NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

HIGH SPEED INTERNET ACCESS USING CELLULAR INFRASTRUCTURE

by

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September 2004

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13. ABSTRACT (maximum 200 words)

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This thesis examines the potential usage of providing Internet access through cellular infrastructure. The cellular evolution path from first generation (1G) to third generation (3G) and fourth generation (4G) systems is studied and presented. The most popular worldwide cellular voice and data network technologies are also described. Additionally, the Cingular Wireless network in Monterey, California is tested in terms of speed and reliability by providing Internet access to a laptop through a mobile phone. The analysis shows that, depending on the cellular network availability, throughput varied from 5 to 25 Kbps and Round Trip Time (RTT) averaged about 1 sec. Furthermore, it is shown that TCP Timestamps and the Explicit Congestion Notification (ECN) were implemented at the end hosts, thus increasing performance.

The thesis concludes that as of July 2004, the 2.5G cellular data networks are a reasonable solution for those who need Internet access anywhere that a cell signal is available, including from moving vehicles, and who can afford its high cost. For others it is not yet an acceptable solution. However, the future 3G networks are an excellent solution in wireless broadband Internet access. These will probably be relatively expensive at first, but the cost should eventually decrease to a reasonable level.

14. SUBJECT TERMS Internet, Wire Line Connections, Dial-Up, xDSL, Cable Modems, Optical Fiber, Wireless, WiFi, WiMAX, MBWA, Satellite, Cell Phone, Networks, First Generation, 1G, Third Generation, 3G, Fourth Generation, 4G, Round Trip Time, RTT, TCP, Explicit Congestion Notification, ECN			**15. NUMBER OF PAGES** 131
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HIGH SPEED INTERNET ACCESS USING CELLULAR INFRASTRUCTURE

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This thesis is dedicated to my wife Sania for her continuous support and patience during my 27 months studying at Naval Postgraduate School, as well as to my beloved daughter Natalie.

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I. INTRODUCTION

A. EARLY HISTORY OF CELLULAR TELEPHONY

Even though the cellular network industry experienced the greatest expansion and became a global phenomenon during the 1990's, the initial efforts for wireless telephony extend back to the end of the 19th century. Alexander Graham Bell on June 1880, just four years after he had patented the telephone invention, constructed a machine named *Photophone* that could transmit sound on a beam of light[1]. Additional efforts were made in other technologies, such as the wireless telegraph by Nicola Tesla in 1893[2] and by Guillermo Marconi in 1896[3], which had successful results[4]. It is notable that the need for wireless communication was conceived at approximately the same time as that of wired communication. In 1921, the Detroit Police began experimenting with patrol vehicles equipped with one–way radios based on Morse code. In 1922, the Federal Radio Commission issued the Detroit Police the first commercial radio license[5]. In 1928, this system was voice based but still one way. Around 1924, Bell Laboratories was already conducting tests in a two way voice based mobile radio telephone, as shown in Figure 1.

Figure 1 Bell Labs First Mobile Phone Trials in 1924 [From Ref. 6].

1 Wikipedia, Web Encyclopedia, [http://en.wikipedia.org/wiki/Photophone], April 2004.

2 Wikipedia, Web Encyclopedia, [http://en.wikipedia.org/wiki/Nikola_Tesla], April 2004.

3 Wikipedia, Web Encyclopedia, [http://en.wikipedia.org/wiki/Guglielmo_Marconi], April 2004.

4 Wikipedia, Web Encyclopedia, [http://en.wikipedia.org/wiki/Wireless_telegraphy], April 2004.

5 The Detroit News, [http://info.detnews.com/history/story/index.cfm?id=35&category=government], April 2004.

6 Bell Labs, [http://www.bell-labs.com/history/75/gallery.html], April 2004.

A technological breakthrough was the development of *Frequency Modulation (FM)* in the-mid 1930's by Edwin Howard Armstrong. The Second World War battlefields were a major test bed for portable two-way FM radio technologies. In June 1946, Bell System introduced the first commercial, half-duplex, radio-telephone service, named *Mobile Telephone Service* (MTS) in Saint Louis, Missouri and later on, to other U.S. cities as well[7]. In December 1947, Bell Laboratories developed the cellular telephony concept and requested additional frequencies for mobile use from the FCC. The FCC finally allocated the additional spectrum in 1949[8]. In 1964, Bell Laboratories introduced the *Improved Mobile Telephone Service* (IMTS), which added full-duplex features to the old MTS system[9]. In 1968 and 1970, the FCC, realizing the huge potentials of mobile telephony, reallocated the frequency spectrum for cellular use. Additionally, in 1968, AT&T proposed a cellular mobile schema to the FCC, which was approved in 1974[10].

The next evolutionary steps begin in the early 1980's with the deployment of the *First Generation* (1G) analog networks based on *Frequency Division Multiplexing* (FDM). The increased demand for mobile communication led to the evolution of *Second Generation* (2G) digital networks in the early 1990's. The introduction of *Time Division Multiplexing* (TDM) on top of the existing FDM, an essential feature of 2G, increased the number of served subscribers per geographical area. In addition, voice quality was improved as well, with the introduction of newer voice coding algorithms. Finally, at the beginning of the third millennium, the first 2.5G networks, which are an upgrade of *Second Generation* and the *Third Generation* (3G) networks were implemented in most countries worldwide.

Since the introduction of the first handheld cellular phones, technological evolution in electronics has altered the devices enormously. Newer phones became smaller, lighter and had better autonomy due to more efficient batteries. The mobile

7 AT&T Milestones, [http://www.att.com/history/milestones.html], April 2004.

8 Federal Communications Commission, The Case History of Cellular Radio, [http://www.fcc.gov/Bureaus/OGC/Reports/cellr.txt], April 2004.

9 Bell Labs Milestones, [http://www.lucent.com/minds/telstar/history.html], April 2004.

10 Theodore S. Rappaport, Wireless Communications Principles and Practices, Second Edition, Prentice Hall, Inc., p. 4, Prentice Hall, Inc., 2002.

screens were enlarged and become colorful. An alternative way of communication over a cellular network was introduced: Text Messaging. With the *Short Message Service* (SMS), a mobile phone can send a text message, usually 160 characters, to another phone. Modern phones also have integrated video cameras and can send digital photos over the cellular network with the *Multimedia Message Service* (MMS). Additionally, numerous other daily life applications are a standard part of mobile phones such as phonebook contacts, calendars, calculators, to-do lists and simple games. Numerous types of phones support the Java programming language, so users can write their own personal applications and tailor them to their needs. Other hardware improvements include Infrared and Bluetooth capabilities for external connectivity with a computer, as well as mp3 players and FM radio receivers for personal amusement. In 2000, an XML based technology named *SyncML* was introduced, which allows the synchronization of data stored in a mobile phone with any relative XML database over the Internet. Global Positioning System (GPS) devices attached to mobile phones were launched in 2004. Nowadays, it is obvious that cell phones are not used just for voice communications, as initially designed, but as small entertainment and business centers as well.

Table 1 presents sample cellular phones of each generation, showing the improvement in size and design over the years. On the left is the first handheld device designed by the Motorola Company in 1973, named *DynaTAC* (Dynamic Adaptive Total Area Coverage). It was finally approved by the FCC in 1983[11] and become commercially available in 1984 in 1G networks. In the middle, the Ericsson *GH218* was introduced in 1994 and operated in 2G networks. On the right, the *LG U8110* was introduced in 2004 and is operating in the newest 3G networks.

11 Motorola History Highlights, [http://www.motorola.com/content/0,,122-286,00.html], April 2004.

Phone:	Motorola DynaTAC (1984)[12]	Ericsson GH218 (1994)[13]	LG U8110 (2004)[14]
Network	1G / AMPS	2G / GSM	3G / WCDMA
Dimension (mm):	228.6 x 127 x 44.5	130 x 49 x36	95 x 49 x 22
Weight (gr):	794	248	126

Table 1 Samples of Mobile Phones from the Three Cellular Network Generations.

Recently, a new kind of mobile phone appeared on the world market, called Smartphones, which are actually PDA devices with embedded cellular phone capabilities. Since the tasks to be handled are more than voice calls, those devices operate under specifically designed Operating Systems (OS). The most well known OS's are made from Symbian, Microsoft and Palm companies. Table 2 presents three types of Smartphones, introduced in 2004 and operating at 2G/GSM and 2.5G/GPRS networks.

12 [http://www.moneycab.com/de/home/lifestyle/kultur/tech/20jahre.ArticlePar.0001.Image.jpg], April 2004.

13 [http://www.zfone.com/mobiles.php/phoneid/10064], April 2004.

14 [http://www.3gtoday.com/devices/devices/device1915.html], April 2004.

Phone:	SonyEricsson P900[15]	Motorola MPx200[16]	Palm-Handspring Treo 600[17]
Dimension (mm):	115 x 57 x 24	88.9 x 47.8 x 26.5	112 x 60 x 22
Weight (gr):	150	113.2	168
Operating System	Symbian OS 7.0	Microsoft Windows Mobile	Palm OS 5.2.1H

Table 2 Latest Types of Smartphones.

B. THE WIRELESS INTERNET EXPANSION

When Arpanet was used for long distance data connections during the 1970's, no one expected that its commercial successor, the Internet, would experience such a growth rate. Especially after the deployment of the *World Wide Web* (WWW) from the World Wide Web Consortium (W3C) in 1990[18], it has become a modern necessity. In the beginning, Internet connectivity was accomplished with the use of dial-up modems through the *Public Switched Telephone Network* (PSTN). Initial rates of just 1200 bits per second (bps) are now in the range of 56 Kbps and with the use of *Integrated Services Digital Network* (ISDN) and corresponding modems, at 64 or 128 Kbps. Connection speeds have increased dramatically during the past few years. At the end of the 1990's,

15 Sony Ericsson [http://www.sonyericsson.com/spg.jsp?cc=us&lc=en&ver=4000&template=pp1_loader&zone=pp&lm=pp1&php=php1_10101&pid=10101], April 2004.

16 Motorola [http://commerce.motorola.com/cgi-bin/ncommerce3/ProductDisplay?prrfnbr=253227&prmenbr=126&phone_cgrfnbr=1&zipcode], April 2004.

17 Palm [http://www.handspring.com/products/communicators/treo600_features.jhtml], April 2004.

18 World Consortium, [http://www.w3.org/History.html], May 2004.

newer technologies introduced broadband capabilities, using *Digital Subscriber Line* (DSL) and *cable modems* and achieved rates up to 1500 Kbps. Nonetheless, limitations in the latter technologies prevent their full deployment. DSL subscribers need to be located less than 15,000 ft. from the *Central Office* (CO) to be qualified. Cable modem subscribers experience dramatic drop in their speed when a large number of other cable users exist on the same line. The restrictions of broadband wire line services deployment led the industry to find alternative ways of accessing the Internet, and more specifically, through wireless networks.

Currently, the offered wireless solutions are implemented through Wireless Local Area Networks (WLAN), Satellite, Fixed Broadband Wireless (FBW) and Cellular networks. The IEEE 802.11 protocol suite, commercially known as *WiFi*, operates at 2.4 or 5 GHz and provides the physical layer platform for wireless networking. It was introduced for Local Area Network (LAN) coverage. Its successful adoption from users seeking wireless connectivity let it expand from home or office use. Numerous wireless available WiFi LAN's, named *Hot Spots,* having an effective range at tenths of meters, are providing subscribers connection speeds up to 54 Mbps. Hotspots are currently operating in airports, hotels, shopping malls and coffee shops. WiFi is considered one of the most widespread wireless Internet solutions in LANs. For example, the T-Mobile Wireless Company is offering available hotspots in 4,593 different locations throughout the United States[19]. Satellite networking provided an alternative method of Internet connectivity to remote users. Typical speeds, through a modem and a corresponding dish, vary from 150-400 Kbps. The Fixed Broadband Wireless technologies used in the *Wireless Local Loop* (WLL) are standardized under the IEEE 802.16 protocol suite[20]. They are Metropolitan Area Networks (MAN) and are also commercially known as WiMAX[21]. An IEEE 802.16a implementation is the *Multichannel Multipoint Distribution Service* (MMDS), operating in a 2.5 GHz area with connection speeds from 1-3 Mbps.

19 T-Mobile, [http://locations.hotspot.t-mobile.com], May 2004.

20 IEEE, [http://standards.ieee.org/getieee802/802.16.html], May 2004.

21 Wi-MAX Forum, [http://www.wimaxforum.org/about/], May 2004.

Local Multipoint Distribution Service (LMDS), operating at 28-31 GHz with speeds at a range of 45 Mbps, is using IEEE 802.16. Figure 2 shows the IEEE 802.16 standard variations.

IEEE 802.16 Standard

Source: WiMAX Forum

	802.16	802.16a/REVd	802.16e
Completed	Dec. 2001	802.16a: Jan 2003 802.16 REVd: Q3 2004	Estimate: 2nd half of 2005
Spectrum	10 to 66 GHz	< 11 GHz	< 6 GHz
Channel Conditions	Line-of-sight only	Non line-of-sight	Non line-of-sight
Bit Rate	32 to 134 Mb/s at 28 MHz channelization	Up to 75 Mb/s at 20 MHz channelization	Up to 15 Mb/s at 5 MHz channelization
Modulation	QPSK, 16 QAM and 64 QAM	OFDM 256, OFDMA 64 QAM, 16 QAM, QPSK, BPSK	Same as REVd
Mobility	Fixed	Fixed and Portable	Mobility, Regional Roaming
Channel Bandwidths	20, 25 and 28 MHz	Selectable channel bandwidths between 1.25 and 20 MHz, with up to 16 logical sub-channels	Same as REVd
Typical Cell Radius	1 to 3 miles	3 to 5 miles; Maximum range 30 miles based on tower height, antenna gain and transmit power (among other parameters)	1 to 3 miles

Figure 2 IEEE 802.16 Standard Evolution [From Ref. 22].

The latest addition in the wireless Internet field is the IEEE 802.20 protocol. It was introduced in late 2002 and is commercially known as *Mobile Broadband Wireless Access* (MBWA). It is operating in the licensed band below 3.5 GHz and aims to provide broadband access at high speed moving users (up to 250 km/h). The network is fully IP-based MAN and promises data rates up to 1Mbps[23].

Cellular infrastructure is constructed as a *Wide Area Network* (WAN). The first analog cellular networks (1G) were designed with voice communication as the sole target. The arrival of the digital Second Generation (2G) co-existed with the Internet explosion during the 1990’s. Thus, the merging of data transfer over cellular networks became feasible. Since then, a 2G cellular phone can operate as a modem and create a circuit switched path between a computer and an Internet host. Those data transfer connections can be made with speeds from 9.6 to 14.4 Kbps. The subscribers are charged for the time the phone is connected to the network, just as with a wired connection, even

22 Wi-MAX Forum, [http://www.wimaxforum.org/news/press_releases/Telephony_WiMAX.pdf], July 2004]

23 IEEE, [http://grouper.ieee.org/groups/802/20/], July 2004.

if the actual data transfer took only a fraction of the duration. The limited speed and the expensive over the air charging prohibited this technique from becoming a commercial success. In the beginning of the third millennium, the need for accessing the Internet for numerous services and applications is more frequent.

The enhancement of mobile devices and the need for higher data rates over cellular networks, led to the 2.5G networks that advertised speeds at a range of 60 Kbps. The innovation was the packet switched based path between host and user. Billing of the latter is calculated only by the volume of data transferred and not by the connection time as in 2G. Modern applications, such as mobile video conferencing, demanded an even higher bandwidth. This factor drove the cellular industry to the design of Third Generation (3G) with speeds of 2 Mbps, which is directly comparable to current DSL or Cable solutions. It is notable that the shift from 1G to 2G occurred due to the need for more voice capacity and better quality, while upgrading from 2G to 2.5G and 3G is driven mostly by the need for higher data rate connections to support mobile graphical user-friendly interface applications. The first commercial 3G service was launched in Japan in October 2001, under the name FOMA, by the company NTT DoCoMo. By April 2004, from its total 43 million customers, 3.6 million are using those services[24]. The same company is one of the few; if not the only cellular provider, whose Research and Development (R&D) department has started research in 4G systems since 1998. The initial target is 100 Mbps in downlink.

Using a cellular phone to access the Internet is provided to the consumers in two different ways. The first is to use the phone as the end device and browse the Internet via the mobile screen with the internal browser. Every web page is written in *Hypertext Markup Language* (HTML) and accessed through the *Hypertext Transfer Protocol* (http). Since the mobile's screen is still relatively small for web browsing, the content of the web page must be reduced in order to be rendered properly. For this reason, the web pages destined for mobile browsing are written in *Wireless Markup Language* (WML)

24 NTT DoCoMo, [http://www.nttdocomo.com/corebiz/foma/index.html], May 2004.

and accessed with the *Wireless Access Protocol* (WAP)[25]. Figure 3 presents the screen of an Ericsson R380 mobile phone accessing a WAP based web page for airline information.

Figure 3 Example of a WAP Web Site [From Ref. 26].

The second method is to use the phone as a "wireless modem" and connect a computer, in most cases a laptop, through it. Thus, the laptop has full Internet capability. A mobile phone can communicate with a computer through a phone's vendor specific cable, Infrared or Bluetooth. The latter two depend on both devices' hardware capabilities. Figure 4 presents a typical schema for a laptop connecting to a server through the mobile phone and the cellular network. If either the phone or network is based on 2G technology, then the connection is circuit switched and charging depends on total call duration. Otherwise, if both the phone and network support 2.5G or 3G technology, then the connection is packet switched, and therefore, charging relies on the amount of data transferred. In the latter situation, there may be a case in which due to the lack of 2.5/3G cellular network support, the connection may be completed as circuit switched.

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25 Open Mobile Alliance, [http://www.wapforum.org/what/technical.htm], May 2004.

26 [http://www.airliners.net/wap/web/], May 2004.

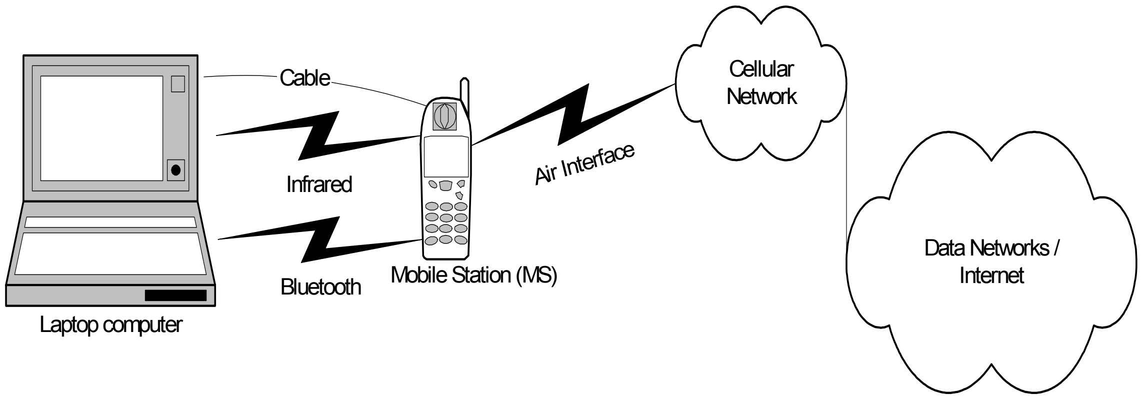

Figure 4 Laptop Internet Connectivity through Cellular Network.

Alternatively, in the previous configuration, the mobile phone can be substituted from a specific cellular card inserted into the laptop in order to allow it access to the cellular network. Figure 5 shows a Type II PC Card provided by Verizon Wireless for accessing its 3G network. Currently, at least in the United States, those cards are used for data transfer only.

Figure 5 Verizon Wireless PC 5220 Card [From Ref. 27].

C. WORLDWIDE CELLULAR EXPANSION

The worldwide mobile community of manufacturers, vendors and providers, by realizing the tremendous growth in cellular communication, is enhancing the infrastructure to accommodate faster data transfers. The cellular expansion phenomenon has taken place in the majority of countries, globally. The following two tables present some basic wired and cellular statistical facts, for continents and independent countries.

27 Verizon Wireless, [http://www.verizonwireless.com/b2c/store/controller?item=phoneFirst&action=viewPhoneDetail&selectedPhoneId=1517], May 2004.

Facts for Africa and Europe include the average figures of their respective countries. Table 3 shows the population density, financial status and landline network figures. Table 4 shows statistical facts regarding the cellular network status.

Region/Country	Population density per km2 (2002)	GDP per capita in $ (2001)	Total telephone subscribers per 100 inhabitants (2002)	Main telephone lines increase ratio per 100 inhabitants 1997-2002 (%)
Africa	27	549.9	7.36	6
Canada	3	22,966	101.26	-0.2
United States	31	35,401	113.4	0.3
China	134	907	32.78	24.3
India	329	474	5.19	16.4
Japan	337	32,554	119.49	1.4
Europe	33	11,670	92.1	2.6
Australia	3	18,462	117.84	1.1

Table 3 Landline Statistics per Country/Region [After Refs. 28 and 29].

Region/Country	Cellular subscribers per 100 inhabitants (2002)	Cellular subscribers increase ratio from 1997-2002 (%)	Internet hosts per 10,000 inhabitants (2002)	Internet users per 10,000 inhabitants (2002)
Africa	4.59	74.7	3.01	123.1
Canada	37.72	22.7	953.07	5,128.29
United States	48.81	20.5	3,998.77	5,513.77
China	16.09	73.3	1.22	460.09
India	1.22	70.5	0.75	159.14
Japan	63.65	16.2	726.65	4,488.56
Europe	51.26	46.3	230.38	2,164.47
Australia	63.98	22.4	1,304.21	4,817.41

Table 4 Cellular and Internet Facts per Country/Region [After Refs. 30 and 31].

28 International Telecommunication Union, [http://www.itu.int/ITU-D/ict/statistics/at_glance/main02.pdf], April 2004.

29 International Telecommunication Union, [http://www.itu.int/ITU-D/ict/statistics/at_glance/basic02.pdf], April 2004.

30 International Telecommunication Union, [http://www.itu.int/ITU-D/ict/statistics/at_glance/cellular02.pdf], April 2004.

31 International Telecommunication Union, [http://www.itu.int/ITU-D/ict/statistics/at_glance/Internet02.pdf], April 2004.

From the above tables, it is easily noticeable that, the most prosperous countries, which had already developed their landline communications during the past decades, experienced a small increase in the number of main telephone lines from 1997 to 2002. In addition, they present a larger increase in the cellular networks. In the United States, since 2000 the wired telephone companies are loosing residential lines while in 2002 almost half of the population is cellular subscribers and more than half are using the Internet. In most European countries, the relative figures for cellular users climb to 85% of the population[32]. Countries such as India and China, when combined account for about one third of the world's total population, present a large increases in the number of main telephone lines and in the cellular network since 1997. For this reason, many Western telecommunication companies are aiming at those emerging markets.

Even though it is too early to assume that cellular networks will render the wired networks obsolete, is almost certain that the easiest way to provide wireless Internet access to a user is through a cellular phone.

D. THESIS OBJECTIVES

The purpose of this thesis is first to provide an overview of Internet access through cellular networks, and especially, through the 2G/GSM, 2.5G/GPRS and 3G/UMTS. Second, in an effort of evaluating cellular data networking, it examines the reliability and performance of the GPRS cellular Internet access network in Monterey, California. Finally, it compares the cellular mobile Internet against the other wired and wireless implemented solutions.

More precisely, Chapter II presents an overview of the cellular evolution, following the path from 1G to 3G and the research done towards 4G.

Chapter III gives an analysis of the most widespread cellular technologies such as GSM, GPRS and UMTS networks focusing on the air interface architecture, design and modulation schemes. Additionally, it presents research conducted in cellular data networks in areas such as Virtual Private Networks (VPN), the implementation of IPv6 and the potential use of VoIP.

32 International Telecommunication Union, [http://www.itu.int/ITU-D/ict/statistics/], April 2004.

Chapter IV records the current market high-speed mobile Internet services from the most well-known U.S. companies such as AT&T Wireless, Cingular Wireless, Verizon Wireless, Sprint, Nextel and T-mobile. Conducted measurements from an actual mobile Internet connection through a GPRS network in Monterey, California are also included. Tasks such as secure file transfer, checking e-mail, web browsing, remote desktop connection through a Citrix client and instant messaging are examined against speed and robustness.

Chapter V discusses performance issues for modern cellular networks such as the Round Trip Time and some TCP Options, as observed during testing in Chapter IV.

Finally, in Chapter VI, the thesis concludes by comparing the cellular data Internet connection with wired solutions such as dial-up and xDSL/Cable as well as with other wireless broadband technologies as Satellite, WiFi, WiMAX and MBWA.

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II. CELLULAR NETWORKS OVERVIEW

This chapter consists of three major parts. The first summarizes the principles of cellular network philosophy. The second gives an overview of the techniques used in the air interface. Finally, the third presents the characteristics and the evolution path in cellular technologies from 1G to 3G.

A. PRINCIPLES OF CELLULAR NETWORKS

In modern cellular systems, the following components and principles are explained:

- The ***Mobile Station*** (MS), also simply known as the mobile phone, is the physical equipment used by the subscriber in order to access the mobile network. In essence, it is the mobile phone.
- The ***Base Transceiver Station*** (BTS), also simply known as base station, is the antenna that provides the radio interface to every MS. It is allocated only a portion of the total number of channels available to the entire system. Within a BTS, multiple MS's can be attached (shown in Figure 6), but according to the cellular system used, only a limited number of those can use the resources simultaneously.
- The ***cell*** is the base station's effective coverage (shown in Figure 6). The radius of a cell depends on the geographical topology of its covering area and to the population density. It can be less than a kilometer (km) in dense urban environments and at the range of 30 kilometers in rural ones.

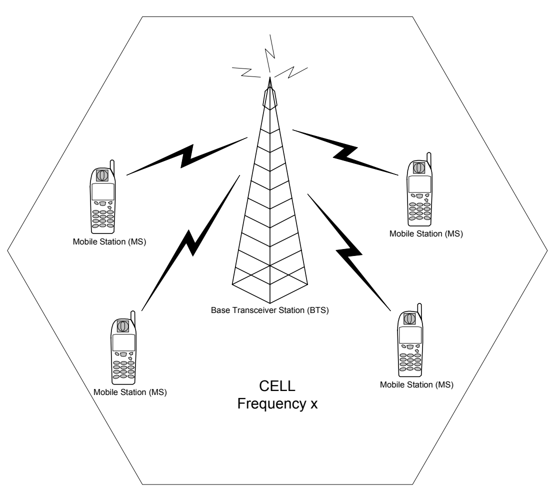

Figure 6 A Cell with the According BTS and Multiple Served MS's Within It.

- ***Frequency reuse*** is a technique that maximizes the number of mobile phones served in a given area by assigning a part of the total available frequency spectrum in different base stations. Therefore, the interference between neighboring base stations is minimized. As shown in Figure 7, a given spectrum may be symmetrically spread in seven cells (named A to G). Thus, the cell reuse factor equals 7.

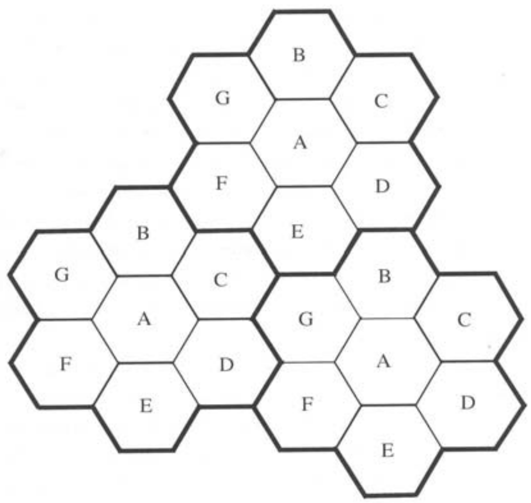

Figure 7 Frequency Planning Reuse [From Theodore S. Rappaport, Wireless Communications Principles and Practices, Second Edition, p. 59, Prentice Hall, 2002.

- The ***Base Station Controller*** (BSC) controls a number of base stations and provides the mobility management (shown in Figure 8).
- The ***Mobile Switching Center*** (MSC) is the switch to which base stations are connected (shown in Figure 8). It is responsible for call routing and interconnection with the Public Switched Telephone Network (PSTN).
- ***Handoff*** (or *Handover*) is the transition of a call made by a mobile phone, from one radio channel to another. It can occur in the following conditions:
    - Call is passed from one base station to another when the mobile phone is leaving the range of the first (shown in Figure 9).
    - Call is passed from one channel of a base station to another (within the same base station) when there is too much traffic in the first.
    - Called is passed when the mobile phone is changing BSC.
    - Call is passed when the mobile phone is changing MSC.

    In older 1G systems, the mobile switching center (MSC) was mainly responsible for the handoffs. From 2G and forward, the mobile phones were able to calculate the receiving signal strength and report it back to the MSC. This technique is called *Mobile Assistant Handoff* (MAHO) and lightens the burden of the MSC in assigning a new appropriate BSC. In general, there are two types of handoffs:

- *Hard handoff,* when the MS is assigned a different radio channel.
- *Soft handoff*, when the MS can communicate, for a very short period of time, with two different BTS simultaneously in order to transit the phone call.

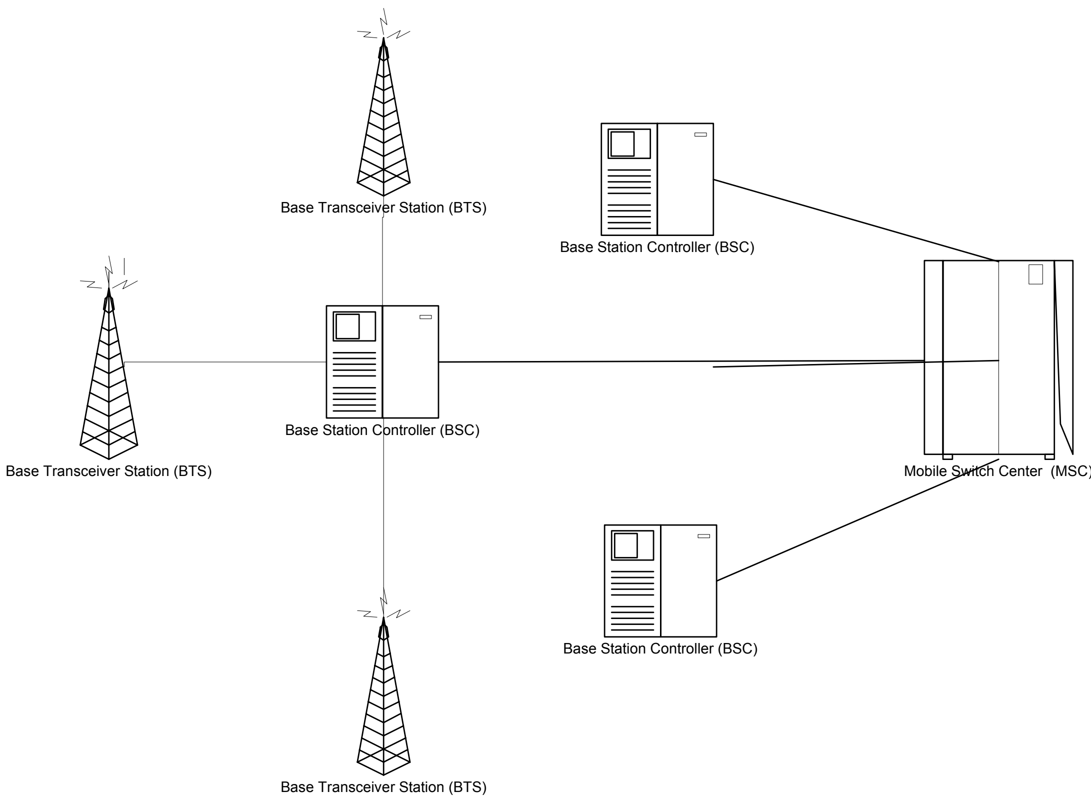

Figure 8 Cellular Network Topology of BTS,BSC,MSC.

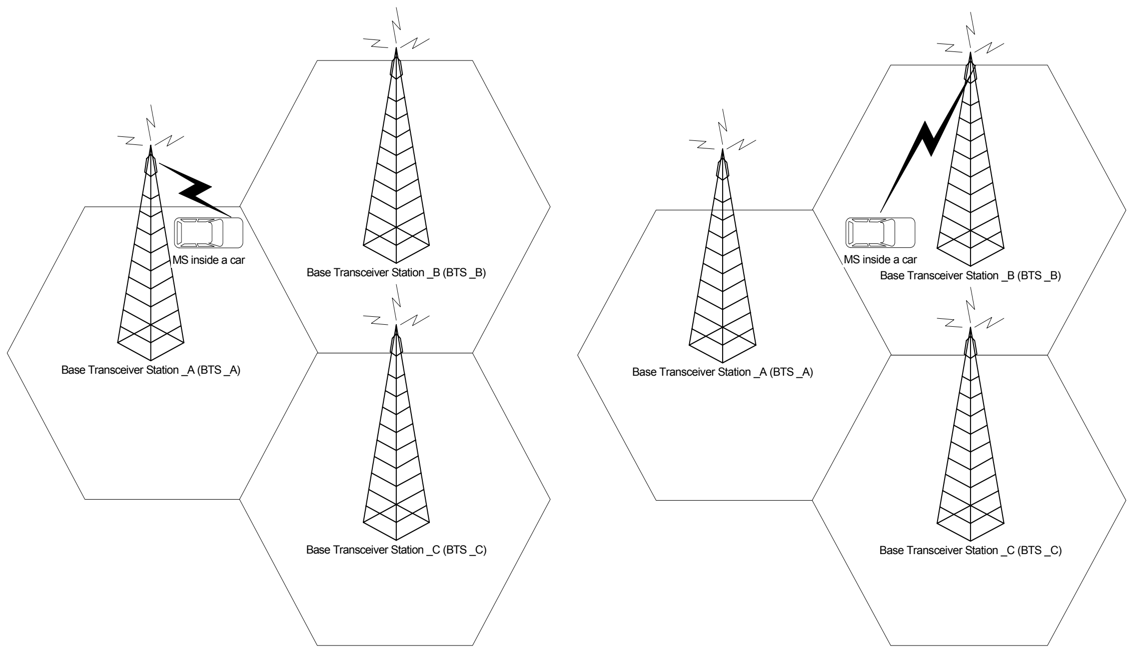

Figure 9 Typical Handoff (a MS located inside a car is initially served from BTS_A and afterwards is switching to BTS_B).

- The ***Roaming*** is the situation occurring when a MS is visiting and served from a BTS of another cellular provider or a BTS that is beyond some geographical limits within the same provider's network. The most frequent case of roaming is when a subscriber is visiting a foreign country and is using the cellular network of a vendor that has an agreement with his home cellular provider. In the United States, this situation can sometimes occur only by visiting another state. When the visiting user activates the MS, it automatically finds the available networks to which it can connect. It can only register in a network that is in the participating list of the home network. Upon successful registration, the home network is notified from the visiting network about the new location of the subscriber. Therefore, all phone calls addressed to the user initially reached the home network, and are now redirected to the visiting network.

B. AIR INTERFACE TECHNIQUES

Despite the differences between the cellular providers in network implementation, the basic techniques used in the air interface are universal. Those include the duplex, multiplexing, multiple access and modulation techniques.

1. Duplex Techniques

Cellular communications are duplex (two-way communication) and the following techniques are used.

a. Frequency Division Duplex (FDD)

Two distinct bands of frequencies are used for each user. The first is used for communication of the network with the mobile and is called *Forward Channel* while the other is for communication of the mobile user to the network and is called *Reverse Channel*. In order to avoid interferences, there is a guard separation frequency called *Channel Separation*. Figure 10 shows that the reverse channel uses frequency x and the forward the (x + Channel Separation).

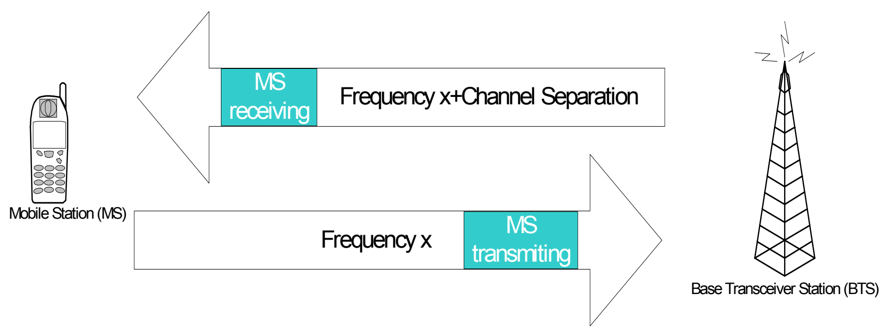

Figure 10 FDD Forward and Reverse Channels.

b. Time Division Duplex (TDD)

Each user shares a single radio frequency with the base station. The mobile phone uses different time slots in order to receive (downlink) or send (uplink) data. Figure 11 shows that user and network are using the same frequency x for communication but in different time slots.

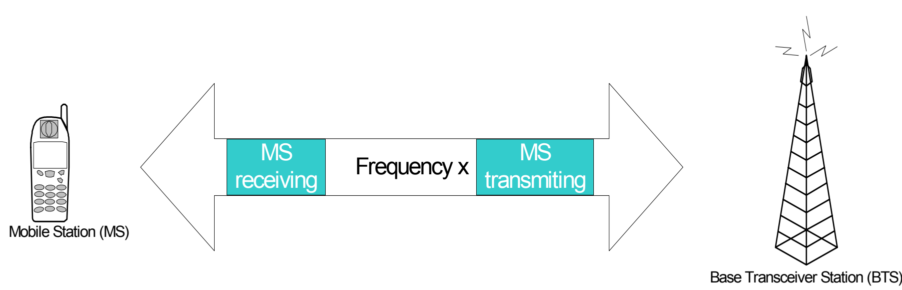

Figure 11 TDD Channel.

2. Multiple Access Techniques

In order to accommodate a large number of users within the same bandwidth, the most commonly used multiple access techniques used are the following.

a. Frequency Division Multiple Access (FDMA)

With the use of *Frequency Division Multiplexing* (FDM), every user is assigned a specific frequency. The maximum number of users is analogous to the channel's bandwidth (the smaller has more users). Figure 12 presents N different users each of whom occupies a single channel. FDMA can be used with either FDD or TDD.

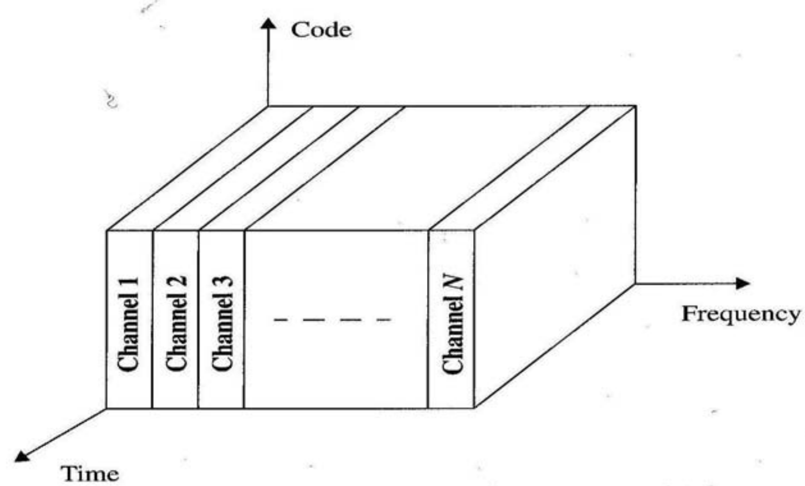

Figure 12 FDMA Scheme in Time Frequency Domain [From Theodore S. Rappaport, Wireless Communications Principles and Practices, Second Edition, Prentice Hall, Inc., 2002, p. 450].

Figure 13 gives a schema of FDMA with two mobile stations A and B communicating with the base station at frequencies x and y, respectively.

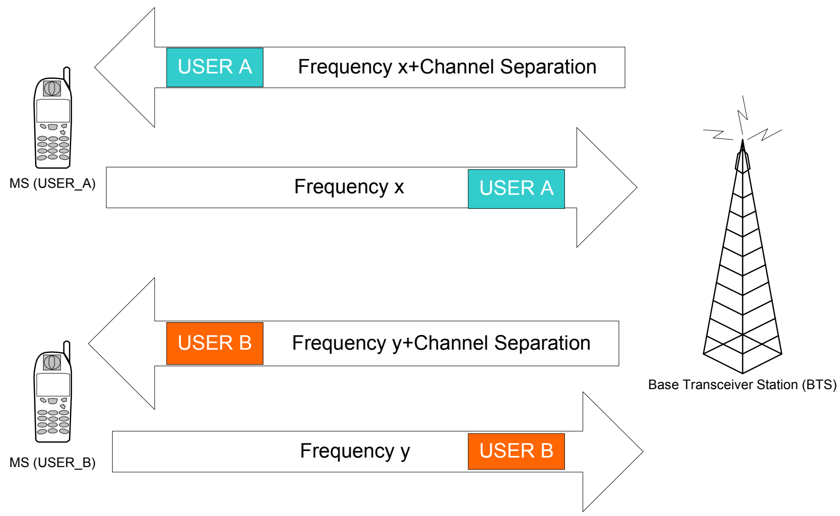

Figure 13 FDMA with FDD for Two Users (A and B).

b. Time Division Multiple Access (TDMA)

With the use of *Time Division Multiplexing* (TDM), in addition to the FDMA, multiple users can be served in the same frequency by being assigned different time slots (the smaller the duration of the time slot, the more users). Figure 14 presents N different users occupying a given frequency each of whom resides in a different timeslot. TDMA can be used with either FDD or TDD.

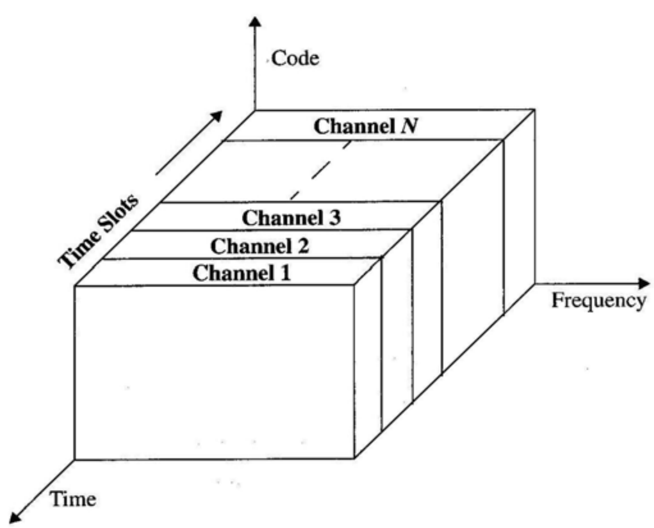

Figure 14 TDMA Scheme In Time Frequency Domain [From Theodore S. Rappaport, Wireless Communications Principles and Practices, Second Edition, Prentice Hall, Inc., 2002, p. 453].

c. Code Division Multiple Access (CDMA)

It is based on the *Direct Sequence Spread Spectrum* (DSSS) technique in which a user's data stream is spread over a larger wideband spectrum. As shown in Figure 15, user's data (i.e., voice) is spread into a wider spectrum by being multiplied with a higher data rate spreading code. This code is a pseudo-random sequence of bits, called "*chips*". The resulting spread signal is modulated and transmitted. The receiving end by multiplying the same spreading code with the signal is recovering the original data. The DSSS provides improved security features and resistance to the *multipath problem*[33]. CDMA was first commercially introduced in 1989 by Qualcomm[34]. With CDMA technique, multiple users can communicate with the network simultaneously by being multiplexed with DSSS in a single radio channel (shown in Figure 16). Each user is differentiated from the other by its unique *spreading code*. The capacity of the system does not rely on the frequency range. Thus, theoretically, there is no maximum number of users. In practice, the more users added, the more the noise level increases, thus creating a higher error rate. Usually 64 users are accommodated in a single channel. One of the biggest advantages of CDMA over TDMA is that it eliminates the need for frequency planning since the cell reuse factor equals one. The amount of time slots dedicated to each user is limited when the level of noise pass a threshold. CDMA can be used with either FDD or TDD.

33 William Stallings, Wireless Communications, Prentice Hall, Inc., 2002, p. 321.

34 QUALCOMM History/Key Milestones, [http://www.qualcomm.com/about/history.html], April 2004.

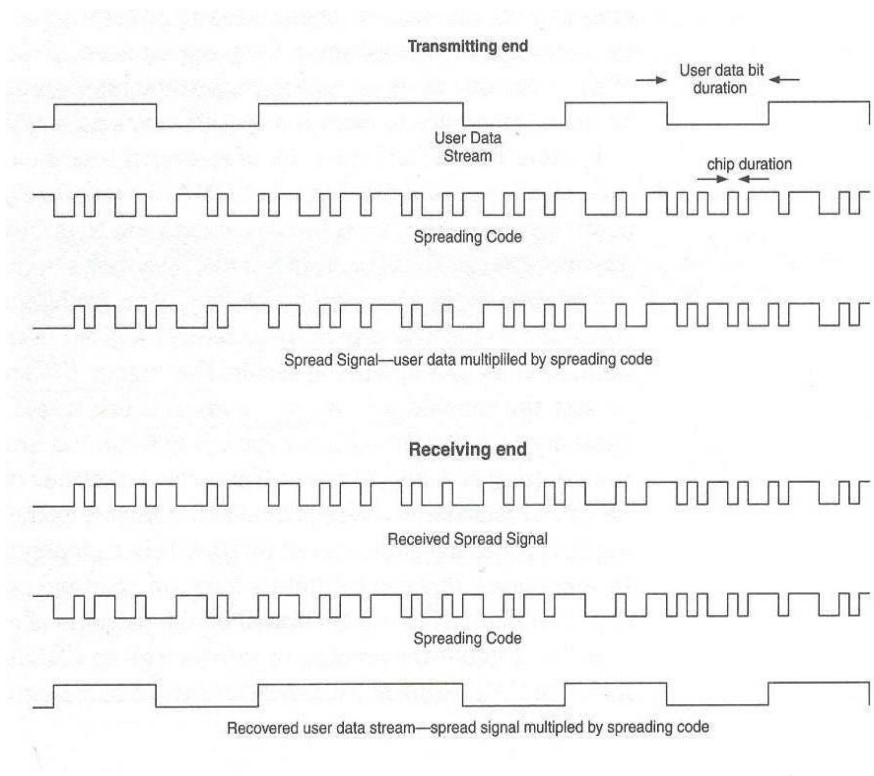

Figure 15 DSSS Spreading Example for a Given User [From Smith & Collins, 3G Wireless Networks, McGraw-Hill, 2002, p. 145].

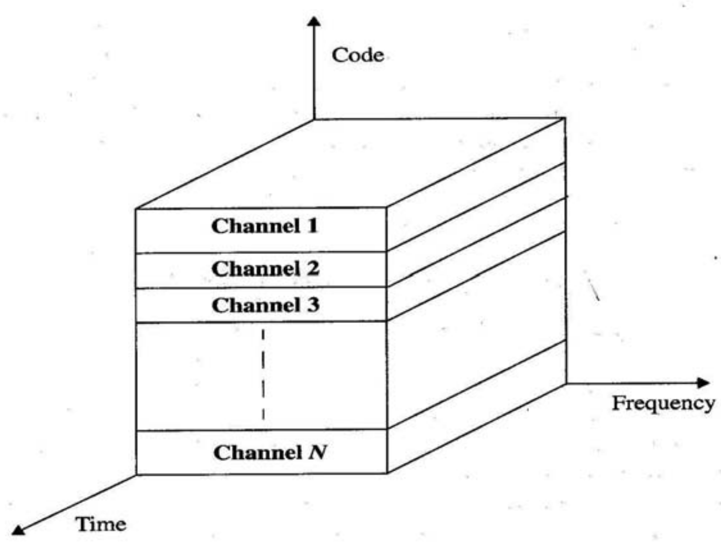

Figure 16 CDMA Scheme in Time Frequency Domain [From Theodore S. Rappaport, Wireless Communications Principles and Practices, 2nd ed, Prentice Hall, Inc., 2002, p. 458].

3. Modulation Techniques

The first generation cellular networks (1G) used analog modulation while the following ones used digital. In general, digital modulation is characterized as *linear* when the amplitude of the transmitted signal is a linear proportion of the modulated digital signal or *non-linear* when the amplitude is constant. Modern systems can use a combination of both.

The most widely spread linear modulation techniques are:

- Binary Phase Shift Keying (BPSK), shown in Figure 17
- Differential Phase shift Keying (DPSK)
- Quadrature Phase shift Keying (QPSK)
- $\pi/4$ QPSK.

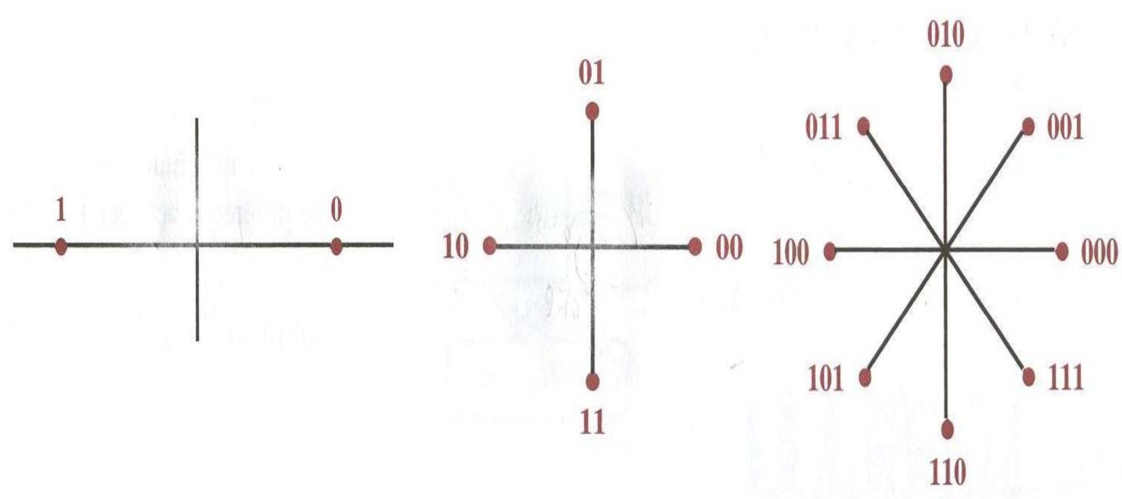

Figure 17 Various PSK Constellation Diagrams [From Behrouz Forouzan, Data Communications and Networking, McGraw-Hill 2nd ed., 2001, pp. 114-116].

The most known non- linear modulation methods are:

- Binary Frequency Shift Keying (BFSK)
- Minimum Shift Keying (MSK)
- Gaussian Minimum Shift Keying (GMSK)

C. CELLULAR NETWORKS EVOLUTION

1. First Generation (1G) Cellular Networks

The first trial system was in Chicago in 1978 used the *Advanced Mobile Phone Service* (AMPS) was first developed from AT&T Bell labs at the end of the 1970's and officially deployed in 1983[35]. In late 1991, the US Digital Cellular (USDC) Standard IS-54 was introduced that supported three users in the same 30 KHz bandwidth. It uses digital modulation ($\pi/4$ QPSK with speech coding in TDMA). The Nippon Telephone and Telegraph (NTT) Company introduced in Japan one cellular system at 800 MHz with 25 KHz channel bandwidth in 1979. In Europe, the Nordic mobile telephone system introduced a cellular system in the 450 MHz band (NMT 450) in 1981. Later, the European Total Access Cellular System (ETACS) introduced in 1985 that worked similar to AMPS. The same year C-450 was launched in Germany[36]. Table 5 summarizes the first generation networks characteristics.

	NTT	*NMNT450*	*AMPS*	*ETACS*	*N-AMPS*	*JTACS*
Year Introduced	1979	1981	1983	1985	1991	1988
Location	Japan	Europe	N. America	Europe	N.America	Japan
Modulation	FM	FM	FM	FM	FM	FM
Multiple Access	FDMA	FDMA	FDMA	FDMA	FDMA	FDMA
Duplex	FDD	FDD	FDD	FDD	FDD	FDD
Forward channel (downlink) range	n/a	463-468 MHz	869-894 MHz	935-960 MHz	869-894 MHz	925 MHz
Reverse channel (uplink) range	n/a	453-458 MHz	824-849 MHz	890-915 MHz	824-849 MHz	860 MHz
Channel Bandwidth	25 KHz	25 KHz	30 KHz	25 KHz	10 KHz	25 KHz
Channel Separation	n/a	10 MHz	45 MHz	45 MHz	45 MHz	n/a
Number of Channel	n/a	200	832	1000	2496	n/a

Table 5 1G Networks Summary [After Rappaport, Wireless Communications Principles and Practices, pp. 7, 9, 537, 594 and Smith & Collins 3G Wireless Networks p. 28].

35 AT&T Milestones, [http://www.att.com/history/milestones.html], April 2004.

36 Theodore S. Rappaport, Wireless Communications Principles and Practices, 2nd ed., Prentice Hall, Inc., 2002, p. 9.

2. Second Generation (2G) Cellular Networks

a. Overview

The need for more user capacity per cell led to the development of 2G technologies. It uses digital modulation formats and TDMA/FDD and CDMA/FDD techniques. All 2G technologies compared to the 1G offer at least triple spectrum efficiency. The most well-known implementations are:

- *Global Systems Mobile* (GSM): The most widely worldwide spread system used in Europe, Asia, Australia, South America and partly in the United States.
- *Interim Standard 54* (IS-54) and Interim Standard 136 (IS-136) known also as North American Digital Cellular (NADC) used in North and South America and Australia.
- *Pacific Digital Cellular* (PDC) used in Japan.
- *Interim Standard 95* (IS-95) used in North and South America, Japan, China and Australia.

The data through 2G technologies are sent over circuit switched modems in a single circuit switched voice channel. Every 2G implementation has its own coding scheme and error protection algorithm. The data rate, though, is for all the same at about 10Kbps. Table 6 summarizes the second generation characteristics.

	GSM 900	***USDC IS-54***	***IS-136 IS-54 RevC***	***DCS-1800***	***IS-95***	***DCS 1900***
Year Introduced	1990	1990	1991	1993	1993	1994
Location	Europe	N.America	N.America	Europe	N.America	N.America
Modulation	GMSK	π/4 DPSK	π/4 DPSK	GMSK	QPSK	GMSK
Multiple Access	TDMA	TDMA	TDMA	TDMA	CDMA	TDMA
Duplex	FDD	FDD	FDD	FDD	FDD	FDD
Forward channel (downlink) range	935-960 MHz	869-894 MHz	869-894 MHz	1805-1880 MHz	1930-1990 MHz	1850-1910 MHz
Reverse channel (uplink) range	890-915 MHz	824-849 MHz	824-849 MHz	1710-1785 MHz	1850-1910 MHz	1930-1990 MHz

	GSM 900	***USDC IS-54***	***IS-136 IS-54 RevC***	***DCS-1800***	***IS-95***	***DCS 1900***
Channel Bandwidth	200 KHz	30 KHz	30 KHz	200 KHz	1250 KHz	200 KHz
Channel Separation	45 MHz	45 MHz	45 MHz	95 MHz	n/a	80 MHz
Number of Channels	124	832	136-198	374	4-12	299

Table 6 2G Networks Summary [After Theodore S. Rappaport, Wireless Communications Principles and Practices, pp. 8, 28, 555, 569, 596 and Smith & Collins, 3G Wireless Networks, pp. 48-49].

b. IS-54 / IS-136

This standard is based on the AMPS system and is commercially known as Digital AMPS (D-AMPS). It introduces Time Division Multiplexing in the AMPS channels. It was standardized from the Telecommunications Industry Association (TIA) in 1990 and it uses the same frequencies with AMPS as are used, but in every time slot up to three full rate or six half rate users are multiplexed[37]. The final version of IS-54Rev-C was called IS-136 and is still in use today.

c. IS-95

In July 1993, the Interim Standard 95 (IS-95) that used CDMA technology was first published from TIA. The first revision named IS-95A was published in May 1995 and describes the structure of the wideband 1.25 MHz CDMA channels. Each radio channel supports up to 64 different users. In addition to voice services, the IS-95A provides circuit-switched data connections with speeds up to 14.4Kbps. The first IS-95A networks were originally deployed in September 1996[38]. Improved capacity, call quality and security made IS-95 a popular choice for wireless providers.

37 Theodore S. Rappaport, Wireless Communications, 2nd Edition, Prentice Hall, Inc., 2002, p. 541.

38 CDMA Development Group, [http://www.cdg.org/technology/2g.asp], April 2004.

d. GSM

GSM stands for Global System for Mobile communication and uses TDMA with FDD and GMSK modulation. It was conceived in 1982 from the Conference on European Postal and Telecommunications (CEPT) in an effort to create a Pan-European network. In 1989, CEPT created the European Telecommunications Standards Institute (ETSI), which was responsible for the specification development[39]. Since July 2000, the GSM become part of 3GPP[40]. The first commercial GSM networks were introduced in 1991-1992. The GSM standard operates at a different set of frequencies (uplink and downlink channels) worldwide and mainly at 850, 900, 1800 and 1900 MHz. Figure 18 presents the GSM worldwide coverage and Figure 19 the GSM coverage in the United States. The GSM standard has become the preferred cellular network worldwide. At the end of March 2004, it operated in 207 countries worldwide, up from 641 operators, and had 1024.3 million subscribers[41]. This fact makes GSM the first truly global cellular network.

Figure 18 GSM Worldwide Coverage [From Ref. 42].

39 Conference on European Postal and Telecommunications, [http://www.cept.org/], April 2004.

40 European Telecommunication Standard Institute Press Release, [www.etsi.org/pressroom/previous/2000/geran.htm], April 2004.

41 GSM Association, [http://www.gsmworld.com/news/statistics/index.shtml], April 2004.

42 3G Americas, [http://www.3gamericas.org/english/maps/coverage_maps/gsm_global.cfm], April 2004.

Figure 19 GSM Coverage in the United States [From Ref. 43].

3. Two and Half Generation (2.5G) Cellular Networks

a. Overview

The need for increased throughput data rates in data transfer (such as web browsing and e-mail) led to the evolution of 2.5G. In addition to the *Hyper Text Transfer Protocol* (HTTP), it supports the *Wireless Access Protocol* (WAP) through which web pages can be viewed on the small screen of a mobile phone or a handheld, which led to *mobile commerce* (m-commerce). In order for the evolution from 2G to 2.5G to be backwards compatible and cost bearable, the following networks were introduced:

- *High Speed Circuit Switched Data* (HSCSD)
- *General Packet Radio Service* (GPRS)
- *Enhanced Data Rates for GSM Evolution* (EDGE) also know as Enhanced GPRS (EGPRS).
- *Interim Standard 95B* (IS95B).

Table 7 presents a summary of the 2.5G network characteristics.

[43] Cingular Wireless, [http://onlinestore.cingular.com/html/Maps/nation_GSMgen_1_29_04.htm], May 2004.

	HSCSD	*GPRS*	*IS-95B*	*EDGE*
Year Introduced	1999	1999	1999	1999
Location	Europe	Europe	N. America	Europe
Modulation	GMSK	GMSK	QPSK	8-PSK
Multiple Access	TDMA	TDMA	CDMA	TDMA
Duplex	FDD	FDD	FDD	FDD
Forward channel (uplink) range	935-960 MHz	935-960 MHz	1930-1990 MHz	935-960 MHz
Reverse channel (downlink) range	890-915 MHz	890-915 MHz	1850-1910 MHz	890-915 MHz
Channel Bandwidth	200 KHz	200 KHz	1250 KHz	200 KHz
Channel Separation	45 MHz	45 MHz	n/a	45 MHz
Number of Channels	124	124	n/a	124

Table 7 2.5G Networks Summary [After Theodore S. Rappaport, Wireless Communications Principles and Practices, p. 32 and Smith & Collins, 3G Wireless Networks, p. 168].

b. HSCSD

High Speed Circuit Switched Data (HSCSD) is the only circuit switched based 2.5G technology. It allows a GSM user to obtain consecutive time slots in the GSM networks. By applying less strict error control in every time slot, it increases the data rate from 9.6 to 14.4Kbps. Thus, when a user obtains four consecutive slots, the total throughput can increase to 57.6Kbps. It requires software upgrades in the GSM base stations and is good for real-time Internet connections.

c. GPRS

It is an asymmetric packet based system and has the same modulation format as the GSM. While in GSM, a user can occupy a single time slot while in GPRS, it can take all eight GSM time slots of the TDMA frame (see Chapter III), thus having a theoretical throughput of raw data 8x21,4Kbps = 171,2Kbps. The major improvement with the *packet switched* capability is that a user can download only when necessary and does not need a permanent connection such as circuit switching. Therefore, even though the end user thinks that it is always connected to the Internet, in practice, every time new data are required, the mobile phone is asking for those resources from the network. It requires new routers and gateways as well as software updates at the base stations. Even though it was initially designed as an upgrade to GSM networks, it was extended to work with the IS-136 system as well.

d. EDGE

This started from the GSM community as a path to 3G. It uses the same basic GSM infrastructure with the difference being that it can use 8-PSK modulation in addition to the GMSK. It has nine different air interfaces, called *Multiple Modulation Coding Schemes* (MCS), which is named from 1-9. Every MCS has a varying control protection and can use either GMSK for a low data rate (8.8-17.6 Kbps) or 8-PSK for a high data rate (22.4-59.2 Kbps) for each time slot. According to the level of error correction needed for the application, every mobile user can adopt whatever MSC is suitable without the error protection and eight time slots taken when it theoretically connects with 8x59.2=547.2 Kbps. A minimum error control and network considerations limit the throughput at 384 Kbps. It requires new hardware (routers, gateways) and software updates at the base stations. Figure 20 presents the worldwide EDGE coverage.

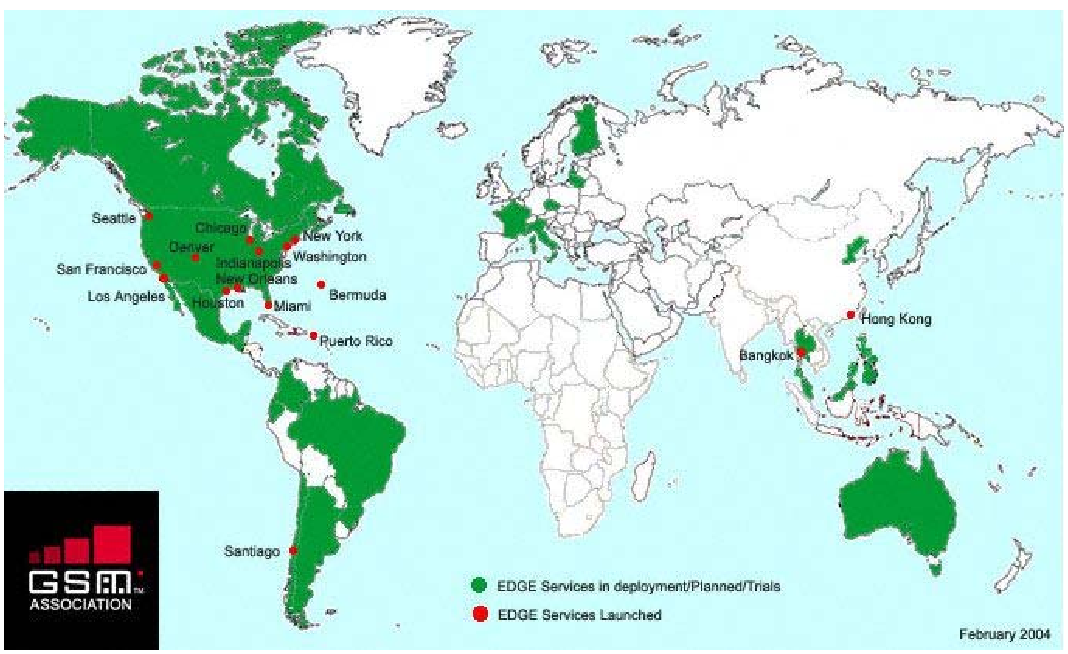

Figure 20 EDGE Geographic World Wide Coverage [From Ref. 44].

44 [www.gsmworld.com], April 2004.

e. IS 95B

Interim Standard 95B (IS-95B) is the revision of IS-95A networks proposed in 1995, which provides packet and circuit switched data access through CDMA radio channels. The term *cdmaOne* is used to describe cellular networks based on IS-95A and IS-95B technology. The first IS-95B networks were originally deployed in September 1999 in Korea[45]. By dedicating eight different orthogonal user channels simultaneously, theoretically it can achieve 8x14.4=115.2Kbps. At the end of 2003, the total CDMA users were 188.6 million, out of which North America had 75.2 million, the Caribbean and Latin America 32 million, Europe, Africa and Russia 3.1 million, while Asia and the Pacific had the remaining 78.3 million[46]. Figure 21 shows the growth rate of worldwide *cdmaOne* subscribers.

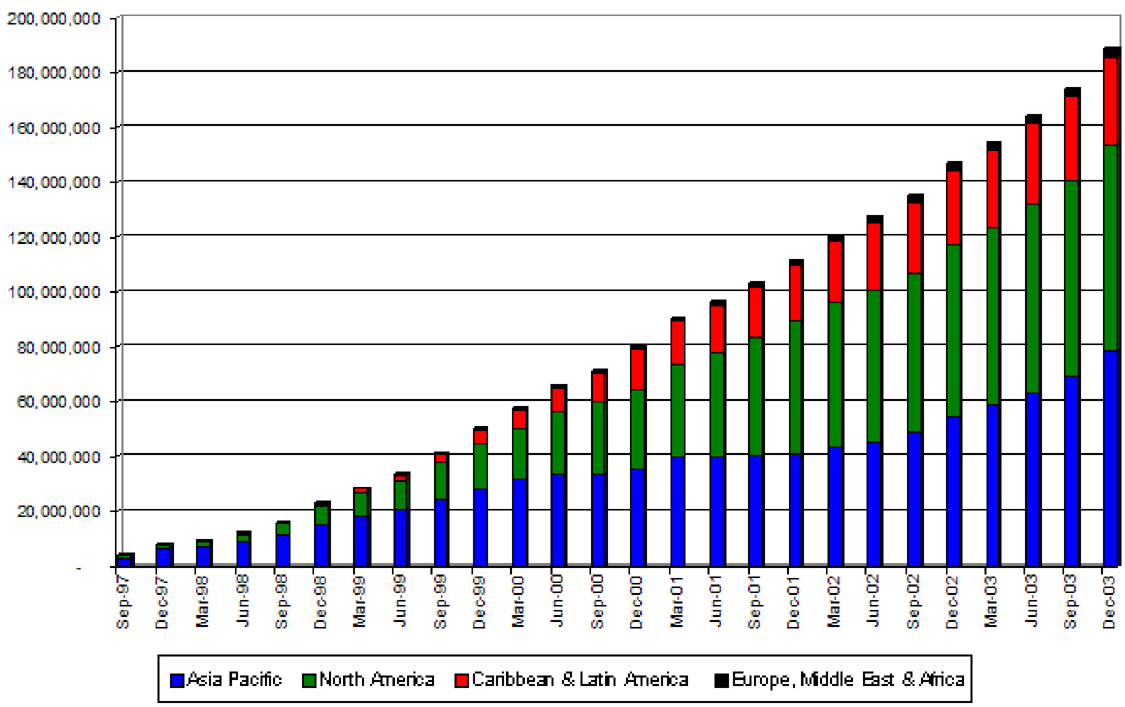

Figure 21 *cdmaOne* Subscribers Growth from 1997 to 2003 [From Ref. 47].

45 CDMA Development Group, [http://www.cdg.org/technology/2g.asp], April 2004.

46 CDMA Development Group, [http://www.cdg.org/worldwide/index.asp], April 2004.

47 CDMA Development Group, [http://www.cdg.org/worldwide/cdma_world_subscriber.asp], April 2004.

4. Third Generation (3G) Cellular Networks

a. Overview

The need for high speed Internet access, live video communications and the simultaneously data and voice transmit led to the third generation cellular networks. The *International Telecommunications Union* (ITU) created a project for a common worldwide cellular standard under the name *International Mobile Telephone 2000* (IMT 2000) in 1998. Since the 2G cellular infrastructures already had different implementation variations, the 3G migration proposed the following standards (shown in Figure 22):

- *Wideband CDMA* (WCDMA)
- *Code Division Multiple Access 2000* (cdma2000)
- *Time Division Synchronous Code Division Multiple Access* (TD-SCDMA)
- *UWC-136*
- *Digital Enhanced Cordless Telephone* (DECT)

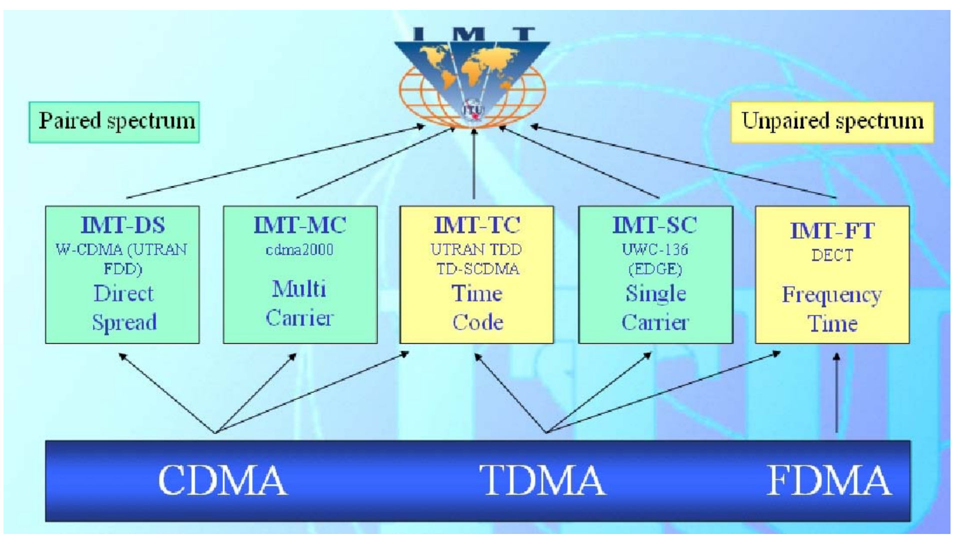

Figure 22 IMT-ITU200 Protocols for 3G, [From ITU-IMT-2000project.pdf], May 2004.

Two major organizations are now responsible for the development of the third generation standards:

- *3G Project Partnership* (3GPP) is working on the WCDMA system specifications[48].
- *3G Project Partnership 2* (3GPP2) is working on the cdma2000 system specifications[49].

b. WCDMA

The European Telecommunication Standards Institute (ETSI), as an upgrade to the GSM, conceived the *Universal Mobile Telecommunications Service* (UMTS) in 1996. It was based on a variation of CDMA modulation and submitted to the IMT 2000 in 1998 as a worldwide standard under the name *UMTS Terrestrial Radio Access* (UTRA). A few years later, it merged with other CDMA proposals under the current name WCDMA. It is backward compatible with 2G systems GSM, IS-136 and PDC as well as with the 2.5G GPRS and EDGE. It uses a variable direct sequence spread spectrum and requires a minimum spectrum allocation of 5 MHz. The chip rates can exceed 16Mchip/sec/user. In addition, it is necessary to change the hardware at the base stations.

c. cdma2000

This protocol is backward compatible with IS-95 / IS-95A / IS-95B. It has been endorsed as a possible 3G solution from TIA in April 1998[50] and is based on the original 1.25Mhz channel bandwidth per user. There are three different proposed types:

- cdma2000 1xRTT
- cdma2000 1XEV
- cdma2000 3xRTT

The *cdma2000 1xRTT* improved the 2G and 2.5G standards by introducing a rapidly adaptable signaling rate and chipping rate for each user. It supports instantaneous data theoretical throughput of 307 Kbps and typically 144 Kbps per user.

48 3GPP, [http://www.3gpp.org/], May 2004.

49 3GPP2, [http://www.3gpp2.org/], May 2004.

50 CDMA Development Group, [http://www.cdg.org/technology/cdma_technology/cdma_milestones.asp], April 2004.

The *cdma2000 1xEV* was developed by the Qualcomm Company to be compatible with the W-CDMA. In August 2001, the ITU include it in the IMT 2000 project. There are two types of systems:

- *cdma2000 1xEV-DO* (Data Only) that dedicates radio channels strictly for data and supports instantaneous data throughput of 2400 Kbps on a specific CDMA channel.
- *cdma2000 1xEV-DV* (Data and Voice) that dedicates radio channels for data and voice and supports throughput of 144 Kbps on a specific CDMA channel.

The *cdma2000 3xRTT* is using three 1.25 MHz radio channels and provides data throughput of 2000 Kbps. If the three radio channels are not adjacent and used individually, then need exists for added hardware at the base stations. If the three channels are adjacent in order to manipulate an instant 3.75 MHz channel, additional hardware at the base stations is needed. Figure 23 presents a graphical representation of cdma2000 and WCDMA. When cdma2000 1xRTT is used, each user communicates within a single 1.25MHz carrier and data are spread with 1.2288 Mcps (Million chips per second). When cdma2000 3xRTT is used, each user can communicate through three consecutive carriers and data are spread with 3.6864 Mcps. In contrast, the WCDMA user resides within a single 5MHz carrier and data are spread with 4.096Mcps.

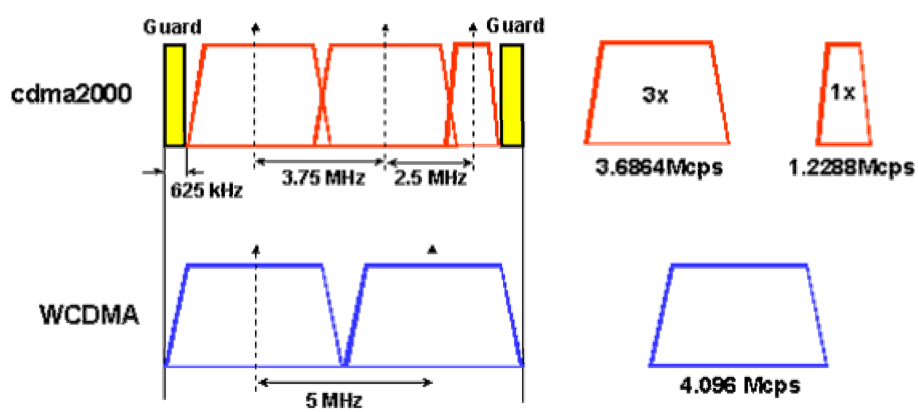

Figure 23 cdma2000 and WCDMA Carrier Comparison [From Ref. 51].

51 [http://www.cellular.co.za/technologies/cdma/cdma_w_paper.htm], May 2004.

d. TD-SCDMA

The China Academy of Communications Technology (CATT), along with Siemens Information and Communication Mobile Group (IC Mobile), developed the Time Division Synchronous Code Division Multiple Access (TD-SCDMA) protocol as an alternative 3G technology in the IMT-2000 project[52]. It uses TDMA/TDD and CDMA techniques for the high speed data transfer over GSM networks up to 384Kbps. It has a 1.6MHz radio channel and a 5msec frame subdivided into seven time slots[53]. In November 2003, the first operating phone using this technology was developed and will be commercially available in 2005[54].

5. Forth Generation (4G) Cellular Networks

Even though the 3G networks have been deployed since 2001 the truly broadband access will be achieved with the fourth generation mobile phones (4G). The Japanese company, NTT DoCoMo, is one of the few; if not the only, cellular provider whose Research and Development (R&D) department has started research in 4G systems since 1998. the Initial target was 100Mbps in downlink. The modulations used in this platform are:

- Variable Spreading Factor Orthogonal Frequency and Code Division Multiplexing (VSF-OFCDM).
- Variable Spreading Factor Code Division Multiple Access (VSF-CDMA).

In October 2002, a maximum of 100Mbps was achieved in downlink and 20mbps in uplink[55]. In June 2004, it was announced that, in a purely experimental environment, a car running at the speed of 30kmh was communicating with 4G base stations located 0.8 to 1Km range and had an average downlink throughput of 135Mbps with a maximum of

52 Siemens Press Release, [http://www.siemens.com/index.jsp?sdc_rh=null&sdc_flags=null&sdc_sectionid=0&sdc_secnavid=0&sdc_3dnvlstid=&sdc_countryid=0&sdc_mpid=0&sdc_unitid=999&sdc_conttype=2&sdc_contentid=230236&sdc_langid=1&], April 2004.

53 Theodore S. Rappaport, Wireless Communications, 2nd Edition, Prentice Hall, Inc., 2002, p. 40.

54 The CHINA Daily, [http://www1.chinadaily.com.cn/en/doc/2003-11/03/content_277863.htm], April 2004.

55 NTT DoCoMo Press Release, [http://www.nttdocomo.com/presscenter/pressreleases/press/pressrelease.html?param[no]=243], July 2004.

300Mbps. This experiment was conducted in ideal environments and the actual throughput is will vary quite a bit in real systems. The Company is declaring commercial deployment by 2010. Spectrum requirements are not officially assigned yet[56].

56 NetworkWorldFusion, [http://www.nwfusion.com/news/2004/0604nttdocom.html], July 2004.

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III. TECHNICAL DESCRIPTION OF MAJOR CELLULAR NETWORKS

This chapter describes the air interface and the ground network architecture of the most known cellular networks. The first part describes the second generation Global System for Mobile (GSM), the second the 2.5G General Packet Radio Service (GPRS) and the third part the third generation Universal Mobile Telecommunication Service (UMTS) networks. Finally, the fourth discusses areas under development in GPRS and UMTS cellular environment such as Virtual Private Networks and IPv6.

A. GSM NETWORK OVERVIEW

1. GSM Network Architecture

Figure 24 presents the general topology of a GSM network.

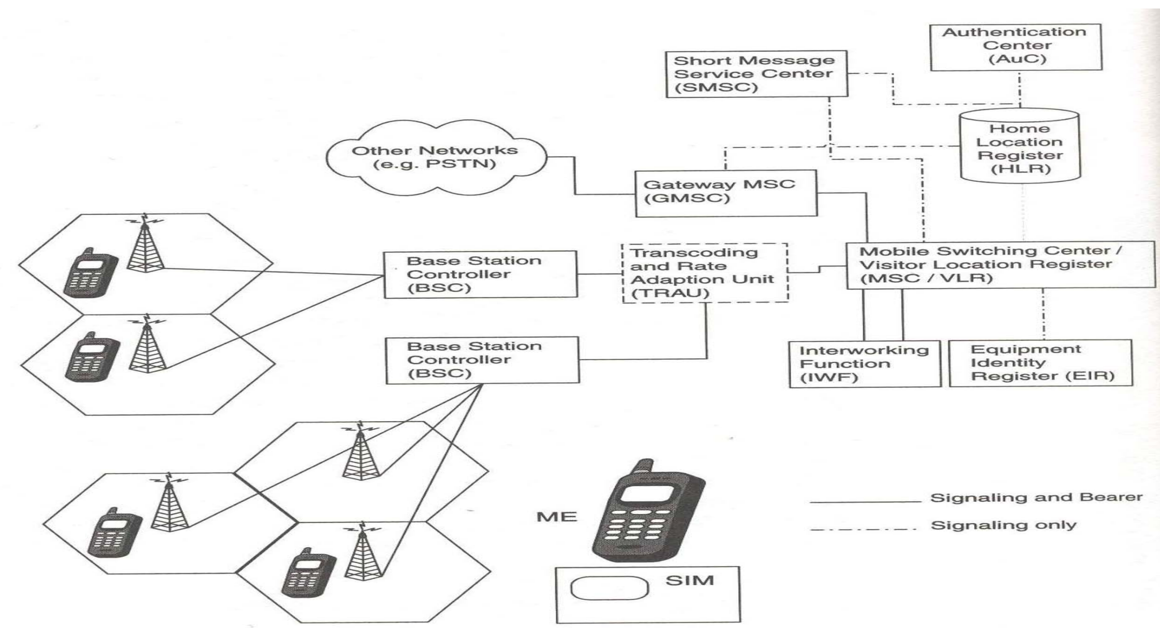

Figure 24 GSM Network Topology [From Smith & Collins, 3G Wireless Networks, McGraw Hill, 2002, p. 60].

The essential parts of the GSM network are:

- The *Mobile Equipment* (ME), which is the term used for the cellular device.
- The *Subscriber Identity Module* (SIM), which is a card containing a chip with a user's profile. It is located in the ME and is used for ME activation. Figure 25 shows the various services that the SIM card . One of the biggest advantages of SIM cards is that a subscriber can change the mobile device without changing the phone number and services.

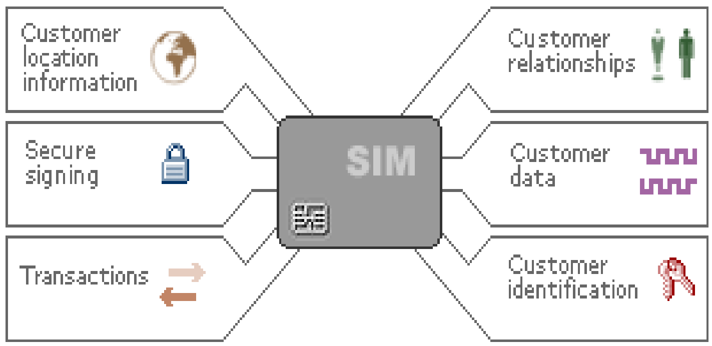

Figure 25 SIM Card Supported Services [From Ref. 57].

- The *Mobile Station* (MS), which consists of the ME and SIM.
- The *Home Location Register* (HLR), which is database that contains the subscriber's data and its supporting services.
- The *Visitor Location Register* (VLR), which is a database that contains the data of subscribers currently visiting the MSC. It is dependent on vendor design and it can reside inside an MSC rather than being an autonomous unit.
- The *Authentication Center* (AuC), which contains the subscriber's authentication data. Interacts with the SIM card, in order to authenticate a user to the network and provide security.
- The *International Mobile Equipment Identity* (IMEI), which is a 15 digit number that identifies the mobile equipment (ME) to the network. It consists of the: *Type Approval Code* (TAC), *Serial Number* (SNR) and *Check Digit* (CD). The IMEI can be found on the manufacturer label of every mobile phone. Figure 26 presents a schematic representation.

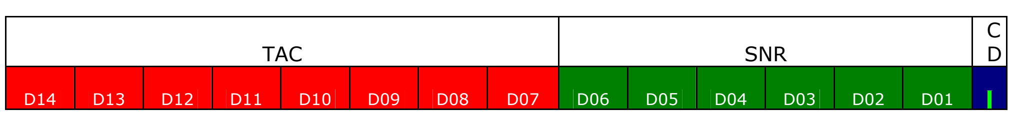

Figure 26 IMEI Representation [From Ref. 58]

57 [http://www.smarttrust.com/sim/default.asp#SIM], April 2004.

- The ***International Mobile Subscriber Identity*** (IMSI), which is a 15 digit number defining a numbering plan for the Mobile Station (MS) and consists of the *Mobile Country Code* (MCC), the *Mobile Network Code* (MNC) and the *Mobile Station Identification Number* (MSIN). According to the ITU-T Recommendation E.212, the United States MCC is allowed to be a number from 310 to 316 followed by a three digit MNC that identifies the cellular provider[59]. Figure 27 presents two different representations of IMSI.

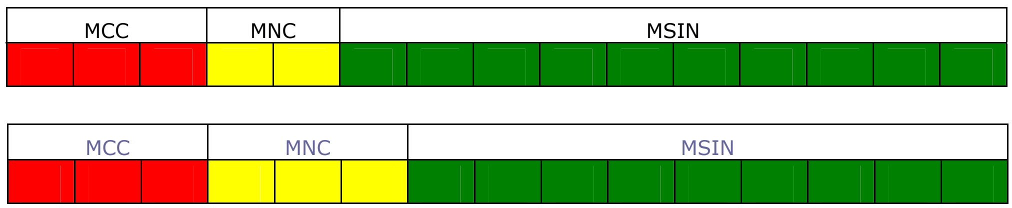

Figure 27 IMSI Representation [From Ref. 60].

Additional components in GSM networks, as shown in Figure 24, are:

- The *Gateway MSC* (GMSC), which receivers the calls from the PSTN, queries the HLR to find the position of the MS and sends the call to the corresponding MSC.
- The *Equipment Identity Register* (EIR), which is a database that identifies the SIM card and assigns the subscriber to one of three states. Either clear to make phone calls or forbidden to make phone calls or the choice is made by the network administrator.
- The *Transcoding and Rate Adaption Unit* (TRAU), which converts the coded speech from PCM based networks to the MS or sends from the MS to the PCM networks using standard 64Kbps.
- The *Inter-Networking Function* (IWF), which is a modem bank that converts the digital data from the MS (modem or fax) to an analog stream to be routed inside the PSTN.
- The *Short Message Service Center* (SMSC), which stores and forwards short messages to and from the MS.

The GSM architecture has the following subsystems:

- The *Base Station Subsystem* (BSS), which consists of a finite set of BSC and BTS (shown in Figure 28 and Figure 29).

58 [http://www.numberingplans.com/index.php?goto=guide&topic=imei], April 2004.

59 International Numbering Plans [http://www.numberingplans.com/index.php?goto=plans&by=E.212&s=US&action=show], April 2004.

60 International Numbering Plans [http://www.numberingplans.com/index.php?goto=guide&topic=E212], April 2004.

- The *Network Switching Sub-System* (NSS), which contains the MSC, VLR, HLR, AuC (shown in Figure 28).
- The *Operation Support Subsystem* (OSS), which supports a set of Operation Maintenance Centers (OMC) that manages the overall network performance (shown in Figure 28 and Figure 29).

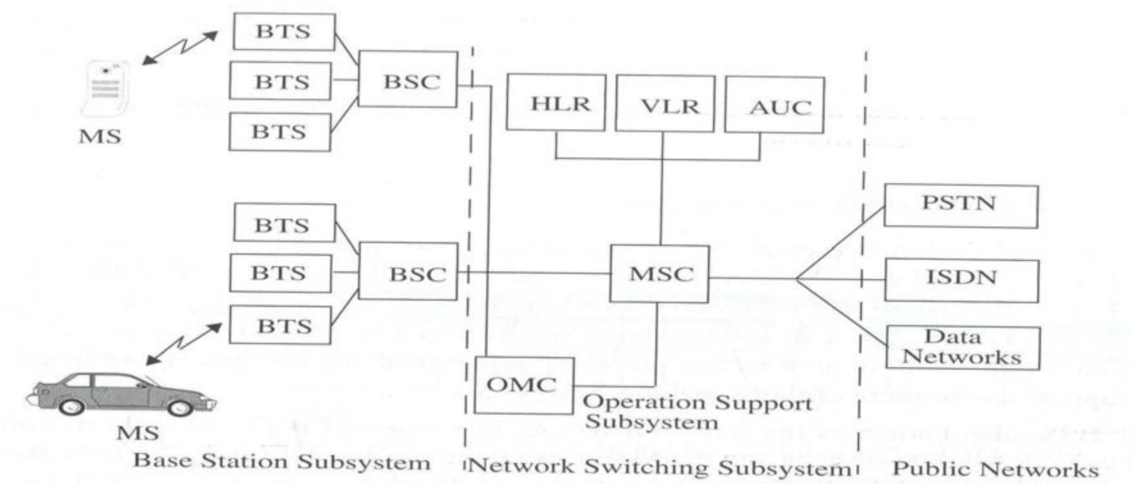

Figure 28 GSM Network Sub-Systems [From Theodore S. Rappaport, Wireless Communications Principles and Practices, 2nd ed, Prentice Hall, Inc., 2002, p. 552].

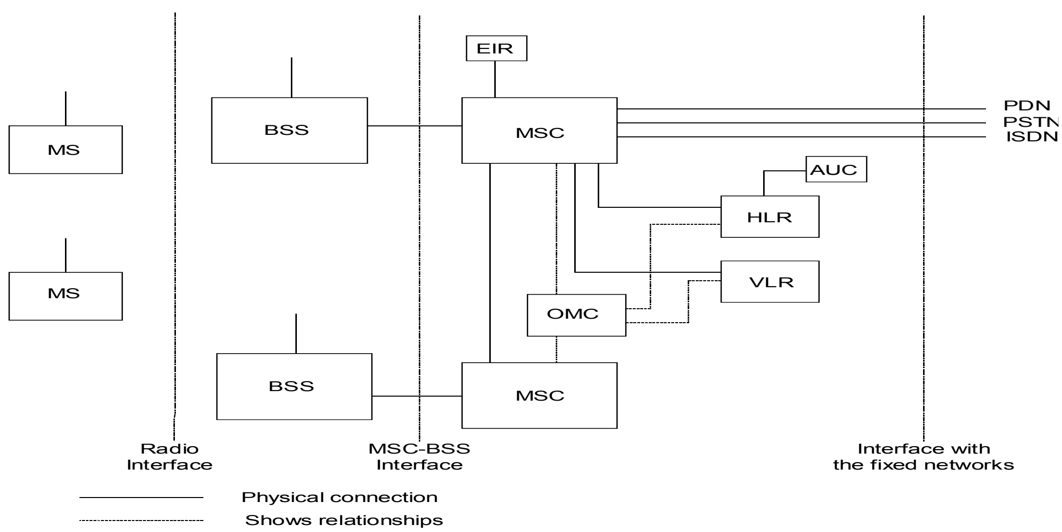

Figure 29 General Description of a GSM Public Land Mobile Network (PLMN) [From Ref. 61].

61 GSM 01.02 version 5.0.0, March 1996.

The GSM network elements communication is based on the following interfaces:

- The *Abis Interface* (Abis) between BTS and BSC.
- The *B Interface* (B) between a MSC and a VLR.
- The *A Interface* (A) between a MSC and a BSC.
- The *Ater Interface* (Ater) between a BSC and a TRAU.

The Mobile Station (MS) communicates with the Base Transceiver Station (BTS) in two different sets of frequencies. The forward channel (935-960MHz) is used for the BTS to talk to the phone, while the reverse channel (890-915MHz) is used for the vise-versa link. Every Base Station Controller (BSC) controls more than one BTS by communicating over an Abis Interface. The Mobile Switching Center (MSC) is one of the most basic components and links with the following:

- A number of BCS through an A Interface
- The Visitor Location Register (VLR) through a B Interface
- The Inter-Networking Function (IWF)
- The Short Message Service Center (SMSC)
- The Home Location Register (HLR)
- The Transcoding and Rate Adaption Unit (TRAU)
- The Gateway MSC (GMSC) for PSTN interaction

2. GSM Air Interface

Every channel is divided into 200 KHz carriers with a 200 KHz separation between them. Every user occupies a forward and its relative reverse carrier separated by 45 MHz during a call. Each carrier consists of eight time slots that form a *TDMA frame*. Figure 30 presents the schema of a GSM frame structure. Each TDMA frame has duration of 4.62 ms and the other frame structures exist such as:

- *Speech multiframes*: 26 consecutive TDMA frames,
- *Control channel multiframes*: 51 consecutive TDMA frames,
- *Superframes*: 51 consecutive speech multiframes or 26 consecutive control channel multiframes,
- *Hyperframes*: 2048 consecutive superframes.

Every time slot has duration of 576.9 μs and it can be assigned either to a specific type of *Traffic Channel* (for a user's voice or data) called TCH or a specific type of *Control Channel* (for network use) called CCH. The TCH's can be used in full mode or half-rate mode. The CCH's provide the necessary information such as signal strength. Figure 31 and Figure 32 present the GSM logical channels in the downlink and uplink, respectively.

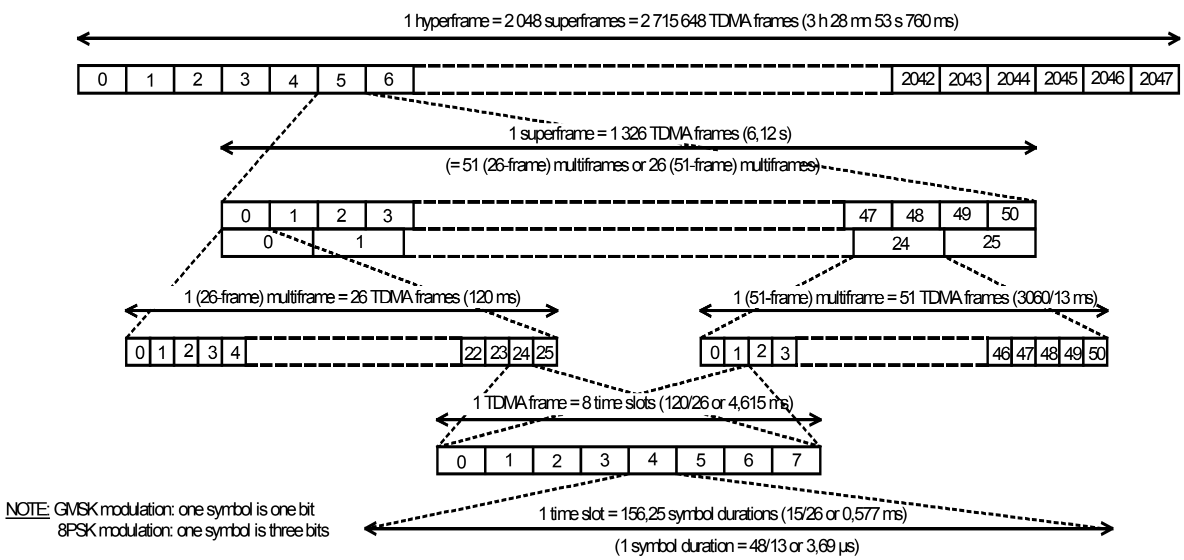

Figure 30 GSM Frame Structure [From Ref. 62].

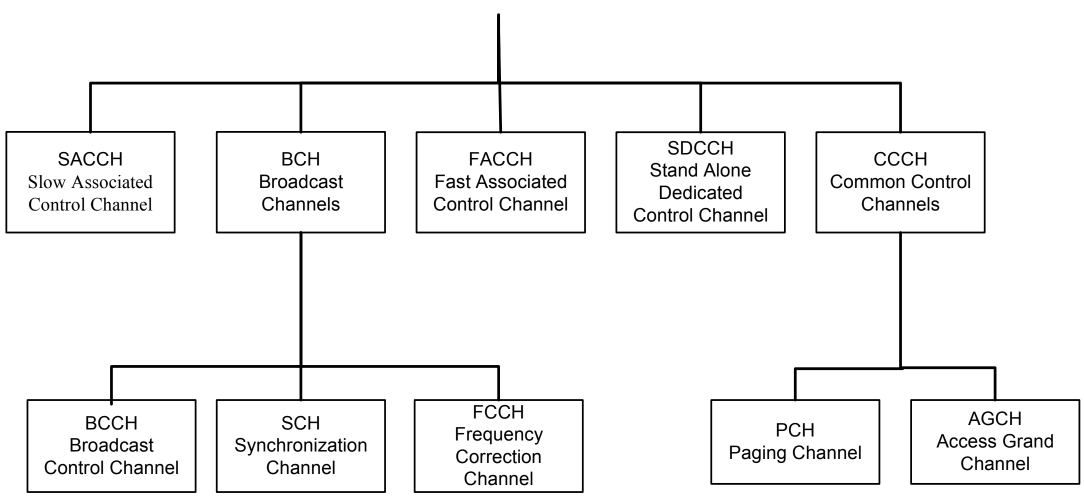

Figure 31 Downlink GSM Channels.

62 3GPP TS 45.001 V6.30, February 2004.

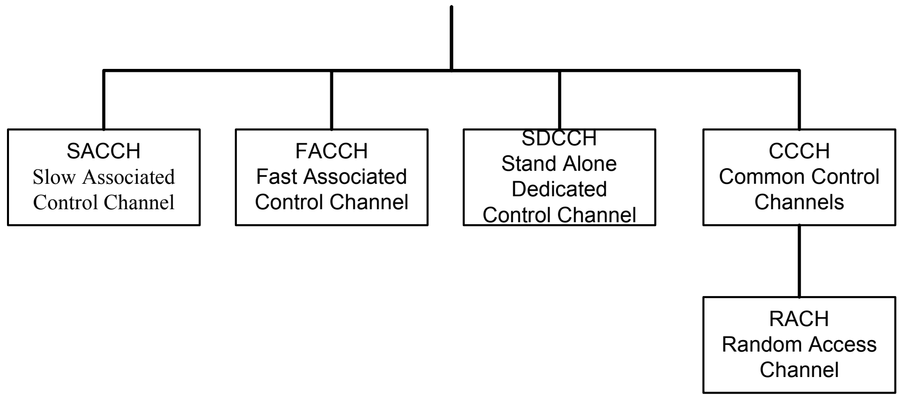

Figure 32 Uplink GSM Channels.

Figure 33 (a) shows the traffic channel organization for the one full rate TCH and Figure 33 (b) for the two half rate TCH.

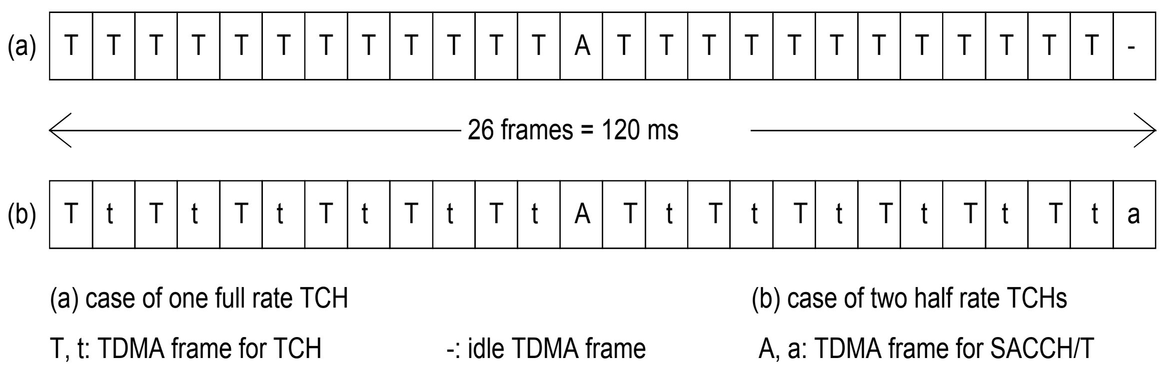

Figure 33 GSM Traffic Channel Organization in TDMA Frames [From Ref. 63].

B. GPRS NETWORK OVERVIEW

1. GPRS Network Architecture

The GPRS network introduced the following elements to the GSM network, in order to support its packet based operations:

- The *Packet Control Unit* (PCU), which is responsible for the packet scheduling over the air interface. Usually, it is located within the BSC.

63 3GPP TS 45.001 V6.30, February 2004.

- The *Serving GPRS Support Node* (SSGN), which is responsible for the mobility management in the packet based network. It is the analogous element of MSC in the circuit switched network.
- The *Gateway GPRS Support Node* (GGSN), which is responsible for the interface with outer packet based networks (i.e., TCP/IP or X.25).

The GPRS network elements communication is based on the following interfaces:

- The *Gb Interface*, between SSGN and BSC.
- The *Gn Interface*, between SSGN and a GGSN.
- The *Gs Interface*, between MSC and SSGN.
- The *Gr Interface*, between HLR and SSGN.
- The *Gc Interface*, between HLR and GGSN.
- The *Gi Interface*, between GGSN and the packet based networks.

Figure 34 presents the GPRS network topology.

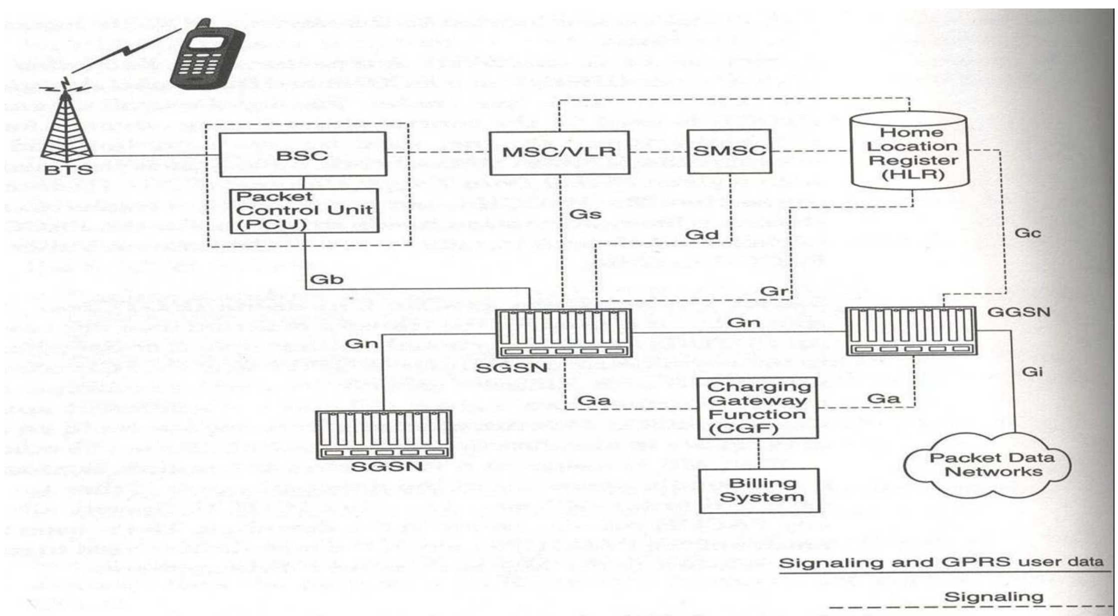

Figure 34 GPRS Network Diagram [From Smith & Collins, 3G Wireless Networks, McGraw Hill, 2002, p. 176].

Figure 35 shows the GPRS protocol stack at the MS, BSS, SSGN, GGSN .The new defined sub-layers above the physical RF layer in the MS are:

- *Medium Access Control* (MAC)
- *Radio Link Control* (RLC)

- *Logical Link Control* (LLC)
- *Sub-Network Dependent Convergence Protocol* (SNDCP)

At the BSS (BTS and BSC), the addition is the BSS GPRS Protocol (BSSGP) and at the SGSN, the *GPRS Tunneling Protocol* (GTP).

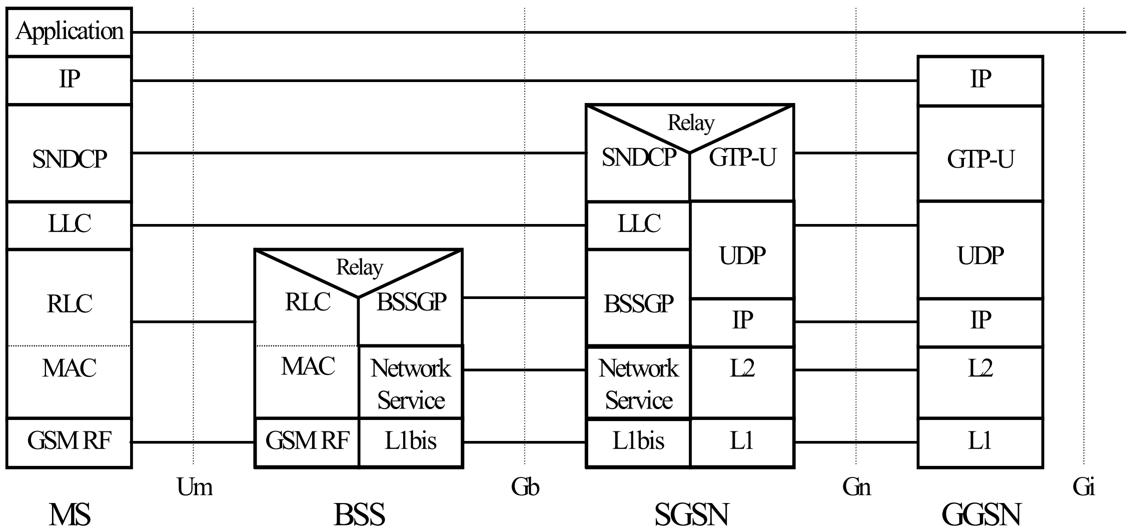

Figure 35 GPRS Transmission Plane [From Ref. 64].

The revolutionary step in GPRS was the fact that the user accessed data networks in packet switched mode rather than circuit switched in GSM. In addition, when there is no GPRS availability, the data routing can be completed through the current GSM system, and when it is incoming to the mobile phone (MS), data traffic from external networks passes through the GGSN where it is formed encapsulated inside a GTP packet. The GTP packets are then forwarded to the SSGN that uses the SNDCP to deliver the data to the mobile phone. In outbound traffic from the mobile phone, the reverse procedure is followed. The GGSN removes the data from the GTP packet and forwards them to the outer network. The role of GGSN is essential to the data packet delivery. While there may be numerous SSGN's in a cellular network topology, only a few GGSN's exist depending on regional and other data traffic requirements. The GGSN, therefore, acts as a proxy server for all mobile data connections. The IP of a GGSN interface towards external data networks is called *Access Point Name* (APN) and it is

64 3GPP TS 23.060 V6.3.0, December 2003.

given to the user by the cellular company (as can be seen in Chapter IV). The data session between the mobile phone and the GGSN is described as the *Packet Data Protocol* (PDP) Context.

A valid GPRS mobile phone can perform the following two actions in the *Public Land Mobile Network* (PLMN)[65]:

- ***GPRS Attach***: when the mobile phone is turned on and indicates its position by asking for service.
- ***GPRS Detach***: when the mobile phone is informing the PLMN and does not require further service. The Detached can be initiated from the MS, SSGN or HLR.

Figure 36 presents the exchange messages between a mobile phone that occur when it requests service from a new SSGN during a handoff controlled by a new MSC.

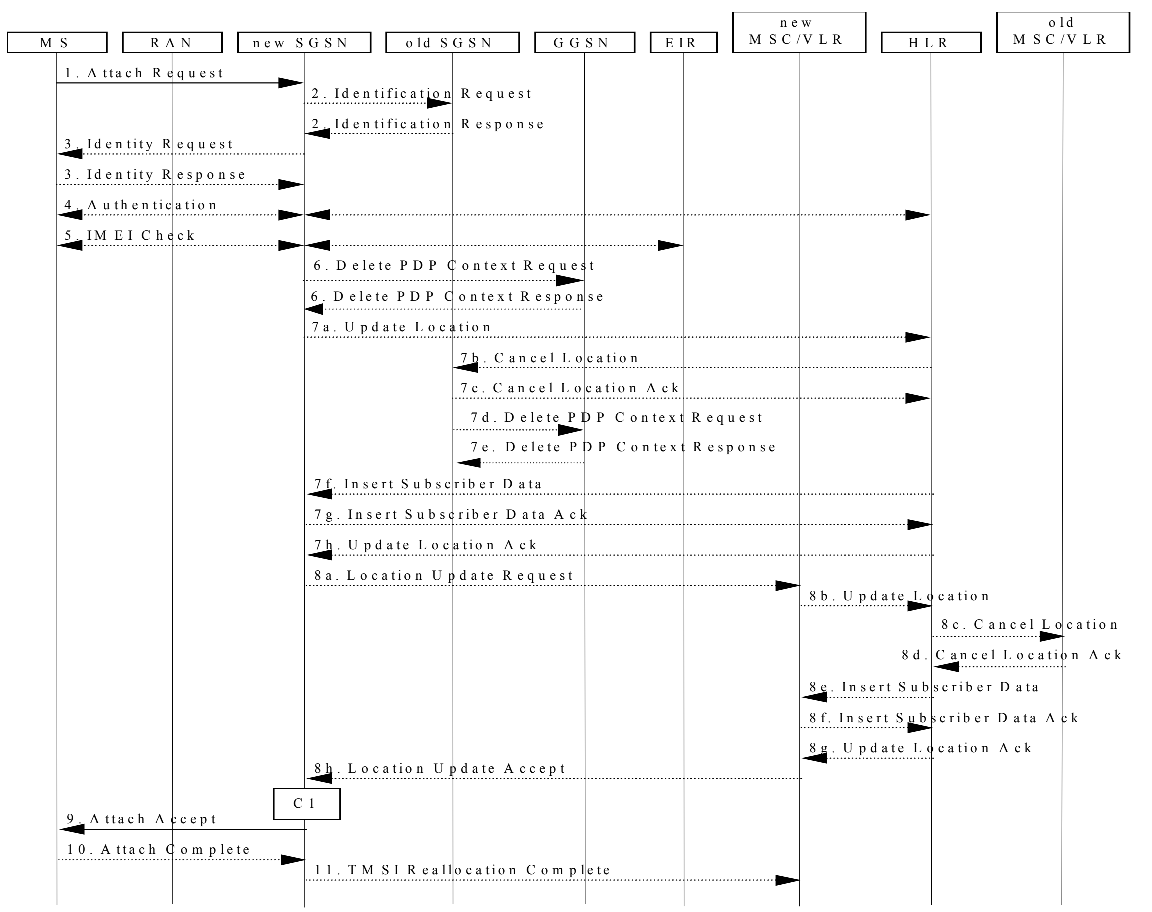

Figure 36 Combined GPRS/IMSI Attach Procedure [From Ref. 66].

65 3GPP TS 22.060 V6.0.0, March 2003.

66 3GPP TS 23.060 V6.3.0, December 2003.

The different states that a mobile phone (MS) can be inside the GPRS network are:

- ***IDLE State***: When the mobile phone is not attached to the GPRS network, thus not using its functions.
- ***READY State***: When the mobile phone is attached to the GPRS network and can have its full functionality.
- ***STANDBY State***: When the times of the READY State expires.

Figure 37 shows the state transitions from the MS and the SGSN perspective. From IDLE, the system moves to READY with a GPRS Attach and when the timer expires, it moves to STANDBY. After a packet data transmission, it moves again to READY, and if not detaching, it can move again in STANDBY.

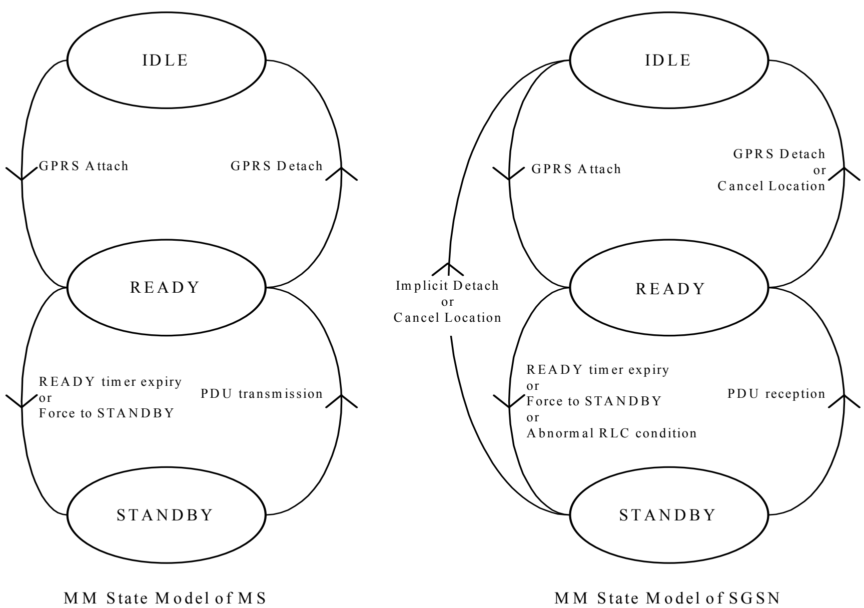

Figure 37 State Models in GPRS [From Ref. 67].

One of the most important attributes of GPRS and UMTS data capable mobile phones is their *Multislot class* capability. Each class is characterized by the number of timeslots (not necessarily contiguous) that the mobile phone can occupy in an eight slot TDMA frame while receiving (Rx), transmitting (Tx) and in total (Sum). Table 8 shows the first 12 of the 29 GPRS classes. Those classes are applicable to mobile phones not required to transmit and receive at the same time.

67 3GPP TS 23.060 V6.3.0, December 2003.

Multislot class	Maximum number of slots			Minimum number of slots			
	Rx	Tx	Sum	T_{ta}	T_{tb}	T_{ra}	T_{rb}
1	1	1	2	3	2	4	2
2	2	1	3	3	2	3	1
3	2	2	3	3	2	3	1
4	3	1	4	3	1	3	1
5	2	2	4	3	1	3	1
6	3	2	4	3	1	3	1
7	3	3	4	3	1	3	1
8	4	1	5	3	1	2	1
9	3	2	5	3	1	2	1
10	4	2	5	3	1	2	1
11	4	3	5	3	1	2	1
12	4	4	5	2	1	2	1

Table 8 The First 12 GPRS Multislot Classes [After Ref. 68].

2. GPRS Air Interface

The GPRS network is using four different coding schemes named CS-1 through CS-4 with the theoretical data rate per time slot from 9.05 to 21.4 Kbps, respectively. Even though the CS-4 has the better throughput, it does not provide error correction, and for this reason, is not efficient practically. Accordingly, CS-3 is not used due to errors on the air interface and CS-1 due to the low data rate. Thus, CS-2 with a 13.4 Kbps data rate is the most commonly used. GPRS uses a 52 multiframe structure. The channels for GPRS are:

- *Packet Data Channel* (PDCH) is the time slot in GPRS and can carry data.
- The GPRS Traffic Channels are named *Packet Data Traffic Channels* (PDTCH) and occupy a time slot. A mobile phone can have multiple PDTCH at the same time (uplink or downlink) and it must listen to the corresponding PDTCH (timeslot) to the downlink or uplink, respectively. Figure 38 and Figure 39 shows the GPRS logical channels in the downlink and uplink, respectively.

68 3GPP TS 05.02 V8.11.0 Annex B1, June 2003.

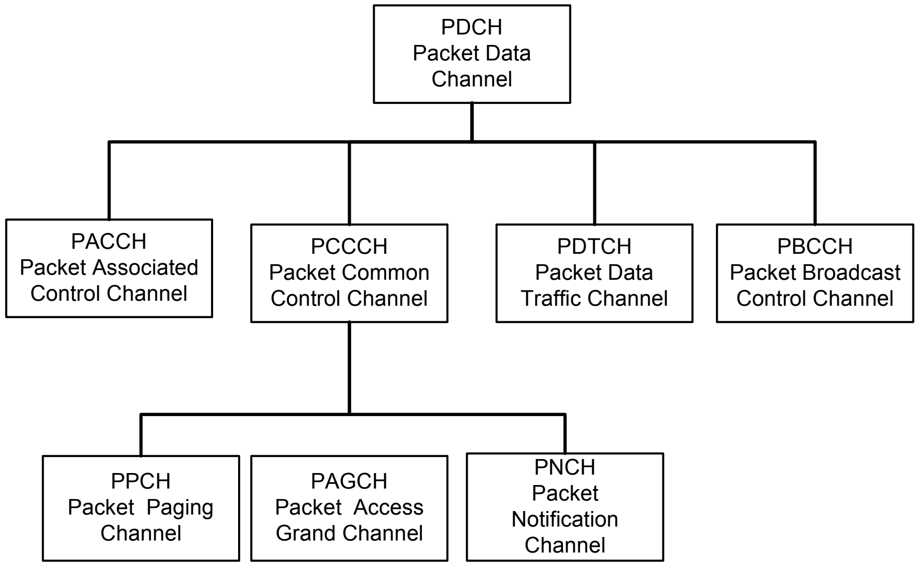

Figure 38 Downlink GPRS Channels.

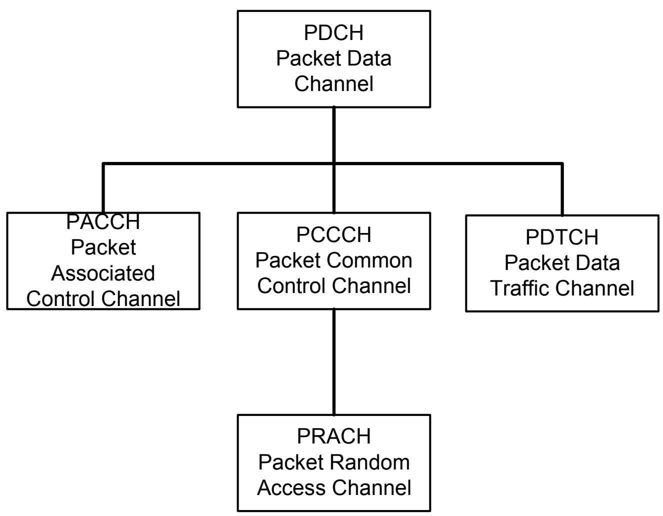

Figure 39 Uplink GPRS Channels.

C. UMTS NETWORK OVERVIEW

1. UMTS Network Architecture

The first *Universal Mobile Telecommunications Service (*UMTS) networks specifications were officially distributed with the 3GPP Release9 in 1999. In the following years, upgrades were included in the 3GPP Releases 4 and 5. Some of the introduced elements in the UMTS networks are:

- The *UMTS Subscriber Identity Module* (USIM), analogous to the GSM SIM card
- The *Node B*, analogous to the GSM BTS
- The *Radio Network Controller* (RNC), analogous to the GSM BSC
- The *Call State Control* Function
- The *Multimedia Resource Function*
- The *Media Gateway* (MGW)
- The *Transport Media Gateway* (T-SGW)
- The *Roaming Signaling Gateway* (R-SGW)
- The *Media Gateway Control Function* (MGCF)

The network elements communicate in the following predefined interfaces:

- The *Iub Interface*, between RNC and Node B.
- The *Iur Interface*, between RNC's.
- The *Gr Interface*, between HLR and GGSN.
- The *Gi Interface*, between GGSN and MGW or other packet based networks.

Figure 40 presents the UMTS Release 5 network topology.

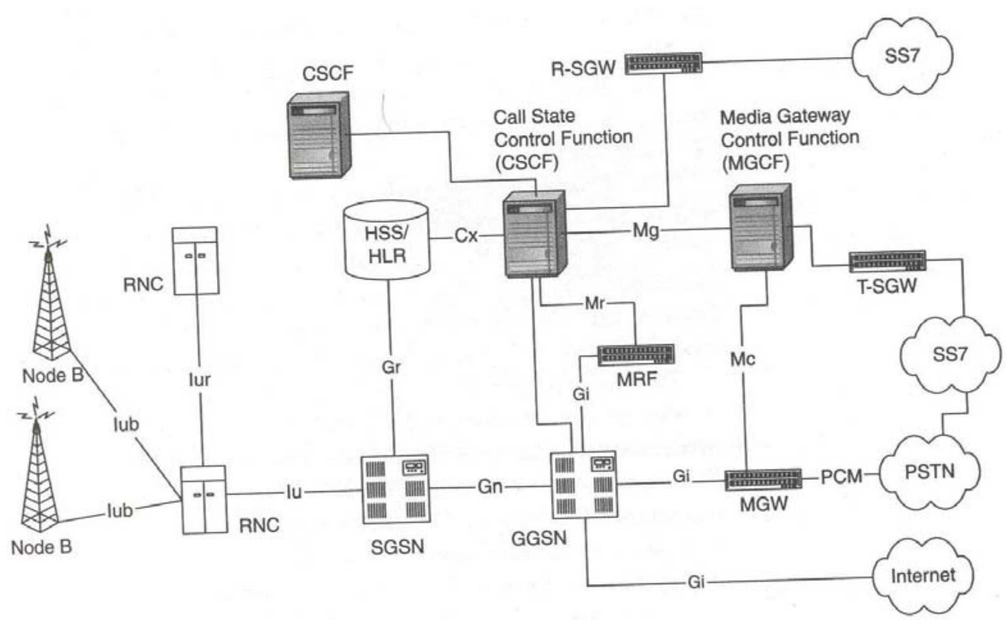

Figure 40 UMTS Network Architecture Release 5 [From Smith & Collins, 3G Wireless Networks, McGraw Hill, 2002, p. 155].

2. Air Interface

The UMTS is using WCDMA with a FDD modulation technique in which a carrier of pair of 5MHz bandwidth is used. The uplink channels use a frequency range from 1920 to 1980 MHz and downlink from 2110-2170 MHz, respectively. Each user's data are spread with the use of a channelization code to the chip rate. Therefore, the data streams of each user are separated. Multiple users' data are then scrambled with the use of a channelization code at the chip rate. Every user has a unique scrambling code and many users may have common channel codes. The chip rate is 3.68Mcps (chips per second). The air interface allocates resources every 10 ms. Figure 41 presents the UMTS radio block.

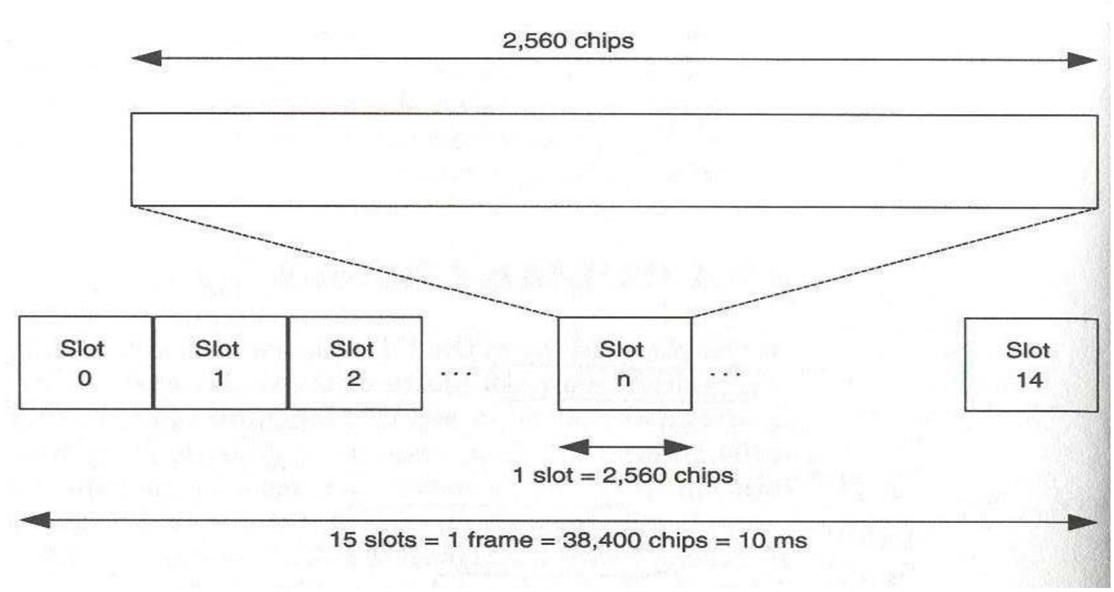

Figure 41 UMTS Air Interface Radio Block [From Smith & Collins, 3G Wireless Networks, McGraw Hill, 2002, p. 240].

Figure 42 shows the transport channels used in the UMTS networks.

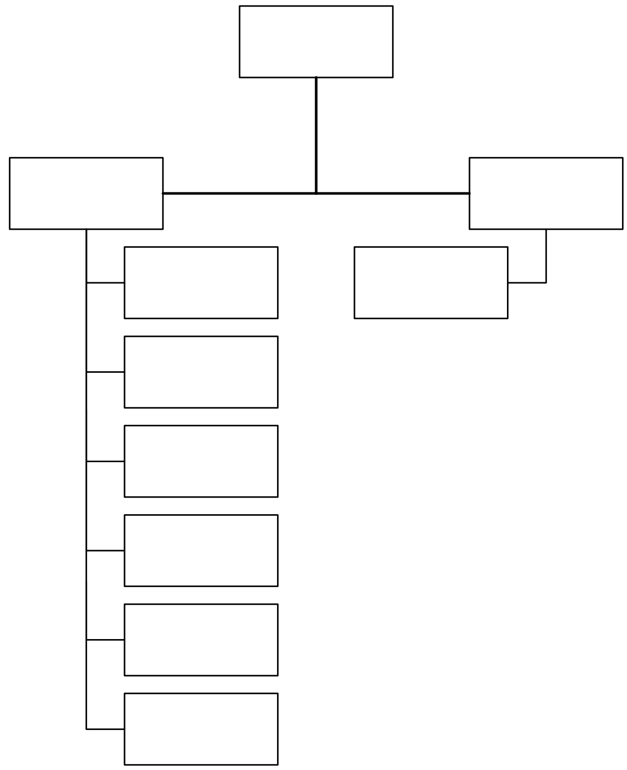

Figure 42 UMTS Transport Channels.

D. NEW TECHNOLOGIES IN CELLULAR DATA NETWORKS

1. Virtual Private Networking (VPN)

One of the most useful applications for enterprise users using 2.5G/3G data networks is a VPN link between their laptop (which is connected to the mobile phone) and to any host within their Corporate Intranet. VPN is creating secure communication by encrypting data traffic in OSI layer 2 (data link layer) with the use of *Point to Point Tunneling Protocol* (PPTP[69]) or the Layer 2 Tunneling Protocol (L2TP[70]). For security in OSI layer 3 (network layer), the IPSec[71] is used. The latter can be implemented between a laptop and a Corporate Intranet Gateway Server (see Figure 43) or between a cellular provider's GGSN and a Corporate Firewall (see Figure 44). A proposed alternative is an implementation between a cellular provider's SGSN and a GGSN server located behind the Corporate Firewall for GTP tunneling over the Internet (see Figure 45).

69 RFC 2637, Point-to-Point Tunneling Protocol, July 1999.

70 RFC 2661, Layer Two Tunneling Protocol L2TP, August 1999.

71 RFC 2401, Security Architecture for the Internet Protocol, November 1998.

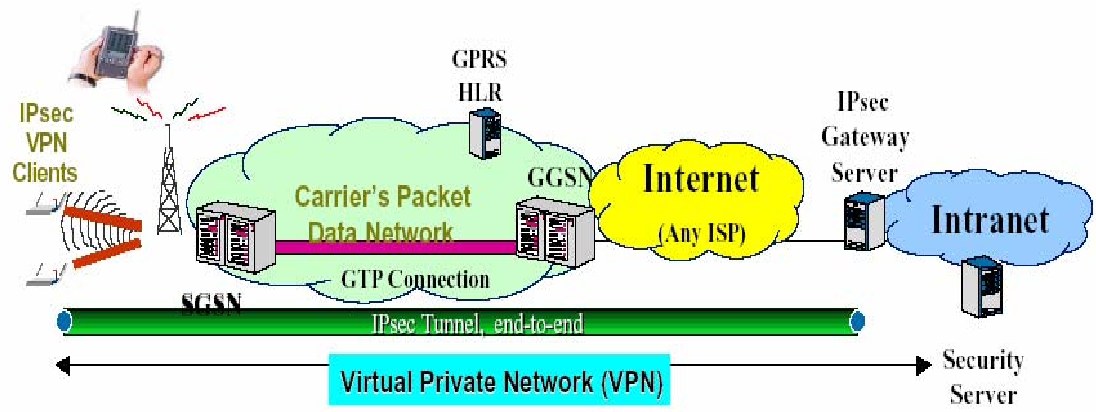

Figure 43 VPN between Mobile Client and Gateway Server [From Ref. 72].

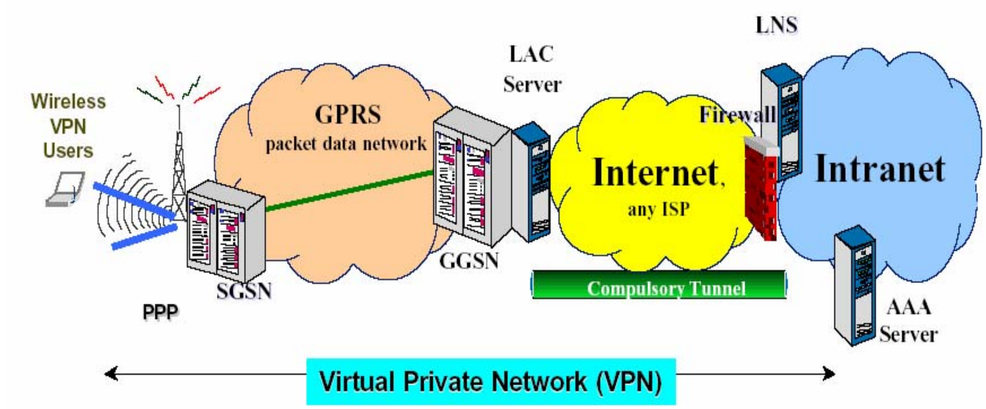

Figure 44 VPN between GGSN and Corporate Firewall [From Ref. 72].

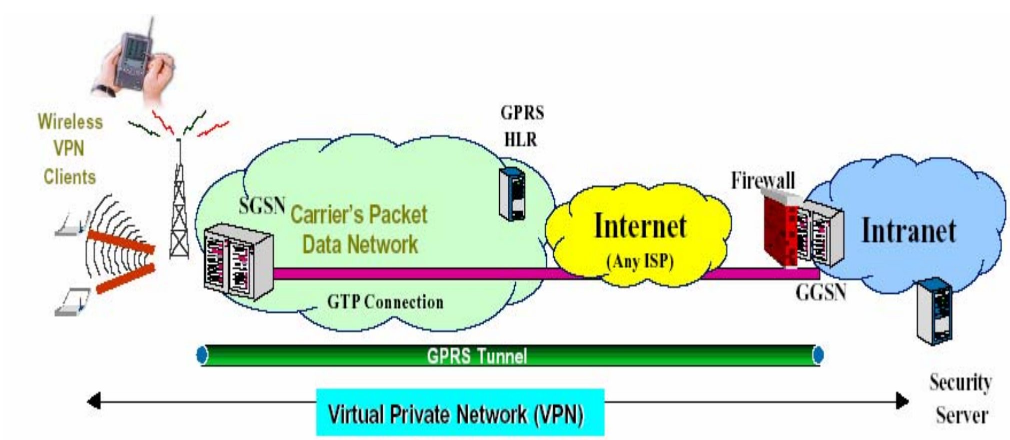

Figure 45 VPN between SGSN and a GGSN behind the Corporate Firewall [From Ref. 72].

72 [http://www.3gsma.com/pdfs/access.pdf], August 2004.

2. IPv6

Due to the lack of IP address space, the IPv6[73] solution was defined. IPv6, besides increasing the size of available IP addresses, provides enhanced support for Mobile IP and IPSec. Additionally, it does not allow fragmentation at intermediate routers and performs data flow control according to the transferred context (i.e., multimedia, file transfer, email or web). The creation of billions of IP's can provide a unique (static) IP in every cellular device. Current cellular data implementations use a temporary IP during the packet exchange. For the cellular environment, the deployment of IPv6 will require changes in GGSN and in mobile devices as well. As of Summer 2004, IPv6 has not yet been implemented on the Internet, but only used experimentally with Intranets.

The transition form IPv4 to IPv6 can be achieved with the following methods:

- By using hosts with the *Dual Ipv4/IPv6 Stack* approach in which a device can communicate with either an IPv6 or IPv4 in the network layer[74].
- By using *Tunneling* in which IPv6 intermediate routers when needed to forward traffic in IPv4 routers, encapsulate the IPv6 datagram inside an IPv4 datagram[74] above.
- By using *IPv4 to IPv6 Protocol Translators* with the use of Network Address Translation-Protocol Translation[75] (NAT-PT).

Figure 46 presents a schema for the transition phases from IPv4 to IPv6. Initially, all nodes support IPv4. In the first phase, the first IPv6 Intranets appear and some mobile devices support the dual stack IPv4/IPv6. In the second phase, Ipv6 is widely deployed in the Internet but tunneling is still used for the remaining IPv4 Intranets. The NAT-PT routers are responsible for traffic between the IPv4 and IPv6 networks. In the third and final phase, IPv6 is the dominant protocol and mobile devices no longer need to support a dual stack.

73 RFC 2460, Internet Protocol, Version 6 (IPv6) Specification, December 1998.

74 RDC 2893, Transition Mechanisms for IPv6 Hosts and Routers, August 2000.

75 RFC 2766, Network Address Translation-Protocol Translation (NAT-PT), February 2000.

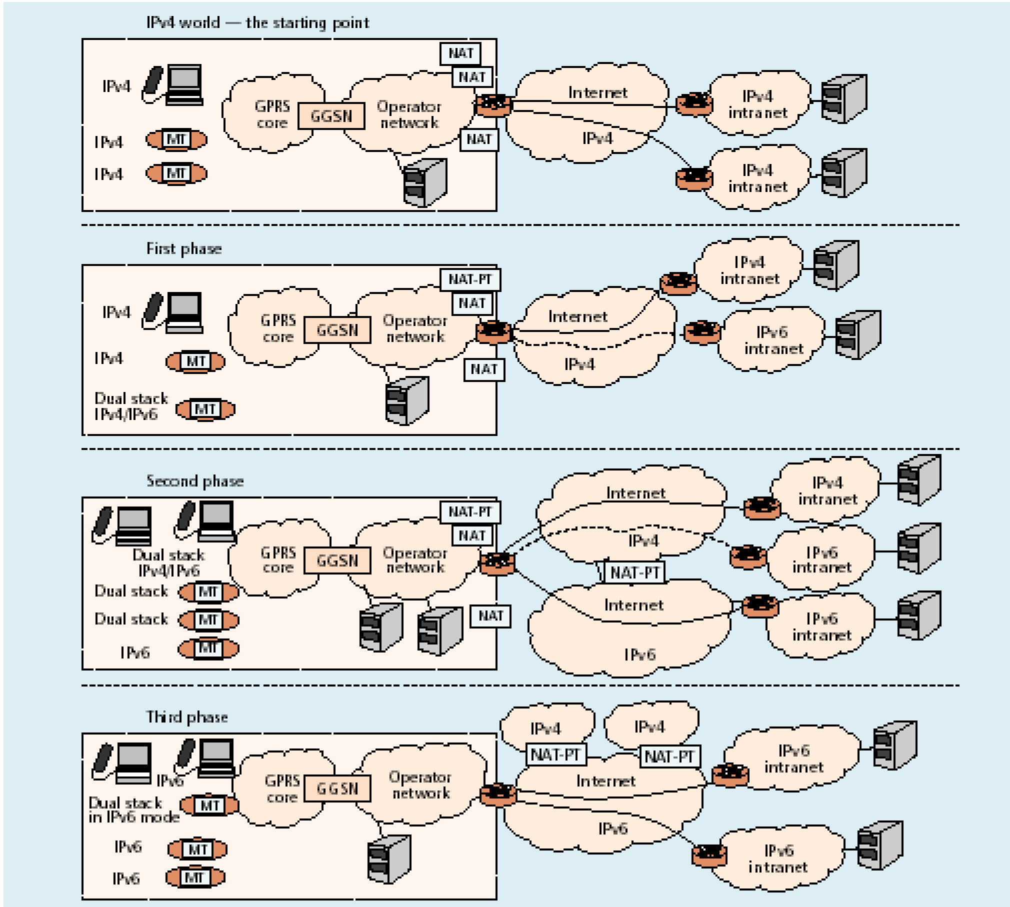

Figure 46 IPv4 to IPv6 Proposed Transition Phases [From Ref. 76].

3. Voice over IP (VoIP)

In traditional ground circuit-switched networks such as PSTN, voice is coded and transported at 64Kbps. The introduction of packet switched technology from 2.5G and forward, along with the implementation of *Adaptive Multi-Rate* (AMR) 12.2Kbps speech codec in 2.5G EDGE and 3G UMTS networks, provide the same voice service at a much lower required bandwidth. The enhanced broadband of 3G networks will eventually thrust the cellular market toward VoIP. This is translated into lower costs for voice service for consumers, especially in long distance calls.

76 Wiljakka Juha, “Transition to IPv6 in GPRS and WCDMA Mobile Networks”, IEEE Magazine Digital Library, April 2002, [http://dl.comsoc.org/cocoon/comsoc/servlets/GetPublication?id=221331], May 2004].

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IV. GPRS CELLULAR DATA NETWORK TESTING

This chapter consists of four parts. In the first, cellular data connection plans from the major providers in the United States are presented. In the second, the procedure followed for a laptop to connect to the Internet through the cellular phone is described. The third part presents various tasks performed through the cellular data connection and the forth includes observations about the GPRS connection performance.

A. CELLULAR INTERNET ACCESS PLANS IN UNITED STATES

The first cellular data networks in the United States started during the 1990's with the introduction of the second generation *Cellular Digital Packet Data* (CDPD) service. At the same time in Japan and Europe, the implemented circuit switched GSM data connections were too expensive to be widely accepted from private consumers and was used primarily by enterprises.

Mobile Internet, as noted in Chapter I, is offered two different ways. The first is for users who want to browse specifically designed text-based Web pages written in the Wireless Markup Language (WML) or use a simple email client through their mobile phone's screen. The second is for users who want to have the full capabilities of an Internet connection on their laptop by using a mobile phone or cellular card as the wireless media platform. The phone can connect to the laptop via a specific cable, Infrared or Bluetooth. If a proper phone is not available, a type II PCMCIA card plugged into the laptop can substitute for the phone.

Since the content in the first category is mostly text based, it is obvious that the amount of data downloaded is much lower than the second category where the content includes multimedia traffic as well. For the mobile oriented type of connection, companies' charge, on average, \$5 to \$10 monthly fees while for the laptop oriented data connection, charges vary according to the transferred data volume. Typical monthly fees for 20MB of data up to unlimited MB access are ranging from \$30 up to \$80.

Each cellular provider, for marketing purposes, gives its own naming to those data connections. Especially for subscribers of the unlimited data plans, it should be in their best interests to restrict usage partially in order to enforce that Mobile Internet as a means of accessing information wirelessly and not substituting for the typical wired connections. Such limitations may be on the amount of downloaded data per connection or the allowed type of connection. As of June 2004, the major U.S. cellular providers are offering data connections based mostly on 2.5G and less in 3G networks. Figure 47 summarizes those plans.

Company	***Type of Network***	***Data plan names***
Verizon Wireless[77]	CDMA 2000 1X	National Access
	CDMA 2000 IX-EVDO	Broadband Access
Cingular Wireless[78]	GPRS EDGE	Wireless Internet Wireless Internet Express Data Connect
AT &T Wireless[79]	GPRS EDGE	mMode Office Online Pro Office Online Premier Mobile Internet Data
Sprint PCS[80]	CDMA 2000 1X	Sprint PCS Fair & Flexible Sprint PCS Free & ClearSM Sprint PCS Vision
Nextel[81]	CDMA 2000 1X	Web Premium Web Total Connect
T-Mobile[82]	GPRS	Mobile Internet Unlimited

Figure 47 Cellular Data Plans from Six Major Providers in the United States, as of June 2004.

77 [http://www.verizonwireless.com/b2c/store/controller?item=planFirst&action=viewInternetPlanOverview], June 2004.

78 [http://www.cingular.com/beyond_voice/wireless_internet], June 2004.

79 [http://www.attwireless.com/business/plans/mobileinternet/], June 2004.

80 [http://www1.sprintpcs.com/explore/servicePlansOptionsV2/DataPlans.jsp?FOLDER%3C%3Efolder_id=1460143&CURRENT_USER%3C%3EATR_SCID=ECOMM&CURRENT_USER%3C%3EATR_PCode=None&CURRENT_USER%3C%3EATR_cartState=group&bmUID=1087256174288], June 2004.

81 [http://nextelonline.nextel.com/services/nextelonline/wirelessweb.shtml], June 2004.

82 [http://www.t-mobile.com/plans/default.asp?tab=internet], June 2004.

B. CELLULAR DATA CONNECTION SETUP

In order to evaluate the cellular network throughput in actual conditions, the author subscribed to a cellular GPRS Internet plan with Cingular Wireless. The specific plan is named *Data Connect* and is used to provide full Internet access to a laptop or PDA. Cingular Wireless is one of the choices for GPRS connectivity in Monterey, California along with AT&T Wireless. Figure 48 shows the company's GPRS/EDGE coverage in the United States and Canada, as of June 2004.

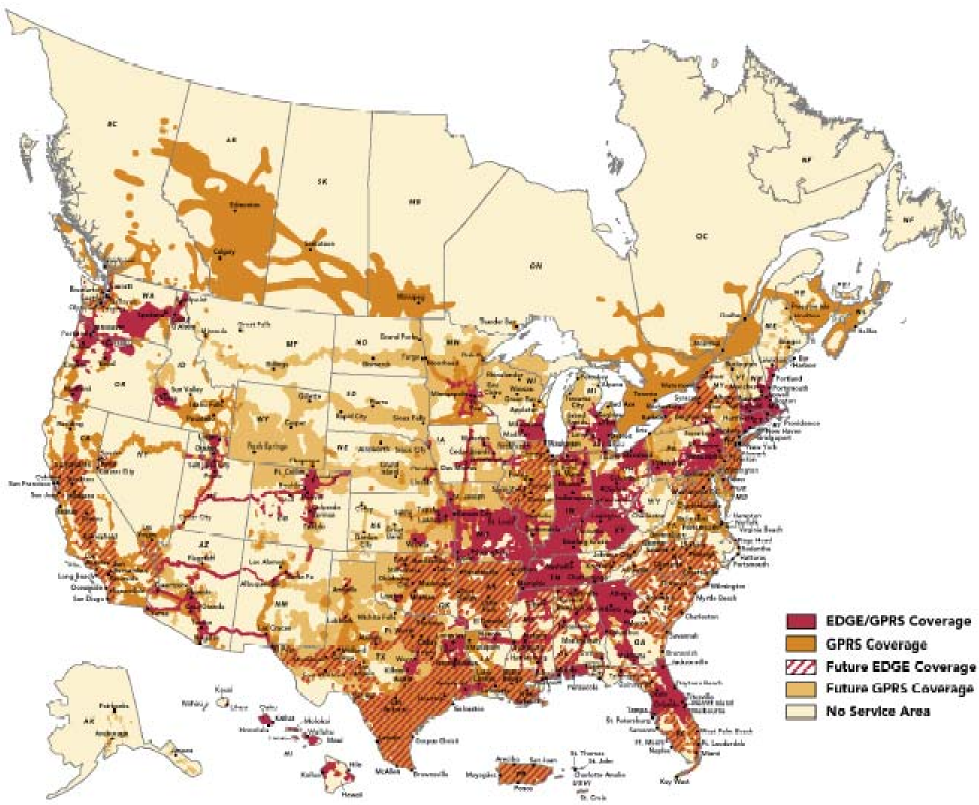


Figure 48 Cingular Wireless GPRS/EDGE Coverage [From Ref. 83].

For laptop to mobile phone connectivity, the Bluetooth solution was selected since it provides greater flexibility. Compared to Infrared, it does not have the restriction of having the phone being in the Line Of Sight of the laptop's sensor. Compared to cable,

83 [http://onlinestore.cingular.com/html/Maps/dataconnect_map.htm], June 2004.

it does not require the phone to be physically attached to the laptop and restricted to the cable's length. With Bluetooth, the phone only needs to be in a range of a few meters (less than 10) from the laptop.

The Cingular Wireless GPRS network supports two up to four out of the eight, in a TDMA frame timeslots in downlink (network to mobile phone). Availability is based on voice congestion. In uplink (mobile phone to network), there is only one dedicated timeslot. The phone used was a Nokia 6310i that is GPRS enabled and is Bluetooth capable. It is a Multislot class 4 phone which indicates that it can receive a maximum of 3 timeslots, transmit in only 1 and occupy 4 timeslots simultaneously (see Table 8). In addition, this phone, as most of the GPRS enabled devices, has an embedded native application, which allows it to count the total bytes of data transferred per session or in total. This feature is rather helpful in order for the user to keep track of the amount of data used in GPRS connections, especially if a certain MB per month plan is used. The Cingular's website can provide the registered user the same information about the data transferred as well.

As of June 2004, the author could not find available drivers in the Windows XP Operating System (OS) to be used for supporting the phone as a Bluetooth wireless media for GPRS connectivity. However, the Macintosh OS X has relative embedded settings. The laptop used in this project was Bluetooth capable and operated under the MAC OS X version 10.3.3. The expected Service Pack 2 (SP2) for Windows XP may embed cellular phone modem configuration as well. Figure 49 presents the pre-described connection schema. A laptop operating under operating system MAC OS X communicates with a GPRS mobile phone with Bluetooth and then uses the cellular provider's data network (through proper SSGN and GGSN) in order to access the Internet.

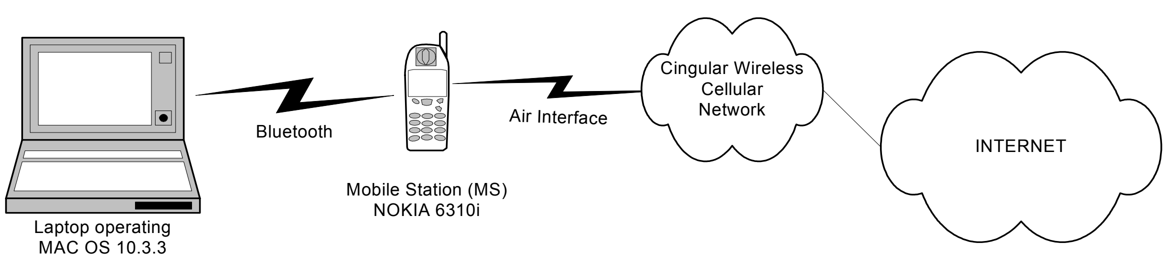


Figure 49 Cellular Internet Connection Schema.

The procedural steps for connecting the phone to the laptop for wireless media is described below. Figure 50 to Figure 55 are screenshots taken from the laptop's screen.

- The phone must be in discoverable mode so any other Bluetooth device can recognize it in order to initiate communication (in this case, the laptop).
- The laptop must be also in discoverable mode for automatic Bluetooth configuration with the mobile phone (path in MAC OS X: System Preferences > Hardware > Bluetooth > Settings).
- The following steps are configured while running the Bluetooth Setup Assistant (path in MAC OS X : taskbar Bluetooth icon > Setup Bluetooth device):
    - Laptop is set to search for Bluetooth enabled phones in its range (Figure 50).
    - Mobile phone discovered by laptop (see Figure 51).
    - Laptop and phone are paired with a random shared passkey (see Figure 52).
    - Laptop setup to use the mobile phone for wireless media access in GPRS or CDMA networks (see Figure 53).
    - Given username and password by the cellular provider are properly inserted in the relative fields (see Figure 54).
    - Proper mobile phone modem script inserted to maximize connection efficiency (see Figure 54).
    - Successful setup of the mobile phone as a wireless access for laptop to the Internet (see Figure 55).

Modem script is a set of instructions that are used as initializing modem settings for error correction, data compression, and flow control prior to connection. A collection of modems scripts for a large variety of cellular phones, written specifically for the MAC OS, can be found in Ross Barkman's Home Page[84]. Connection to the GPRS network was done simply by invoking the specific modem script with the cellular provider's username and password. After testing all available Nokia modem strings, the one found that worked best for the used mobile phone was the Nokia GPRS 57.6K CID1. The user's authentication was made through the mobile phone's SIM card. On the contrary, subscribers using PCMCIA cards (such as the one presented in Figure 5), instead of a

84 Ross Barkman's Home Page, [http://www.taniwha.org.uk/], June 2004.

mobile device, do not set the data connection manually. This is done instead through the cellular provider's GUI software and all the setting details are apparent to the user.

Figure 50 Initial Connection from Laptop to Mobile Phone via Bluetooth.

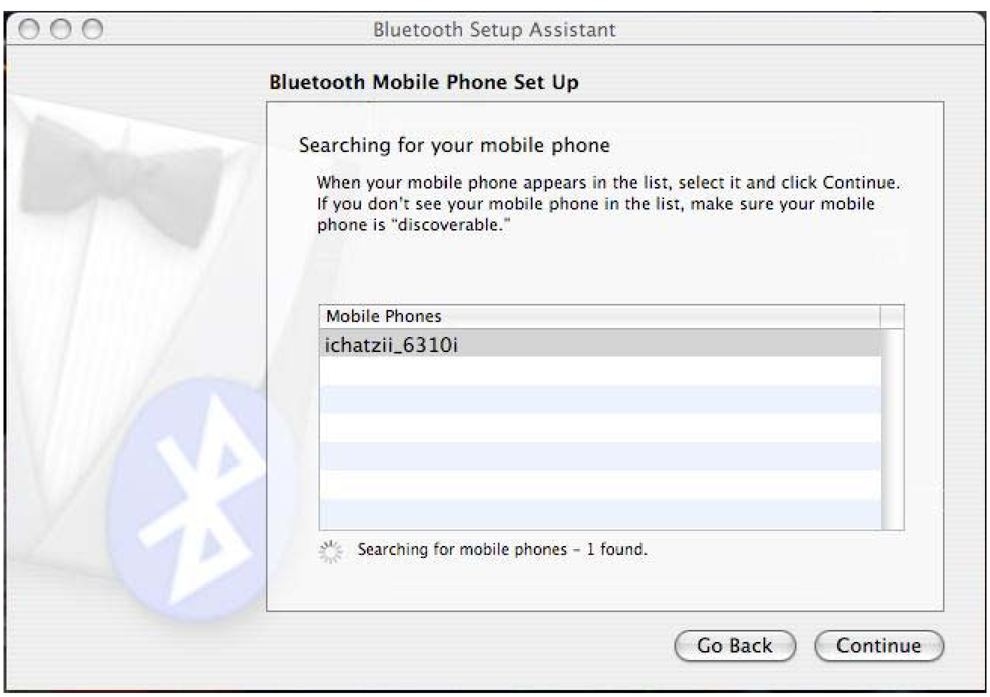


Figure 51 Mobile Phone Discovered by the Laptop.

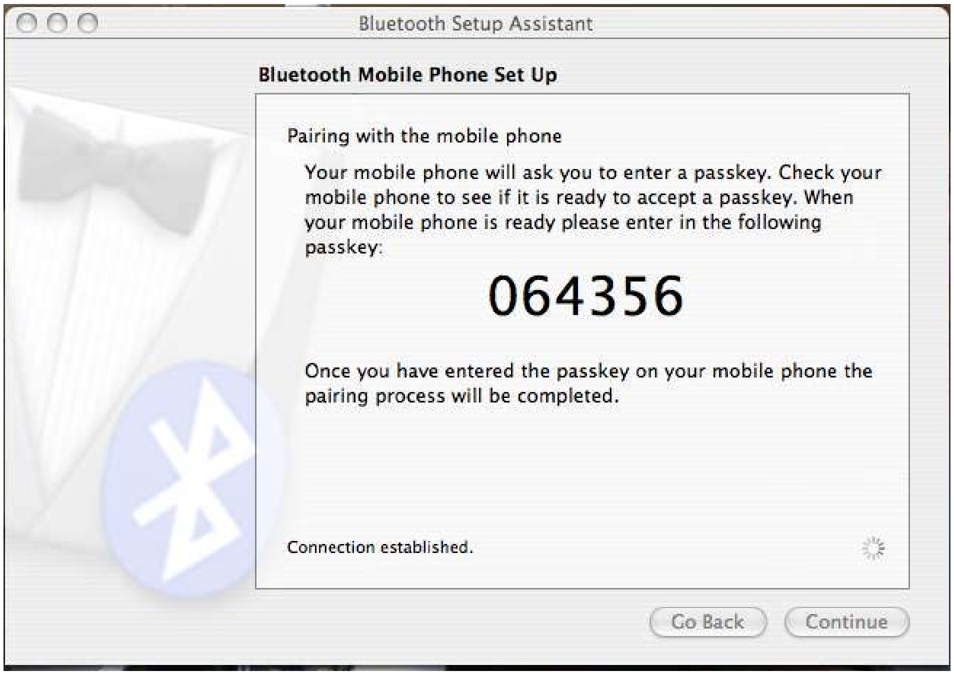


Figure 52 Laptop and Mobile Phone Paired with a Secret Key.

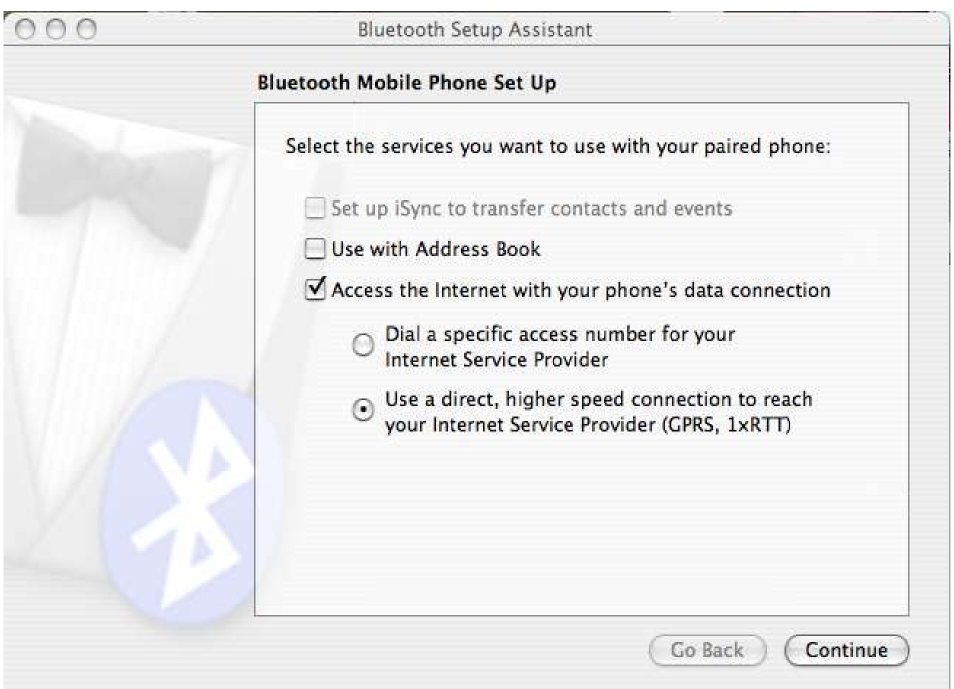


Figure 53 Laptop Setup to Use Mobile Phone for Wireless Data Access.

Figure 54 Laptop Setup Cellular Provider's Information (Username and Password).

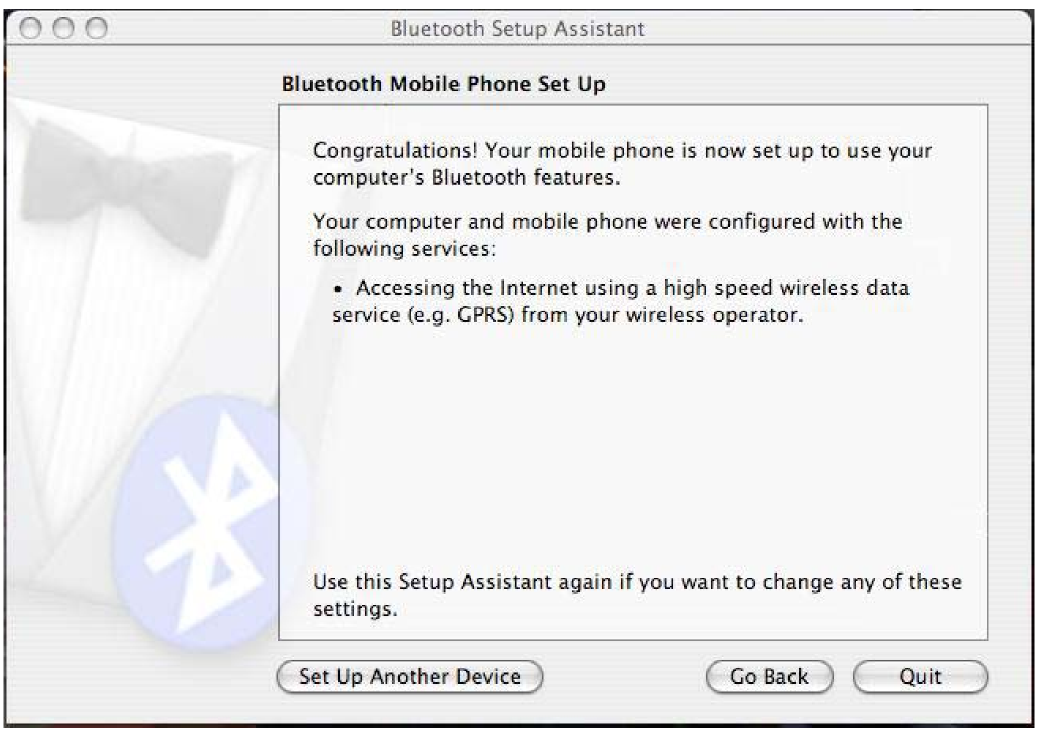


Figure 55 Mobile Phone Setup Completed Successfully.

C. GPRS NETWORK SPEED TESTING

One way to measure the throughput of a network connection is to download a file of known size from a server and measure the time of transfer. Then, by adding the file's size and the overhead and dividing it by the transfer time, the data rate is calculated. For simplicity, the same procedure is performed by various websites that send a predefined size of data to the requested host, and by measuring the transfer time, the average throughput is calculated. The author accessed the www.bandwidth.com website with the GPRS cellular connection and performed a speed test. Figure 56 shows the results of this test between the mobile phone's dynamic IP 166.138.196.6 (provided by Cingular Wireless) and the website's relative server. The 1MB data transfer was completed in 41.2 sec, thus giving a connection speed of 203.7 Kbps.

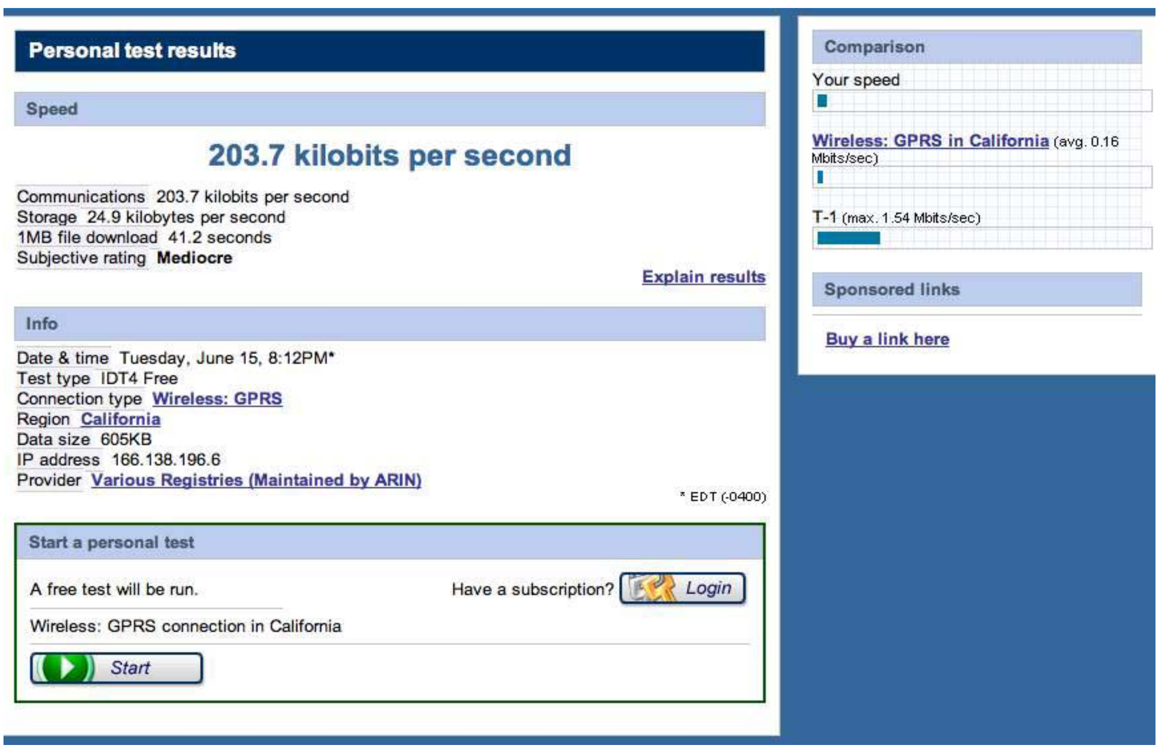


Figure 56 Cellular Data Connection Speed [From Ref. 85].

The 203.7 Kbps throughput is rather optimistic, given that the theoretical GPRS data rate is 115.2 Kbps. The inaccuracy probably occurred because the amount of

85 [www.bandwidth.com], June 2004.

downloaded data was less than the advertised 1 MB. The author accessed alternative speed testing websites such as http://www.numion.com/YourSpeed, but the results were also above 150 Kbps and considered too high to be accepted.

In order to evaluate the mobile data connection further and calculate the average throughput, the author conducted the following tasks relative to the common Internet applications.

- The first task was to connect to a server in the NPS Intranet and download and upload a certain file of known size (secure file transfer).
- The second was to access various web pages.
- The third task was to check the author's NPS e-mail account and send/receive e-mails with a certain file attachment.
- The fourth was to remotely login into the NPS secure Citrix server and access the author's native account in the npgs domain.
- Finally, the fifth task was to use messaging services for video communication with other hosts.

In order to create a spherical point of view, the measurements were taken either static in different areas of Monterey, California at various hours during the day or by moving with slowly on the highway at 60 mph.

1. Task 1: Connect to an NPS ssh Server and Transfer a Certain File

There are only a few servers inside the NPS firewall that allow inbound telnet traffic from non NPS-RAS connections. Specifically, they allow only secure telnet (secure shell-ssh[86]). The author created an account on such an NPS ssh server; specifically, the jay.nps.navy.mil (IP: 131.120.254.103) and placed two files that could be used for speed measurement. The first, named GPRS.doc, is a 64,512 bytes Microsoft Office Word document and the second, named GPRS.jpeg, is a 151,921 bytes digital photo. The scope of the test is to measure the throughput of downloading and uploading (secure FTP) those files back and forth from the ssh server to the laptop via the GPRS connection. *Ethereal* is an open source network packet analyzer software[87]. Version

86 Open ssh, [http://www.openssh.org/], June 2004.

87 Ethereal Network Analyzer, [www.ethereal.com], June 2004.

0.10.0a was used to capture and demonstrate the various packets exchanged between the mobile phone and server. Additionally, the specific software is capable of calculating the total size of packet traffic per session (data and overhead), the total transfer time, and thus, the average bit rate in bytes per second. The client ssh software used on the laptop was the open source *fugu*[88]. It is a graphical front-end application that connects with ssh servers and performs secure FTP sessions. It should be noted that the sent/received packets from the laptop are forwarded to and from the mobile phone via the Bluetooth connection. The Bluetooth bit rate is theoretically in the range of 1 Mbps, so a bottleneck is not created.

Figure 57 presents a traceroute from the dynamically assigned to the mobile phone IP, towards the NPS ssh server jay.nps.navy.mil (IP: 131.120.254.103). Nodes 1 to 7 are part of the cellular network. Nodes 8 to 21 belong to ground wired networks.

Figure 58 shows the fugu software interface in the MAC OS X. On the left side, the laptop's local files are shown and on the right, the files on the ssh server (IP: 131.120.254.103).

Figure 59 presents the packets exchanged between the mobile phone (IP: 166.138.202.32) and the ssh server during the initial connection. According to the Ethereal analysis, the 82 packets needed to accomplish the connection had a total size of 12,968 bytes and were exchanged at 27.032 sec. The average packet size was 156.241 bytes and the average bit rate 479.734 bytes/sec (or *3.84 Kbps*).

Figure 60 shows the packets exchanged during the download of the GPRS.doc file (64,512 bytes) from the ssh server to the laptop. This screenshot is not a continuation of the previous figure since it was taken at a different time. According to the Ethereal analysis, the 116 packets needed to complete the download, had a total size of 72,384 bytes and were exchanged at 31.498 sec. The average packet size was 624 bytes and the average bit rate 2298.022 bytes/sec (or *18.38 Kbps*).

Additional tests of downloading/uploading the two files, GPRS.doc (64,512 bytes) and the GPRS.jpeg (151,921 bytes), from/to the ssh server are presented in Table 9. As expected, download speeds are higher than upload speeds. The initial connection to

88 Research Systems Unix Group, [http://rsug.itd.umich.edu/software/fugu/], June 2004.

the ssh server is performed at a slower speed than the actual file transfer since the user's authentication is involved. The average measured speed for static Internet access is in the range of 15-20 Kbps and while moving at 60mph it is 10-15 Kbps. In one occasion, there was a file transfer with almost 30 Kbps.

```
Traceroute has started ...

traceroute to 131.120.254.103 (131.120.254.103), 30 hops max, 40 byte packets
 1  66.102.160.10 (66.102.160.10)  1383.67 ms  726.637 ms  712.01 ms
 2  66.102.160.1 (66.102.160.1)  885.053 ms  606.351 ms  1049.42 ms
 3  10.45.80.111 (10.45.80.111)  698.039 ms  998.243 ms  946.977 ms
 4  10.45.80.1 (10.45.80.1)  863.831 ms  1118.31 ms  826.103 ms
 5  66.102.163.133 (66.102.163.133)  661.377 ms  719.311 ms  736.135 ms
 6  66.209.15.129 (66.209.15.129)  910.499 ms  817.542 ms  708.557 ms
 7  66.10.13.1 (66.10.13.1)  684.243 ms  802.972 ms  559.906 ms
 8  bb2-g1-3-0.nycmny.sbcglobal.net (66.10.48.226)  683.386 ms  896.18 ms  745.98 ms
 9  ex1-p8-0.nycmny.sbcglobal.net (151.164.240.222)  688.047 ms  757.782 ms  732.277 ms
10  core2-p3-0.crhnva.sbcglobal.net (151.164.188.198)  704.641 ms  847.954 ms  717.437 ms
11  bb2-p5-0.hrndva.sbcglobal.net (151.164.243.138)  706.015 ms  703.153 ms  710.567 ms
12  ex2-p11-0.eqabva.sbcglobal.net (151.164.40.53)  716.861 ms  690.827 ms  567.222 ms
13  sl-st20-ash-14-0.sprintlink.net (144.223.246.37)  700.784 ms  768.641 ms  738.618 ms
14  0.so-5-0-0.br1.dca5.alter.net (204.255.168.13)  680.382 ms  780.58 ms  617.621 ms
15  0.so-2-2-0.xl2.dca5.alter.net (152.63.43.174)  745.713 ms  748.195 ms  741.923 ms
16  0.so-2-2-0.xl2.dca8.alter.net (152.63.41.138)  718.29 ms  811.154 ms  754.951 ms
17  pos7-0.gw2.dca8.alter.net (152.63.39.149)  724.099 ms  808.02 ms  732.915 ms
18  at-3-3-1.wae.dren.net (157.130.49.2)  697.053 ms  912.794 ms  594.441 ms
19  t3-0-0-0.nps.dren.net (138.18.4.13)  770.195 ms  938.402 ms  661.224 ms
20  cperouter.nps.dren.net (138.18.186.2)  778.699 ms  806.684 ms  681.713 ms
21  jay.nps.navy.mil (131.120.254.103)  805.395 ms !H  1020.88 ms !H  665.847 ms !H
```

Figure 57 Traceroute from Mobile Phone to the jay.nps.navy.mil (IP: 131.120.254.103).

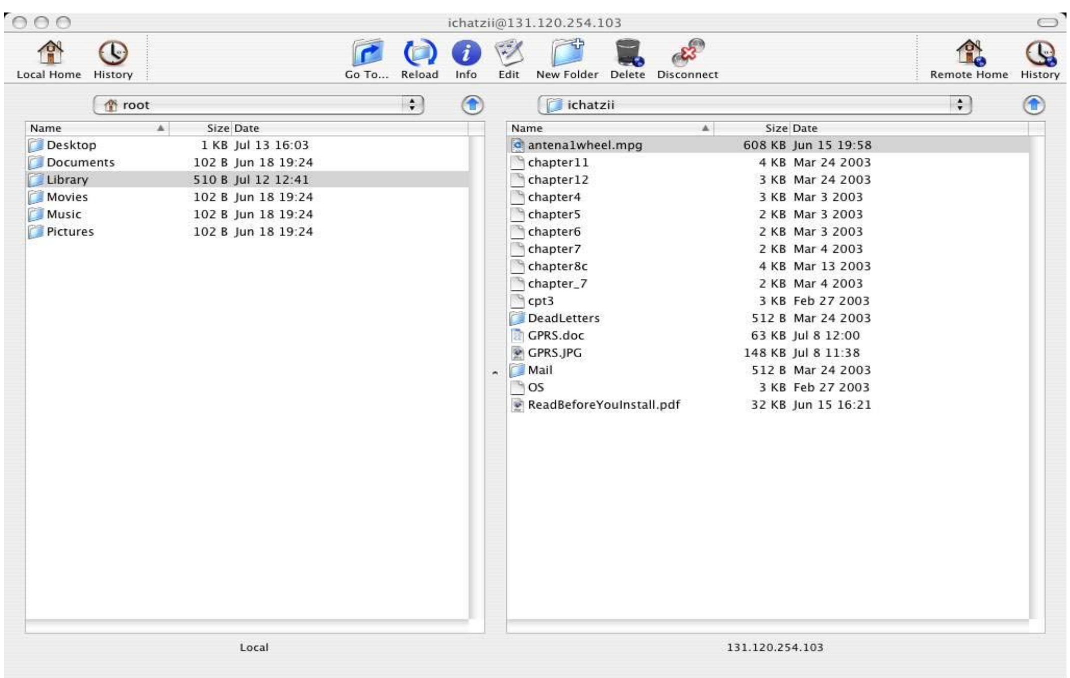


Figure 58 Fugu Software Interface in an ssh connection to jay.nps.navy.mil (IP: 131.120.254.103). Secure FTP can be performed only by dragging and dropping on top of the drop files from one window to the other.

No.	Time	Source	Destination	Protocol	Info
1	0.000000	166.138.202.32	jay.nps.navy.mil	TCP	50031 > 22 [SYN] Seq=2537882150 Ack=0 Win=8192 Len=0
2	1.292151	jay.nps.navy.mil	166.138.202.32	TCP	22 > 50031 [SYN, ACK] Seq=2620531172 Ack=2537882151 Win=24616 Len=0
3	1.292243	166.138.202.32	jay.nps.navy.mil	TCP	50031 > 22 [ACK] Seq=2537882151 Ack=2620531173 Win=8192 Len=0
4	2.406153	jay.nps.navy.mil	166.138.202.32	SSH	Server Protocol: SSH-2.0-Sun_SSH_1.0
5	2.407530	166.138.202.32	jay.nps.navy.mil	SSH	Client Protocol: SSH-2.0-OpenSSH_3.6.1p1+CAN-2003-0693
6	2.411628	166.138.202.32	atliserv1.mycingular.net	DNS	Standard query PTR 103.254.120.131.in-addr.arpa
7	3.117260	166.138.202.32	atliserv2.mycingular.net	DNS	Standard query PTR 103.254.120.131.in-addr.arpa
8	3.222220	jay.nps.navy.mil	166.138.202.32	TCP	22 > 50031 [ACK] Seq=2620531193 Ack=2537882189 Win=24616 Len=0
9	3.322274	atliserv1.mycingular.net	166.138.202.32	DNS	Standard query response PTR jay.nps.navy.mil
10	3.633242	jay.nps.navy.mil	166.138.202.32	SSHv2	Server: Key Exchange Init
11	3.823484	166.138.202.32	atliserv1.mycingular.net	DNS	Standard query PTR 103.254.120.131.in-addr.arpa
12	3.832872	166.138.202.32	jay.nps.navy.mil	TCP	50031 > 22 [ACK] Seq=2537882189 Ack=2620531793 Win=8192 Len=0
13	3.835084	166.138.202.32	atliserv1.mycingular.net	DNS	Standard query A jay.nps.navy.mil
14	3.933384	atliserv2.mycingular.net	166.138.202.32	DNS	Standard query response PTR jay.nps.navy.mil
15	3.933459	166.138.202.32	atliserv2.mycingular.net	ICMP	Destination unreachable
16	4.508300	atliserv1.mycingular.net	166.138.202.32	DNS	Standard query response PTR jay.nps.navy.mil
17	4.508369	166.138.202.32	atliserv1.mycingular.net	ICMP	Destination unreachable
18	4.540466	166.138.202.32	atliserv2.mycingular.net	DNS	Standard query A jay.nps.navy.mil
19	4.568219	atliserv1.mycingular.net	166.138.202.32	DNS	Standard query response A 131.120.254.103
20	5.245866	166.138.202.32	atliserv1.mycingular.net	DNS	Standard query A jay.nps.navy.mil
21	5.399723	166.138.202.32	jay.nps.navy.mil	SSHv2	Client: Key Exchange Init
22	5.405268	atliserv2.mycingular.net	166.138.202.32	DNS	Standard query response A 131.120.254.103
23	5.405332	166.138.202.32	atliserv2.mycingular.net	ICMP	Destination unreachable
24	5.960345	atliserv1.mycingular.net	166.138.202.32	DNS	Standard query response A 131.120.254.103
25	5.960415	166.138.202.32	atliserv1.mycingular.net	ICMP	Destination unreachable
26	6.560230	jay.nps.navy.mil	166.138.202.32	TCP	22 > 50031 [ACK] Seq=2620531793 Ack=2537882733 Win=24616 Len=0
27	6.560317	166.138.202.32	jay.nps.navy.mil	SSHv2	Client: Diffie-Hellman Key Exchange Init
28	7.534284	jay.nps.navy.mil	166.138.202.32	TCP	22 > 50031 [ACK] Seq=2620531793 Ack=2537882877 Win=24616 Len=0
29	7.917236	jay.nps.navy.mil	166.138.202.32	SSHv2	Server: Diffie-Hellman Key Exchange Reply
30	7.934181	166.138.202.32	jay.nps.navy.mil	SSHv2	Client: New Keys
31	8.657314	jay.nps.navy.mil	166.138.202.32	SSHv2	Server: New Keys
32	8.657608	166.138.202.32	jay.nps.navy.mil	SSHv2	Client: Unknown (215)
33	9.542301	jay.nps.navy.mil	166.138.202.32	TCP	22 > 50031 [ACK] Seq=2620532257 Ack=2537882941 Win=24616 Len=0
34	9.624363	jay.nps.navy.mil	166.138.202.32	SSHv2	Encrypted response packet len=48
35	9.624730	166.138.202.32	jay.nps.navy.mil	SSHv2	Encrypted request packet len=64
36	10.567342	jay.nps.navy.mil	166.138.202.32	TCP	22 > 50031 [ACK] Seq=2620532305 Ack=2537883005 Win=24616 Len=0
37	10.682396	jay.nps.navy.mil	166.138.202.32	SSHv2	Encrypted response packet len=64
38	10.735174	166.138.202.32	jay.nps.navy.mil	SSHv2	Encrypted request packet len=144
39	11.642367	jay.nps.navy.mil	166.138.202.32	TCP	22 > 50031 [ACK] Seq=2620532369 Ack=2537883149 Win=24616 Len=0
40	11.879405	jay.nps.navy.mil	166.138.202.32	SSHv2	Encrypted response packet len=32
41	11.879994	166.138.202.32	jay.nps.navy.mil	SSHv2	Encrypted request packet len=64
42	12.817423	jay.nps.navy.mil	166.138.202.32	TCP	22 > 50031 [ACK] Seq=2620532401 Ack=2537883213 Win=24616 Len=0
43	12.881435	jay.nps.navy.mil	166.138.202.32	SSHv2	Encrypted response packet len=48
44	12.881837	166.138.202.32	jay.nps.navy.mil	SSHv2	Encrypted request packet len=64
45	13.797410	jay.nps.navy.mil	166.138.202.32	TCP	22 > 50031 [ACK] Seq=2620532449 Ack=2537883277 Win=24616 Len=0
46	13.957484	jay.nps.navy.mil	166.138.202.32	SSHv2	Encrypted response packet len=80
47	13.957875	166.138.202.32	jay.nps.navy.mil	SSHv2	Encrypted request packet len=48
48	14.854448	jay.nps.navy.mil	166.138.202.32	TCP	22 > 50031 [ACK] Seq=2620532529 Ack=2537883325 Win=24616 Len=0
49	14.981480	jay.nps.navy.mil	166.138.202.32	SSHv2	Encrypted response packet len=48
50	14.982248	166.138.202.32	jay.nps.navy.mil	SSHv2	Encrypted request packet len=48
51	15.897476	jay.nps.navy.mil	166.138.202.32	TCP	22 > 50031 [ACK] Seq=2620532577 Ack=2537883373 Win=24616 Len=0
52	16.023661	jay.nps.navy.mil	166.138.202.32	SSHv2	Encrypted response packet len=112
53	16.034770	166.138.202.32	jay.nps.navy.mil	TCP	50031 > 22 [ACK] Seq=2537883373 Ack=2620532689 Win=8192 Len=0
54	16.132026	166.138.202.32	jay.nps.navy.mil	SSHv2	Encrypted request packet len=80
55	16.994465	jay.nps.navy.mil	166.138.202.32	TCP	22 > 50031 [ACK] Seq=2620532689 Ack=2537883453 Win=24616 Len=0
56	17.143581	jay.nps.navy.mil	166.138.202.32	SSHv2	Encrypted response packet len=112
57	17.144080	166.138.202.32	jay.nps.navy.mil	SSHv2	Encrypted request packet len=80
58	18.079489	jay.nps.navy.mil	166.138.202.32	TCP	22 > 50031 [ACK] Seq=2620532801 Ack=2537883533 Win=24616 Len=0
59	18.942589	jay.nps.navy.mil	166.138.202.32	SSHv2	Encrypted response packet len=80
60	18.968307	166.138.202.32	jay.nps.navy.mil	SSHv2	Encrypted request packet len=80
61	20.016500	jay.nps.navy.mil	166.138.202.32	TCP	22 > 50031 [ACK] Seq=2620532881 Ack=2537883613 Win=24616 Len=0
62	20.142721	jay.nps.navy.mil	166.138.202.32	SSHv2	Encrypted response packet len=80
63	20.146857	166.138.202.32	jay.nps.navy.mil	SSHv2	Encrypted request packet len=80
64	21.079550	jay.nps.navy.mil	166.138.202.32	TCP	22 > 50031 [ACK] Seq=2620532961 Ack=2537883693 Win=24616 Len=0
65	21.259633	jay.nps.navy.mil	166.138.202.32	SSHv2	Encrypted response packet len=80
66	21.260151	166.138.202.32	jay.nps.navy.mil	SSHv2	Encrypted request packet len=80
67	22.179619	jay.nps.navy.mil	166.138.202.32	TCP	22 > 50031 [ACK] Seq=2620533041 Ack=2537883773 Win=24616 Len=0
68	22.259619	jay.nps.navy.mil	166.138.202.32	SSHv2	Encrypted response packet len=64
69	22.261323	166.138.202.32	jay.nps.navy.mil	SSHv2	Encrypted request packet len=64
70	23.179588	jay.nps.navy.mil	166.138.202.32	TCP	22 > 50031 [ACK] Seq=2620533105 Ack=2537883837 Win=24616 Len=0
71	23.854550	jay.nps.navy.mil	166.138.202.32	SSHv2	Encrypted response packet len=1448
72	24.035843	166.138.202.32	jay.nps.navy.mil	TCP	50031 > 22 [ACK] Seq=2537883837 Ack=2620534553 Win=8192 Len=0
73	24.204543	jay.nps.navy.mil	166.138.202.32	SSHv2	Encrypted response packet len=1448
74	24.236093	166.138.202.32	jay.nps.navy.mil	TCP	50031 > 22 [ACK] Seq=2537883837 Ack=2620536001 Win=8192 Len=0
75	24.285801	jay.nps.navy.mil	166.138.202.32	SSHv2	Encrypted response packet len=784
76	24.286859	166.138.202.32	jay.nps.navy.mil	SSHv2	Encrypted request packet len=64
77	24.981591	jay.nps.navy.mil	166.138.202.32	TCP	22 > 50031 [ACK] Seq=2620536785 Ack=2537883901 Win=24616 Len=0
78	25.098616	jay.nps.navy.mil	166.138.202.32	SSHv2	Encrypted response packet len=80
79	25.099094	166.138.202.32	jay.nps.navy.mil	SSHv2	Encrypted request packet len=64
80	26.016654	jay.nps.navy.mil	166.138.202.32	TCP	22 > 50031 [ACK] Seq=2620536865 Ack=2537883965 Win=24616 Len=0
81	26.167703	jay.nps.navy.mil	166.138.202.32	SSHv2	Encrypted response packet len=64
82	26.236471	166.138.202.32	jay.nps.navy.mil	TCP	50031 > 22 [ACK] Seq=2537883965 Ack=2620536929 Win=8192 Len=0

Figure 59 Packets Exchanged Between Mobile Phone (IP: 166.138.202.32) and ssh server jay.nps.navy.mil (IP: 131.120.254.103) during the Initial ssh Connection.

File Edit Capture Display Tools Help

No.	Time	Source	Destination	Protocol	Info
1	0.000000	166.138.207.68	131.120.254.103	SSH	Encrypted request packet len=80
2	1.419295	131.120.254.103	166.138.207.68	TCP	22 > 49583 [ACK] Seq=734057955 Ack=3878671598 Win=24616 Len=0
3	1.482328	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=80
4	1.483190	166.138.207.68	131.120.254.103	SSH	Encrypted request packet len=80
5	2.350269	131.120.254.103	166.138.207.68	TCP	22 > 49583 [ACK] Seq=734058035 Ack=3878671678 Win=24616 Len=0
6	2.491339	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=80
7	2.491844	166.138.207.68	131.120.254.103	SSH	Encrypted request packet len=96
8	4.439581	166.138.207.68	131.120.254.103	SSH	Encrypted request packet len=96
9	4.609321	131.120.254.103	166.138.207.68	TCP	22 > 49583 [ACK] Seq=734058115 Ack=3878671774 Win=24616 Len=0
10	4.772403	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=64
11	4.794842	166.138.207.68	131.120.254.103	SSH	Encrypted request packet len=64
12	5.290314	131.120.254.103	166.138.207.68	TCP	22 > 49583 [ACK] Seq=734058179 Ack=3878671774 Win=24616 Len=0
13	5.968311	131.120.254.103	166.138.207.68	TCP	22 > 49583 [ACK] Seq=734058179 Ack=3878671838 Win=24616 Len=0
14	6.700162	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
15	6.893312	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671838 Ack=734059627 Win=8192 Len=0
16	7.039178	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
17	7.093372	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671838 Ack=734061075 Win=8192 Len=0
18	7.460182	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
19	7.493451	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671838 Ack=734062523 Win=8192 Len=0
20	7.792172	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
21	7.809364	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=48
22	7.893549	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671838 Ack=734064019 Win=8192 Len=0
23	8.423294	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
24	8.493664	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671838 Ack=734065467 Win=8192 Len=0
25	8.599183	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
26	8.693717	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671838 Ack=734066915 Win=8192 Len=0
27	8.900222	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
28	9.093803	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671838 Ack=734068363 Win=8192 Len=0
29	9.656217	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
30	9.693897	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671838 Ack=734069811 Win=8192 Len=0
31	10.114229	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
32	10.294058	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671838 Ack=734071259 Win=8192 Len=0
33	10.497237	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
34	10.694164	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671838 Ack=734072707 Win=8192 Len=0
35	10.977271	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
36	11.094256	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671838 Ack=734074155 Win=8192 Len=0
37	11.298255	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
38	11.494348	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671838 Ack=734075603 Win=8192 Len=0
39	11.800253	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
40	11.894413	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671838 Ack=734077051 Win=8192 Len=0
41	12.343267	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
42	12.494535	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671838 Ack=734078499 Win=8192 Len=0
43	12.761283	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
44	12.894612	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671838 Ack=734079947 Win=8192 Len=0
45	12.943270	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
46	13.000356	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=516
47	13.094678	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671838 Ack=734081911 Win=8192 Len=0
48	13.758293	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
49	13.894792	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671838 Ack=734083359 Win=8192 Len=0
50	14.159299	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
51	14.294887	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671838 Ack=734084807 Win=8192 Len=0
52	14.995503	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
53	15.095006	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671838 Ack=734086255 Win=8192 Len=0
54	15.539356	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
55	15.695107	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671838 Ack=734087703 Win=8192 Len=0
56	15.794320	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
57	15.895150	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671838 Ack=734089151 Win=8192 Len=0
58	16.420446	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
59	16.472425	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=492
60	16.475482	166.138.207.68	131.120.254.103	SSH	Encrypted request packet len=96
61	17.729562	131.120.254.103	166.138.207.68	TCP	22 > 49583 [ACK] Seq=734091091 Ack=3878671934 Win=24616 Len=0
62	18.515494	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
63	18.695558	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671934 Ack=734092539 Win=8192 Len=0
64	18.775395	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
65	18.895644	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671934 Ack=734093987 Win=8192 Len=0
66	21.325540	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
67	21.496061	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671934 Ack=734095435 Win=8192 Len=0
68	21.838542	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
69	21.858569	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=48
70	21.896161	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671934 Ack=734096931 Win=8192 Len=0
71	22.161556	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
72	22.296272	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671934 Ack=734098379 Win=8192 Len=0
73	22.498479	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
74	22.696395	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671934 Ack=734099827 Win=8192 Len=0
75	22.861576	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
76	22.896477	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671934 Ack=734101275 Win=8192 Len=0
77	23.186581	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
78	23.296583	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671934 Ack=734102723 Win=8192 Len=0
79	23.815498	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
80	23.896718	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671934 Ack=734104171 Win=8192 Len=0
81	23.959525	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
82	24.096799	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671934 Ack=734105619 Win=8192 Len=0
83	24.279612	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
84	24.296866	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671934 Ack=734107067 Win=8192 Len=0
85	24.598601	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
86	24.696995	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671934 Ack=734108515 Win=8192 Len=0
87	24.941800	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
88	25.097102	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671934 Ack=734109963 Win=8192 Len=0
89	25.310629	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
90	25.497211	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671934 Ack=734111411 Win=8192 Len=0
91	25.675544	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
92	25.697290	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671934 Ack=734112859 Win=8192 Len=0
93	25.981636	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
94	26.097415	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671934 Ack=734114307 Win=8192 Len=0
95	26.336649	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
96	26.497551	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671934 Ack=734115755 Win=8192 Len=0
97	26.723646	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
98	26.897686	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671934 Ack=734117203 Win=8192 Len=0
99	27.034652	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
100	27.097769	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671934 Ack=734118651 Win=8192 Len=0
101	27.365596	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
102	27.497899	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671934 Ack=734120099 Win=8192 Len=0
103	27.706685	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
104	27.720721	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=16
105	27.720788	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671934 Ack=734121547 Win=8192 Len=0
106	28.106575	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=1448
107	28.106670	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878671934 Ack=734123011 Win=8192 Len=0
108	28.108659	166.138.207.68	131.120.254.103	SSH	Encrypted request packet len=48
109	29.567763	131.120.254.103	166.138.207.68	TCP	22 > 49583 [ACK] Seq=734123011 Ack=3878671982 Win=24616 Len=0
110	29.567846	166.138.207.68	131.120.254.103	SSH	Encrypted request packet len=64
111	30.426819	131.120.254.103	166.138.207.68	TCP	22 > 49583 [ACK] Seq=734123011 Ack=3878672046 Win=24616 Len=0
112	30.514875	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=80
113	30.544347	166.138.207.68	131.120.254.103	SSH	Encrypted request packet len=64
114	31.351811	131.120.254.103	166.138.207.68	TCP	22 > 49583 [ACK] Seq=734123091 Ack=3878672110 Win=24616 Len=0
115	31.474884	131.120.254.103	166.138.207.68	SSH	Encrypted response packet len=64
116	31.498388	166.138.207.68	131.120.254.103	TCP	49583 > 22 [ACK] Seq=3878672110 Ack=734123155 Win=8192 Len=0

Figure 60 Packets Exchanged Between Mobile Phone (IP: 166.138.207.68) and ssh Server jay.nps.navy.mil (IP: 131.120.254.103) during the Download of the File GPRS.doc.

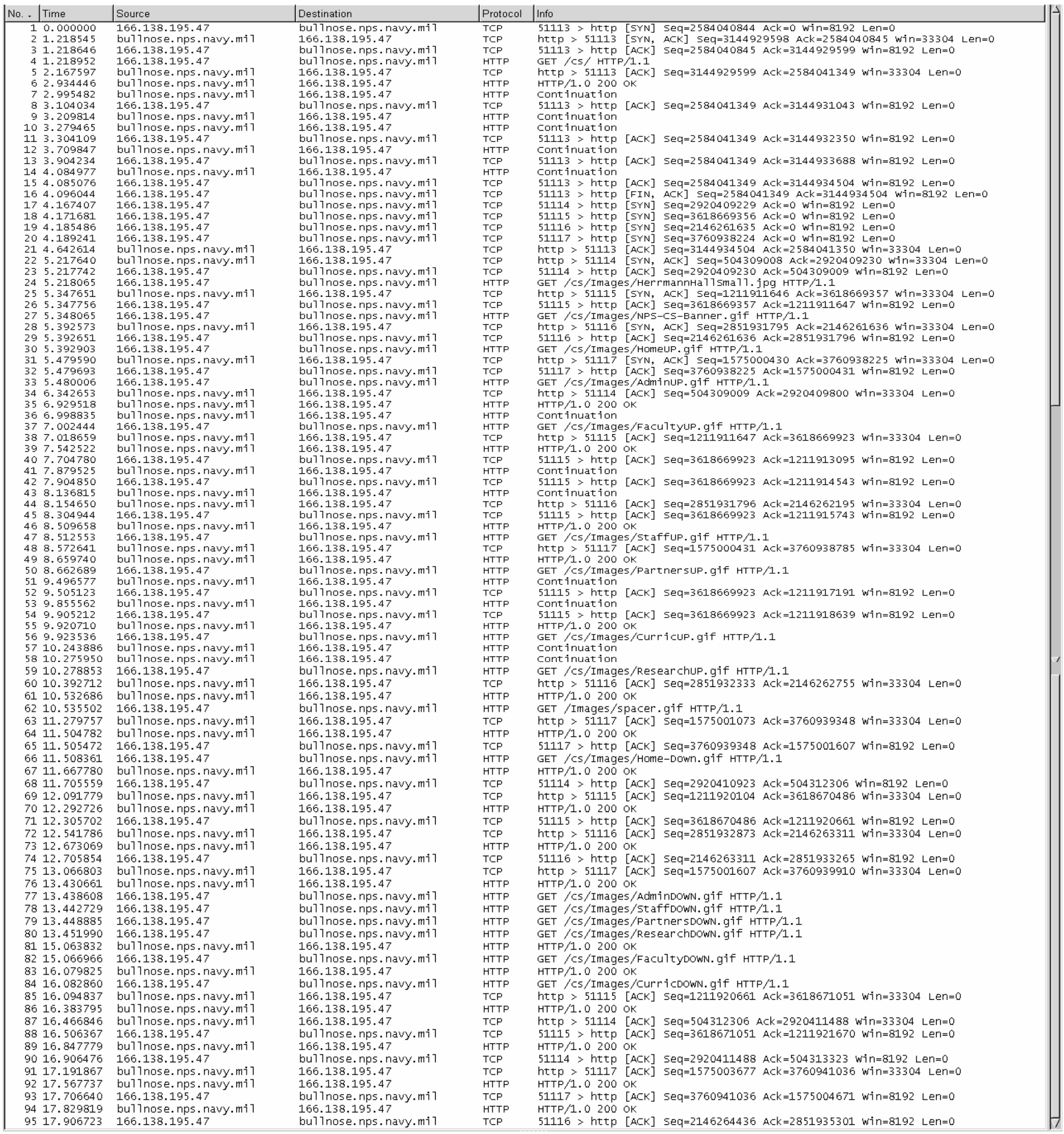
User's position (time)	*Task 1 Secure FTP through ssh connection*	*Total size of traffic (data and overhead in bytes)*	*Transfer time (sec)*	*Connection Average throughput (Kbps)*
Static (time 12:00)	Initial ssh connection between phone and server	12,880	26.236	*3.93*
Static (time 18:00)	Initial ssh connection between phone and server	15,976	39.249	*3.25*
Static (time 16:00)	Download file GPRS.doc through ssh connection	72,384	31.498	*18.38*
Static (time 10:00)	Download file GPRS.doc through ssh connection	72,296	31.335	*18.46*
Static (time 17:00)	Download file GPRS.doc through ssh connection	85,787	35.190	*19.5*
Static (time 17:10)	Upload file GPRS.doc through ssh connection	77,760	41.040	*15.16*
Static (time 17:30)	Download file GPRS.jpg through ssh connection	167,296	45.542	*29.38*
Static (time 17:40)	Upload file GPRS.jpg through ssh connection	178,504	79.888	*18.04*
On highway with speed 60mph (time 18:00)	Download file GPRS.jpg through ssh connection	180,144	93.536	*15.4*
On highway with speed 60mph (time 18:30)	Upload file GPRS.jpg through ssh connection	173,672	129.233	*10.75*

Table 9 GPRS Speed Comparison in Static and Moving Environment with File Transfer through an ssh Connection.

2. Task 2: Accessing Web Pages

In this task, the NPS Computer Science Department webpage http://www.nps.navy.mil/cs/, which is placed on the bullnose.nps.navy.mil web server (IP: 131.120.251.15), was used as a reference since its content is not updated often. Figure 61 reveals the packets exchanged between mobile phone (IP: 166.138.195.47) and the CS web page. For measurement accuracy, before accessing the page each time, the cache files were deleted, in order for all the objects of the web page to be opened from the beginning. According to the Ethereal analysis, the 95 packets needed to accomplish the web access totaling 42,453 bytes and were exchanged in 17.907 sec. The average packet size was 446.874 bytes and the average bit rate 2370.786 bytes/sec (or *19 Kbps*).

Additional results with alternate web pages appear in Table 10. The tests were conducted on different days and at different times of the day during July 2004. Pages were also accessed that required secure a http connection (htpps) such as the Navy Federal online account. Due to the required user's authentication, the specific web page was downloaded slower than the others. The www.cnn.com and www.in.gr web pages were tested the same day since their content is constantly changing. The average data speed in web page accessing is the same rates as in task1.



No.	Time	Source	Destination	Protocol	Info
1	0.000000	166.138.195.47	bullnose.nps.navy.mil	TCP	51113 > http [SYN] Seq=2584040844 Ack=0 Win=8192 Len=0
2	1.218545	bullnose.nps.navy.mil	166.138.195.47	TCP	http > 51113 [SYN, ACK] Seq=3144929598 Ack=2584040845 Win=33304 Len=0
3	1.218646	166.138.195.47	bullnose.nps.navy.mil	TCP	51113 > http [ACK] Seq=2584040845 Ack=3144929599 Win=8192 Len=0
4	1.218952	166.138.195.47	bullnose.nps.navy.mil	HTTP	GET /cs/ HTTP/1.1
5	2.167597	bullnose.nps.navy.mil	166.138.195.47	TCP	http > 51113 [ACK] Seq=3144929599 Ack=2584041349 Win=33304 Len=0
6	2.934446	bullnose.nps.navy.mil	166.138.195.47	HTTP	HTTP/1.0 200 OK
7	2.995482	bullnose.nps.navy.mil	166.138.195.47	HTTP	Continuation
8	3.104034	166.138.195.47	bullnose.nps.navy.mil	TCP	51113 > http [ACK] Seq=2584041349 Ack=3144931043 Win=8192 Len=0
9	3.209814	bullnose.nps.navy.mil	166.138.195.47	HTTP	Continuation
10	3.279465	bullnose.nps.navy.mil	166.138.195.47	HTTP	Continuation
11	3.304109	166.138.195.47	bullnose.nps.navy.mil	TCP	51113 > http [ACK] Seq=2584041349 Ack=3144932350 Win=8192 Len=0
12	3.709847	bullnose.nps.navy.mil	166.138.195.47	HTTP	Continuation
13	3.904234	166.138.195.47	bullnose.nps.navy.mil	TCP	51113 > http [ACK] Seq=2584041349 Ack=3144933688 Win=8192 Len=0
14	4.084977	bullnose.nps.navy.mil	166.138.195.47	HTTP	Continuation
15	4.085076	166.138.195.47	bullnose.nps.navy.mil	TCP	51113 > http [ACK] Seq=2584041349 Ack=3144934504 Win=8192 Len=0
16	4.096044	166.138.195.47	bullnose.nps.navy.mil	TCP	51113 > http [FIN, ACK] Seq=2584041349 Ack=3144934504 Win=8192 Len=0
17	4.167407	166.138.195.47	bullnose.nps.navy.mil	TCP	51114 > http [SYN] Seq=2920409229 Ack=0 Win=8192 Len=0
18	4.171681	166.138.195.47	bullnose.nps.navy.mil	TCP	51115 > http [SYN] Seq=3618669356 Ack=0 Win=8192 Len=0
19	4.185486	166.138.195.47	bullnose.nps.navy.mil	TCP	51116 > http [SYN] Seq=2146261635 Ack=0 Win=8192 Len=0
20	4.189241	166.138.195.47	bullnose.nps.navy.mil	TCP	51117 > http [SYN] Seq=3760938224 Ack=0 Win=8192 Len=0
21	4.642614	bullnose.nps.navy.mil	166.138.195.47	TCP	http > 51113 [ACK] Seq=3144934504 Ack=2584041350 Win=33304 Len=0
22	5.217640	bullnose.nps.navy.mil	166.138.195.47	TCP	http > 51114 [SYN, ACK] Seq=504309008 Ack=2920409230 Win=33304 Len=0
23	5.217742	166.138.195.47	bullnose.nps.navy.mil	TCP	51114 > http [ACK] Seq=2920409230 Ack=504309009 Win=8192 Len=0
24	5.218065	166.138.195.47	bullnose.nps.navy.mil	HTTP	GET /cs/Images/HerrmannHallSmall.jpg HTTP/1.1
25	5.347651	bullnose.nps.navy.mil	166.138.195.47	TCP	http > 51115 [SYN, ACK] Seq=1211911646 Ack=3618669357 Win=33304 Len=0
26	5.347756	166.138.195.47	bullnose.nps.navy.mil	TCP	51115 > http [ACK] Seq=3618669357 Ack=1211911647 Win=8192 Len=0
27	5.348065	166.138.195.47	bullnose.nps.navy.mil	HTTP	GET /cs/Images/NPS-CS-Banner.gif HTTP/1.1
28	5.392573	bullnose.nps.navy.mil	166.138.195.47	TCP	http > 51116 [SYN, ACK] Seq=2851931795 Ack=2146261636 Win=33304 Len=0
29	5.392651	166.138.195.47	bullnose.nps.navy.mil	TCP	51116 > http [ACK] Seq=2146261636 Ack=2851931796 Win=8192 Len=0
30	5.392903	166.138.195.47	bullnose.nps.navy.mil	HTTP	GET /cs/Images/HomeUP.gif HTTP/1.1
31	5.479590	bullnose.nps.navy.mil	166.138.195.47	TCP	http > 51117 [SYN, ACK] Seq=1575000430 Ack=3760938225 Win=33304 Len=0
32	5.479693	166.138.195.47	bullnose.nps.navy.mil	TCP	51117 > http [ACK] Seq=3760938225 Ack=1575000431 Win=8192 Len=0
33	5.480006	166.138.195.47	bullnose.nps.navy.mil	HTTP	GET /cs/Images/AdminUP.gif HTTP/1.1
34	6.342653	bullnose.nps.navy.mil	166.138.195.47	TCP	http > 51114 [ACK] Seq=504309009 Ack=2920409800 Win=33304 Len=0
35	6.929518	bullnose.nps.navy.mil	166.138.195.47	HTTP	HTTP/1.0 200 OK
36	6.998835	bullnose.nps.navy.mil	166.138.195.47	HTTP	Continuation
37	7.002444	166.138.195.47	bullnose.nps.navy.mil	HTTP	GET /cs/Images/FacultyUP.gif HTTP/1.1
38	7.018659	bullnose.nps.navy.mil	166.138.195.47	TCP	http > 51115 [ACK] Seq=1211911647 Ack=3618669923 Win=33304 Len=0
39	7.542522	bullnose.nps.navy.mil	166.138.195.47	HTTP	HTTP/1.0 200 OK
40	7.704780	166.138.195.47	bullnose.nps.navy.mil	TCP	51115 > http [ACK] Seq=3618669923 Ack=1211913095 Win=8192 Len=0
41	7.879525	bullnose.nps.navy.mil	166.138.195.47	HTTP	Continuation
42	7.904850	166.138.195.47	bullnose.nps.navy.mil	TCP	51115 > http [ACK] Seq=3618669923 Ack=1211914543 Win=8192 Len=0
43	8.136815	bullnose.nps.navy.mil	166.138.195.47	HTTP	Continuation
44	8.154650	bullnose.nps.navy.mil	166.138.195.47	TCP	http > 51116 [ACK] Seq=2851931796 Ack=2146262195 Win=33304 Len=0
45	8.304944	166.138.195.47	bullnose.nps.navy.mil	TCP	51115 > http [ACK] Seq=3618669923 Ack=1211915743 Win=8192 Len=0
46	8.509658	bullnose.nps.navy.mil	166.138.195.47	HTTP	HTTP/1.0 200 OK
47	8.512553	166.138.195.47	bullnose.nps.navy.mil	HTTP	GET /cs/Images/StaffUP.gif HTTP/1.1
48	8.572641	bullnose.nps.navy.mil	166.138.195.47	TCP	http > 51117 [ACK] Seq=1575000431 Ack=3760938785 Win=33304 Len=0
49	8.659740	bullnose.nps.navy.mil	166.138.195.47	HTTP	HTTP/1.0 200 OK
50	8.662689	166.138.195.47	bullnose.nps.navy.mil	HTTP	GET /cs/Images/PartnersUP.gif HTTP/1.1
51	9.496577	bullnose.nps.navy.mil	166.138.195.47	HTTP	Continuation
52	9.505123	166.138.195.47	bullnose.nps.navy.mil	TCP	51115 > http [ACK] Seq=3618669923 Ack=1211917191 Win=8192 Len=0
53	9.855562	bullnose.nps.navy.mil	166.138.195.47	HTTP	Continuation
54	9.905212	166.138.195.47	bullnose.nps.navy.mil	TCP	51115 > http [ACK] Seq=3618669923 Ack=1211918639 Win=8192 Len=0
55	9.920710	bullnose.nps.navy.mil	166.138.195.47	HTTP	HTTP/1.0 200 OK
56	9.923536	166.138.195.47	bullnose.nps.navy.mil	HTTP	GET /cs/Images/CurricUP.gif HTTP/1.1
57	10.243886	bullnose.nps.navy.mil	166.138.195.47	HTTP	Continuation
58	10.275950	bullnose.nps.navy.mil	166.138.195.47	HTTP	Continuation
59	10.278853	166.138.195.47	bullnose.nps.navy.mil	HTTP	GET /cs/Images/ResearchUP.gif HTTP/1.1
60	10.392712	bullnose.nps.navy.mil	166.138.195.47	TCP	http > 51116 [ACK] Seq=2851932333 Ack=2146262755 Win=33304 Len=0
61	10.532686	bullnose.nps.navy.mil	166.138.195.47	HTTP	HTTP/1.0 200 OK
62	10.535502	166.138.195.47	bullnose.nps.navy.mil	HTTP	GET /Images/spacer.gif HTTP/1.1
63	11.279757	bullnose.nps.navy.mil	166.138.195.47	TCP	http > 51117 [ACK] Seq=1575001073 Ack=3760939348 Win=33304 Len=0
64	11.504782	bullnose.nps.navy.mil	166.138.195.47	HTTP	HTTP/1.0 200 OK
65	11.505472	166.138.195.47	bullnose.nps.navy.mil	TCP	51117 > http [ACK] Seq=3760939348 Ack=1575001607 Win=8192 Len=0
66	11.508361	166.138.195.47	bullnose.nps.navy.mil	HTTP	GET /cs/Images/Home-Down.gif HTTP/1.1
67	11.667780	bullnose.nps.navy.mil	166.138.195.47	HTTP	HTTP/1.0 200 OK
68	11.705559	166.138.195.47	bullnose.nps.navy.mil	TCP	51114 > http [ACK] Seq=2920410923 Ack=504312306 Win=8192 Len=0
69	12.091779	bullnose.nps.navy.mil	166.138.195.47	TCP	http > 51115 [ACK] Seq=1211920104 Ack=3618670486 Win=33304 Len=0
70	12.292726	bullnose.nps.navy.mil	166.138.195.47	HTTP	HTTP/1.0 200 OK
71	12.305702	166.138.195.47	bullnose.nps.navy.mil	TCP	51115 > http [ACK] Seq=3618670486 Ack=1211920661 Win=8192 Len=0
72	12.541786	bullnose.nps.navy.mil	166.138.195.47	TCP	http > 51116 [ACK] Seq=2851932873 Ack=2146263311 Win=33304 Len=0
73	12.673069	bullnose.nps.navy.mil	166.138.195.47	HTTP	HTTP/1.0 200 OK
74	12.705854	166.138.195.47	bullnose.nps.navy.mil	TCP	51116 > http [ACK] Seq=2146263311 Ack=2851933265 Win=8192 Len=0
75	13.066803	bullnose.nps.navy.mil	166.138.195.47	TCP	http > 51117 [ACK] Seq=1575001607 Ack=3760939910 Win=33304 Len=0
76	13.430661	bullnose.nps.navy.mil	166.138.195.47	HTTP	HTTP/1.0 200 OK
77	13.438608	166.138.195.47	bullnose.nps.navy.mil	HTTP	GET /cs/Images/AdminDOWN.gif HTTP/1.1
78	13.442729	166.138.195.47	bullnose.nps.navy.mil	HTTP	GET /cs/Images/StaffDOWN.gif HTTP/1.1
79	13.448885	166.138.195.47	bullnose.nps.navy.mil	HTTP	GET /cs/Images/PartnersDOWN.gif HTTP/1.1
80	13.451990	166.138.195.47	bullnose.nps.navy.mil	HTTP	GET /cs/Images/ResearchDOWN.gif HTTP/1.1
81	15.063832	bullnose.nps.navy.mil	166.138.195.47	HTTP	HTTP/1.0 200 OK
82	15.066966	166.138.195.47	bullnose.nps.navy.mil	HTTP	GET /cs/Images/FacultyDOWN.gif HTTP/1.1
83	16.079825	bullnose.nps.navy.mil	166.138.195.47	HTTP	HTTP/1.0 200 OK
84	16.082860	166.138.195.47	bullnose.nps.navy.mil	HTTP	GET /cs/Images/CurricDOWN.gif HTTP/1.1
85	16.094837	bullnose.nps.navy.mil	166.138.195.47	TCP	http > 51115 [ACK] Seq=1211920661 Ack=3618671051 Win=33304 Len=0
86	16.383795	bullnose.nps.navy.mil	166.138.195.47	HTTP	HTTP/1.0 200 OK
87	16.466846	bullnose.nps.navy.mil	166.138.195.47	TCP	http > 51114 [ACK] Seq=504312306 Ack=2920411488 Win=33304 Len=0
88	16.506367	166.138.195.47	bullnose.nps.navy.mil	TCP	51115 > http [ACK] Seq=3618671051 Ack=1211921670 Win=8192 Len=0
89	16.847779	bullnose.nps.navy.mil	166.138.195.47	HTTP	HTTP/1.0 200 OK
90	16.906476	166.138.195.47	bullnose.nps.navy.mil	TCP	51114 > http [ACK] Seq=2920411488 Ack=504313323 Win=8192 Len=0
91	17.191867	bullnose.nps.navy.mil	166.138.195.47	TCP	http > 51117 [ACK] Seq=1575003677 Ack=3760941036 Win=33304 Len=0
92	17.567737	bullnose.nps.navy.mil	166.138.195.47	HTTP	HTTP/1.0 200 OK
93	17.706640	166.138.195.47	bullnose.nps.navy.mil	TCP	51117 > http [ACK] Seq=3760941036 Ack=1575004671 Win=8192 Len=0
94	17.829819	bullnose.nps.navy.mil	166.138.195.47	HTTP	HTTP/1.0 200 OK
95	17.906723	166.138.195.47	bullnose.nps.navy.mil	TCP	51116 > http [ACK] Seq=2146264436 Ack=2851935301 Win=8192 Len=0

Figure 61 Packets Exchanged Between Mobile Phone (IP: 166.138.195.47) for Accessing the CS Department Web Page on bullnose.nps.navy.mil (IP: 131.120.251.15).

User's position (time)	***Task 2 Accessing web page***	***Total size of traffic (data and overhead in bytes)***	***Transfer time (s)***	***Connection Average throughput (Kbps)***
Static (time 12:00)	http://www.nps.navy.mil/cs/	43,886	23.815	*14.74*
Static (time 16:00)	http://www.nps.navy.mil/cs/	43,349	19.746	*17.56*
Static (time 18:30)	http://www.nps.navy.mil/cs/	62,057	25.989	*19.1*
Static (time 19:30)	https://myaccounts.navyfcu.org/cgi-bin/ifsewwwc	97,602	75.813	*10.3*
Static (time 17:00)	www.cnn.com	322,744	113.442	*22.76*
Static (time 17:30)	www.in.gr	135,561	66.181	*16.38*
Static (time 16:00)	www.numiom.com	237,860	118.53	*16.05*
On highway with speed 60mph (time 16:00)	http://www.nps.navy.mil/cs/	45,612	24.977	*14.61*
On highway with speed 60mph (time 18:00)	http://www.nps.navy.mil/cs/	50,987	29.138	*14*
On highway with speed 60mph (time 18:10)	https://myaccounts.navyfcu.org/cgi-bin/ifsewwwc	226,311	255.841	*7.08*
On highway with speed 60mph (time 19:10)	www.cnn.com	307,058	167.725	*14.65*
On highway with speed 60mph (time 18:30)	www.in.gr	68,336	48.664	*11.23*

Table 10 GPRS Speed Comparison in Static and Moving Environment through Web Page Downloading.

3. Task 3: Connecting to the NPS E-Mail Server

This task evaluates e-mail traffic through the mobile connection between the mobile phone and the author's NPS incoming e-mail server monterey.nps.navy.mil (IP: 131.120.18.61) and the outgoing e-mail server capella.nps.navy.mil (IP: 131.120.254.83)

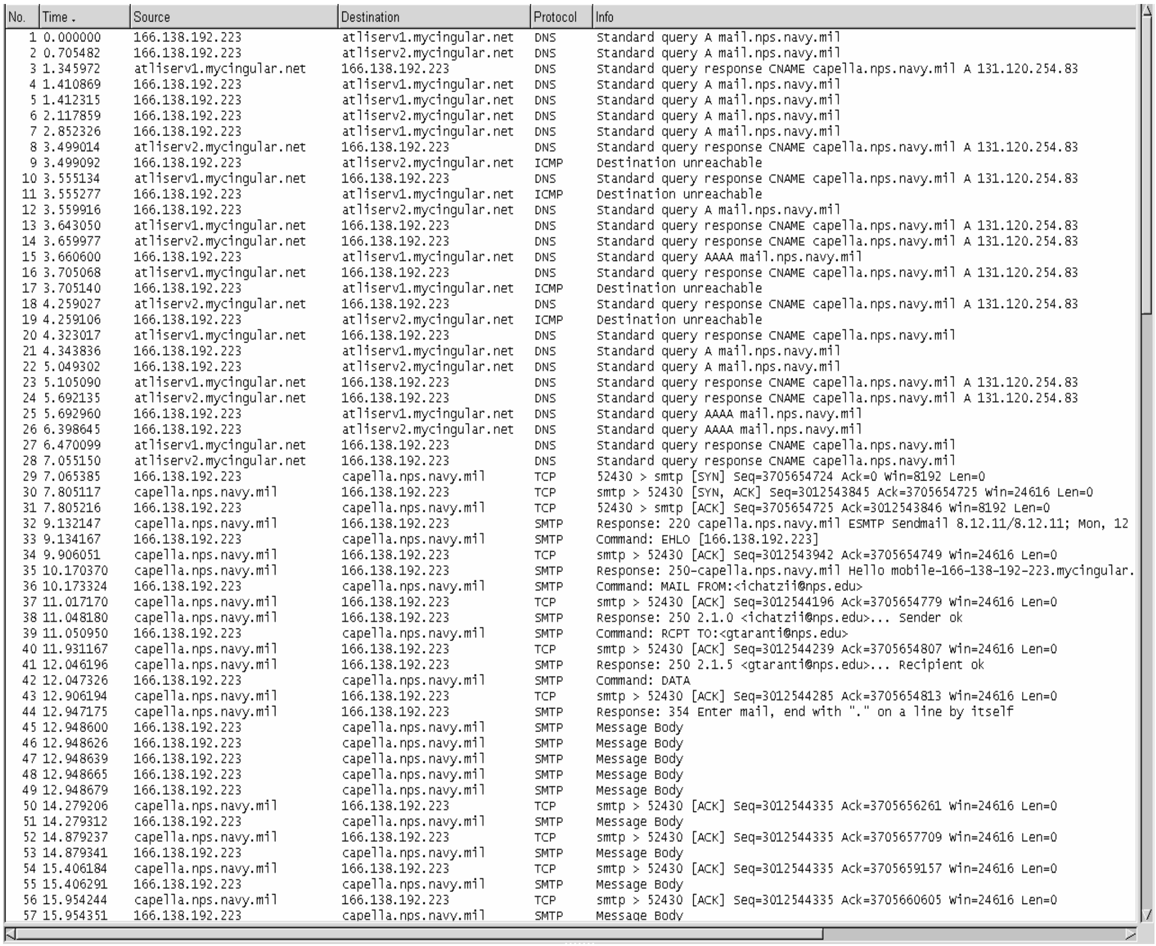
Figure 62 presents packets exchanged between the mobile phone (IP: 166.138. 201.224) and the incoming mail server during the initial connection. In this case, there were no incoming e-mails. According to the Ethereal analysis, the 100 packets needed to accomplish the connection totaled 8,894 bytes and were exchanged in 17.342 sec. The average packet size was 88.94 bytes and the average bit rate 512.862 bytes/sec (or *4.1 Kbps*).

One of the most interesting measurements for task 3 is presented in Figure 63, where packets are exchanged between the mobile phone (IP: 166.138.192.223) and the outgoing mail server during the initial connection. The account ichatzii@nps.edu sent an e-mail with the GPRS.JPG file as an attachment to the gtaranti@nps.edu account. According to the Ethereal analysis, the 170 packets needed to accomplish the mail transfer totaled 100,137 bytes and were exchanged in 48.42 sec. The average packet size was 589.041 bytes and the average bit rate 2068.104 bytes/sec (or *16.55 Kbps*).

Additional tests can be found in Table 11. In most cases, with a few exceptions, the measured throughput was relatively low compared to the web access speed.

No.	Time	Source	Destination	Protocol	Info
1	0.000000	166.138.201.24	atliserv1.mycingular.net	DNS	Standard query A homepage.mac.com
2	0.803557	166.138.201.24	atliserv2.mycingular.net	DNS	Standard query A homepage.mac.com
3	0.841490	166.138.201.24	atliserv1.mycingular.net	DNS	Standard query A monterey.nps.navy.mil
4	1.319621	atliserv1.mycingular.net	166.138.201.24	DNS	Standard query response A 17.250.248.34
5	1.508988	166.138.201.24	atliserv1.mycingular.net	DNS	Standard query A homepage.mac.com
6	1.509821	166.138.201.24	atliserv1.mycingular.net	DNS	Standard query AAAA homepage.mac.com
7	1.546910	166.138.201.24	atliserv2.mycingular.net	DNS	Standard query A monterey.nps.navy.mil
8	2.110671	atliserv2.mycingular.net	166.138.201.24	DNS	Standard query response A 17.250.248.34
9	2.110751	166.138.201.24	atliserv2.mycingular.net	ICMP	Destination unreachable
10	2.205630	atliserv1.mycingular.net	166.138.201.24	DNS	Standard query response A 131.120.18.61
11	2.215068	166.138.201.24	atliserv2.mycingular.net	DNS	Standard query AAAA homepage.mac.com
12	2.252257	166.138.201.24	atliserv1.mycingular.net	DNS	Standard query A monterey.nps.navy.mil
13	2.253455	166.138.201.24	atliserv1.mycingular.net	DNS	Standard query AAAA monterey.nps.navy.mil
14	2.374647	atliserv1.mycingular.net	166.138.201.24	DNS	Standard query response A 17.250.248.34
15	2.374715	166.138.201.24	atliserv1.mycingular.net	ICMP	Destination unreachable
16	2.395615	atliserv1.mycingular.net	166.138.201.24	DNS	Standard query response
17	2.436618	atliserv2.mycingular.net	166.138.201.24	DNS	Standard query response A 131.120.18.61
18	2.436679	166.138.201.24	atliserv2.mycingular.net	ICMP	Destination unreachable
19	2.920408	166.138.201.24	atliserv1.mycingular.net	DNS	Standard query AAAA homepage.mac.com
20	2.933724	atliserv2.mycingular.net	166.138.201.24	DNS	Standard query response
21	2.933785	166.138.201.24	atliserv2.mycingular.net	ICMP	Destination unreachable
22	2.958831	166.138.201.24	atliserv2.mycingular.net	DNS	Standard query AAAA monterey.nps.navy.mil
23	3.254717	atliserv1.mycingular.net	166.138.201.24	DNS	Standard query response A 131.120.18.61
24	3.254787	166.138.201.24	atliserv1.mycingular.net	ICMP	Destination unreachable
25	3.303614	atliserv1.mycingular.net	166.138.201.24	DNS	Standard query response
26	3.664183	166.138.201.24	atliserv1.mycingular.net	DNS	Standard query AAAA monterey.nps.navy.mil
27	3.756318	166.138.201.24	atliserv1.mycingular.net	DNS	Standard query A homepage.mac.com
28	3.866717	atliserv1.mycingular.net	166.138.201.24	DNS	Standard query response
29	3.866785	166.138.201.24	atliserv1.mycingular.net	ICMP	Destination unreachable
30	4.003696	atliserv2.mycingular.net	166.138.201.24	DNS	Standard query response
31	4.003763	166.138.201.24	atliserv2.mycingular.net	ICMP	Destination unreachable
32	4.461972	166.138.201.24	atliserv2.mycingular.net	DNS	Standard query A homepage.mac.com
33	4.631349	166.138.201.24	atliserv1.mycingular.net	DNS	Standard query A monterey.nps.navy.mil
34	4.717629	atliserv1.mycingular.net	166.138.201.24	DNS	Standard query response
35	4.717696	166.138.201.24	atliserv1.mycingular.net	ICMP	Destination unreachable
36	4.870742	atliserv1.mycingular.net	166.138.201.24	DNS	Standard query response A 17.250.248.34
37	5.167628	166.138.201.24	atliserv1.mycingular.net	DNS	Standard query A homepage.mac.com
38	5.171933	166.138.201.24	atliserv1.mycingular.net	DNS	Standard query AAAA homepage.mac.com
39	5.336997	166.138.201.24	atliserv2.mycingular.net	DNS	Standard query A monterey.nps.navy.mil
40	5.556806	atliserv2.mycingular.net	166.138.201.24	DNS	Standard query response A 17.250.248.34
41	5.556874	166.138.201.24	atliserv2.mycingular.net	ICMP	Destination unreachable
42	5.605684	atliserv1.mycingular.net	166.138.201.24	DNS	Standard query response A 131.120.18.61
43	5.878162	166.138.201.24	atliserv2.mycingular.net	DNS	Standard query AAAA homepage.mac.com
44	6.068605	166.138.201.24	atliserv1.mycingular.net	DNS	Standard query A monterey.nps.navy.mil
45	6.071383	166.138.201.24	atliserv1.mycingular.net	DNS	Standard query AAAA monterey.nps.navy.mil
46	6.217817	atliserv1.mycingular.net	166.138.201.24	DNS	Standard query response A 17.250.248.34
47	6.217888	166.138.201.24	atliserv1.mycingular.net	ICMP	Destination unreachable
48	6.254756	atliserv1.mycingular.net	166.138.201.24	DNS	Standard query response
49	6.305785	atliserv2.mycingular.net	166.138.201.24	DNS	Standard query response A 131.120.18.61
50	6.305853	166.138.201.24	atliserv2.mycingular.net	ICMP	Destination unreachable
51	6.583923	166.138.201.24	atliserv1.mycingular.net	DNS	Standard query AAAA homepage.mac.com
52	6.776948	166.138.201.24	atliserv2.mycingular.net	DNS	Standard query AAAA monterey.nps.navy.mil
53	6.867693	atliserv2.mycingular.net	166.138.201.24	DNS	Standard query response
54	6.867761	166.138.201.24	atliserv2.mycingular.net	ICMP	Destination unreachable
55	6.980702	atliserv1.mycingular.net	166.138.201.24	DNS	Standard query response A 131.120.18.61
56	6.980768	166.138.201.24	atliserv1.mycingular.net	ICMP	Destination unreachable
57	7.005672	atliserv1.mycingular.net	166.138.201.24	DNS	Standard query response
58	7.141704	atliserv1.mycingular.net	166.138.201.24	DNS	Standard query response
59	7.141771	166.138.201.24	atliserv1.mycingular.net	ICMP	Destination unreachable
60	7.453154	166.138.201.24	homepage.mac.com	TCP	50860 > http [SYN] Seq=4211161869 Ack=0 Win=8192 Len=0
61	7.482465	166.138.201.24	atliserv1.mycingular.net	DNS	Standard query AAAA monterey.nps.navy.mil
62	7.728752	atliserv2.mycingular.net	166.138.201.24	DNS	Standard query response
63	7.728817	166.138.201.24	atliserv2.mycingular.net	ICMP	Destination unreachable
64	8.380513	166.138.201.24	monterey.nps.navy.mil	TCP	50863 > pop3 [SYN] Seq=1225798350 Ack=0 Win=8192 Len=0
65	8.508737	homepage.mac.com	166.138.201.24	TCP	http > 50860 [SYN, ACK] Seq=3855331962 Ack=4211161870 Win=33304 Len=0
66	8.508826	166.138.201.24	homepage.mac.com	TCP	50860 > http [ACK] Seq=4211161870 Ack=3855331963 Win=8192 Len=0
67	8.567606	166.138.201.24	homepage.mac.com	HTTP	HEAD /bertlundy/.cv/thumbs/me.thumbnail HTTP/1.0
68	8.945722	atliserv1.mycingular.net	166.138.201.24	DNS	Standard query response
69	8.945789	166.138.201.24	atliserv1.mycingular.net	ICMP	Destination unreachable
70	9.367703	monterey.nps.navy.mil	166.138.201.24	TCP	pop3 > 50863 [SYN, ACK] Seq=3776118652 Ack=1225798351 Win=24616 Len=0
71	9.367795	166.138.201.24	monterey.nps.navy.mil	TCP	50863 > pop3 [ACK] Seq=1225798351 Ack=3776118653 Win=8192 Len=0
72	9.554721	homepage.mac.com	166.138.201.24	TCP	http > 50860 [ACK] Seq=3855331963 Ack=4211162058 Win=33304 Len=0
73	9.872039	homepage.mac.com	166.138.201.24	HTTP	HTTP/1.0 404 Not Found
74	9.872429	166.138.201.24	homepage.mac.com	TCP	50860 > http [FIN, ACK] Seq=4211162058 Ack=3855332268 Win=8192 Len=0
75	9.903806	homepage.mac.com	166.138.201.24	TCP	http > 50860 [FIN, ACK] Seq=3855332268 Ack=4211162058 Win=33304 Len=0
76	9.903888	166.138.201.24	homepage.mac.com	TCP	50860 > http [FIN, ACK] Seq=4211162058 Ack=3855332269 Win=8192 Len=0
77	10.606794	monterey.nps.navy.mil	166.138.201.24	POP	Response: +OK Microsoft Exchange 2000 POP3 server version 6.0.6487.0 (ellis.
78	10.608066	166.138.201.24	monterey.nps.navy.mil	POP	Request: USER ichatzii
79	10.797687	homepage.mac.com	166.138.201.24	TCP	http > 50860 [ACK] Seq=3855332269 Ack=4211162059 Win=33304 Len=0
80	11.354692	monterey.nps.navy.mil	166.138.201.24	TCP	pop3 > 50863 [ACK] Seq=3776118744 Ack=1225798366 Win=24616 Len=0
81	11.596783	monterey.nps.navy.mil	166.138.201.24	POP	Response: +OK
82	11.597610	166.138.201.24	monterey.nps.navy.mil	POP	Request: PASS fgboubouf463
83	12.454757	monterey.nps.navy.mil	166.138.201.24	TCP	pop3 > 50863 [ACK] Seq=3776118749 Ack=1225798385 Win=24616 Len=0
84	12.579835	monterey.nps.navy.mil	166.138.201.24	POP	Response: +OK User successfully logged on.
85	12.580817	166.138.201.24	monterey.nps.navy.mil	POP	Request: STAT
86	13.441827	monterey.nps.navy.mil	166.138.201.24	TCP	pop3 > 50863 [ACK] Seq=3776118783 Ack=1225798391 Win=24616 Len=0
87	13.558864	monterey.nps.navy.mil	166.138.201.24	POP	Response: +OK 57 8740845
88	13.563990	166.138.201.24	monterey.nps.navy.mil	POP	Request: UIDL 1
89	14.433847	monterey.nps.navy.mil	166.138.201.24	TCP	pop3 > 50863 [ACK] Seq=3776118799 Ack=1225798399 Win=24616 Len=0
90	14.542824	monterey.nps.navy.mil	166.138.201.24	POP	Response: +OK 1 AAg4HRFAAAwX7T5GIg2Ve+Er74j6nC6U
91	14.543623	166.138.201.24	monterey.nps.navy.mil	POP	Request: UIDL 57
92	15.393857	monterey.nps.navy.mil	166.138.201.24	TCP	pop3 > 50863 [ACK] Seq=3776118839 Ack=1225798408 Win=24616 Len=0
93	15.517903	monterey.nps.navy.mil	166.138.201.24	POP	Response: +OK 57 AAgPIRFAAAwX7T5GIg2Ve+Er74j6nC6U
94	15.518697	166.138.201.24	monterey.nps.navy.mil	POP	Request: QUIT
95	16.378882	monterey.nps.navy.mil	166.138.201.24	TCP	pop3 > 50863 [ACK] Seq=3776118880 Ack=1225798414 Win=24616 Len=0
96	16.531981	monterey.nps.navy.mil	166.138.201.24	POP	Response: +OK Microsoft Exchange 2000 POP3 server version 6.0.6487.0 signing
97	16.534049	166.138.201.24	monterey.nps.navy.mil	TCP	50863 > pop3 [FIN, ACK] Seq=1225798414 Ack=3776118953 Win=8192 Len=0
98	16.578878	monterey.nps.navy.mil	166.138.201.24	TCP	pop3 > 50863 [FIN, ACK] Seq=3776118953 Ack=1225798414 Win=24616 Len=0
99	16.578961	166.138.201.24	monterey.nps.navy.mil	TCP	50863 > pop3 [FIN, ACK] Seq=1225798414 Ack=3776118954 Win=8192 Len=0
100	17.341889	monterey.nps.navy.mil	166.138.201.24	TCP	pop3 > 50863 [ACK] Seq=3776118954 Ack=1225798415 Win=24616 Len=0

Figure 62 Packets Exchanged for Checking Incoming E-Mail Between Mobile Phone (IP:166.138.201.24) and monterey.nps.navy.mil (IP: 131.120.18.61).



No.	Time	Source	Destination	Protocol	Info
1	0.000000	166.138.192.223	atliserv1.mycingular.net	DNS	Standard query A mail.nps.navy.mil
2	0.705482	166.138.192.223	atliserv2.mycingular.net	DNS	Standard query A mail.nps.navy.mil
3	1.345972	atliserv1.mycingular.net	166.138.192.223	DNS	Standard query response CNAME capella.nps.navy.mil A 131.120.254.83
4	1.410869	166.138.192.223	atliserv1.mycingular.net	DNS	Standard query A mail.nps.navy.mil
5	1.412315	166.138.192.223	atliserv1.mycingular.net	DNS	Standard query A mail.nps.navy.mil
6	2.117859	166.138.192.223	atliserv2.mycingular.net	DNS	Standard query A mail.nps.navy.mil
7	2.852326	166.138.192.223	atliserv1.mycingular.net	DNS	Standard query A mail.nps.navy.mil
8	3.499014	atliserv2.mycingular.net	166.138.192.223	DNS	Standard query response CNAME capella.nps.navy.mil A 131.120.254.83
9	3.499092	166.138.192.223	atliserv2.mycingular.net	ICMP	Destination unreachable
10	3.555134	atliserv1.mycingular.net	166.138.192.223	DNS	Standard query response CNAME capella.nps.navy.mil A 131.120.254.83
11	3.555277	166.138.192.223	atliserv1.mycingular.net	ICMP	Destination unreachable
12	3.559916	166.138.192.223	atliserv2.mycingular.net	DNS	Standard query A mail.nps.navy.mil
13	3.643050	atliserv1.mycingular.net	166.138.192.223	DNS	Standard query response CNAME capella.nps.navy.mil A 131.120.254.83
14	3.659977	atliserv2.mycingular.net	166.138.192.223	DNS	Standard query response CNAME capella.nps.navy.mil A 131.120.254.83
15	3.660600	166.138.192.223	atliserv1.mycingular.net	DNS	Standard query AAAA mail.nps.navy.mil
16	3.705068	atliserv1.mycingular.net	166.138.192.223	DNS	Standard query response CNAME capella.nps.navy.mil A 131.120.254.83
17	3.705140	166.138.192.223	atliserv1.mycingular.net	ICMP	Destination unreachable
18	4.259027	atliserv2.mycingular.net	166.138.192.223	DNS	Standard query response CNAME capella.nps.navy.mil A 131.120.254.83
19	4.259106	166.138.192.223	atliserv2.mycingular.net	ICMP	Destination unreachable
20	4.323017	atliserv1.mycingular.net	166.138.192.223	DNS	Standard query response CNAME capella.nps.navy.mil
21	4.343836	166.138.192.223	atliserv1.mycingular.net	DNS	Standard query A mail.nps.navy.mil
22	5.049302	166.138.192.223	atliserv2.mycingular.net	DNS	Standard query A mail.nps.navy.mil
23	5.105090	atliserv1.mycingular.net	166.138.192.223	DNS	Standard query response CNAME capella.nps.navy.mil A 131.120.254.83
24	5.692135	atliserv2.mycingular.net	166.138.192.223	DNS	Standard query response CNAME capella.nps.navy.mil A 131.120.254.83
25	5.692960	166.138.192.223	atliserv1.mycingular.net	DNS	Standard query AAAA mail.nps.navy.mil
26	6.398645	166.138.192.223	atliserv2.mycingular.net	DNS	Standard query AAAA mail.nps.navy.mil
27	6.470099	atliserv1.mycingular.net	166.138.192.223	DNS	Standard query response CNAME capella.nps.navy.mil
28	7.055150	atliserv2.mycingular.net	166.138.192.223	DNS	Standard query response CNAME capella.nps.navy.mil
29	7.065385	166.138.192.223	capella.nps.navy.mil	TCP	52430 > smtp [SYN] Seq=3705654724 Ack=0 Win=8192 Len=0
30	7.805117	capella.nps.navy.mil	166.138.192.223	TCP	smtp > 52430 [SYN, ACK] Seq=3012543845 Ack=3705654725 Win=24616 Len=0
31	7.805216	166.138.192.223	capella.nps.navy.mil	TCP	52430 > smtp [ACK] Seq=3705654725 Ack=3012543846 Win=8192 Len=0
32	9.132147	capella.nps.navy.mil	166.138.192.223	SMTP	Response: 220 capella.nps.navy.mil ESMTP Sendmail 8.12.11/8.12.11; Mon, 12
33	9.134167	166.138.192.223	capella.nps.navy.mil	SMTP	Command: EHLO [166.138.192.223]
34	9.906051	capella.nps.navy.mil	166.138.192.223	TCP	smtp > 52430 [ACK] Seq=3012543942 Ack=3705654749 Win=24616 Len=0
35	10.170370	capella.nps.navy.mil	166.138.192.223	SMTP	Response: 250-capella.nps.navy.mil Hello mobile-166-138-192-223.mycingular.
36	10.173324	166.138.192.223	capella.nps.navy.mil	SMTP	Command: MAIL FROM:<ichatzii@nps.edu>
37	11.017170	capella.nps.navy.mil	166.138.192.223	TCP	smtp > 52430 [ACK] Seq=3012544196 Ack=3705654779 Win=24616 Len=0
38	11.048180	capella.nps.navy.mil	166.138.192.223	SMTP	Response: 250 2.1.0 <ichatzii@nps.edu>... Sender ok
39	11.050950	166.138.192.223	capella.nps.navy.mil	SMTP	Command: RCPT TO:<gtaranti@nps.edu>
40	11.931167	capella.nps.navy.mil	166.138.192.223	TCP	smtp > 52430 [ACK] Seq=3012544239 Ack=3705654807 Win=24616 Len=0
41	12.046196	capella.nps.navy.mil	166.138.192.223	SMTP	Response: 250 2.1.5 <gtaranti@nps.edu>... Recipient ok
42	12.047326	166.138.192.223	capella.nps.navy.mil	SMTP	Command: DATA
43	12.906194	capella.nps.navy.mil	166.138.192.223	TCP	smtp > 52430 [ACK] Seq=3012544285 Ack=3705654813 Win=24616 Len=0
44	12.947175	capella.nps.navy.mil	166.138.192.223	SMTP	Response: 354 Enter mail, end with "." on a line by itself
45	12.948600	166.138.192.223	capella.nps.navy.mil	SMTP	Message Body
46	12.948626	166.138.192.223	capella.nps.navy.mil	SMTP	Message Body
47	12.948639	166.138.192.223	capella.nps.navy.mil	SMTP	Message Body
48	12.948665	166.138.192.223	capella.nps.navy.mil	SMTP	Message Body
49	12.948679	166.138.192.223	capella.nps.navy.mil	SMTP	Message Body
50	14.279206	capella.nps.navy.mil	166.138.192.223	TCP	smtp > 52430 [ACK] Seq=3012544335 Ack=3705656261 Win=24616 Len=0
51	14.279312	166.138.192.223	capella.nps.navy.mil	SMTP	Message Body
52	14.879237	capella.nps.navy.mil	166.138.192.223	TCP	smtp > 52430 [ACK] Seq=3012544335 Ack=3705657709 Win=24616 Len=0
53	14.879341	166.138.192.223	capella.nps.navy.mil	SMTP	Message Body
54	15.406184	capella.nps.navy.mil	166.138.192.223	TCP	smtp > 52430 [ACK] Seq=3012544335 Ack=3705659157 Win=24616 Len=0
55	15.406291	166.138.192.223	capella.nps.navy.mil	SMTP	Message Body
56	15.954244	capella.nps.navy.mil	166.138.192.223	TCP	smtp > 52430 [ACK] Seq=3012544335 Ack=3705660605 Win=24616 Len=0
57	15.954351	166.138.192.223	capella.nps.navy.mil	SMTP	Message Body

Figure 63 The First 57 (from 170) Exchanged Packets during Sending an E-Mail from the Mobile Phone (IP: 166.138.192.223) to the NPS Outgoing Mail Server capella.nps.navy.mil (IP: 131.120.254.83).

User's position (time)	***Task 3 Email access***	***Total size of traffic (data and overhead in bytes)***	***Transfer time (s)***	***Connection Average throughput (Kbps)***
Static (16:00)	Receiving e-mails from ichatzii@nps.edu account	16,814	35.236	*3.82*
Static (13:00)	Sending email with GPRS.doc attachment from ichatzii@nps.edu to gtaranti@nps.edu	100,137	48.42	*16.54*
Static (19:00)	Receiving e-mails from ichatzii@nps.edu account	88,599	132.977	*5.33*
Static (15:00)	Sending email with GPRS.jpg attachment from ichatzii@nps.edu to gtaranti@nps.edu	236,341	281.399	*6.72*
On highway with speed 60mph (18:00)	Receiving e-mails from ichatzii@nps.edu account	30,778	37.79	*6.52*
On highway with speed 60mph (19:00)	Receiving e-mails from ichatzii@nps.edu account	13,423	90.457	*1.18*
On highway with speed 60mph (13:00)	Sending a text based email from ichatzii@nps.edu to gtaranti@nps.edu	15,064	22.737	*5.3*
On highway with speed 60mph (12:00)	Sending a small text based email from ichatzii@nps.edu to pmatsang@nps.edu	5,526	15.146	*2.87*

Table 11 GPRS Speed Comparison in Static and Moving Environment While Connecting to NPS Mail Server.

4. Task 4: Connect to the NPS Intranet via the Citrix Client

Remote users using the Internet through wired service providers such as AOL, EarthLink, NetZero, etc., are able obtain their secure account information from the NPS Intranet, for example Python and the Daily Check-in, by installing the Citrix client software. It can be downloaded from the NPS website or from the Citrix Systems website[89]. It provides a remote desktop window as if the user was in the NPS Intranet. For this connection, the miami.ad.nps.navy.mil (IP: 131.120.18.63) server is used. With

89 Citrix Systems, [http://www.citrix.com/site/SS/downloads/index.asp], July 2004.

the Citrix client editor, the author configured a client (right window in Figure 64) that was used in cellular connection. The left window is revealed when the button "Browse" in the right window is pressed.

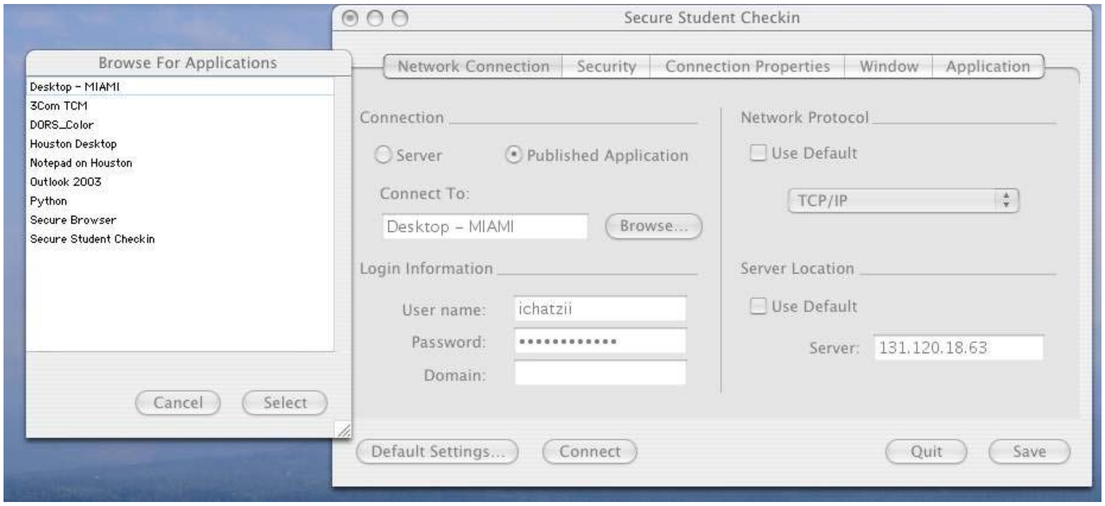


Figure 64 Citrix Client Configuration for Accessing the NPS Secure Intranet.

The drawback of this task is that it requires large data transfer. After the main window has opened and the user starts a new process, such as opening the web browser or the e-mail client, a large portion of data are retransmitted to refresh the remote desktop window. In the case of a GPRS cellular connection, this large amount of data transfer is valuable.

A few settings that can speed up the process and gain valuable data transfer in this specific connection through the GPRS are:

- Add the user's information in the login information screen of the Citrix Client, thus having the user name and password send automatically to the secure server with the initial connection request.
- If Citrix is used for accessing the NPS Check-in web page, then this should be the default web page of Internet Explorer.

Figure 65 presents the first 116 packets exchanged between the mobile phone (IP: 166.138.205.224) and the NPS server miami.ad.nps.navy.mil (IP: 131.120.18.63) during the initial connection. According to the Ethereal analysis, the 355 packets needed to accomplish the connection totaled 88,450 bytes and were exchanged in 74.443 sec. The average packet size was 249.155 bytes and the average bit rate 1188.159 bytes/sec (or *9.5*

Kbps). Additional Citrix remote desktop test results in different dates and hours of the day can be found in Table 12. Since the amount of required data transfer is large and includes the user's authentication procedures, the given average throughput for this type of connection is low.

User's position (time)	***Total size of traffic (data and overhead in bytes)***	***Transfer time (ms)***	***Connection Average throughput (Kbps)***
Static (time 15:00)	101,225	153.612	*5.27*
Static (time 18:00)	80,973	89.721	*7.22*
On highway with speed 60mph (time 18:00)	76,569	83.139	*7.37*

Table 12 GPRS Speed Comparison in Static and Moving Environment While Connecting to the NPS Server (IP: 131.102.18.63) Supporting Citrix Clients.

No.	Time	Source	Destination	Protocol	Info
1	0.000000	166.138.205.224	atliserv1.mycingular.ne	DNS	Standard query A mobile-166-138-205-224.mycingular.net
2	0.705649	166.138.205.224	atliserv2.mycingular.ne	DNS	Standard query A mobile-166-138-205-224.mycingular.net
3	1.385776	atliserv1.mycingular.ne	166.138.205.224	DNS	Standard query response, No such name
4	1.411020	166.138.205.224	atliserv1.mycingular.ne	DNS	Standard query A mobile-166-138-205-224.mycingular.net
5	2.278228	166.138.205.224	miami.ad.nps.navy.mil	UDP	Source port: 49162 Destination port: 1604
6	2.298801	atliserv2.mycingular.ne	166.138.205.224	DNS	Standard query response, No such name
7	2.298866	166.138.205.224	atliserv2.mycingular.ne	ICMP	Destination unreachable
8	2.375794	atliserv1.mycingular.ne	166.138.205.224	DNS	Standard query response, No such name
9	2.375861	166.138.205.224	atliserv1.mycingular.ne	ICMP	Destination unreachable
10	3.467992	166.138.205.224	miami.ad.nps.navy.mil	UDP	Source port: 49162 Destination port: 1604
11	3.532763	miami.ad.nps.navy.mil	166.138.205.224	UDP	Source port: 1604 Destination port: 49162
12	3.534064	166.138.205.224	miami.ad.nps.navy.mil	UDP	Source port: 49162 Destination port: 1604
13	4.314736	miami.ad.nps.navy.mil	166.138.205.224	UDP	Source port: 1604 Destination port: 49162
14	4.373728	miami.ad.nps.navy.mil	166.138.205.224	UDP	Source port: 1604 Destination port: 49162
15	4.374697	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [SYN] Seq=3203341133 Ack=0 Win=8192 Len=0
16	5.297813	miami.ad.nps.navy.mil	166.138.205.224	TCP	1494 > 49158 [SYN, ACK] Seq=1283213772 Ack=3203341134 Win=24616 Len=0
17	5.297905	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [ACK] Seq=3203341134 Ack=1283213773 Win=8192 Len=0
18	6.460742	miami.ad.nps.navy.mil	166.138.205.224	TCP	1494 > 49158 [PSH, ACK] Seq=1283213773 Ack=3203341134 Win=24616 Len=6
19	6.465352	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203341134 Ack=1283213779 Win=8192 Len=6
20	7.357837	miami.ad.nps.navy.mil	166.138.205.224	TCP	1494 > 49158 [ACK] Seq=1283213779 Ack=3203341140 Win=24616 Len=0
21	7.584072	miami.ad.nps.navy.mil	166.138.205.224	TCP	1494 > 49158 [PSH, ACK] Seq=1283213779 Ack=3203341140 Win=24616 Len=178
22	7.597625	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203341140 Ack=1283213957 Win=8192 Len=145
23	7.604276	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203341285 Ack=1283213957 Win=8192 Len=63
24	7.638095	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203341348 Ack=1283213957 Win=8192 Len=43
25	7.672302	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203341391 Ack=1283213957 Win=8192 Len=44
26	7.706629	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203341435 Ack=1283213957 Win=8192 Len=315
27	7.757376	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203341750 Ack=1283213957 Win=8192 Len=197
28	7.798316	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203341947 Ack=1283213957 Win=8192 Len=81
29	7.825133	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342028 Ack=1283213957 Win=8192 Len=54
30	7.859162	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342082 Ack=1283213957 Win=8192 Len=59
31	7.893082	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342141 Ack=1283213957 Win=8192 Len=51
32	7.927126	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342192 Ack=1283213957 Win=8192 Len=57
33	7.961193	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342249 Ack=1283213957 Win=8192 Len=59
34	7.995097	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342308 Ack=1283213957 Win=8192 Len=51
35	8.029083	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342359 Ack=1283213957 Win=8192 Len=51
36	8.063102	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342410 Ack=1283213957 Win=8192 Len=51
37	8.820868	miami.ad.nps.navy.mil	166.138.205.224	TCP	1494 > 49158 [ACK] Seq=1283213957 Ack=3203341348 Win=24616 Len=0
38	8.935838	miami.ad.nps.navy.mil	166.138.205.224	TCP	1494 > 49158 [ACK] Seq=1283213957 Ack=3203341391 Win=24616 Len=0
39	9.082772	miami.ad.nps.navy.mil	166.138.205.224	TCP	1494 > 49158 [ACK] Seq=1283213957 Ack=3203341435 Win=24616 Len=0
40	9.257872	miami.ad.nps.navy.mil	166.138.205.224	TCP	1494 > 49158 [ACK] Seq=1283213957 Ack=3203341750 Win=24616 Len=0
41	9.797905	miami.ad.nps.navy.mil	166.138.205.224	TCP	1494 > 49158 [ACK] Seq=1283213957 Ack=3203341947 Win=24616 Len=0
42	9.840896	miami.ad.nps.navy.mil	166.138.205.224	TCP	1494 > 49158 [ACK] Seq=1283213957 Ack=3203342082 Win=24616 Len=0
43	10.032935	miami.ad.nps.navy.mil	166.138.205.224	TCP	1494 > 49158 [ACK] Seq=1283213957 Ack=3203342192 Win=24616 Len=0
44	10.066914	miami.ad.nps.navy.mil	166.138.205.224	TCP	1494 > 49158 [ACK] Seq=1283213957 Ack=3203342249 Win=24616 Len=0
45	10.175037	miami.ad.nps.navy.mil	166.138.205.224	TCP	1494 > 49158 [ACK] Seq=1283213957 Ack=3203342359 Win=24616 Len=0
46	10.695879	miami.ad.nps.navy.mil	166.138.205.224	TCP	1494 > 49158 [ACK] Seq=1283213957 Ack=3203342461 Win=24616 Len=0
47	10.940162	miami.ad.nps.navy.mil	166.138.205.224	TCP	1494 > 49158 [PSH, ACK] Seq=1283213957 Ack=3203342461 Win=24616 Len=228
48	10.970412	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342461 Ack=1283214185 Win=8192 Len=3
49	11.996845	miami.ad.nps.navy.mil	166.138.205.224	TCP	1494 > 49158 [ACK] Seq=1283214185 Ack=3203342464 Win=24616 Len=0
50	12.096840	miami.ad.nps.navy.mil	166.138.205.224	TCP	1494 > 49158 [PSH, ACK] Seq=1283214185 Ack=3203342464 Win=24616 Len=4
51	12.109357	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342464 Ack=1283214189 Win=8192 Len=5
52	12.177218	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342469 Ack=1283214189 Win=8192 Len=16
53	13.148934	miami.ad.nps.navy.mil	166.138.205.224	TCP	1494 > 49158 [ACK] Seq=1283214189 Ack=3203342485 Win=24616 Len=0
54	13.296946	miami.ad.nps.navy.mil	166.138.205.224	TCP	1494 > 49158 [PSH, ACK] Seq=1283214189 Ack=3203342485 Win=24616 Len=18
55	13.316575	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342485 Ack=1283214207 Win=8192 Len=52
56	14.259000	miami.ad.nps.navy.mil	166.138.205.224	TCP	1494 > 49158 [ACK] Seq=1283214207 Ack=3203342537 Win=24616 Len=0
57	14.373937	miami.ad.nps.navy.mil	166.138.205.224	TCP	1494 > 49158 [PSH, ACK] Seq=1283214207 Ack=3203342537 Win=24616 Len=14
58	14.433253	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [ACK] Seq=3203342537 Ack=1283214221 Win=8192 Len=0
59	15.028326	miami.ad.nps.navy.mil	166.138.205.224	TCP	1494 > 49158 [ACK] Seq=1283214221 Ack=3203342537 Win=24616 Len=878
60	15.033398	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [ACK] Seq=3203342537 Ack=1283215099 Win=8192 Len=0
61	15.295354	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342537 Ack=1283215099 Win=8192 Len=20
62	15.295950	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342557 Ack=1283215099 Win=8192 Len=16
63	15.296152	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342573 Ack=1283215099 Win=8192 Len=18
64	15.520859	miami.ad.nps.navy.mil	166.138.205.224	TCP	1494 > 49158 [ACK] Seq=1283215099 Ack=3203342537 Win=24616 Len=1448
65	15.633599	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [ACK] Seq=3203342591 Ack=1283216547 Win=8192 Len=0
66	15.859874	miami.ad.nps.navy.mil	166.138.205.224	TCP	1494 > 49158 [ACK] Seq=1283216547 Ack=3203342537 Win=24616 Len=1448
67	15.913222	miami.ad.nps.navy.mil	166.138.205.224	TCP	1494 > 49158 [PSH, ACK] Seq=1283217995 Ack=3203342537 Win=24616 Len=284
68	16.033714	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [ACK] Seq=3203342591 Ack=1283218279 Win=8192 Len=0
69	16.473054	miami.ad.nps.navy.mil	166.138.205.224	TCP	1494 > 49158 [ACK] Seq=1283218279 Ack=3203342573 Win=24616 Len=0
70	16.563322	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342591 Ack=1283218279 Win=8192 Len=16
71	16.658085	miami.ad.nps.navy.mil	166.138.205.224	TCP	1494 > 49158 [ACK] Seq=1283218279 Ack=3203342591 Win=24616 Len=0
72	17.509972	miami.ad.nps.navy.mil	166.138.205.224	TCP	1494 > 49158 [PSH, ACK] Seq=1283218279 Ack=3203342591 Win=24616 Len=978
73	17.524915	miami.ad.nps.navy.mil	166.138.205.224	TCP	1494 > 49158 [ACK] Seq=1283219257 Ack=3203342607 Win=24616 Len=0
74	17.550437	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342607 Ack=1283219257 Win=8192 Len=28
75	17.550879	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342635 Ack=1283219257 Win=8192 Len=14
76	17.551022	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342649 Ack=1283219257 Win=8192 Len=14
77	18.110339	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342663 Ack=1283219257 Win=8192 Len=14
78	18.396989	miami.ad.nps.navy.mil	166.138.205.224	TCP	1494 > 49158 [ACK] Seq=1283219257 Ack=3203342649 Win=24616 Len=0
79	18.577051	miami.ad.nps.navy.mil	166.138.205.224	TCP	1494 > 49158 [ACK] Seq=1283219257 Ack=3203342663 Win=24616 Len=0
80	18.859035	miami.ad.nps.navy.mil	166.138.205.224	TCP	1494 > 49158 [PSH, ACK] Seq=1283219257 Ack=3203342663 Win=24616 Len=40
81	19.034148	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [ACK] Seq=3203342677 Ack=1283219297 Win=8192 Len=0
82	19.597002	miami.ad.nps.navy.mil	166.138.205.224	TCP	1494 > 49158 [ACK] Seq=1283219297 Ack=3203342663 Win=24616 Len=1448
83	19.634286	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [ACK] Seq=3203342677 Ack=1283220745 Win=8192 Len=0
84	19.971007	miami.ad.nps.navy.mil	166.138.205.224	TCP	1494 > 49158 [ACK] Seq=1283220745 Ack=3203342663 Win=24616 Len=1448
85	20.034427	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [ACK] Seq=3203342677 Ack=1283222193 Win=8192 Len=0
86	20.108190	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342677 Ack=1283222193 Win=8192 Len=20
87	20.124486	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342697 Ack=1283222193 Win=8192 Len=16
88	20.141167	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342713 Ack=1283222193 Win=8192 Len=16
89	20.157883	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342729 Ack=1283222193 Win=8192 Len=16
90	20.174726	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342745 Ack=1283222193 Win=8192 Len=14
91	20.191493	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342759 Ack=1283222193 Win=8192 Len=16
92	20.208540	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342775 Ack=1283222193 Win=8192 Len=16
93	20.225457	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342791 Ack=1283222193 Win=8192 Len=16
94	20.241995	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342807 Ack=1283222193 Win=8192 Len=16
95	20.258802	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342823 Ack=1283222193 Win=8192 Len=16
96	20.275604	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342839 Ack=1283222193 Win=8192 Len=14
97	20.292411	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342853 Ack=1283222193 Win=8192 Len=14
98	20.309280	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342867 Ack=1283222193 Win=8192 Len=16
99	20.343086	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342883 Ack=1283222193 Win=8192 Len=14
100	20.359654	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342897 Ack=1283222193 Win=8192 Len=16
101	20.376519	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342913 Ack=1283222193 Win=8192 Len=14
102	20.394330	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342927 Ack=1283222193 Win=8192 Len=14
103	20.410169	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342941 Ack=1283222193 Win=8192 Len=14
104	20.427009	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342955 Ack=1283222193 Win=8192 Len=16
105	20.443839	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342971 Ack=1283222193 Win=8192 Len=14
106	20.460662	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342985 Ack=1283222193 Win=8192 Len=14
107	20.477476	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203342999 Ack=1283222193 Win=8192 Len=16
108	20.494199	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203343015 Ack=1283222193 Win=8192 Len=16
109	20.511078	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203343031 Ack=1283222193 Win=8192 Len=16
110	20.527916	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203343047 Ack=1283222193 Win=8192 Len=14
111	20.544692	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203343061 Ack=1283222193 Win=8192 Len=16
112	20.608191	miami.ad.nps.navy.mil	166.138.205.224	TCP	1494 > 49158 [ACK] Seq=1283222193 Ack=3203342663 Win=24616 Len=1448
113	20.634566	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [ACK] Seq=3203343077 Ack=1283223641 Win=8192 Len=0
114	20.858031	miami.ad.nps.navy.mil	166.138.205.224	TCP	1494 > 49158 [PSH, ACK] Seq=1283223641 Ack=3203342663 Win=24616 Len=1023
115	20.888175	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203343077 Ack=1283224664 Win=8192 Len=67
116	20.935623	166.138.205.224	miami.ad.nps.navy.mil	TCP	49158 > 1494 [PSH, ACK] Seq=3203343144 Ack=1283224664 Win=8192 Len=15

Figure 65 The First 116 Packets (from 355) Exchanged during a Connection to the miami.ad.nps.navy.mil Server (IP: 131.120.18.63) from the Mobile Phone (IP: 166.138.205.224).

5. Task 5: Communicating with Messaging Service

One of the most popular Internet features is the capability of a multimedia conversation between two hosts through messaging services. Since the mobile phones themselves provide voice service, an interesting experiment would be a video conversation between the laptop and another host. For this purpose, the author used the Yahoo messenger service. The video conversation was conducted between the laptop, which was connecting to the Yahoo servers through the GPRS mobile connection, and a desktop host running Windows XP, which was connected to the same servers through a residential dial-up connection.

While the communication between hosts was successful in instant messaging, the video conversation could not be held more than a few seconds. This probably occurred because of the increased bandwidth demand of real time video that the GPRS network could not constantly support. In all tests performed, and according to the Ethereal packet analysis, the throughput of the video connection varied from 5 to 15kbps. Figure 66 presents a portion of the exchanged packets between the laptop (IP: 166.138.194.53) and desktop (IP: 66.81.155.79) through the Yahoo messenger servers.

31	27.103923	166.138.194.53	216.155.193.148	YMSG	Message, Unknown Status: 1515563605
32	27.992445	216.155.193.148	166.138.194.53	TCP	mmcc > 49153 [ACK] Seq=724 Ack=722 Win=24616 Len=0 TSV=378591809 TSER=2908926857
33	28.923609	216.155.193.148	166.138.194.53	YMSG	YAHOO_SERVICE_NOTIFY, YAHOO_STATUS_BRB
34	29.028122	166.138.194.53	216.155.193.148	TCP	49153 > mmcc [ACK] Seq=722 Ack=828 Win=8192 Len=0 TSV=2908926861 TSER=378591897
35	29.078457	166.138.194.5	166.138.194.53	TCP	redstorm_find > commplex-main [SYN] Seq=0 Ack=0 Win=8760 Len=0 MSS=1460
36	35.293567	166.138.194.5	166.138.194.53	TCP	redstorm_find > commplex-main [SYN] Seq=0 Ack=0 Win=8760 Len=0 MSS=1460
37	36.198683	216.155.193.148	166.138.194.53	YMSG	YAHOO_SERVICE_NOTIFY, YAHOO_STATUS_BRB
38	36.228962	166.138.194.53	216.155.193.148	TCP	49153 > mmcc [ACK] Seq=722 Ack=911 Win=8192 Len=0 TSV=2908926875 TSER=378592625
39	37.115720	216.155.193.148	166.138.194.53	YMSG	YAHOO_SERVICE_NOTIFY, YAHOO_STATUS_BRB
40	37.229155	166.138.194.53	216.155.193.148	TCP	49153 > mmcc [ACK] Seq=722 Ack=1015 Win=8192 Len=0 TSV=2908926877 TSER=378592717
41	44.717413	166.138.194.53	216.155.193.148	YMSG	Unknown Service: 80, YAHOO_STATUS_AVAILABLE
42	46.062800	216.155.193.148	166.138.194.53	TCP	mmcc > 49153 [ACK] Seq=1015 Ack=786 Win=24616 Len=0 TSV=378593600 TSER=2908926892
43	46.121854	216.155.193.148	166.138.194.53	YMSG	Unknown Service: 80, YAHOO_STATUS_BRB
44	46.174341	166.138.194.53	216.155.194.76	TCP	49166 > 5100 [SYN] Seq=0 Ack=0 Win=8192 Len=0 MSS=1460 WS=0 TSV=2908926895 TSER=0
45	46.230175	166.138.194.53	216.155.193.148	TCP	49153 > mmcc [ACK] Seq=786 Ack=1111 Win=8192 Len=0 TSV=2908926895 TSER=378593617
46	46.891804	216.155.194.76	166.138.194.53	TCP	5100 > 49166 [SYN, ACK] Seq=0 Ack=1 Win=24616 Len=0 TSV=378593697 TSER=2908926895 WS=0 MSS=
47	46.891901	166.138.194.53	216.155.194.76	TCP	49166 > 5100 [ACK] Seq=1 Ack=1 Win=8192 Len=0 TSV=2908926897 TSER=378593697
48	46.892682	166.138.194.53	216.155.194.76	TCP	49166 > 5100 [PSH, ACK] Seq=1 Ack=1 Win=8192 Len=8 TSV=2908926897 TSER=378593697
49	47.761815	216.155.194.76	166.138.194.53	TCP	5100 > 49166 [ACK] Seq=1 Ack=9 Win=24616 Len=0 TSV=378593781 TSER=2908926897
50	47.761906	166.138.194.53	216.155.194.76	TCP	49166 > 5100 [PSH, ACK] Seq=9 Ack=1 Win=8192 Len=23 TSV=2908926898 TSER=378593781
51	48.531854	216.155.194.76	166.138.194.53	TCP	5100 > 49166 [PSH, ACK] Seq=1 Ack=32 Win=24616 Len=23 TSV=378593864 TSER=2908926898
52	48.532586	166.138.194.53	216.155.194.76	TCP	49166 > 5100 [RST, ACK] Seq=32 Ack=24 Win=8192 Len=0
53	48.582792	216.155.194.76	166.138.194.53	TCP	5100 > 49166 [FIN, ACK] Seq=24 Ack=32 Win=24616 Len=0 TSV=378593864 TSER=2908926898
54	48.582861	166.138.194.53	216.155.194.76	TCP	[TCP ZeroWindow] 49166 > 5100 [RST] Seq=32 Ack=542441069 Win=0 Len=0
55	48.635670	166.138.194.53	216.155.194.70	TCP	49167 > 5100 [SYN] Seq=0 Ack=0 Win=8192 Len=0 MSS=1460 WS=0 TSV=2908926900 TSER=0
56	50.153905	166.138.194.5	166.138.194.53	TCP	ms-olap3 > 6129 [SYN] Seq=0 Ack=0 Win=8760 Len=0 MSS=1460
57	50.769868	166.138.194.5	166.138.194.53	TCP	ms-olap3 > 6129 [SYN] Seq=0 Ack=0 Win=8760 Len=0 MSS=1460
58	50.837840	216.155.194.70	166.138.194.53	TCP	5100 > 49167 [SYN, ACK] Seq=0 Ack=1 Win=24616 Len=0 TSV=378594091 TSER=2908926900 WS=0 MSS=
59	50.837931	166.138.194.53	216.155.194.70	TCP	49167 > 5100 [ACK] Seq=1 Ack=1 Win=8192 Len=0 TSV=2908926905 TSER=378594091
60	50.838719	166.138.194.53	216.155.194.70	TCP	49167 > 5100 [PSH, ACK] Seq=1 Ack=1 Win=8192 Len=8 TSV=2908926905 TSER=378594091
61	51.672880	216.155.194.70	166.138.194.53	TCP	5100 > 49167 [ACK] Seq=1 Ack=9 Win=24616 Len=0 TSV=378594175 TSER=2908926905
62	51.672973	166.138.194.53	216.155.194.70	TCP	49167 > 5100 [PSH, ACK] Seq=9 Ack=1 Win=8192 Len=129 TSV=2908926906 TSER=378594175
63	52.626909	216.155.194.70	166.138.194.53	TCP	5100 > 49167 [ACK] Seq=1 Ack=138 Win=24616 Len=0 TSV=378594273 TSER=2908926906
64	52.653909	216.155.194.70	166.138.194.53	TCP	5100 > 49167 [PSH, ACK] Seq=1 Ack=138 Win=24616 Len=13 TSV=378594274 TSER=2908926906
65	52.830881	166.138.194.53	216.155.194.70	TCP	49167 > 5100 [ACK] Seq=138 Ack=14 Win=8192 Len=0 TSV=2908926909 TSER=378594274
66	53.551936	216.155.194.70	166.138.194.53	TCP	5100 > 49167 [ACK] Seq=14 Ack=138 Win=24616 Len=13 TSV=378594365 TSER=2908926906
67	53.631015	166.138.194.53	216.155.194.70	TCP	49167 > 5100 [ACK] Seq=138 Ack=27 Win=8192 Len=0 TSV=2908926910 TSER=378594365
68	54.161747	216.155.194.70	166.138.194.53	TCP	5100 > 49167 [ACK] Seq=27 Ack=138 Win=24616 Len=1448 TSV=378594365 TSER=2908926906
69	54.231128	166.138.194.53	216.155.194.70	TCP	49167 > 5100 [ACK] Seq=138 Ack=1475 Win=8192 Len=0 TSV=2908926911 TSER=378594365
70	54.371876	166.138.194.53	66.81.155.79	TCP	49168 > 5100 [SYN] Seq=0 Ack=0 Win=8192 Len=0 MSS=1460 WS=0 TSV=2908926912 TSER=0

Figure 66 Packets Captured Prior to Video Communication with Yahoo Messenger Service between the Laptop (IP: 166.138.194.53) and the Desktop (IP: 66.81.155.79) through Yahoo Messenger Servers.

D. REMARKS CONCERNING THE GPRS CELLULAR DATA PERFORMANCE

The author used the Cingular Wireless GPRS cellular Internet connection in Monterey, California for two months. According to hands-on experience, the following observations and remarks for this type of connection are:

- Throughput average up to 16-20 Kbps in download and 8-12 Kbps in upload.
- Even though the mobile phone had the ability to connect to either the permanent or temporary IP to the cellular GPRS network, this was never noticed. For the entire length of each session, the phone was assigned a dynamic IP from the provider's DHCP server.
- The cellular provider enforces a timeout period in which, if the phone does not have a data traffic connection, it ends to prevent valuable air bandwidth misuse. The mobile phone returns to the IDLE state (see Figure 37).
- Data rates most of the times are analogous to the phones signal reception. The nearer the mobile phone is to the base station, the better signal. Accordingly, the mobile data connection has fewer errors in transmission, and thus, achieves its maximum rates.
- The size of overhead in the transmitted packers is analogous to the cellular network availability. A weak signal leads to a more error prone link, thus, more error correction is required, which creates more overhead, and finally, decreases the throughput.
- In most cases, when the mobile phone's signal level is low (one or two bars out of seven in the used mobile phone screen), the authentication process of the user to the cellular network could not completed.
- The Bluetooth packaging adds an extra layer in the protocol stack between the phone and laptop. It is not believed to create a bottleneck since the Bluetooth's bit rate is much higher that the GPRS (at a range of 1 Mbps). In addition, it provides great flexibility and ease of connectivity between the mobile phone and laptop.

V. PERFORMANCE ISSUES IN CELLULAR DATA NETWORKS

This chapter consists of three parts. The first analyzes the measured Round Trip Times observed during the GPRS data testing (see Chapter IV). The second discusses some proposed solutions for enhancing TCP performance and if they were implemented in the tested GPRS connection. Finally, the third part provides a summary.

A. ROUND TRIP TIME MEASUREMENTS

One of the main considerations in wireless networks performance is the limitations of the *Transmission Control Protocol* (TCP) in the radio environment. This protocol was initially designed for ground networks with small throughput for today's standards[90]. The physical layer in wireless environments is the air, which is much more sensitive to external parameters than the ground wired layer, and thus, experiences burst packet losses and high packet delays. Cellular data networking could not overcome these problems easily. In order to achieve high performance data transfers, some techniques have been added to TCP.

One of the most important attributes in networking performance is the *Round Trip Time* (RTT). This is calculated as the time needed for a packet to leave a sending host, reach a remote receiving host and finally return back to the sending host. This is measured by a *ping* or *traceroute* to a remote host. A *Long Network* (LN) has a high Round Trip Time (RTT) packet; usually above 500msec. Geosynchronous Satellite links are considered long networks. A *Fat Network* (FN) is has a high bandwidth such as xDSL or fiber connections. A *Thin Network* (TN) has a small bandwidth such as a standard dial-up connection[91].

The *Bandwidth Delay Product* (BDP) is the amount of data that can be transferred in a network pipeline without being buffered by either the sender or the receiver. It is calculated by multiplying the available bandwidth (BW) with the round trip time (RTT), thus BDP= BW * RTT. For wireless links, the theoretical RTT is 200ms. So,

90 RFC 0793, Transmission Control Protocol Specification, September 1981.

91 RFC 2757, Long Thin Networks, January 2000.

- For 2.5G networks: theoretical BW=384Kbps, thus BDP = 384Kbps*200ms = 76800b = 9,4KB
- For 3G networks: theoretical BW=2000Kbps, thus BDP = 2000Kbps*200ms = 400000b = 48,8KB

Therefore, the 2.5G networks are considered *Long Thin Networks* (LTN) and the 3G networks *Long Fat Networks* (LFN).

In order to evaluate the Round Trip Time (RTT) in the GPRS cellular environment, the author "pinged" different websites in the United States and Greece from the laptop. The measured RTT's of the GPRS connection are compared with a wired residential wired dial-up connection at 36 Kbps. For measurement accuracy, each website was pinged six different times. It should be noted that each RTT value is the calculated average of 10 ICMP packets of 64 bytes each. Table 13 shows the results of RTT measurements with the GPRS and dial-up connection, which were taken within a two hour period.

The author performed additional RTT measurements with the GPRS connection at the websites of Table 13 while moving 50-60 mph with a car on a highway. The average values recorded where at least 30% higher than those of Table 13. Interestingly, in some low level signal areas of the highway, RTT values exceeded 5 secs.

As an alternative method of measuring the RTT, the VisualRoute software[92] was used to traceroute three websites included in Table 13, each located on a different continent. The calculated RTT was above 1 sec in all cases. Figure 67, Figure 68 and Figure 69 are screenshots of those measurements on the laptop with a GPRS static connection.

92 Visualware Inc., [http://www.visualware.com/], July 2004.

Web server	Average RTT values measured through static GPRS connection [ms]	Average RTT values measured through dial-up residential connection [ms]
www.yahoo.gr IP: 216.109.118.60	876, 885, 824, 905, 888, 985	277, 211, 210, 209, 212, 208
www.megatv.gr IP: 207.239.159.89	727, 791, 895, 2633, 930, 1094	216, 216, 214, 199, 201, 205
www.naftemporiki.gr IP: 194.30.220.71	1469, 1387, 3679, 1578, 1845, 1909	344, 343, 342, 340, 350, 507
www.nokia.gr IP: 195.167.100.121	912, 960, 1024, 1250, 1090, 1107	336, 335, 337, 336, 335, 339
www.nokia.com IP: 147.243.3.73	1045, 1118, 1585, 969, 1024, 1019	314, 312, 314, 315, 315, 319
www.honda.com IP: 164.109.25.248	1108, 1217, 820, 935, 850, 845	722, 307, 204, 203, 202, 215
www.nttdocomo.com IP: 64.56.174.15	1656, 2415, 1123, 1256, 1015, 1108	511, 512, 509, 510, 511, 506
www.netflix.com IP: 216.35.131.200	881, 948, 900, 899, 1033, 972	133, 135, 133, 133, 138, 135
www.apple.com IP: 17.254.0.91	840, 1140, 945, 882, 1940, 794	411, 135, 135, 131, 133, 140
www.ericsson.com IP: 204.60.219.170	830, 877, 871, 832, 1130, 824	217, 215, 216, 215, 218, 212

Table 13 RTT Comparison Chart Between Cellular and Wired Data Connection

Hop	%Loss	IP Address	Node Name	Location	Tzone	ms	Graph	Network
0		166.138.207.29	mobile-166-138-207-029.mycingular.net	*			0 2398	166.138.207.0
1		66.102.160.10	-			1173		66.102.160.0
2		66.102.160.1	-			1184		66.102.160.0
3		10.45.80.112	-	...		1257		(private use)
4		10.45.80.1	-	...		1212		(private use)
5		66.102.163.133	-			1196		66.102.163.0
6		66.209.15.129	-			1521		Click on an item in the table to see more information
7	10	66.10.13.1	-			1783		66.10.13.0
8		66.10.48.242	bb2-g8-3-0.nycmny.sbcglobal.net			1748		66.10.48.0
9	10	151.164.240.222	-			1826		151.164.240.0
10	10	151.164.188.198	-			1813		151.164.188.0
11		151.164.243.138	-			1757		151.164.243.0
12		151.164.191.138	ex2-p5-0.eqabva.sbcglobal.net			1685		151.164.191.0
13		144.223.246.37	sl-st20-ash-14-0.sprintlink.net	-		1716		144.223.246.0
14		192.205.32.165	sprint-gw.dc.att.net	-		1676		192.205.32.0
15	10	12.123.9.82	tbr1-p014001.wswdc.ip.att.net	Washington, DC, USA	-05:00	1764		12.123.9.0
16		12.122.10.30	tbr1-cl4.sl9mo.ip.att.net	St. Louis, MO, USA	-06:00	1687		12.122.10.0
17		12.122.10.42	-			1637		12.122.10.0
18		12.122.2.245	-			1599		12.122.2.0
19	10	12.124.34.38	-			1648		12.124.34.0
20	10	17.112.8.11	-			1593		17.112.8.0
21		17.112.153.31	-			1595		17.112.153.0
22		**17.112.152.32**	www.apple.com			1583		17.112.152.0

Roundtrip time to www.apple.com, average = 1583ms, min = 1234ms, max = 1962ms -- Jul 26, 2004 3:47:17 PM

Figure 67 Traceroute to www.apple.com (IP: 17.112.152.32) from the Mobile Phone (IP: 166.138.207.29). Average RTT=1583ms.

Hop	%Loss	IP Address	Node Name	Location	Tzone	ms	Graph	Network
0		166.138.207.29	mobile-166-138-207-029.mycingular.net	*			0 1834	166.138.207.0
1	10	66.102.160.10	-			1288		66.102.160.0
2	10	66.102.160.1	-			1318		66.102.160.0
3	10	10.45.80.112	-	...		1291		(private use)
4	10	10.45.80.1	-	...		1271		(private use)
5	30	66.102.163.133	-			1304		66.102.163.0
6	10	66.209.15.129	-			1156		66.209.15.0
7	20	66.10.13.1	-			1146		66.10.13.0
8	10	66.10.48.242	bb2-g8-3-0.nycmny.sbcglobal.net			1223		66.10.48.0
9	10	151.164.189.145	ex1-p9-0.eqnwnj.sbcglobal.net			1168		Click on an item in the table to see more information
10	10	206.223.131.6	eqx1.new.seabone.net			1142		206.223.131.0
11	10	195.22.218.19	ge6-0-pal5-pala.pal.seabone.net	Palermo, Sicily, Italy	+01:00	1291		TI Sparkle Seabone Palermo POP
12	10	195.22.218.106	customer-side-hellasonline-1-gr-pal5.pal.se	Palermo, Sicily, Italy	+01:00	1301		TI Sparkle Seabone Palermo POP
13	10	62.38.4.66	vlan15.ath01.msfc.hol.gr	Athens, Greece	+02:00	1319		Hellas On Line S.A.
14		**194.30.220.71**	www.naftemporiki.gr	Athens, Greece	+02:00	1551		Hellas On Line S.A.

Roundtrip time to www.naftemporiki.gr, average = 1551ms, min = 879ms, max = 1819ms -- Jul 26, 2004 3:49:21 PM

Figure 68 Traceroute to www.naftemporiki.gr (IP: 194.30.220.71) from the Mobile Phone (IP: 166.138.207.29) Average RTT=1551ms.

Hop	%Loss	IP Address	Node Name	Location	Tzone	ms	Graph	Network
0		166.138.207.29	mobile-166-138-207-029.mycingular.net	*			0 8730	166.138.207.0
1	60	66.102.160.10	-			1751		66.102.160.0
2	60	66.102.160.1	-			1726		66.102.160.0
3	50	10.45.80.112	-	...		2370		(private use)
4	60	10.45.80.1	-	...		1690		(private use)
5	60	66.102.163.133	-			1984		66.102.163.0
6	60	66.209.15.129	-			1961		66.209.15.0
7	60	66.10.13.1	-			2004		66.10.13.0
8	60	66.10.48.225	bb1-g1-3-0.nycmny.sbcglobal.net			2055		66.10.48.0
9	60	151.164.189.62	bb1-p9-0.pxnyny.sbcglobal.net			2170		151.164.189.0
10	60	151.164.248.82	asn3561-cwusa.pxnyny.sbcglobal.net			2123		151.164.248.0
11	60	206.24.194.103	agr3-loopback.newyork.savvis.net	-		2056		206.24.194.0
12	60	206.24.207.77	dcr1-so-7-3-0.newyork.savvis.net	-		1942		206.24.207.0
13	60	208.172.34.107	-			2094		208.172.34.0
14	60	208.172.47.2	bpr1-ae1.losangeles.savvis.net	Los Angeles, CA, USA	-08:00	21		Click on an item in the table to see more information
15	60	208.173.57.26	-			2535		208.173.57.0
16	60	158.205.192.45	-			2701		158.205.192.0
17	60	158.205.192.150	ge3-0.tokg1.idc.ad.jp			2628		158.205.192.0
18	60	158.205.250.146	-			2488		158.205.250.0
19	60	64.56.161.234	csr02-ve242.tkyo01.idc.ad.jp			2528		64.56.161.0
20	60	64.56.174.186	-			2683		64.56.174.0
21	70	64.56.174.15	-			2055		64.56.174.0
22	70	**64.56.174.15**	www.nttdocomo.com			2019		64.56.174.0

Roundtrip time to www.nttdocomo.com, average = 2019ms, min = 1188ms, max = 6513ms -- Jul 26, 2004 3:26:17 PM

Figure 69 Traceroute to www.nttdocomo.com (IP: 64.56.174.15) from the Mobile Phone (IP: 166.138.207.29) Average RTT=2019ms.

B. TCP PERFORMANCE CONSIDERATIONS

Since the commonest Internet applications such as web browsing, file transfer and e-mail using TCP as their embedded protocol, the TCP optimizing performance over wireless broadband network environments is a key issue. In order to maintain the highest possible throughput in the wireless link, some recommendations were made in the configuration of the following areas[93].

1. TCP Window Size

By initial design, the TCP header uses a 16 bit field to declare the receive window to the sending host. Therefore, the maximum buffer size allowed at the receiver is 2^{16} bits or 64 KB. Each Operating System (OS) enforcing the TCP window size should not be smaller than the Bandwidth Delay Product (BDP). Typically, the TCP window size in most OS is initially set to 8 or 16 KB. According to the measurements taken for the GPRS connection in Chapter IV, the average bandwidth is in the range of 20 Kbps while standing. The average RTT from Table 13 is in the range of 1000 ms. Thus, the actual BDP = 20 Kbps*1000 ms = 20000 b = 2.44 KB. This value is much smaller than the theoretical 9.4 KB for the 2.5G networks and within the limits of 64 KB.

Due to the need for supporting data links that have BDP above 64KB, the window scale extension was presented[94]. It expands the TCP window header from 16 to 32 bits by using a scale factor to carry the 32-bit value in the 16-bit window field header. To accommodate this feature, a new three byte TCP Option was introduced called *Window Scale Option* that is sent in a SYN segment. In essence, window scaling is used to adjust the default buffer size for both the sender and receiver in order to allow a larger window as needed.

Maximum Transmission Unit (MTU) is the maximum size in bytes of the OSI layer 3 IP packets in order to be accommodated in OSI link layer 2. *Maximum Segment Size* (MSS) is the amount of data in bytes that can be transferred in the packet of each network (headers not included). The majority of networks globally are based on the

93 RFC 3481, TCP over 2.5G and 3G Wireless Networks, February 2003.

94 RFC 1323, TCP Extensions for High Performance, May 1992.

Ethernet, which has a MTU of 1500 bytes. The TCP/IP headers without options are 40 bytes, thus giving an MSS of 1460 bytes. Congestion control algorithms for the TCP packets following the three way handshake allow the initial window of one segment. Afterwards, and given the traffic load, the TCP window can be increased accordingly. A proposed solution is to enforce the upper bound of the initial window to be increased up to 4 KB, and specifically, by the formula:

Initial Window <= min {4*MSS, max (2*MSS, 4380Bytes)}[95]

In the above formula, if MSS less is than 1095 bytes, then the window is less than 4*MSS. If the MSS is between 1095 and 2190 bytes, then the window must be less than 4380 bytes. Finally, if the MSS is greater than 2190 bytes, then window must be less than 2*MSS. According to the packet analysis of the GPRS data connection conducted by the author, this proposal has not been implemented in any of the accessed servers.

2. Limited Transmit and Retransmission Time Out

A sender host detect that a segment did not reach the destination in order to resent it, in which case,

- an acknowledgement is not received within a specific amount of time called *Retransmission Time Out* (RTO) or,
- the *Fast Retransmit* algorithm occurs in which three duplicate acknowledgements (ACK) for a single segment are received.

After a segment has been declared lost, the sender host resends it by following mechanisms such as *Slow Start* or *Fast Recovery*[96]. The RTO is computed according to the RTT measurements taken during the connection. If it is calculated to be less than a second, then it is rounded up to 1 sec[97]. Due to the high latency of the cellular networks, the RTO value of 1sec is too small and may lead to spurious timeouts. As shown in the beginning of this chapter, the average RTT measured during the testing of the GPRS connection was in the range of 1sec and most of the times were much higher. In addition,

95 RFC 3390, Increasing TCP's Initial Window, October 2002.

96 RFC 3782, The NewReno Modification to TCP's Fast Recovery Algorithm, April 2004.

97 RFC 2988, Computing TCP's Retransmission Timer, November 2000.

the Limited Transmit algorithm proposes that the sender host should retransmit a segment in the first two consecutive duplicate ACKs under certain conditions before the RTO expires [98].

Therefore, using the Limited Transmit algorithm and setting the RTO value higher than 1 sec, it is highly recommended in cellular data links.

3. Maximum Transmission Unit (MTU)

The path between two communicating hosts consists of various types of networks; each one with its own MTU. Typical values for the Internet's known networks are 576 bytes for X25, 1006bytes for Slip, 1500 bytes for Ethernet and 4352 for FDDI. The minimum allowed MTU size is 68 bytes and a maximum of 65535 bytes. One of the reasons for slowing the link is that the packets sent from the sending host must be fragmented in order for the middle hosts to forward them properly. Fragmentation creates overhead by increasing the number of packets needed for forwarding. For this reason, a sender host forwards packets with the *Don't Fragment* (DF) flag on the IP header set. In case a middle router cannot forward the packet because it exceeds the MTU of the next hop network, it returns an ICMP Destination Unreachable message to the sender including this MTU value. The sender either removes the DF flag and fragmentation occurs, or it creates new packets with the lower MTU value. This mechanism is known as *Path MTU Discovery*[99] since it allows the sender host to find the minimum MTU size needed for reaching the receiver host without IP fragmentation.

4. Selective Acknowledgements (SACK)

According to the initial design of TCP, the receiving host sends back a cumulative acknowledgement to the sender for the packets received. If only a few packets were missing within a larger block, with the cumulative ACK, the sender host would have to resend the packets already received. The *Selective Acknowledgement* (SACK) strategy[100]

98 RFC 3042, Enhancing TCP's Loss Recovery with limited Transmit, January 2001.

99 RFC 1191, Path MTU Discovery, November 1990.

100 RFC 2018, TCP Selective Acknowledgment Options, October 1996.

uses two TCP header options and allows the receiver host to inform the sender host about segments that did not successfully arrive (even if not consecutive) within a larger block. Therefore, the sender may retransmit only the missing ones and not the whole block again. This avoids redundant packet transmit, which directly affects the throughput.

5. Explicit Congestion Notification (ECN)

This feature allows a receiver host to inform the sender host of congestion in the network, in order for the latter to reduce its congestion window, and therefore, reduce the number of dropped packets[101]. It requires the setting of relative flags in the TCP and IP headers of packets exchanged between the communicating hosts. Each host implementing ECN sets the *ECN-Capable Transport* (ECT) flag in the IP header. If a router somewhere in the path towards the receiver confronts congestion, instead of discarding the packet, it forwards it with the *ECN-CE* IP header flag set. The receiver, upon evaluating the CE-packet, acknowledges the sender by setting the *ECN-Echo* flag of the TCP header. The sender then sets the *Congestion Window Reduced* (CWR) flag of the TCP header to acknowledge the ECN-Echo packet.

The values of the ECN flags can be seen in the packet analysis in Figures 70 to 75. All hosts accessed during the GPRS testing were ECN capable; the laptop's browser included. In the packets captured by the author, no packets found had the CE flag set. This does not imply, however, that the network was never congested.

6. TCP Timestamps

The RTT measurement is essential to TCP performance. Many TCP implementations are calculating RTT only in one packet per window. For rather slow networks (like the tested GPRS), this works adequately, but for the LFN that have a large window size, this sampling is inadequate. A way of providing more accurate RTT measurement is to enforce the *TCP timestamps*[102]. With this method, the sender host is

101 RFC 3168, The Addition of Explicit Congestion Notification (ECN) to IP, September 2001.

102 RFC 1323, TCP Extensions for High Performance, May 1992.

adding a timestamp in each segment. When the receiver replies back, the ACK segment embeds its own timestamp. The sender calculates the links RTT by subtracting the two timestamps. The TCP timestamps option adds 12 bytes to the 20 byte TCP header.

Figures 70 to 75 are single packet analysis. They were captured with Ethereal during the GPRS testing. More precisely, Figures 70 and 71 show the SYN packet from the laptop (IP: 166.138.195.47) to the NPS CS Department web page (IP: 131.120.251.15) and the SYN/ACK reply (essentially the first two packets of the TCP three way handshake). Accordingly, Figures 72 and 73 are from the communication between the laptop (IP: 166.138.202.32) and the NPS ssh server (IP: 131.120.254.103) and Figures 74 and 75 are the communication between the laptop (IP: 166.138.203.204) and the NPS mail server (IP: 131.120.18.61).

As can be seen from Figures 70, 72 and 74, the sending host (the laptop with the MAC OS X) advertised window is 8192 bytes, the MSS is 1460 bytes, there is no window scaling, and includes the timestamp option. Figure 72 reveals that the NPS CS web server advertised window size is 33,304 bytes, the MSS is 1460 bytes, the window scaling is value 1 and includes the timestamp option. Figures 74 and 75 show that the ssh and mail server advertised window size is 24,616 bytes, the MSS is 1460 bytes, there is no window scaling, and includes the timestamp option. The use of the timestamp option in every segment evaluates the RTT value better, and therefore, reduces the risk of spurious timeouts.

7. TCP/IP Header Compression

The TCP/IP header size (without options) of 40 bytes compared to the typical MTU of 576 bytes creates a significant overhead in the link. The TCP/IP header compression algorithm does not transmit the entire headers, but only changes in the headers of consecutive segments[103]. This scheme proved not to work efficiently in the

103 RFC 1144, Compressing TCP/IP Headers, February 1990.

links with a high packet error rate. Newer algorithms were presented to address those issues[104]. Header compression should not be enabled in wireless links unless the packet loss probability between the compressor and de-compressor hosts is low[105].

```
Frame 5 (64 bytes on wire, 64 bytes captured)
    Arrival Time: Jul 13, 2004 17:39:56.863693000
    Time delta from previous packet: 0.001421000 seconds
    Time since reference or first frame: 2.049907000 seconds
    Frame Number: 5
    Packet Length: 64 bytes
    Capture Length: 64 bytes
Point-to-Point Protocol
    Address: 0xff
    Control: 0x03
    Protocol: IP (0x0021)
Internet Protocol, Src Addr: 166.138.195.47 (166.138.195.47), Dst Addr: 131.120.251.15
(131.120.251.15)
    Version: 4
    Header length: 20 bytes
    Differentiated Services Field: 0x00 (DSCP 0x00: Default; ECN: 0x00)
        0000 00.. = Differentiated Services Codepoint: Default (0x00)
        .... ..0. = ECN-Capable Transport (ECT): 0
        .... ...0 = ECN-CE: 0
    Total Length: 60
    Identification: 0xc011 (49169)
    Flags: 0x04
        .1.. = Don't fragment: Set
        ..0. = More fragments: Not set
    Fragment offset: 0
    Time to live: 64
    Protocol: TCP (0x06)
    Header checksum: 0x9268 (correct)
    Source: 166.138.195.47 (166.138.195.47)
    Destination: 131.120.251.15 (131.120.251.15)
Transmission Control Protocol, Src Port: 51066 (51066), Dst Port: http (80), Seq: 0, Ack: 0, Len: 0
    Source port: 51066 (51066)
    Destination port: http (80)
    Sequence number: 0
    Header length: 40 bytes
    Flags: 0x0002 (SYN)
        0... .... = Congestion Window Reduced (CWR): Not set
        .0.. .... = ECN-Echo: Not set
        ..0. .... = Urgent: Not set
        ...0 .... = Acknowledgment: Not set
        .... 0... = Push: Not set
        .... .0.. = Reset: Not set
        .... ..1. = Syn: Set
        .... ...0 = Fin: Not set
    Window size: 8192
    Checksum: 0x7059 (correct)
    Options: (20 bytes)
        Maximum segment size: 1460 bytes
        NOP
        Window scale: 0 (multiply by 1)
        NOP
        NOP
        Time stamp: tsval 339912298, tsecr 0
```

Figure 70 SYN Packet Analysis by Ethereal Sent from the Laptop (IP: 166.138.195.47) to the NPS CS Department Web Page (IP: 131.120.251.15).

---

104 RFC 2507, IP Header Compression, February 1999.

105 RFC 3150, End to End Performance Implications of Slow Links, July 2001.

```
Frame 8 (64 bytes on wire, 64 bytes captured)
    Arrival Time: Jul 13, 2004 17:39:58.233129000
    Time delta from previous packet: 0.056748000 seconds
    Time since reference or first frame: 3.419343000 seconds
    Frame Number: 8
    Packet Length: 64 bytes
    Capture Length: 64 bytes
Point-to-Point Protocol
    Address: 0xff
    Control: 0x03
    Protocol: IP (0x0021)
Internet Protocol, Src Addr: 131.120.251.15 (131.120.251.15), Dst Addr: 166.138.195.47
(166.138.195.47)
    Version: 4
    Header length: 20 bytes
    Differentiated Services Field: 0x00 (DSCP 0x00: Default; ECN: 0x00)
        0000 00.. = Differentiated Services Codepoint: Default (0x00)
        .... ..0. = ECN-Capable Transport (ECT): 0
        .... ...0 = ECN-CE: 0
    Total Length: 60
    Identification: 0x82c9 (33481)
    Flags: 0x04
        .1.. = Don't fragment: Set
        ..0. = More fragments: Not set
    Fragment offset: 0
    Time to live: 62
    Protocol: TCP (0x06)
    Header checksum: 0xd1b0 (correct)
    Source: 131.120.251.15 (131.120.251.15)
    Destination: 166.138.195.47 (166.138.195.47)
Transmission Control Protocol, Src Port: http (80), Dst Port: 51066 (51066), Seq: 0, Ack: 1, Len: 0
    Source port: http (80)
    Destination port: 51066 (51066)
    Sequence number: 0
    Acknowledgement number: 1
    Header length: 40 bytes
    Flags: 0x0012 (SYN, ACK)
        0... .... = Congestion Window Reduced (CWR): Not set
        .0.. .... = ECN-Echo: Not set
        ..0. .... = Urgent: Not set
        ...1 .... = Acknowledgment: Set
        .... 0... = Push: Not set
        .... .0.. = Reset: Not set
        .... ..1. = Syn: Set
        .... ...0 = Fin: Not set
    Window size: 33304
    Checksum: 0xd448 (correct)
    Options: (20 bytes)
        NOP
        NOP
        Time stamp: tsval 1198492948, tsecr 339912298
        NOP
        Window scale: 1 (multiply by 2)
        Maximum segment size: 1460 bytes
    SEQ/ACK analysis
        This is an ACK to the segment in frame: 5
        The RTT to ACK the segment was: 1.369436000 seconds
```

Figure 71 SYN/ACK Reply Packet Analysis by Ethereal Sent from the NPS CS Department Web Page (IP: 131.120.251.15) to the Laptop (IP: 166.138.195.47). Measured RTT 1.369 sec.

```
Frame 1 (64 bytes on wire, 64 bytes captured)
    Arrival Time: Jul 12, 2004 12:21:57.973890000
    Time delta from previous packet: 0.000000000 seconds
    Time since reference or first frame: 0.000000000 seconds
    Frame Number: 1
    Packet Length: 64 bytes
    Capture Length: 64 bytes
Point-to-Point Protocol
    Address: 0xff
    Control: 0x03
    Protocol: IP (0x0021)
Internet Protocol, Src Addr: 166.138.202.32 (166.138.202.32), Dst Addr: 131.120.254.103
(131.120.254.103)
    Version: 4
    Header length: 20 bytes
    Differentiated Services Field: 0x00 (DSCP 0x00: Default; ECN: 0x00)
        0000 00.. = Differentiated Services Codepoint: Default (0x00)
        .... ..0. = ECN-Capable Transport (ECT): 0
        .... ...0 = ECN-CE: 0
    Total Length: 60
    Identification: 0x733d (29501)
    Flags: 0x04
        .1.. = Don't fragment: Set
        ..0. = More fragments: Not set
    Fragment offset: 0
    Time to live: 64
    Protocol: TCP (0x06)
    Header checksum: 0xd4f3 (correct)
    Source: 166.138.202.32 (166.138.202.32)
    Destination: 131.120.254.103 (131.120.254.103)
Transmission Control Protocol, Src Port: 50031 (50031), Dst Port: ssh (22), Seq: 0, Ack: 0, Len: 0
    Source port: 50031 (50031)
    Destination port: ssh (22)
    Sequence number: 0
    Header length: 40 bytes
    Flags: 0x0002 (SYN)
        0... .... = Congestion Window Reduced (CWR): Not set
        .0.. .... = ECN-Echo: Not set
        ..0. .... = Urgent: Not set
        ...0 .... = Acknowledgment: Not set
        .... 0... = Push: Not set
        .... .0.. = Reset: Not set
        .... ..1. = Syn: Set
        .... ...0 = Fin: Not set
    Window size: 8192
    Checksum: 0x0a15 (correct)
    Options: (20 bytes)
        Maximum segment size: 1460 bytes
        NOP
        Window scale: 0 (multiply by 1)
        NOP
        NOP
        Time stamp: tsval 1329234492, tsecr 0
```

Figure 72 SYN Packet Analysis by Ethereal Sent from the Laptop (IP: 166.138.202.32) to the NPS ssh Server (IP: 131.120.254.103).

```
Frame 2 (64 bytes on wire, 64 bytes captured)
    Arrival Time: Jul 12, 2004 12:21:59.266041000
    Time delta from previous packet: 1.292151000 seconds
    Time since reference or first frame: 1.292151000 seconds
    Frame Number: 2
    Packet Length: 64 bytes
    Capture Length: 64 bytes
Point-to-Point Protocol
    Address: 0xff
    Control: 0x03
    Protocol: IP (0x0021)
Internet Protocol, Src Addr: 131.120.254.103 (131.120.254.103), Dst Addr: 166.138.202.32
(166.138.202.32)
    Version: 4
    Header length: 20 bytes
    Differentiated Services Field: 0x00 (DSCP 0x00: Default; ECN: 0x00)
        0000 00.. = Differentiated Services Codepoint: Default (0x00)
        .... ..0. = ECN-Capable Transport (ECT): 0
        .... ...0 = ECN-CE: 0
    Total Length: 60
    Identification: 0x1b5d (7005)
    Flags: 0x04
        .1.. = Don't fragment: Set
        ..0. = More fragments: Not set
    Fragment offset: 0
    Time to live: 62
    Protocol: TCP (0x06)
    Header checksum: 0x2ed4 (correct)
    Source: 131.120.254.103 (131.120.254.103)
    Destination: 166.138.202.32 (166.138.202.32)
Transmission Control Protocol, Src Port: ssh (22), Dst Port: 50031 (50031), Seq: 0, Ack: 1, Len: 0
    Source port: ssh (22)
    Destination port: 50031 (50031)
    Sequence number: 0
    Acknowledgement number: 1
    Header length: 40 bytes
    Flags: 0x0012 (SYN, ACK)
        0... .... = Congestion Window Reduced (CWR): Not set
        .0.. .... = ECN-Echo: Not set
        ..0. .... = Urgent: Not set
        ...1 .... = Acknowledgment: Set
        .... 0... = Push: Not set
        .... .0.. = Reset: Not set
        .... ..1. = Syn: Set
        .... ...0 = Fin: Not set
    Window size: 24616
    Checksum: 0x28a0 (correct)
    Options: (20 bytes)
        NOP
        NOP
        Time stamp: tsval 1187945558, tsecr 1329234492
        NOP
        Window scale: 0 (multiply by 1)
        Maximum segment size: 1460 bytes
    SEQ/ACK analysis
        This is an ACK to the segment in frame: 1
        The RTT to ACK the segment was: 1.292151000 seconds
```

Figure 73 SYN/ACK Reply Packet Analysis by Ethereal Sent from the NPS ssh Server (IP: 131.120.254.103) to the Laptop (IP: 166.138.202.32). Measured RTT 1.292 sec

```
Frame 40 (64 bytes on wire, 64 bytes captured)
    Arrival Time: Jul 19, 2004 14:55:01.898965000
    Time delta from previous packet: 0.069602000 seconds
    Time since reference or first frame: 8.067177000 seconds
    Frame Number: 40
    Packet Length: 64 bytes
    Capture Length: 64 bytes
Point-to-Point Protocol
    Address: 0xff
    Control: 0x03
    Protocol: IP (0x0021)
Internet Protocol, Src Addr: 166.138.203.204 (166.138.203.204), Dst Addr: 131.120.18.61
(131.120.18.61)
    Version: 4
    Header length: 20 bytes
    Differentiated Services Field: 0x00 (DSCP 0x00: Default; ECN: 0x00)
        0000 00.. = Differentiated Services Codepoint: Default (0x00)
        .... ..0. = ECN-Capable Transport (ECT): 0
        .... ...0 = ECN-CE: 0
    Total Length: 60
    Identification: 0x19dd (6621)
    Flags: 0x04
        .1.. = Don't fragment: Set
        ..0. = More fragments: Not set
    Fragment offset: 0
    Time to live: 64
    Protocol: TCP (0x06)
    Header checksum: 0x18d3 (correct)
    Source: 166.138.203.204 (166.138.203.204)
    Destination: 131.120.18.61 (131.120.18.61)
Transmission Control Protocol, Src Port: 49368 (49368), Dst Port: pop3 (110), Seq: 0, Ack: 0, Len: 0
    Source port: 49368 (49368)
    Destination port: pop3 (110)
    Sequence number: 0
    Header length: 40 bytes
    Flags: 0x0002 (SYN)
        0... .... = Congestion Window Reduced (CWR): Not set
        .0.. .... = ECN-Echo: Not set
        ..0. .... = Urgent: Not set
        ...0 .... = Acknowledgment: Not set
        .... 0... = Push: Not set
        .... .0.. = Reset: Not set
        .... ..1. = Syn: Set
        .... ...0 = Fin: Not set
    Window size: 8192
    Checksum: 0xe6dd (correct)
    Options: (20 bytes)
        Maximum segment size: 1460 bytes
        NOP
        Window scale: 0 (multiply by 1)
        NOP
        NOP
        Time stamp: tsval 835631757, tsecr 0
```

Figure 74 SYN Packet Analysis by Ethereal Sent from the Laptop (IP: 166.138.203.204) to the NPS Mail Server (IP: 131.120.18.61).

```
Frame 41 (64 bytes on wire, 64 bytes captured)
    Arrival Time: Jul 19, 2004 14:55:02.629244000
    Time delta from previous packet: 0.730279000 seconds
    Time since reference or first frame: 8.797456000 seconds
    Frame Number: 41
    Packet Length: 64 bytes
    Capture Length: 64 bytes
Point-to-Point Protocol
    Address: 0xff
    Control: 0x03
    Protocol: IP (0x0021)
Internet Protocol, Src Addr: 131.120.18.61 (131.120.18.61), Dst Addr: 166.138.203.204
(166.138.203.204)
    Version: 4
    Header length: 20 bytes
    Differentiated Services Field: 0x00 (DSCP 0x00: Default; ECN: 0x00)
        0000 00.. = Differentiated Services Codepoint: Default (0x00)
        .... ..0. = ECN-Capable Transport (ECT): 0
        .... ...0 = ECN-CE: 0
    Total Length: 60
    Identification: 0x4bb7 (19383)
    Flags: 0x04
        .1.. = Don't fragment: Set
        ..0. = More fragments: Not set
    Fragment offset: 0
    Time to live: 62
    Protocol: TCP (0x06)
    Header checksum: 0xe8f8 (correct)
    Source: 131.120.18.61 (131.120.18.61)
    Destination: 166.138.203.204 (166.138.203.204)
Transmission Control Protocol, Src Port: pop3 (110), Dst Port: 49368 (49368), Seq: 0, Ack: 1, Len: 0
    Source port: pop3 (110)
    Destination port: 49368 (49368)
    Sequence number: 0
    Acknowledgement number: 1
    Header length: 40 bytes
    Flags: 0x0012 (SYN, ACK)
        0... .... = Congestion Window Reduced (CWR): Not set
        .0.. .... = ECN-Echo: Not set
        ..0. .... = Urgent: Not set
        ...1 .... = Acknowledgment: Set
        .... 0... = Push: Not set
        .... .0.. = Reset: Not set
        .... ..1. = Syn: Set
        .... ...0 = Fin: Not set
    Window size: 24616
    Checksum: 0xbaf5 (correct)
    Options: (20 bytes)
        NOP
        NOP
        Time stamp: tsval 274715743, tsecr 835631757
        NOP
        Window scale: 0 (multiply by 1)
        Maximum segment size: 1460 bytes
    SEQ/ACK analysis
        This is an ACK to the segment in frame: 40
        The RTT to ACK the segment was: 0.730279000 seconds
```

Figure 75 SYN/ACK Reply Packet Analysis by Ethereal Sent from the NPS Mail Server (IP: 131.120.18.61) to the Laptop (IP: 166.138.203.204). Measured RTT 0.730 sec.

C. GPRS TCP PERFORMANCE SUMMARY

During GPRS testing, the measured RTT values range from 800-1000ms. For the wired dialup connection, the relative values range between 150-350ms. Faster wired connections such as DSL or fiber optic, may have even smaller RTT. The cellular connection presented high latency variation, due to the physical layer propagation delays. In contrast, the wired RTT measurements are very close to each other, thus having very small variation. The GPRS throughput is low due to the high latency that is increasing the number of TCP retransmissions. The reasons for this behavior are possible link outage due to the temporary loss of radio coverage (signal). Especially for moving hosts, the improper handovers and re-routing packets from old to new base stations further increase the latency.

The measured BDP for the tested GPRS data communication is 2.44KB, which is within the limits of the TCP window size. Various options were added to the TCP segment to limit the number of packet retransmissions and reduce the packet loss, thus increasing the throughput. From those, TCP Timestamps and the Explicit Congestion Notification (ECN) were implemented according to the analysis of captured packets during the GPRS testing. In contrast, TCP/IP Header Compression, Selective Acknowledgements (SACK), MTU Path discovery and Limited Transmit were not implicitly noticed.

VI. CONCLUSION

A. SUMMARY

The first truly mobile Internet access was achievable through the 2G circuit switched cellular networks during the mid-1990's. The 2.5G networks (GPRS, EDGE and IS-95B) introduced packet switched technology and, as with the 3G networks (UMTS and cdma2000), offered increased bandwidth. Other wireless networking protocols introduced in recent years include: IEEE 802.11 (known as WiFi), IEEE 802.16 (known as WiMAX) and the newest IEEE 802.20 (known as Mobile Broadband Wireless Access). The latter two are not widely implemented but are expected to gain market share in the next years.

As of June 2004 in the United States, the offered cellular data plans for 2.5G/3G networks cost from $10 up to $80 according to the type of service; either limited Internet functionality in the mobile phone itself or full functionality in a computer with the phone used as a *wireless modem*. According to the tests reported in Chapter IV, the GPRS network in Monterey, California has a throughput of 20Kbps on average. Other 3G data plans in the United States advertise speeds up to 500kbps.

The usage of cellular data networking is approached and examined according to two major factors: speed and portability. With 2G systems, the available bandwidth is inadequate to support modern technologies. A GSM throughput of 10Kbps was enough to support older text based websites but not modern multimedia ones incorporating audio, video and large size photos. The circuit switched technology was too slow and expensive to be widely used by average users. Packet switched technology in cellular environments maximizes the available bandwidth usage because the idle users do not consume valuable resources. Since cellular data rates are not yet high speed, the main advantage they provide is mobility. Cellular infrastructure has been deployed in Wide Area Networks (WAN) in almost every inhabited area worldwide. Wherever there is coverage and available data service from cellular providers, there is a potential connection to the Internet. One of the limitations for high speed networking in cellular environments is the large Round Trip Time (RTT) delay. During the GPRS network testing (see Chapter IV), the average values were in the range of 1 sec and much higher in low signal areas. This creates latency and degrades performance. Numerous techniques were proposed to solve those issues (see Chapter V). Only Timestamps and the Explicit Congestion Notification (ECN) Options were observed during the test of the GPRS data network.

In order to evaluate the current market position of the cellular Internet, a comparison with other wired and wireless technologies was made and is summarized below.

1. Cellular Data Networks Compared to Wired Data Networks

Wire line solutions include the standard dial-up connection, which offers speeds ranging from 30-50Kbps and monthly fees from $10 to $25. The ISDN, even though never fully deployed in the United States, but being a standard in Europe, offer speeds at 64 or 128 Kbps. Satellite access offered up to 500 Kbps connection for average monthly fees of $70. Broadband solutions such as xDSL and cable provide higher throughput up to 1.5Mbps at a $50 average monthly price. Fiber optic solutions offer much higher data rates, but due to high costs, are mainly used in corporations.

The current 2.5G cellular GPRS solution with data rates at the measured range of 20 Kbps and monthly fees, for unlimited MB plans, up to $80 per month, is considered slow and expensive for residential or corporate usage. As for speed, the 2.5G cellular data connections cannot be considered an alternative to wired line networking. Only the upcoming 3G networks will provide an attractive alternative to current wire-line technologies, and only in case their prices are comparable. It must be considered that mobile technologies are not the only ones evolving over time. The deployment of fiber optics in every house *may* take place in the next few years, and xDSL or cable *may* offer higher bandwidth for the same price, as well. If this is the status of the near future, then only the 4G cellular data networks may be considered an option, given that they could provide comparable broadband services in speed and pricing.

It is obvious that cellular data networks cannot easily replace wired data networks in the near future. Their only current advantage over the wired solutions is not speed but mobility. They can be used whenever the user has a cell signal. If speed is not the priority, but access to information at any place, cellular Internet (2.5G or 3G) is the best implemented solution today.

2. Cellular Data Networks Compared to Wireless Data Networks

Wireless data networking based on IEEE 802.11 protocol has been commercially available the last few years. One of its limitations is that the typical distance of a provided service is in the range of hundreds of feet. For this reason, WiFi is the favored choice for Local Area Networks (LAN). The need for greater coverage in Metropolitan Area Networks (MAN) is driving the WiMAX and MBWA technologies as a possible solution for mobile broadband users. Since wireless home networking has become popular as well, the prices for 802.11 devices have decreased and now the relative hardware is usually embedded in laptops and PDA's. Since the hardware was easily obtainable, various types of services were offered. Numerous WiFi access points (HotSpots) have been deployed worldwide and high speed Internet is available in airports, hotels and other business areas. In the case of WiMAX or MWBA, special devices are needed since they operate at different frequencies. One of the disadvantages is that the goal of those technologies is not home wireless computing, and therefore, the price of relative hardware will decrease at a much slower rate. As of Summer 2004, these are not considered fully deployed.

In the case of cellular data networking, the hardware is already available to consumers. A mobile phone handling voice can also handle data. Developed countries experienced a small increase rate in wired telephone networks between 1997 and 2002 (see Table 3) and a great increase rate in cellular networks (seeTable 4). Especially for the United States, at the end of 2002, almost 50% of the population is cellular subscribers while the four remaining Bell companies since the end of 2000 have lost approximately 18% of their local ground phone lines and are currently loosing 4% of their residential lines per year[106]. This makes the path to mobile Internet through cellular phones much easier. As of Summer 2004 in the United States, the most widely implemented networks use 2.5G technologies with the first 3G networks available in big cities only. Devices that support 2.5G EDGE or other 3G services such as UMTS, are commercially available as well, but they are not yet preferred by consumers due to the lack of a relative infrastructure from the cellular providers.

As far as speed is concerned, the GPRS Internet access is not as fast as the WiFi. The latter is the preferred access method in areas that can support it. The third generation networking is closing the gap. When a consumer is located in remote or rural areas, 2.5G or 3G is an excellent alternative. The commercial deployment of WiMAX and WMBA will supplement the lack of WiFi in Metropolitan Area Networks (MAN) and they will be directly comparable to 3G or the upcoming 4G systems.

B. CONTRIBUTION OF THIS THESIS

This thesis provides an overview of cellular data networking and evaluates the 2.5G network of Cingular Wireless in Monterey, California against throughput and mobility issues. Measurements taken either static or traveling at 60mph, showed that a laptop connected to the GPRS cellular data network achieved throughput from 5-25Kbps and that RTT values vary around 1 sec. The GPRS performance was strongly affected by network congestion and air interface limitations.

The thesis concludes that cellular data access is a preferred solution for private consumers using their mobile phone screen for limited Internet capability (such as text based web pages and email). This service is offered at a reasonable cost. In case full Internet capability is needed for a laptop through cellular data networks, the high cost and limited bandwidth of 2.5G networks makes them a less attractive solution for residential usage. The 3G networks promise to be much faster, but still cannot be considered broadband. As a result, the cellular data connections (2.5G and 3G) intended for laptops best fit enterprise users who want to have Internet access where speed is not the first

106 The Wall Street Journal, 8/25/04, [Article: Heavy Toll, by Ken Brown and Almar Latour].

priority, but rather the availability of information. In particular, the usage of Virtual Private Networking (VPN) over cellular data networks will allow secure access to information practically anywhere, even while moving at speeds of 60 mph.

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