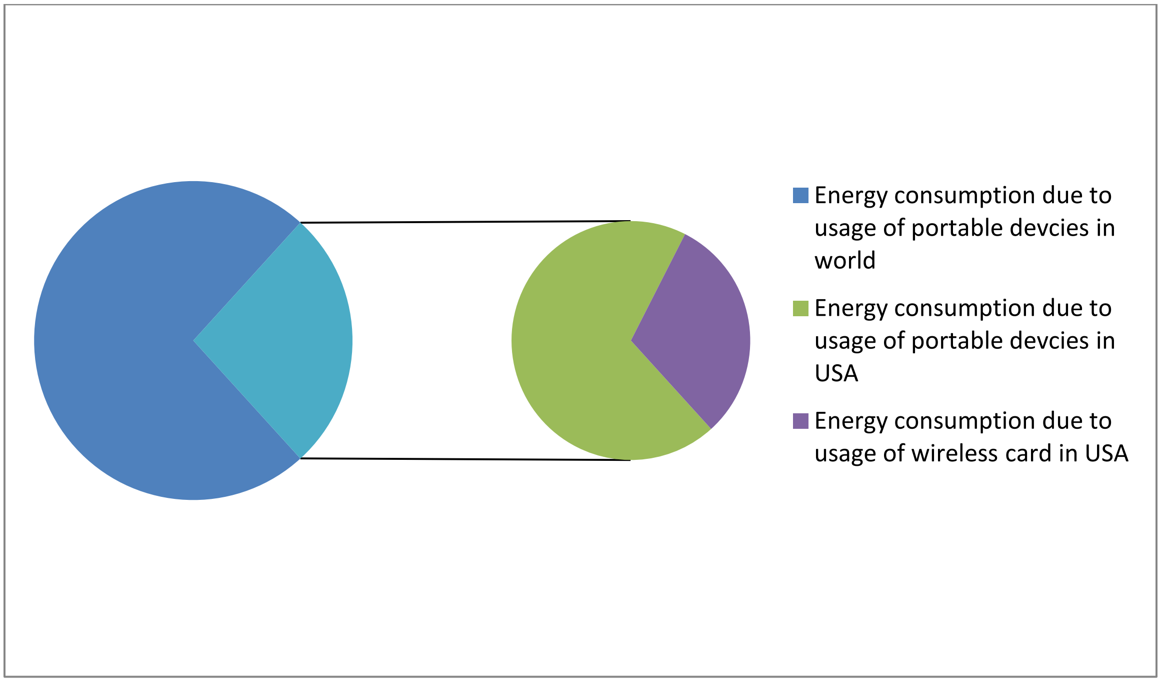

Figure 8.1 Energy consumption of Wi-Fi card usage from a global perspective

Future Work

An accounting was done on the energy consumption of each application for all major portable wireless devices that support Wi-Fi, and the environmental impact was calculated. Future work in this area would be to derive appropriate algorithms that may increase efficiency, thus reducing energy consumption. A list of future work follows:

- The energy consumption and its environmental impact can be accounted for cellular interface
- Manufacturing and recycling costs in terms of energy is other field which needs to be studied as longer the lifespan of these portable devices, lower would be recycling and manufacturing energy costs.

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