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USB dongles for mobile broadband

Data communications for laptop computers

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Master's Thesis

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Abstract

Today a growing number of people need to work on laptops with wireless Internet connection. There are two common wireless Internet access solutions: wireless local area network (WLAN) via hotspot, and high speed wide area cellular network via mobile broadband device such as 3G/4G Universal Serial Bus (USB) dongle. USB dongle was the pioneer product in 3G/4G market, and it is still a popular device in many countries. Mobile broadband can offer both high speed access and mobility. Technically mobile broadband allows Internet connection as long as your mobile transceiver can access your cellular network operator's network. However, in practice the data rates experienced by a user via mobile broadband are not comparable to the data rates that are available via WLAN. Moreover, mobile broadband has been implemented according to multiple different standards. Hence, in order to provide a user with locally optimal service requires that user must make use of *heterogeneous* networks. Furthermore, the variety of networks gets increasing due to the emergence of various 4G networks.

The aim of this thesis is to explore how heterogeneous networks could be exploited to provide a user of a laptop computer with locally optimal service, while hiding the complexity of this heterogeneous service. The research focuses on the implications of integrating multiple network interfaces into a single USB dongle. Our research shows that multi-mode USB dongle is still needed in market, though there are competitions from smartphones and mobile WiFi devices. We point out that the PPP (Point to Point Protocol) based USB dongle should update to Ethernet USB protocols such as RNDIS (Remote Network Driver Interface Specification) or USB CDC (Communications Device Class) protocols. Furthermore, we suggest a USB dongle should be able to work as a WLAN access point to share Internet with other mobile devices, and it should also work as a WLAN client which can join other hotspots. If hotspot operators can authenticate USB dongles by SIM cards, then users can easily access a great number of hotspots belong to these operators.

Keywords

Data communications, USB, WLAN, 3G, 4G

Sammanfattning

Mer än någonsin behöver människan arbeta med bärbara datorer med anslutning till trådlöst Internet. Det finns två vanliga trådlösa Internet-anslutningar: trådlöst lokalt nätverk (WLAN på engelska) via en hotspot, eller höghastighets mobilnät via mobilt bredband som 3G/4G Universal Serial Bus (USB) dongel. USB dongeln var pionjär produkten inom 3G/4G marknaden, och den är fortfarande en populär enhet i många länder. Mobilt bredband kan erbjuda både tillgång till höga hastighet och bra mobilitet. Mobilt bredband tillåter, rent tekniskt, användaren hålla en Internet-anslutning så länge mobilen har tillgång till mobilnätets operatörsnät. Men i praktiken är datahastigheterna, som användaren upplever ha via det mobila bredbandet, inte jämförbar med de datahastigheter som är tillgängliga via WLAN. Dessutom har mobilt bredband implementerats enligt flera olika standarder. Således, för att förutse en användare med en optimal lokal tjänst, krävs det att användaren måste använda *heterogena* nätverk. Dessutom blir olika nätverk allt större på grund av uppkomsten av olika 4G-nät.

Syftet med denna avhandling är att undersöka hur heterogena nätverk skulle kunna utnyttjas för att förutse en laptop användare med optimal lokal nätverksservice, samtidigt dölja komplexiteten för användaren om den heterogena tjänsten. Forskningen fokuserar på konsekvenserna av att integrera flera nätverksgränssnitt till en enda USB-dongel. Vår forskning visar att det fortfarande behövs en multi-mode USB dongel på marknaden, dock existerar det konkurrens från smartphones och mobila WiFi-enheter. Vi påpekar även i avhandlingen att PPP (Point-to-Point Protocol) baserade USB dongeln bör uppdateras till Ethernet USB-protokoll, såsom RNDIS (Remote Network Driver Interface Specification) eller USB CDC (Communications Device Class) protokoll. Vidare föreslår vi att en USB-dongel bör kunna fungera som en kopplingspunkt för att dela Internet med andra mobila enheter, och att den också bör fungera som en WLAN-klient som kan ansluta sig till andra hotspots. Om hotspot operatörer kan autentisera USB-donglar genom SIM-kort, så kan användarna enkelt få tillgång till ett stort antal hotspots som tillhör dessa operatörer.

Nyckelord

Datakommunication, USB, WLAN, 3G, 4G

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I would like to express my sincere gratitude to my examiner and academic adviser Professor Gerald Q. Maguire Jr. who is the most intelligent, knowledgeable, efficient, and vigorous person I have ever seen. Probably that is the reason why we call him "Chip". Professor Maguire is not only an outstanding scientist,, but also a very popular teacher who has supervised hundreds of bachelor and master students. I would never have been able to finish my thesis without his brilliant guidance and continuous support thought the thesis. It has been a long journey to complete this thesis, fortunately with the help of Professor Maguire, the journey is finally turning to be a gift to my life, a master degree with invaluable experience.

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List of Acronyms and Abbreviations

1G	First Generation
2G	Second Generation
3G	Third Generation
3GPP	3rd Generation Partnership Project
4G	Fourth Generation
AAA	Authentication, Authorization and Accounting
ACK	Acknowledgement
ACM	Abstract Control Model
AP	Access Point
CDC	Communications Device Class
CDMA2000	Code Division Multiple Access 2000
CH	Correspondent Host
CPU	Central Processing Unit
CRC	Cyclic Redundancy Check
CSCF	Call Session Control Function
DECT	Digital Enhanced Cordless Telecommunications
DHCP	Dynamic Host Configuration Protocol
DNS	Domain Name System
DSL	Digital Subscriber Line
EAP	Extensible Authentication Protocol
ETSI	European Telecommunications Standards Institute
FCS	Frame Check Sequence
GGSN	Gateway GPRS Support Node
GPS	Global Positioning System
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
HDLC	High-Level Data Link Control
HSS	Home Subscriber Server
HSPA	High Speed Packet Access
I-CSCF	Interrogating CSCF
ICT	Information and Communication Technologies
IEEE	Institute of Electrical and Electronics Engineers
I/O	Input/Output
IMS	IP Multimedia Subsystem
IoT	Internet of Things
IP	Internet Protocol
IRP	I/O Request Packet
IRQ	Interrupt Request
ISP	Internet Service Provider
LAN	Local Area Network
LTE	Long Term Evolution
MDL	Memory Descriptor List
MDS	Multi-access Data Server
MIMO	Multiple Input Multiple Output
NAK	Negative Acknowledgement
NAT	Network Address Translation

NCM	Network Control Model
OFDMA	Orthogonal Frequency Division Multiple Access
OS	Operating System
P-CSCF	Proxy CSCF
PCMCIA	Personal Computer Memory Card International Association
PCI	Peripheral Component Interconnect
PDA	Personal Digital Assistant
PID	Packet ID
PNP	Plug and Play
PPP	Point to Point Protocol
QMI	Qualcomm MSM Interface
QoS	Quality of Service
RADIUS	Remote Authentication Dial in User Service
RAN	Radio Access Network
RAS	Remote Access Service
RNC	Radio Network Controller
RNDIS	Remote Network Driver Interface Specification
S-CSCF	Serving CSCF
SGSN	Serving GPRS Support Node
SIM	Subscriber Identification Module
SIP	Session Initiation Protocol
SMS	Short Message Service
SNR	Signal to Noise Ratio
STCP	Stream Transmission Control Protocol
TD-SCDMA	Time Division Synchronous Code Division Multiple Access
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
URB	USB Request Block
USB	Universal Serial Bus
USB-IF	USB Implementers Forum
UTRAN	UMTS Terrestrial Radio Access Network
WCDMA	Wideband Code Division Multiple Access
Wi-Fi	Wireless Fidelity
WLAN	Wireless Local Area Network

1 Introduction

Information and communication technologies (ICT) have completely changed the world in a relatively short period of time. Only two to three decades ago, the telegraph was still widely used for long distance message transmission in many countries, and most people had never heard the word “Internet”. Today the Internet has become an indispensable part of people’s lives throughout the world. Instead of going to the post office to send a telegram, you can generally reach nearly anyone by simply sending an email from any location that has Internet connectivity.

Another remarkable change brought about by ICT is the widespread popularity of mobile phones. Today the number of mobile phone subscribers is much greater than the number of landline subscribers. Many countries have a mobile phone penetration rate above 100%. For instance, Europe has the highest mobile penetration rate in the world, with the total number of connections being 132% of the population of Europe in 2012 [1].

With the increasing use of the Internet and mobile phones, there has been a spontaneous market demand for convergence of these two technologies. Customers are not content to access the Internet via a fixed desktop computer, but expect to surf and access the Internet wirelessly, from any location that has network connectivity. This demand has stimulated the deployment of many types of wireless networks. Two of the most prevalent types of wireless networks are the wireless local area network (WLAN) and high speed wide area cellular networks (often called “mobile broadband”). Today the most popular instance of the later type of network is the various types of third generation (3G) and more recently fourth generation (4G) cellular networks. In this thesis, unless otherwise stated, we will simply equate mobile broadband, with one specific type of 3G network: Universal Mobile Telecommunications System (UMTS) - Wideband Code Division Multiple Access (WCDMA). We make this simplification since this project started originally during 2009, during that time the most wide-spread type of 3G network was WCDMA and WCDMA offered the highest peak data rates of the various 3G networks – thus with respect to our analysis it presented the strongest alternative to WLAN. To be specific, we will focus on the cellular standards introduced by the 3rd Generation Partnership Project (3GPP). By 2015 the new mobile network Long Term Evolution (LTE) has been widely deployed in many countries. LTE uses a different wireless communication standard than WCDMA; however, this thesis focuses on the communication interface with a laptop computer, rather than external radio links, so our research did not shift to LTE. The conclusions should be valid for both WCDMA and LTE radio interfaces. Therefore, throughout this thesis the term “mobile broadband” simply refers to *high speed wide area wireless access to the Internet*.

1.1 Problem statement

Wireless Internet access has become very common in recent years, and there are many different access solutions. People can connect their laptop to the Internet via a WLAN hotspot, through a mobile phone, portable modem, or other similar device, implemented for example, as a 3G Universal Serial Bus (USB) dongle. There are various USB dongles are available in the market and the market is huge. Huawei, a Chinese telecommunications manufacturer, announced that the company shipped more than 50 million mobile broadband units in 2012, including data cards, dongles, embedded modules, etc. [2]. An example of such a USB dongle is shown in Figure 1-1.

Figure 1-1: Huawei E1550 - a 3G USB dongle

Today mobile broadband offers both high speed access and mobility. Technically mobile broadband allows Internet access as long as your mobile transceiver can access your cellular network operator's network. However, in practice the data rates experience by a user via mobile broadband are not comparable to the data rates that users experience via WLAN, especially as the data rate that the user experiences is both unstable and often lower than the data rate that users are used to when using their home or office WLAN. Moreover, 3G based mobile broadband was developed based upon an infrastructure that was optimized for telephony, i.e., the focus was on voice service. Such an infrastructure is not an optimal solution for high speed data service. For this reason 3GPP has introduced new standards and 3G operators have been modifying their core networks to better support packet data. Additionally, there are several different standards for 3G mobile broadband, hence to provide a user with locally optimal service requires that the user make use of heterogeneous networks. Furthermore, the variety of networks has increased due to the emergence of 4G networks. The research about heterogeneous networks has attracted many researchers, there are a lot of explorations about this area [3][4][5].

With the increasing prevalence of smartphones and tablet computers, current mobile broadband networks can provide users with acceptable data rates together with mobility. The popularity of smartphones and tablets, however, does not mean these devices have yet replace laptop computers, people still need wireless access to the Internet via their laptops. Laptops have many prominent advantages, such as physical keyboards, bigger screens, more disk storage, greater computing performance, and file & software compatibility with desktop computers. The research question that we have addressed is: How to smoothly make use of heterogeneous networks to provide laptop users with better Internet service?

1.2 Research purpose

Today, WLAN modules are integrated in laptops, so laptop users are used to accessing the Internet wirelessly by WLAN. Common mainstream laptops do not have modules to connect to cellular networks, therefore many users utilize a USB dongle for wide area mobile broadband connectivity. While smartphones can share Internet connection with laptops by wireless tethering, USB dongles are much smaller and cheaper than smartphones. Additionally, USB dongles are specifically designed for

providing network connectivity. A USB dongle which combines WLAN and cellular modules together would give laptop users a lot of convenience. Users would not need to manually search for available wireless connections and decide which network is better, they would simply plug such a dongle into their laptop, and then the dongle would try to connect with the user's preferred network (usually a WLAN offering the best communication quality). If there are no accessible WLANs, then the dongle would connect via a wide area cellular operator's mobile broadband service; for example, via a 3G network. Not only users, but mobile network operators would benefit from this combined dongle, since they can use the WLAN network for mobile data offloading to ease the traffic burdens due to the explosion growth of Internet data traffic via their cellular networks. Because the communication modules are inside the USB dongles, rather than integrated with laptops or smartphones, it is much easier to modify and upgrade to new dongles (to get access to new types of wireless networks), which is good news for dongle producers.

The aim of the thesis is to explore how heterogeneous networks could be *exploited* to provide a laptop user with locally optimal service, *while hiding the complexity* of this heterogeneous service. The goal is to understand the implications of integrating multiple network interfaces into a single USB dongle. Questions that this thesis should answer include:

1. Is there a market for a dongle that contains some specific set of wireless interfaces?
2. What should be the communication interface between this dongle and the host operating system?
3. What parameters might the user want to be able to configure using this interface to the dongle?
4. What should be the future direction for development of 3G/4G dongles?

There are various research strategies and methods for ICT research topics. To apply the appropriate research methods, we need explicitly aware of our research aim and questions, clearly understand what type of information is helpful to answer the questions, and then select the methods which can generate the requisite data. This thesis focuses on design research, literature studies, and experimental tests as the main methods. Common methods for social research such as interviews and questionnaires were not utilized as when the work started there were no dongles available that provided heterogeneous wireless Internet connectivity and much of the technical community was either focused on high speed cellular networks *or* LANs, thus there seemed to be little that could be gained by asking people about a device that would exploit heterogeneous networks.

In the years that have passed since this project started there has been a growing interest in heterogonous networks, especially for off-loading macro cellular networks. One of the main reasons to complete this thesis project was the chance to revisit some of the design decisions and questions that this thesis raised long ago and to see if the questions and answers have changed.

1.3 General background about wireless networks

Wireless communications technology is not new, Guglielmo Marconi developed the first wireless telegraph system in 1896 [6]. Today consumer adoption of wireless technology is a major telecommunications trend. Wireless communication technology is evolving rapidly and there are an increasing number of wireless communication applications in use every day. Examples of this technology include broadcast radio and television, various satellite navigation systems (such as GPS), WLANs, cordless & mobile telephones, and the explosion in the use of tablets and smartphones. In this thesis we will focus on two of these technologies: WLANs and the wide area cellular networks that have evolved to support mobile phones.

WLANs offer an efficient complement to wired LANs. Most WLANs use unlicensed radio frequencies to transmit and receive data over the air. Some of the major reasons for the success of WLAN have been that WLANs can easily be deployed, WLAN equipment is available at low cost, and

WLAN interfaces offer data rates comparable to wired local area networks. Typically a WLAN is implemented as part of a home or corporate network. Some WLANs are open to public users, for example in libraries, airports, and restaurants. The popularity of WLAN has led to more and more users using it. Additionally, the popularity of WLANs has led to the incorporation of WLAN interfaces in all current laptop computers and an increasing fraction of handheld devices (including mobile phones).

Today mobile phones are so common that a mobile phone is probably the first device you think of when hearing of wireless services. Mobile telephony (also known as cellular telephony) operators generally use licensed spectrum to provide telephone services over a contiguous area, normally a large area covered by numerous cells. Cellular technology is the underlying technology for these wide area mobile wireless communication systems. Each cell provides wireless connectivity for a given area, while the mobile network's core infrastructure provides the required functions to enable a user to be authenticated, to be reachable despite the terminal move from one cell to another, and to provide connectivity to devices within a cell.

The original cellular networks, now referred to as the first-generation (1G), used analog traffic channels. The second-generation (2G) networks were based on digital technologies. These 2G devices were introduced into the telecommunication market in the 1990s. The 2G vendors and operators had great success and 2G technologies are still used today (although in a number of countries these devices are being phased out, and many operators are planning to terminate 2G service). Voice telephony was the main focus of 1G and 2G mobile phone services; however, data services have become increasingly important in recent years, especially after the introduction of third-generation (3G) technologies. The high data rates (7 Mbps in the downlink direction and nearly 1 Mbps in the uplink direction in the first 3G devices and networks) made mobile web browsing smooth and convenient. The wide deployment of fourth-generation (4G) cellular networks further promotes this trend. In addition to web browsing, an ever-increasing variety of Internet based services are becoming available via mobile broadband. These services range from simple services (such as uploading and downloading documents, images, etc.) to augmented reality (such as Layar (http://www.layar.com) and Wikitude (http://www.wikitude.org/)).

1.4 Modems and USB dongles

The term "modem" is derived from a contraction of the words "modulation" and "demodulation". The original modems worked exactly and only as the name implies, i.e., at the transmitter the device modulated a signal based upon an input and at the receiver the device demodulated the signal to reproduce the input. Current modems are more sophisticated products and offer many extra functions, such as integrated routers and firewalls. The point-to-point protocol (PPP) is widely used together with modems and simple links in order to transport data between two peers. PPP is a full duplex, bit oriented protocol that can run over synchronous or asynchronous links [7]. PPP was not specifically designed for any particular type of higher layer protocols. PPP supports data transfers over many types of physical media, including (but not limited to) serial & parallel twisted pair links and cellular networks. In practice, PPP is widely used as a data link layer protocol to encapsulate IP packets for transmission over modem links

A mobile phone could be used as a wireless modem to connect a laptop computer to the Internet. Using a USB cable was once the mainstream way to connect a mobile phone and a laptop, but a Bluetooth or infrared link could also be used (depending upon the phone). Nowadays connecting via WLAN to a smartphone is very popular and this allows the computer connected via the WLAN interface to utilize the wide area cellular connectivity of the smartphone. This sharing of wide area or local area connectivity through one device is often referred to as "tethering" or "Internet Sharing". If the tethering is not done over WLAN, then generally the software of the laptop uses the mobile phone as if it were a dialup modem. Hence the protocol used for this data communication is PPP.

Instead of connecting the laptop with a mobile phone, several types of wireless modem cards can be directly inserted into the computer. Traditionally many of these devices used the Personal Computer Memory Card International Association (PCMCIA) card format or the later ExpressCard format. The early designs of these devices were made to look like a dialup modem to the computer; hence the data communications protocol used was PPP. While this may have been convenient from the point of view of being able to utilize the modem software built into many operating systems; unfortunately, this approach lead to the software treating this link as it would a dial-up modem; hence the behavior is to connect and then remain continuously connected until the connection is explicitly terminated. This has a number of undesirable effects, including unnecessary power consumption when there is not continuous user traffic and vendors & network operators thought in terms of "connected" services, hence delaying the transition to packet-based services.

Current laptop computers have one or more universal serial bus (USB) interfaces. USB version 2.0 offers a maximum data rate of 480 Mbps and compatibility with many products. The latest USB 3.1 (also known as SuperSpeed+ USB) increases the maximum data rate to 10 Gbps. Today the USB interface has even replaced the traditional RS-232 serial interface, PS2 keyboard port, and PS2 mouse port on most desktop computers. Because of the USB Forum's efforts to foster the standardization and interoperability of USB devices, a very wide range of devices exist with USB interfaces. Among these devices are flash drives, modems, and Ethernet interfaces.

A USB wireless adapter is often called dongle, although this term was originally used for devices that were used by applications to check that an application should be able to run on *this* computer. In this earlier usage the "dongle" acted like a hardware key that was required in order to run the application. However, according to BCE Inc. the word dongle is now widely used to refer to a broadband wireless adapter [8].

There are 3G/4G USB dongles in various sizes and shapes. Most look similar to USB flash drives (with various types of antennas attached to them). These dongles can indeed be used as flash drives or memory stick, since there are flash memories present in these dongles. This flash memory contains a file system with software which the host computers can load and run. This software frequently includes a driver for one or more operating systems (OSs) and a management application so that the user can control the dongle. However, this flash memory could be used to provide other software – for example the software could provide routing software to route packets to WLAN or 3G interfaces. All the necessary drivers and software are stored in the dongle by the manufacturer so that the user can conveniently use the dongle immediately (or soon) after they plug the dongle into their laptop.

Each USB dongle contains a small modem and transceiver inside the dongle, enabling the device to connect to a 3G/4G network. To access the Internet via a cellular network the OS frequently makes use of the dongle as a modem to connect to a terminal server via PPP. The OS begins by negotiating the protocol family it is going to use, gets assigned an IP address, and then the OS encapsulates IP packets into PPP frames and transmits these frames over the PPP link to their destination. If the connection is lost, then the process has to start all over again. This is the approach used by many current dongles, but in this thesis a new approach is proposed.

This thesis proposes that a dongle should look like a WLAN or Ethernet interface (rather than a modem). The device would simply send and receive link frames which encapsulate IP packets. This network interface could make better use of the underlying network's packet capabilities by sending individual packets *without the overhead of initiating a PPP session*. Such a network interface would remove the need for the Internet service provider (ISP) to provide a PPP server. If the ISP has an IPv6 network, then the device simply needs to know the IPv6 prefix of the network and it could proceed to send IPv6 packets (this leaves aside the question of how the device authenticates itself and how it would be authorized to use the network – these questions are left as future work – see section 5.2).

1.5 Limitations

It is important to note that this project started in 2009, long before the introduction of 3GPP's Long Term Evolution (LTE) networks. This thesis will not consider the case of LTE networks; however the use of such networks rather than or in addition to UMTS WCDMA networks is largely a matter of the difference in the radio links and does not change the communication between the laptop computer and an external radio communication module.

After this project was started the USB Implementers Forum (USB-IF) defined a number of USB Communications Device Class (CDC) protocols to provide this virtual Ethernet functionality, such as CDC ACM (Abstract Control Model). In addition, Microsoft defined their own Remote Network Driver Interface Specification (RNDIS) to provide similar functionality for their Windows OS machines.

The start of this thesis also predates the standardization and introduction of USB CDC Network Control Model (NCM). NCM in fact eliminates the need for the PPP encapsulation of IP packets, thus showing that in fact the idea that was initially proposed in 2009 for this thesis project was a good idea.

1.6 Structure of thesis

This first chapter has introduced the general background and stated the problem that is the focus of this thesis project. Chapter 2 will give more background about the different types of networks that will be considered and how the user can make use of these heterogeneous networks. Chapter 3 describes the research methods and details of applying this method to solve the problem. Chapter 4 describes some technical parameters of the new designed dongle and business analysis for the market. Finally, Chapter 5 summarizes the conclusions, suggests future work, and sets this thesis in the context of economic, social, environmental, and ethical considerations relevant to this thesis project.

2 Background

There are several different wireless internet access technologies available for mobile users. Of these the most common are WLAN and cellular networks. This chapter provides some background information about these two types of access technologies, and then presents some of the methods that can be used to couple them.

2.1 WLAN

The Institute of Electrical and Electronics Engineers (IEEE) has approved a set of standards for WLANs: the IEEE 802.11 family. Table 2-1 shows some of the most frequently used IEEE 802.11 standards. Wireless Fidelity (Wi-Fi™) is a trademark of the Wi-Fi Alliance, and the label "Wi-Fi Certified" on a product means that the product has been tested to comply with the indicated standard. However, the term Wi-Fi is often misused by many writers as a synonym for IEEE 802.11 or another type of WLAN.

Table 2-1: Examples of IEEE 802.11 standards [9][10]

Standard	Frequency	Data rates (max)	Max range (indoor)
802.11b	2.4 GHz	11 Mbps	38 meters
802.11a	5 GHz	54 Mbps	35 meters
802.11g	2.4 GHz	54 Mbps	38 meters
802.11n	2.4/5 GHz	600 Mbps	70 meters
802.11ac	5 GHz	1.7/3.5 Gbps	35 meters

WLANs have occupied an important place in the local area network (LAN) market during the past twenty years. Today deploying a WLAN is a compulsory complement to traditional LANs in many organizations. In some cases, businesses only deploy WLANs and only deploy wired LANs within their data centers. WLANs offer an efficient solution for places that are not easily served by wired LANs.

The coverage area of a WLAN is often called a Wi-Fi hotspot, as Wi-Fi has become a *de facto* synonym for WLAN and because the coverage area is often a location where there are likely to be users. The use of the term *hotspot* is often used to emphasize the difference in expectation of coverage, i.e., a WLAN is expected to provide only localized coverage, while a wide area cellular network is expected to provide (nearly) ubiquitous coverage. Viewed another way, lack of WLAN coverage is expected to be the norm; while lack of wide area cellular network coverage is expected to be an exception. Interestingly in 2015, the lack of WLAN is increasingly exceptional and unexpected; while, the lack of wide area cellular coverage *indoors* is becoming more common in Stockholm (due to the high loss to the radio frequencies being used - caused by the energy efficient windows that are increasingly installed in buildings).

There are two operational modes defined in the IEEE 802.11 WLAN standards: infrastructure mode and *ad hoc* mode. An access point (AP) is a vital component in an infrastructure mode network. An AP acts as a bridge to allow WLAN interface equipped devices to connect to a backbone network (see Figure 2-1). Note that this backbone network could be a wired or wireless network. In contrast in an *ad hoc* network, an AP is not necessary as the devices communicate directly.

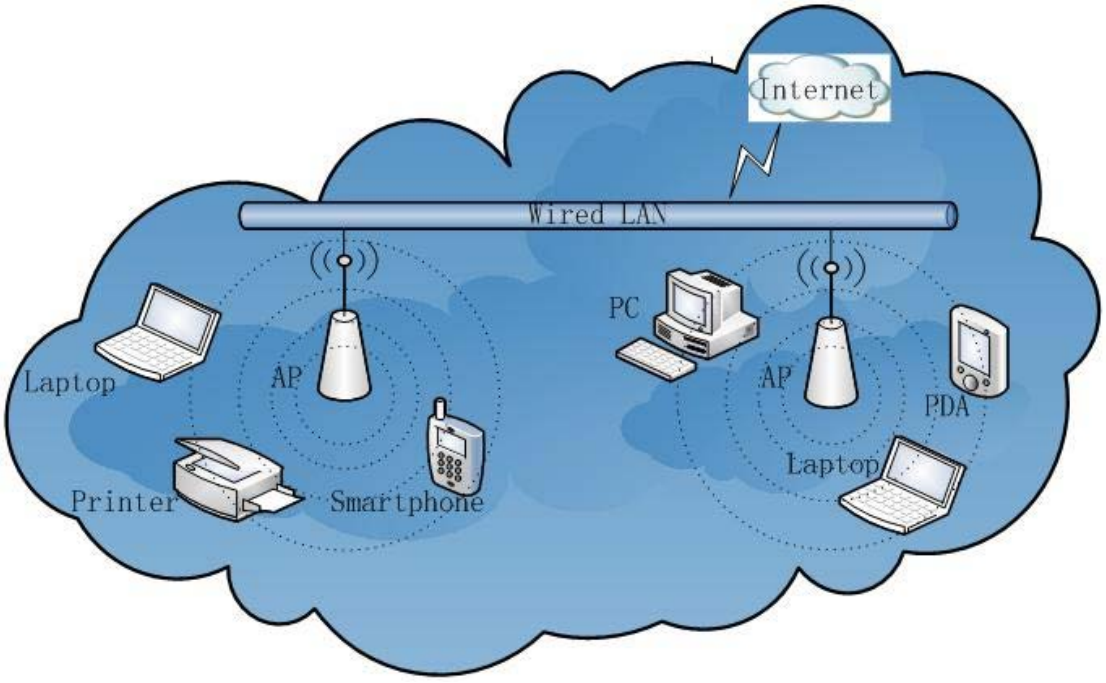

Figure 2-1: Architecture of an infrastructure mode WLAN

IEEE working groups have developed a number of WLAN standards. The maximum theoretical data rates of the commonly available IEEE 802.11 standards were shown in Table 2-1. Due to the high data rates of WLAN, there is little difference for a typical user when surfing the Internet via WLAN or LAN. Because of the very large numbers of devices made and the fact that the majority of the devices are customer installed WLAN is relatively cheap and easy to deploy, hence it has become very popular. However, WLAN does have an obvious flaw. As the name suggests, WLAN is a technology for *local* access, which means that the wireless coverage area is not a very large area; hence as noted earlier these coverage areas are often called “hotspots”. Because of this limited coverage, users can not count on hotspots being everywhere nor are all hotspots open to the public.

Another problem of WLAN is caused by the frequency band(s) used by these devices. The popular IEEE 802.11 b/g/n standards devices share the unlicensed 2.4 GHz radio frequency with many other devices, e.g., Bluetooth, microwave ovens, cordless phones, etc., so there is a potential for conflict when attempting to transmit as well as interference when multiple devices are operating in close proximity. However, in Europe in practice most cordless phones are Digital Enhanced Cordless Telecommunications (DECT) phones and hence use the 1.88-1.9 GHz band assigned to DECT and most consumer microwave ovens are single frequency (hence represent only a narrow band interferer) and are well shielded; thus the major interferer is Bluetooth – which hops all over the 2.4 GHz band – thus generating the maximum interference, all be it in a narrow band at any given time hence for a given IEEE 802.11 b/g/n channel this appears as short term interference.

2.2 Cellular networks

The term *cellular* refers to the fact that a geographical area is partitioned into a number of geographic coverage areas, known as cells. Each cell contains a base station, which transmits signals to and receives signals from, the mobile stations in its cell [11]. This approach is the basis of the cellular network technology used by mobile phones today. Before the introduction of cellular networks, radio telephone service was provided by powerful transmitters connected to a large antenna in order to provide a long transmission radius – typically around 70-80 km [12]. Unfortunately, although the area was large the system’s bandwidth was only sufficient to support about 25 channels at a time (with one user per analog channel). This meant that only a few people could enjoy mobile phone service

within that huge area at any given time. In contrast modern cellular networks use numerous lower power base stations, and divide the area into smaller cells, each cell is assigned a band of frequencies, time slots, or codes (depending upon the particular system technology), so that thousands of users (or more) can use their mobile phones at the same time.

With the widespread deployment of 3G and 4G, more and more people are using cellular networks to access the Internet. There were three main types of 3G networks available when 3G were launched into the market in the beginning of 21st century: Wideband Code Division Multiple Access (WCDMA), Code Division Multiple Access 2000 (CDMA2000), and Time Division Synchronous Code Division Multiple Access (TD-SCDMA). WCDMA had been deployed worldwide, while CDMA2000 is primarily used in North America and South Korea, and TD-SCDMA is commercially available only in China. Nowadays most WCDMA networks have been upgraded into High Speed Packet Access (HSPA) and Evolved HSPA (also called HSPA+) which offer much higher data rates and significant improvement in battery life. Since the second decade of this century, 4G networks are becoming globally deployed. Several 4G candidate systems were developed, but now only two 4G standards are commercially in the market: Mobile Worldwide Interoperability for Microwave Access (Mobile WiMAX) and Long Term Evolution (LTE). Of these two, LTE is the current dominant 4G network worldwide. A distinct feature of 4G is that it is not designed for the traditional circuit-switched telephony network, but rather it was designed to support IP packet-switched services. 4G networks even use IP within their core networks, hence these cellular + core networks are often called all-IP networks. The spread spectrum radio technology used in 3G systems was abandoned in 4G and replaced by Orthogonal Frequency Division Multiple Access (OFDMA) and other frequency domain equalization schemes. Combined with Multiple Input Multiple Output (MIMO) technique, 4G networks can transfer much higher data rates than its predecessor networks [13]. However, as we mentioned in the first chapter, the research in thesis is based on 3G technology and the market penetration of 3G is still much bigger than 4G.

The biggest advantage of a wide area cellular network is the large coverage area. Users can access the Internet anywhere as long as their device can transmit & receive a sufficiently strong signal. However, the main disadvantages of these wide area cellular networks are their higher traffic charges and comparatively lower data rates in comparison with WLAN, although data rates increased a lot with the introduction of 3G/4G technologies. In some areas that are not yet covered by 3G/4G service the user might only have access to a 2G service such as General Packet Radio Service (GPRS) or even Global System for Mobile Communications (GSM) which offers much lower maximum data rates.

2.3 Coupling WLAN and 3G

3G networks provide what appears to the user to be “always on wide area internet connectivity”. While these networks allow high mobility, their disadvantage is relatively low user data rates and high traffic charges. While WLANs offer users much higher and more stable data rates, this is at the cost of low mobility and limited geographic service areas. The advantages and disadvantages of 3G and WLAN with respect to peak data rate make these two technologies complementary. Hence integration of 3G and WLAN is a natural demand from the market. In response to this demand, more and more service providers have started to offer such a service. Many proposals have been presented in the literature for how to solve the many technical problems concerning the design and implementation of such a heterogeneous network, such as how to do authentication, authorization, and accounting (AAA); billing; support mobility; and provide quality of service (QoS) guarantees. The 3rd Generation Partnership Project (3GPP) proposed in a preliminary feasibility study [14] six possible 3G/WLAN integration scenarios based on the service experienced by the user. Each scenario extends the preceding one towards tighter integration. These six scenarios are show in Table 2-2.

In addition to combining WLAN and 3G service to achieve the best possible user throughput in a given location, there are also many reasons for performing so-called vertical handovers between these two technologies. An analysis of such vertical handovers to minimize battery power consumption is

described in [15]. Additionally, devices that are equipped with several interfaces might want to use multiple interfaces at the same time, as described in [16].

Table 2-2: 3G/WLAN scenarios and their capabilities [14]

Scenarios / Service and operational capabilities	**Scenario 1**: Common Billing and Customer Care	**Scenario 2**: 3GPP system based Access Control and Charging	**Scenario 3**: Access to 3GPP system Packet Switched based services	**Scenario 4**: Service continuity	**Scenario 5**: Seamless services	**Scenario 6**: Access to 3GPP system Circuit Switched based Services
Common billing	X	X	X	X	X	X
Common customer care	X	X	X	X	X	X
3GPP system based access control		X	X	X	X	X
3GPP system based access charging		X	X	X	X	X
Access to 3GPP system packet switched based services from WLAN			X	X	X	X
Service continuity				X	X	X
Seamless service continuity					X	X
Access to 3GPP system circuit switched based services with seamless mobility						X

Generally speaking there are two different main approaches to design a heterogeneous 3G/WLAN network: loose coupling and tight coupling. These two approaches were initially proposed by the European Telecommunications Standards Institute (ETSI). We will discuss these methods in detail in the following subsections. As mentioned in the beginning of the thesis, we choose UMTS WCDMA as the target 3G network, since it was the most wide spread type of 3G network when this project started, thus offering the most popular alternative to WLAN. Hereafter we will refer to this technology simply as UMTS (since in the discussion of the different types of couplings it does not matter which of the 3G link technologies is used). Figure 2-2 shows the architectures of loose and tight coupling. Details of the figure are explained in the following subsections.

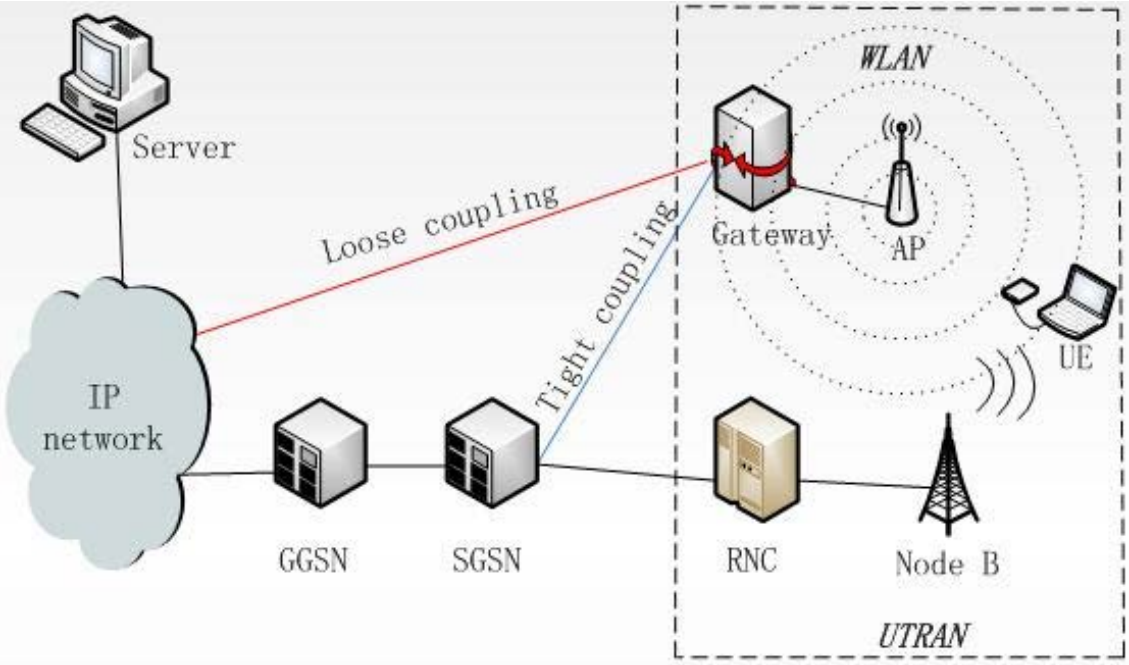

Figure 2-2: UMTS/WLAN loose coupling and tight coupling

UE: User equipment; RNC: Radio network controller; UTRAN: UMTS terrestrial radio access network, SGSN: Serving GPRS Support Node; GGSN: Gateway GPRS Support Node

2.3.1 Loose coupling

In a loose coupling interworking architecture, the WLAN gateway connects with the core IP network *without* a direct connection to the UMTS network elements. The data paths of WLAN and UMTS traffic are separate, and the interconnected networks are loosely coupled *independent* networks. The data traffic from a mobile node in a WLAN to user equipment (a 3G terminal) does not go directly to the UMTS network; rather the traffic passes first through an IP network (such as the Internet), then through a gateway to the UMTS network.

The disadvantage of this architecture is that roaming agreements with multiple different WLANs need to be established. However, the advantage is that WLAN and UMTS networks can be deployed independently by different providers and the user can freely choose which network they wish to use when both are available. Considering the large number of WLAN providers, establishing roaming agreements between UMTS and WLAN operators is an expensive and complex problem (as generally these agreements are bi-lateral agreements – so each pair of operators have to reach an agreement; however, in some places there are exchanges where all the operators can connect and there is a standard settlement agreement via the exchange). Another advantage of loose coupling is that it avoids potential traffic bottlenecks in the UMTS network, since data traffic can be routed directly via IP networks.

In literature about roaming in a heterogeneous infrastructure, the loosely coupled architecture is a frequent researched architecture. For example, Ruggeri, Iera, and Polito [17] cited several similar works and indicated that IEEE 802.1X, EAP (extensible authentication protocol), and RADIUS (Remote Authentication Dial In User Service) can be used for AAA. An alternative offering non-binary authentication using traffic shaping has been explored in [18]. In Raul Garcia's Master's thesis [19] he shows mobility can be supported via Mobile IP and the Session Initiation Protocol (SIP).

2.3.2 Tight coupling

In a tight coupling approach a WLAN network is an integral part of a UMTS network, acting as a radio access network (RAN), just like other RANs that are attached to that UMTS network. The WLAN gateway must support all the protocols required in a UTRAN. In this scenario a mobile node in a WLAN must connect to a UMTS network before it can access the Internet. The communications between UMTS and WLAN occur just as between any other cells. The coupling could occur at the Gateway GPRS Support Node (GGSN) or a Serving GPRS Support Node (SGSN). Mobile IP or other UMTS mobility protocols could be used for interworking.

Normally tight coupling solutions have shorter handoff latencies than loose coupling solutions, because the interworking occurs at a closer point to the mobile terminal. Simulation results of real-time services and applications [20] show that loose coupling based on Mobile IP suffers longer handoff latency than a tight coupling approach. Siddiqui, Zeadally, and Yaprak [21] indicate that the overall delays (not only handoff latencies) are much lower when the data exchange is done through the GGSN node as compared to when the networks are connected through the SGSN node. Another clear strength of a tight coupling architecture is that the Authentication, Authorization and Accounting (AAA), billing, mobility, and QoS support in UMTS networks can potentially be reused over the WLAN cells; however, this is only feasible if WLAN and UMTS networks belong to the same operator. Unfortunately, in practice it is unlikely that a mobile user can always connect via networks operated by the same operator. Moreover, both UMTS and WLAN devices and configurations needed to be modified to realize this tight coupling, and the UMTS backbone network must be modified to handle the increased data traffic from WLAN APs. Due to these drawbacks, this architecture is more difficult to deploy and fewer researchers have focused on this approach as compared to loose coupling.

2.4 Policy based handoff

In cellular telecommunications, the term handoff or handover refers to the process of transferring an ongoing call or data session from one channel/link connected to a base station to another (channel/link or another base station). As a fundamental operation for any cellular networks, handoff management ensures mobile users maintain network connectivity despite users moving to different cells. Details of this process have a great impact on how the old links are released and new links are established. Traditionally handoff depends on measurements of the signals (between the mobile device and the base station(s) and the reverse). For example, if the original link signal continues to decrease in signal strength and the signal strength of a potential new link is increasing then a handoff would be initiated. However, in many cases, there may be a need to decide upon *when* to make the handoff based on other rules (or policies) such as a terminal's capabilities, application types, costs, or user preferences. This kind of handoff is called a policy based handoff.

In heterogeneous UMTS/WLAN networks, a handoff also occurs when a mobile user roams between different networks. A laptop in a UMTS network may want to change from UMTS to WLAN, when WLAN connectivity is available, because normally the data rate in a WLAN is higher than UMTS and generally traffic charges are flat rate or lower than the cellular data traffic charges. A handoff occurring between two dissimilar networks is called a vertical handoff, while a horizontal handoff occurs when roaming between different cells/subnets that use the same technology, for instance, a handoff from one cellular network cell to another cell. Furthermore, vertical handoff could be classified as upward or downward. Upward vertical handoff is a handoff from a small sized cell to a larger sized cell, e.g., from WLAN to UMTS, whereas downward refers to movement form larger cell to small cell. Figure 2-3 illustrates the difference between horizontal and vertical handoff.

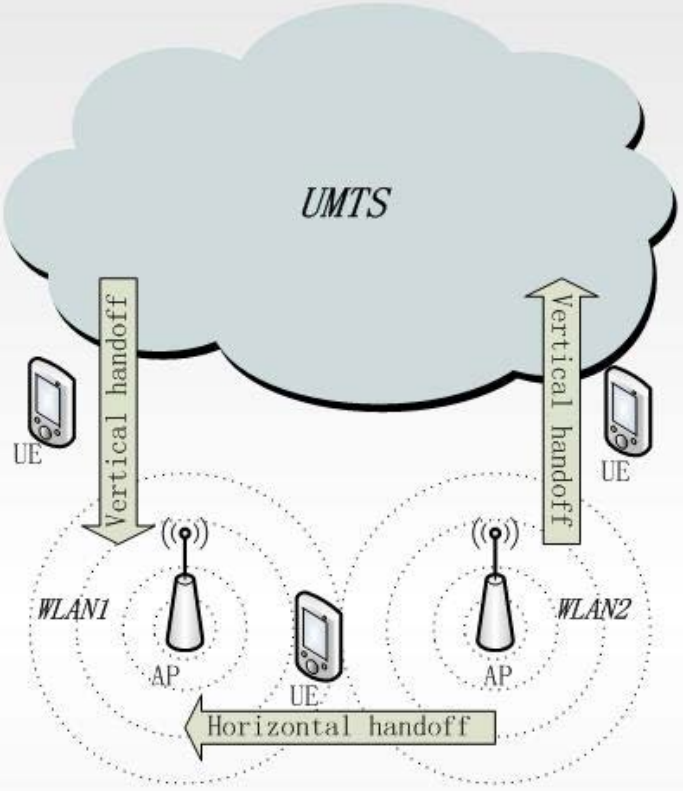

Figure 2-3: Horizontal handoff and vertical handoff

Horizontal handoff can be triggered based upon parameters such as signal to noise ratio (SNR), bit error rates, frame error rates, etc. [22]. For example, we can simply define that a handoff should take place when the SNR of a new WLAN hotspot is greater than the SNR of the current hotspot; however, this simplified method is not appropriate for dissimilar networks, since it is not meaningful to compare the SNR from different technologies. For upward vertical handoff, from WLAN to UMTS, the trigger can be when no WLAN hotspots are detected, whereas downward vertical handoff from UMTS to WLAN needs more considerations (especially as there may not be an *appropriate* WLAN AP to make the handoff to). Certainly a downward vertical handoff could be triggered by the user, but since our aim is reduce the burden on users, a more sophisticated handoff policy involving parameters such as potential data rate, power consumption, cost, reliability, etc. should be used. Additional important parameters that can be taken into account, for all kind of handoffs, are the velocity of the mobile node and what are the current & near term expected requirements upon the link. A dwell timer can be utilized to avoid the so called *ping pong effect* that is caused by mobile nodes frequently performing handoffs back and forth between a pair of networks.

This thesis concerns the use of heterogeneous networks by applications running on a laptop computer, rather than a smartphone or tablet computer. Due to the nature of a laptop (large size, moderate to heavy weight, and large screen size) we can assume that the laptop is stationary when it is used, hence we do not need to be concerned about rapid handoff due to node mobility, and hence we focus on vertical handoff, especially on downward vertical handoff – as this can reduce the load on the operator's macro cell, increase the user's average and maximum data rates, and potentially reduce the costs for the user (both economic cost and battery power consumption).

2.5 Related work

Coupling 3G and WLAN networks has attracted a lot of interest from researchers, leading to many different proposals. This section presents some of this related work, both proposals in academic literature as well as industrial examples.

2.5.1 Policy based loose coupling framework

There already exists extensive literature concerning proposed 3G and WLAN coupling architectures, especially those proposing loosely coupling. The common feature for all the proposed architectures using loose coupling is the use of Mobile IP as the basic instrument of inter-system mobility and the high level perspective of the integration process [23]. Another important focus is policy based handoff. Since in practice a handoff decision is not only based on signal strength, but might depend on many parameters, thus policy based handoff is a common solution. An example of a loose coupling policy based handoff framework, proposal by S. Balasubramaniam and J. Indulska [24], is presented below.

This proposed framework categorizes policy parameters as “static context” or “dynamic context”. Static contexts refer to parameters that do not change very often, such as the devices, networks, and their QoS requirements; while dynamic contexts include *current* information about users and networks, that change dynamically when user location or network conditions change. These contexts are gathered in a "Context Repository" which is one of two crucial functional modules in their framework. The other module is an "Adaptability Manager" which decides how to adapt to context changes and when to execute a handoff. This manager is divided into two different processes: vertical handoff decision and QoS mapping. Heterogeneous networks within a domain are formed as a domain network cluster, with each cluster supported by its own adaptability manager and context repository. There is also a proxy in each network which receives notifications about requested handoff operations from the adaptability manager and redirects communication streams between different domains, such as a correspondent host (CH) domain and a network domain.

A characteristic of this proxy is that it bi-casts the communication stream during handoffs (i.e., the proxy delivers two streams). A mobile host’s traffic follows a route from network 1 to network 2 and then on to a UMTS network. Initially a communication stream is transmitted through the proxies in CH and network 1 to the mobile host. When a handoff is triggered, the stream is not only forwarded to the mobile host but a copy is also forwarded to the new proxy in the network that the mobile host is moving into. The bi-casting operation is terminated as soon as the redirected packets begin to arrive. Bi-casting minimizes QoS violations during handoff, in terms of exceeding bounds on delay, jitter, or packet loss.

This proposal also includes a detailed handoff decision algorithm. Their experiments with a prototype showed that smart decision mechanisms are necessary for smooth adaptation of the communication streams under different conditions.

2.5.2 An IMS-SIP based coupling framework

In tight coupling architectures, a WLAN is directly attached to a UMTS component (such as the GGSN or SGSN). A clear advantage is the possibility to reuse the UMTS mobility management techniques. However, tight coupling is difficult to implement in networks belonging to different operators, and less literature exists about this approach than for loose coupling. Rather than using Mobile-IP, some frameworks based on the IP Multimedia Subsystem (IMS) and Session Initiation Protocol (SIP) have been proposed for tight coupling. Before presenting this type of framework, we give a brief overview of IMS and SIP.

IMS is based upon internet protocols. IMS is a network architecture aiming to merge Internet and cellular worlds by providing a horizontal control layer that isolates the access network from the service layer. It is seen as a promising solution for facilitating multimedia service creation and deployment, as

well as supporting interoperability and network convergence. IMS was specified by 3GPP and was introduced in UMTS releases 5 and 6 [25]. SIP is widely used in IMS for creating, modifying, and terminating sessions consisting of one or more media streams. SIP is an application layer protocol designed to be independent of the underlying transport layer (such as TCP, UDP, or STCP).

The Call Session Control Function (CSCF) is a key element in IMS as it processes control messages and all signaling via SIP. The CSCF can be categorized into 3 parts: Proxy CSCF (P-CSCF), Interrogating CSCF (I-CSCF), and Serving CSCF (S-CSCF). The P-CSCF is a proxy for all SIP messages from end points to the rest of the IMS network. Normally it resides in the subscriber's home network, but could also be in a visited network. The I-CSCF acts as an entrance from a P-CSCF to an S-CSCF, and it acts a Home Subscriber Server (HSS) to determine the relevant S-CSCF once it receives a SIP message. Finally an S-CSCF is the node that eventually performs the actual user registration and session control.

An IMS-SIP based framework proposed by Munasinghe, et al. [26]. Although this is not strictly a tight coupling architecture; it is a closely coupled framework. In this framework, there are two initial steps before establishing a SIP session. In the beginning, a MH does not know the IP address of the P-CSCF. After learning the IP address of the P-CSCF the MH acts as a SIP client and sends a SIP registration message through the P-CSCF to the S-CSCF and HSS. After registration the MH can establish or be invited to a SIP session. In an MH originated session, the session data flow is initiated by a SIP INVITE message sent from the MH, and is followed by several SIP messages such as Provisional ACK, UPDATE, and ACK. Although the transmission mechanism in this framework is very different from the Mobile-IP based approach used in previous section, the handoff solution is logically very similar. Their framework also utilizes policy based decision making and introduces a network entity called a "Mobility Manager" to manage vertical handoff.

2.5.3 Industrial proposals

Devices combining 3G and WLAN interfaces are available in the market, for instance, as incorporated into wireless routers and some netbooks. Plugging a 3G USB dongle into a pocket size wireless router such as the Huawei D100 or Option Globesurfer X.1, customers can access the Internet by wirelessly connecting to the router. A similar product originally from Novatel Wireless, Inc. called the MiFi does not even need a USB dongle; this credit card size device can be turned into a hotspot by simply insert a Subscriber Identity Module (SIM) card. Netbooks can also access the Internet via built-in 3G **and** WLAN modules, but they lost the market after the great success of Apple's iPad, and since 2011 many personal computer manufacturers produce Chromebooks for the same segment of the market that netbooks serviced.

However, all of above products have obvious drawbacks. For example, a netbook can access both 3G and WLAN networks, but it is not able to automatically perform a handoff between a 3G network and a WLAN. If there is a new high speed WLAN available, then the user must manually switch to this network. As regards wireless routers, such as the MiFi, they simply utilize a 3G network while providing the functionality of a local WLAN AP. In addition, many wireless routers need external power, which substantially decreases their portability.

Customers need products that exploit both 3G/4G and WLAN interfaces, while automatically performing handoffs between these two technologies. For vendors this is fortunate, because it means there is a great *potential market*, therefore many companies are working in this area, and each hopes to design such a coupling device, although some of these designs may require modifications to the infrastructure networks.

Alcatel a proposed aWLAN/3G interworking architecture [27]. This architecture provides extensive integration of UMTS and WLAN by using Mobile IP. It offers seamless connectivity without requiring any user interaction, i.e., the coupling is transparent to the user. Some important components of this architecture are an Intelligent GGSN (I-GGSN), multi-access data server (MDS), and real-time content charging manager.

The MDS is responsible for UMTS/WLAN roaming and implements AAA mechanisms. When a mobile user needs to access a WLAN while connected to a cellular network, the AAA server in the MDS of the WLAN forwards an authentication request to the subscriber's home network. A session can be initiated if the authentication was successful. In this architecture all WLAN accounting information is stored in the AAA server of the cellular network. There are two methods to perform authentication. One reuses the SIM card mechanisms and Extensible Authentication Protocol (EAP); while the other uses a one-time password which could be sent as a Short Message Service (SMS) message.

Billing in WLAN is normally hard to handle, hence Alcatel's architecture reuses the existing billing mechanisms of the cellular network. In particular:

- WLAN access network APs generate the relevant accounting information and send it to the MDS of UMTS, which makes it available for postpaid bill processing.
- Data traffic associated with the user's WLAN session activity can be securely tunneled to the UMTS I-GGSN so that value-added real-time content can be charged for using enhanced on-line or off-line billing. This is the responsibility of the real-time content charging manager.

2.6 Chapter summary

This chapter first introduced some background knowledge about WLAN, 3G, coupling, and policy based routing, and then described some relevant academic and industrial work concerning 3G/WLAN coupling. Loose coupling was given more attention than tight coupling, since loose coupling is easy to deploy and can couple networks belonging to different operators. However, it seems very difficult to implement the upper service levels of 3GPP's six integration scenarios [17](shown in Table 2-2 on page 10). Tight coupling can implement the upper level 3GPP scenarios, and these approaches are expected to offer low handoff latency than loose coupling, but must face the serious disadvantage of a bottleneck arising due to the amount of data from/to WLAN APs – as the UMTS backbone was not designed to support these high data rates nor the high aggregated data rates. Another drawback is that the coupled networks need to belong to the same operator or have agreements with operators, which could not be a easy work in practice. Table 2-3 summarizes some of differences between loose and tight coupling.

Table 2-3: Comparison between loose coupling and tight coupling

	Loose coupling	Tight coupling
Data bottleneck	No	Yes
Deployment problems	Common AAA solution, Mobile IP in UMTS and WLAN	Modifications on UMTS/WLAN components and terminals
Deployment preference	WLAN providers	Cellular network operators
Deployment complexity	Low/Medium	Medium/High
Handoff performance	Low/Medium	Medium/High

Loose coupling normally utilizes Mobile IP for handoff management. This approach is most suitable for the 3G USB modems which using PPP connections. Many tight coupling solutions employ IMS and SIP. These solutions are well adapted to services which are not based on PPP. Although tight coupling is currently more difficult to implement, many researchers believe that tight integration is the next logical step toward the implementation of seamless handoff in an integrated WLAN/UMTS environment [25].

From a user's perspective, however, it does not matter how the underlying UMTS and WLAN are utilized, because the user simply wants a device that utilizes some mechanism *to choose the right wireless network automatically and transparently*. This suggests that the solution is **policy based** and need **not** be coupled to the specific types of underlying networks that might be utilized.

3 Method

The purpose of this chapter is to describe the research methods used in this thesis and what we have done based on the methods. First we provide an overview of the research methods and research process in section 3.1. Section 3.2 focuses the power consumption test for USB dongle. Section 3.3 describes the USB communication between the dongle and laptop, and demonstrates the whole Internet connection process by using a USB dongle. Section 3.4 introduces two communication interfaces between dongle and laptop and compares the differences. Finally, based on results from research methods, section 3.5 shows the general architecture for our designed dongle.

3.1 Research method

How to select the appropriate scientific method is an issue that we must take into account in the beginning of each research project. There are a number of well-established research strategies and methods, such as survey, experiment, case study, observation study, etc. However, there is no standard solution which is good for all research; therefore, researchers should deliberately choose suitable research methods for each research project. Researchers must be explicitly aware of the questions they are going to figure out, and know what type of information is required to answer the questions, and then select the methods that can produce the required information and data. So we need to carefully consider the research questions before we can choose suitable methods for this thesis project.

The aim of the thesis is to explore how heterogeneous networks could be *exploited* to provide a laptop user with locally optimal service, *while hiding the complexity* of this heterogeneous service. The goal is to understand the implications of integrating multiple network interfaces into a single USB dongle. Section 1.2 (on page 2) listed some of the questions that this thesis should answer.

To answer these questions, we need to know related background information, the features of a traditional USB dongle, what interface is used by the dongle, and how the dongle works. Then based on this information, we propose an improved solution for a USB dongle and analyze the advantages and market prospects of this new dongle.

The first method we applied was a literature study - a special kind of observational study where related documents and information are checked. By using this method we found both academia and industry have fully understood the market requirement for coupling cellular networks and WLAN, and realized the traditional USB dongle's deficiency is working as a dial up modem. These publications and products are also evidence to show that our research is not simply exploring a scientific question for our own personal interests, but rather a development driven by many researchers and by market needs.

To comprehend the operation of a USB dongle, an experimental method has been adopted as the research method. Since power is a significant issue for mobile device, we compared the power consumption of a USB dongle for WLAN and for a 3G network, to demonstrate if whether using the cellular network consumes more power than when using a WLAN (see Section 3.2). To thoroughly understand the communications between USB dongle and laptop computer, we monitored the whole Internet connection process when using a USB dongle (see Sections 3.3 and 3.4).

Based on our literature study and experimental tests, after careful analysis and extensive search on the Internet, we select RNDIS as the interface between USB dongle and laptop. To evaluate the market acceptance for a product, typically questionnaire or interviews are applied as the research method. Due to various containts these methods were not employed. However, since the time that this project began in 2009 several vendors have produced products similar to what was proposed in 2009, we can use information about these products to evaluate our earlier design decisions and conclusions. Therefore, we reviewed the market in recent years in order to extract information from customers'

feedback regarding this product and then use this to indicate some potential future trends. This analysis is presented in Chapter 4.

3.2 Power consumption

One of the important features of USB is that it is able to provide a limited amount of power to a device. Users do not need search for an external electrical outlet to supply power to the device; they simply plug the USB dongle into their laptop. This makes a USB dongle an easily portable device. Moreover, the user does not have to worry about charging a battery in the device. Customers, however, often are concern about the power consumption of the laptop's power when they are in mobile environment, i.e., without a connection to an external power supply. It would be a serious drawback if the dongle consumes too much power from the laptop via the USB. So it is necessary to understand the USB dongle's power consumption. This section describes an experiment to measure this power consumption. We measured the voltage and current flowing to a Huawei E1550 3G USB dongle by cutting a USB extension cable and connecting it to a multimeter to form either a series circuit to measure the current (I) or parallel circuit to measure the voltage (V). Based upon these measurements we can calculate the power consumption using the formula P = VI. Figure 3-1 shows the equipment used for this test.

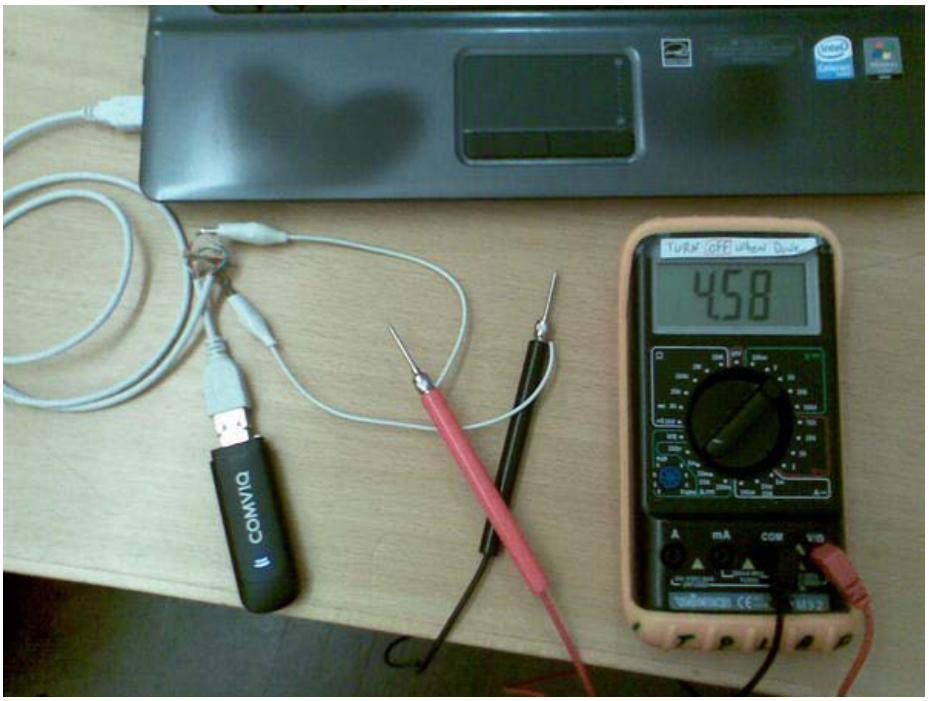

Figure 3-1: Test voltage in parallel circuit

The USB voltage output by the author's laptop is 5.08V when no device is plugged in. After a USB dongle is plugged and connected to the Internet, the current varies from 0.05 A to 0.27 A. The current is higher when data throughput increases, whereas the voltage decreases somewhat at lower data rates. We identified 5 different usage phases and present the details of these phases in Table 3-1. From this table, we can see that the 3G USB dongle starts to consume power after it is plugged into the laptop, no matter whether the dongle has established a connection to the Internet or not. After connecting to the Internet, the power consumption of the dongle is about 0.65 W when there is no active communication and around 0.75 W at very low data throughput. Once the throughput exceeds roughly 10 Kbps, the power consumption quickly rises; the more data transferred per unit time the more work that has to be done by the USB dongle. Note that in this state the voltage and current vary over a relatively small range and the power consumption when uploading or downloading is very similar.

Table 3-1: Huawei E1550 USB dongle power consumption

Usage Phase	Voltage (V)	Current (A)	Power (W)
USB dongle connected to laptop, but not connected to the Internet	4.86-4.87	0.05-0.06	0.2435-0.2916
Connected to the Internet, but no active data communication	4.57-4.58	0.14-0.15	0.6412-0.6855
Very low throughput (below 10Kbps)	4.50-4.51	0.16-0.17	0.7216-0.765
High upload throughput	4.22-4.23	0.25-0.26	1.0575-1.0972
High download throughput	4.20-4.23	0.25-0.27	1.0575-1.134

To measure the power consumed during the period when there is a high upload throughput, we use TCP-spray as a packet generator to send packets to a server. When using TCP-spray we can set the packet size and rate to generate the desired upload traffic. Figure 3-2 shows the command used for this test. With these parameters TCP-spray generates 1000 packets with a size of 2048 bytes to the server at IP address 130.237.209.214. A total of 2,050,048 bytes are sent in 53.961 seconds, and the average transmission speed is about 37 kbytes/s. It should be noted that this command sends the traffic to a TCP service called “discard” on the target computer, thus before running this command we need to turn this service on, since usually it is turned off for security reasons. For testing during high download throughput, we viewed an online video, since this load is representative of the highest download throughput application used by most users. We can see from the test results that the power consumption for this service could be more than 1.1W. Related graphs are provided in **Error! Reference source not found.**.

Figure 3-2: Generating packets using TCP-spray

These tests utilized a Huawei E1550 3G USB dongle. An interesting question is how this power consumption compares to the power consumption when accessing the Internet by WLAN. One might assume that using a WLAN interface* should require less power than using a 3G interface because the cellular base stations are likely to be further away and it requires more energy to move a given amount of data over a longer distance within the same time period. Based upon mobile users’ feedback available on the Internet, most users feel 3G communication requires more power than comparable communication over a WLAN. However, Andrew Baxter reports that the actual WLAN power consumption is very similar to the 3G power consumption [28]. By using the formula below, we can calculate the battery lifetime in hours of a laptop with/without a USB dongle.

Laptop Battery lifetime in Hours = Battery Capacity / Power Consumption

* More specifically a IEEE 802.11g interface was used.

The battery capacity and power consumption can be measured by a program called BatteryMon [29]. When the author's laptop (with a battery capacity of 40759 mWh) is playing an online video by WLAN and the screen brightness is high the power consumption is 20304 mW. This power consumption is shown in Figure 3-3.

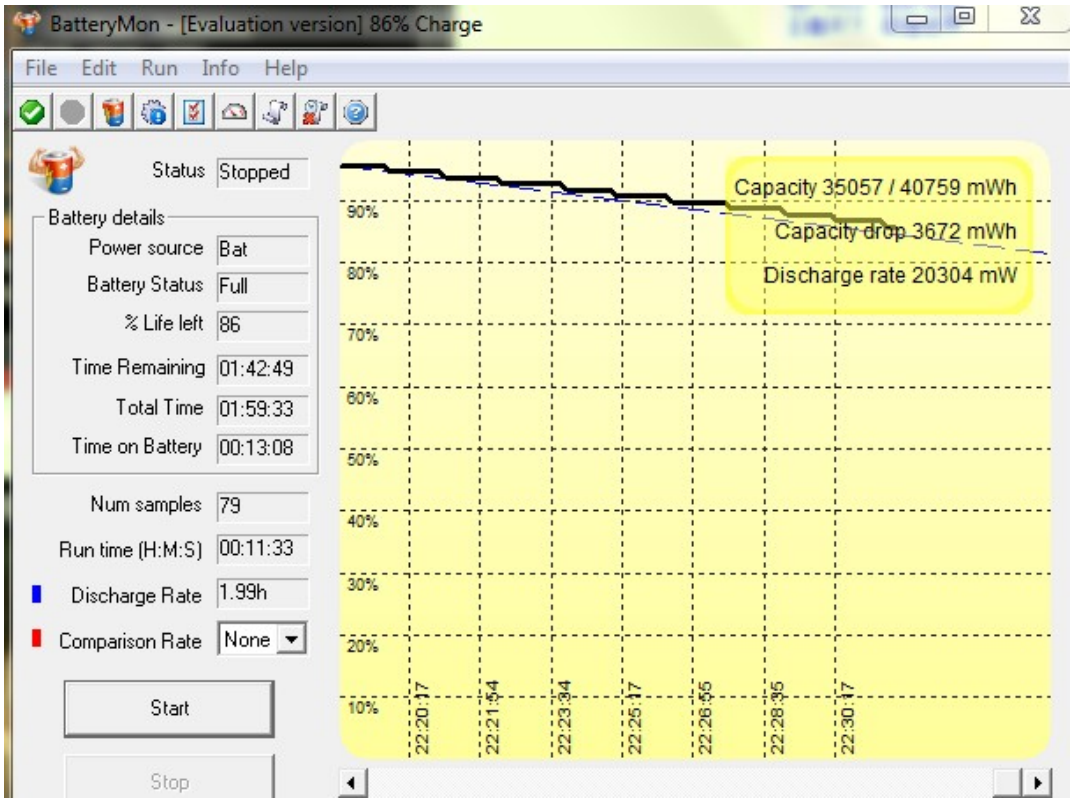

Figure 3-3: Laptop power information from BatteryMon when using the WLAN interface

Based upon the formula given above, the battery lifetime in hours is 40759mWh / 20304mW = 2 hours and 0.5 minute.

I repeated the test in the same environment, but used a 3G USB dongle instead of the Wi-Fi interface. According to the results shown in Figure 3-4, the battery operating with 3G is:

3G Battery Hours = 40759mWh / 20347mW = 2 hours and 0.2 minute

So there is only 0.3 minute difference between the two scenarios, thus most customers will experience a negligible difference in battery operating times. This test demonstrates that a 3G USB dongle is no more power consuming than using WLAN when streaming a video from an internet server.

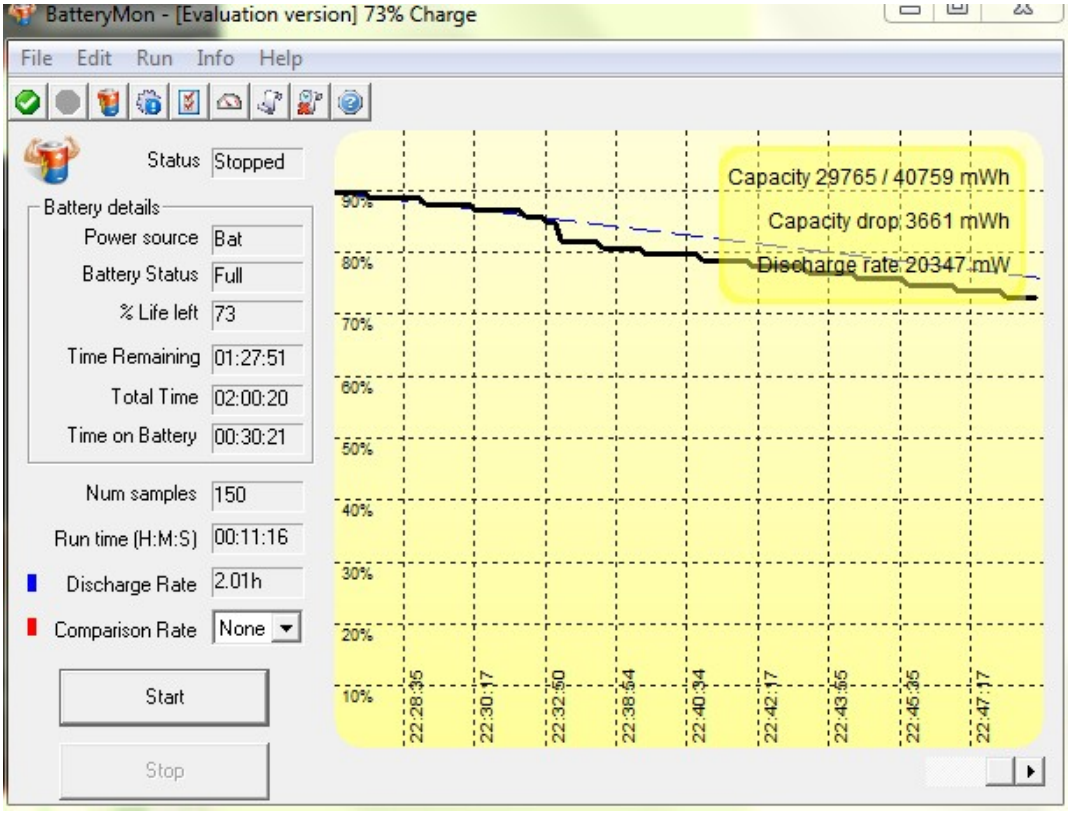

Figure 3-4: Laptop power information from BatteryMon when using 3G interface

3.3 Watching USB communication using USBTrace

To understand how the USB interface works, we analyze the data communication across the USB interface. There are several USB analysis tools available on the Internet for downloading, such as SnoopyPro [30], SniffUSB [31], and USBTrace [32]. Since USBTrace has good support for Windows system, the operating system running on the author's laptop, I choose to use USBTrace as the analysis software. Before using this powerful USB analyzer, we first give an overview of USB communication.

3.3.1 USB communication overview

USB provides an easy-to-use solution to connect various devices to computers by a standard interface. USB is host controlled, thus there has to be a host acting as a bus master. The communication utilizes token, data, and handshaking frames (here after referred to as packets). The USB protocol stack has several layers. The maximum data rate of USB 2.0* (in high speed mode) is 480 Mbps, 1.5 Mbps in low speed, and 12 Mbps in full speed mode. Unlike other similar serial interfaces in which the data format is not clearly defined, USB communication utilizes transactions, similar to Ethernet frames, but with each USB transaction consisting of 3 packets: a token packet, a data packet, and a handshake packet. The formats of these three types of packets are shown in Figure 3-5.

* USB 3.0 was not defined at the time that this project started; hence this thesis will not consider USB 3.0.

Token packet

Sync	PID	ADDR	ENDP	CRC5	EOP
8/32 bits	*8 bits*	*7bits*	*4bits*	*5bits*	*n/a*

Data packet

Sync	PID	Data	CRC16	EOP
8/32 bits	*8 bits*	*0-1024 bytes*	*16bits*	*n/a*

Handshake packet

Sync	PID	EOP
8/32 bits	*8 bits*	*n/a*

Figure 3-5: USB packet types

"n/a" in this figure means not applicable

All USB packets start with a synchronization (sync) field. This field is used for synchronization of the clock in the receiver with the clock in the transmitter, and it is 8 bits long in both low & full speed and 32 bits long in high speed mode. The next field is a Packet ID (PID). This ID indicates the type of the packet. The cyclic redundancy check (CRC) field is 5 bits long in a token packet and 16 bits in a data packet. The last field of every packet is End-of-Packet (EOP). This field terminates the packet.

The token packet specifies which device and endpoint the packet is to be sent to. Thus there is an address (ADDR) and an endpoint (ENDP) field in the token packet. A USB host can support at most 127 devices, since the ADDR field has 7 bits, and address 0 is not valid.

There are three different handshake packets: ACK which acknowledges to the sender that a packet has been successfully received; NAK which indicates that the packet could temporarily not be sent or received; and STALL which indicates that the endpoint halted or a control request is not supported. All of these handshake types are distinguished based upon their PID values.

These three different packets (token, data, and handshake) comprise a **USB transaction**. A complete USB communication procedure consists of numerous such transactions. The procedure can be divided into three stages: setup stage, data transfer stage, and status stage. Figure 3-6 illustrates these three stages. Note that during the data transfer stage, the data is separated into the fixed sized payloads, except for the last one.

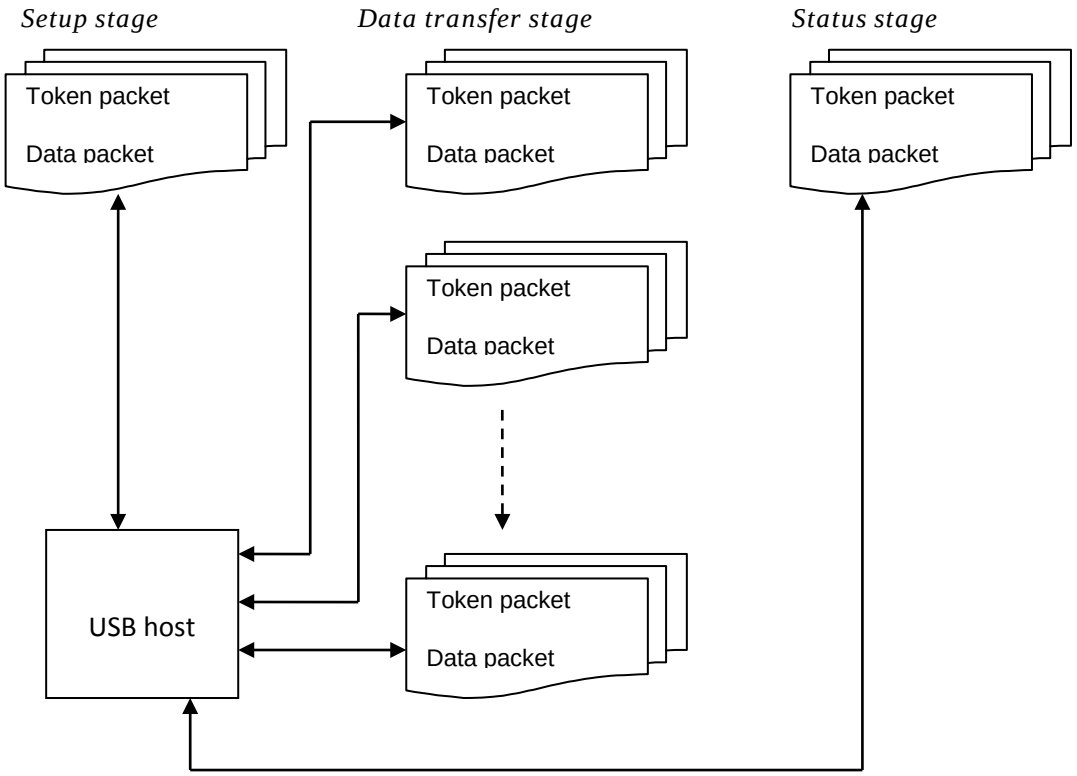

Figure 3-6: Three USB communication stages

Under Microsoft's Windows operating system, Plug and Play (PnP) (a type of hot swapping) enables adding or removing peripheral components without shutting down the host system. PnP is an important characteristic of USB. The PnP manager, a subsystem of Microsoft's Windows I/O manager, provides the PnP functionality. As PnP technology is implemented for USB, the host OS automatically configures each device after it is added. Note that the USB host controls all the communications, so there is no need for each external device to be allocated an Interrupt Request (IRQ) vector slot or I/O addresses. However, the USB bus controller inside the computer does have an assigned IRQ and an address on the PCI bus which is used for communication between the CPU and all devices on the USB. As a result, all of the devices attached to a single USB host interface share a single interrupt and a single I/O address [33]. To recognize different USB devices sharing the same interface, USB uses a technique called enumeration to find all of the devices, and then the operating system associates each device with a device descriptor.

When a USB device is plugged into a USB host, the host will perform an enumeration to determine all of the devices attached to this USB controller. The host will recognize the presence of the device and assign it a unique 7 bit device address. After assigning each of the devices an address, the host queries each device for its descriptors. These descriptors contain information about each specific device. USB devices have a hierarchy of descriptors. These descriptors are shown in Figure 3-7. Each USB device can only have one device descriptor, but can have more than one configuration descriptor. Most devices, however, only have one configuration descriptor since changing the configuration requires all activity on each endpoint to stop [34], thus it is inconvenient to do so in practice. A single configuration can have many interfaces, and each interface looks like a group of endpoints that accomplish a single function of a composite USB device. All communication between the USB host and a USB device is addressed to a specific endpoint of the device (keeping in mind that a given device can implement multiple endpoints). The endpoint can be a source of data (or the sink for data output by the USB host). All data is transferred through a virtual serial pipe between the host and this endpoint. There are four transfer types for endpoints: control, interrupt, isochronous, and bulk. For a USB dongle, the data is transferred using a bulk transfer.

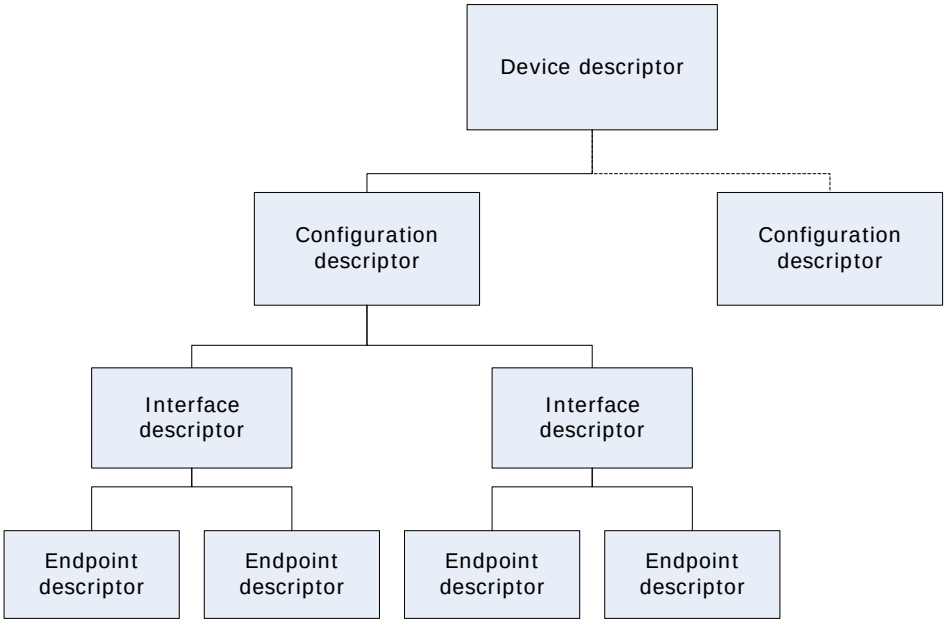

Figure 3-7: USB descriptors

3.3.2 Watching USB communication

We used USBTrace to monitor the communication in order to understand the entire device enumeration process. Other software analyzers, such as SnoopyPro, use a filter driver to capture USB bus activity; however, a serious limitation when using such a driver is that we cannot log any activity until the driver for the device is loaded, so this driver would miss the USB enumeration process between the host and the device. USBTrace avoids this limitation, thus we can monitor the communication starting immediately after a USB dongle is plugged into a host computer.

Figure 3-8 shows the first 21 requests in the enumeration process after a 3G USB dongle is plugged into the author's laptop. The packets supporting the PnP process are I/O request packets (IRPs). The first request is an IRP_MN_QUERY_CAPABILITIES. This request is sent by the PnP manager to learn the capabilities of a device, such as whether the device can be locked or ejected. The first time stamp is 7.782311 second, but this is not when the enumeration began, rather the timer started when the user clicks the "*Start Monitor*" icon in the graphical interface of USBTrace. Thus this time stamp indicates how quickly the user plugged in the USB device after starting the monitoring program. The next three PnP IRPs are QUERY_INTERFACE, QUERY_ID, and QUERY_DEVICE_TEXT. All of these are minor functions to the major function IRP_MJ_PNP. The PnP manager sends these IRPs to gather device information such as Capabilities, UINumber, HardwareID, LogConf\BootConfig, etc.

Seq	Type	Time	Request	I/O	EndPoint	Device Object	IRP	Status	Buffer Snippet	Buffer Size
0	START	0.000000	START OF LOG							
1	PNP	7.782311	QUERY_CAPABILITIES	OUT	0	0xD6E1A030	0xDA3F6490	STATUS_NOT_SUPPORTED		0
2	PNP	7.782316	QUERY_CAPABILITIES	IN	0	0xD6E1A030	0xDA3F6490	STATUS_SUCCESS		0
3	PNP	7.782340	QUERY_CAPABILITIES	OUT	0	0xD6E1A030	0xDA3F6490	STATUS_NOT_SUPPORTED		0
4	PNP	7.782342	QUERY_CAPABILITIES	IN	0	0xD6E1A030	0xDA3F6490	STATUS_SUCCESS		0
5	PNP	7.782365	QUERY_CAPABILITIES	OUT	0	0xD6E1A030	0xDA3F6490	STATUS_NOT_SUPPORTED		0
6	PNP	7.782367	QUERY_CAPABILITIES	IN	0	0xD6E1A030	0xDA3F6490	STATUS_SUCCESS		0
7	PNP	7.782389	QUERY_CAPABILITIES	OUT	0	0xD6E1A030	0xDA3F6490	STATUS_NOT_SUPPORTED		0
8	PNP	7.782391	QUERY_CAPABILITIES	IN	0	0xD6E1A030	0xDA3F6490	STATUS_SUCCESS		0
9	PNP	7.782412	QUERY_CAPABILITIES	OUT	0	0xD6E1A030	0xDA3F6490	STATUS_NOT_SUPPORTED		0
10	PNP	7.782415	QUERY_CAPABILITIES	IN	0	0xD6E1A030	0xDA3F6490	STATUS_SUCCESS		0
11	PNP	7.782435	QUERY_CAPABILITIES	OUT	0	0xD6E1A030	0xDA3F6490	STATUS_NOT_SUPPORTED		0
12	PNP	7.782438	QUERY_CAPABILITIES	IN	0	0xD6E1A030	0xDA3F6490	STATUS_SUCCESS		0
13	PNP	7.782457	QUERY_INTERFACE	OUT	0	0xD6E1A030	0xDA3F6490	STATUS_NOT_SUPPORTED		0
14	PNP	7.782463	QUERY_INTERFACE	IN	0	0xD6E1A030	0xDA3F6490	STATUS_NOT_SUPPORTED		0
15	PNP	7.782488	QUERY_ID	OUT	0	0xD6E1A030	0xD4567440	STATUS_NOT_SUPPORTED		0
16	PNP	7.782492	QUERY_ID	IN	0	0xD6E1A030	0xD4567440	STATUS_SUCCESS		0
17	PNP	7.782505	QUERY_CAPABILITIES	OUT	0	0xD6E1A030	0xD4567440	STATUS_NOT_SUPPORTED		0
18	PNP	7.782508	QUERY_CAPABILITIES	IN	0	0xD6E1A030	0xD4567440	STATUS_SUCCESS		0
19	PNP	7.782548	QUERY_DEVICE_TEXT	OUT	0	0xD6E1A030	0xD4567440	STATUS_NOT_SUPPORTED		0
20	PNP	7.782552	QUERY_DEVICE_TEXT	IN	0	0xD6E1A030	0xD4567440	STATUS_SUCCESS		0
21	PNP	7.782556	QUERY_DEVICE_TEXT	OUT	0	0xD6E1A030	0xD4567440	STATUS_NOT_SUPPORTED		0

Figure 3-8: The beginning of USB enumeration

As we can see in Figure 3-9 the PnP process continues until packet 44. The PnP manager learns the resource requirements and filters for these resources by QUERY_RESOURCE_REQUIREMENTS and FILTER_RESOURCE_REQUIREMENTS, and then it sends an IRP_MN_START_DEVICE to enable the driver(s) to start the device. Starting with packet 45, USB Request Block (URB) functions are used to control the device. However, the PnP manager occasionally sends some IRPs: QUERY_CAPABILITIES, QUERY_DEVICE_RELATIONS, and QUERY_PNP_DEVICE_STATE, to collect capability information, finding child devices, and changing configuration - respectively.

Seq	Type	Time	Request	I/O	EndPoint	Device Object	IRP	Status	Buffer Snippet	Buffer Size
37	PNP	7.785216	QUERY_LEGACY_BUS_INFORMATION	OUT	0	0xD6E1A030	0xD4567440	STATUS_NOT_SUPPORTED		0
38	PNP	7.785219	QUERY_LEGACY_BUS_INFORMATION	IN	0	0xD6E1A030	0xD4567440	STATUS_NOT_SUPPORTED		0
39	PNP	7.785424	QUERY_RESOURCE_REQUIREMENTS	OUT	0	0xD6E1A030	0xD4567440	STATUS_NOT_SUPPORTED		0
40	PNP	7.785427	QUERY_RESOURCE_REQUIREMENTS	IN	0	0xD6E1A030	0xD4567440	STATUS_NOT_SUPPORTED		0
41	PNP	7.785524	FILTER_RESOURCE_REQUIREMENTS	OUT	0	0xD6E1A030	0xD4567440	STATUS_NOT_SUPPORTED		0
42	PNP	7.785527	FILTER_RESOURCE_REQUIREMENTS	IN	0	0xD6E1A030	0xD4567440	STATUS_NOT_SUPPORTED		0
43	PNP	7.811380	START_DEVICE	OUT	0	0xD6E1A030	0xDA3F6490	STATUS_SUCCESS		0
44	PNP	7.812228	START_DEVICE	IN	0	0xD6E1A030	0xDA3F6490	STATUS_SUCCESS		0
45	URB	7.812242	GET_DESCRIPTOR_FROM_DEVICE	OUT	0	0xD6E1A030	0xD4567440	STATUS_SUCCESS		0
46	URB	7.812247	GET_DESCRIPTOR_FROM_DEVICE	OUT	0	0x877BBB30	0xD4567440	STATUS_SUCCESS		0
47	URB	7.812329	CONTROL_TRANSFER	IN	0	0x877BBB30	0xD4567440	STATUS_PENDING		0
48	URB	7.813584	CONTROL_TRANSFER	IN	0	0x877BBB30	0xD4567440	STATUS_SUCCESS	12 01 00 02 0...	18
49	URB	7.813623	GET_DESCRIPTOR_FROM_DEVICE	OUT	0	0xD6E1A030	0xD4567440	STATUS_SUCCESS		0
50	URB	7.813628	GET_DESCRIPTOR_FROM_DEVICE	OUT	0	0x877BBB30	0xD4567440	STATUS_SUCCESS		0
51	URB	7.813683	CONTROL_TRANSFER	IN	0	0x877BBB30	0xD4567440	STATUS_PENDING		0
52	URB	7.815585	CONTROL_TRANSFER	IN	0	0x877BBB30	0xD4567440	STATUS_SUCCESS	09 02 37 00 0...	9

Figure 3-9: The beginning of URB

A USB Request Block (URB) is a data structure designed for USB communications. Instead of direct communication, the USB device driver transfers URBs to the bus driver. The USB controller uses these URBs to execute the requests. If we compare the USB bus to a highway, then URBs are comparable to vehicles travelling on the highway. Some fields in the URB are common, although there are many URB functions with their own specific fields. By using USBTrace we can see the detailed URB information by clicking on a specific packet. For example, Figure 3-10 shows the detailed information about packet 48 - a URB_FUNCTION_CONTROL_TRANSFER.

URB_FUNCTION_CONTROL_TRANSFER

Urb Field	Value
Length	0x50
USBD Status	USBD_STATUS_SUCCESS (0x0)
EndpointAddress	0x0
PipeHandle	0xD68B998C
TransferFlags	0x72004F (USBD_TRANSFER_DIRECTION_IN USBD_SHORT_TRANSFER_OK)
TransferBufferLength	0x12
TransferBuffer	0x84FC8578
TransferBufferMDL	0xDA667078
UrbLink	0x0

Figure 3-10: Detailed URB information

From the figure we can see that the *EndpointAddress* is 0. Note that the *EndpointAddress* is not only 0 in packet 48, but also in all packets shown in Figure 3-9. Endpoint 0 is the default address and it receives all of the device control and status requests during enumeration. *PipeHandle* contains the control pipe handle used for I/O transactions on the virtual pipe created by the endpoint. *TransferFlags* specifies the direction of the transfer: in or out. Data may be read from or written to a resident buffer or Memory Descriptor List (MDL). In either case, the size of the buffer is shown in *TransferBufferLength*. The resident buffer address is in field *TransferBuffer* and the address of the MDL is in the field *TransferBufferMDL*. Normally either *TransferBuffer* or *TransferBufferMDL* should be null. For example, if the driver initializes the *TransferBufferMDL* to be null, then the USB stack will use *TransferBuffer* to exchange data. However, internally the USB stack might create an MDL, store a pointer to the MDL in *TransferBufferMDL*, and use this MDL to pass data down the stack. Although the USB stack frees the MDL memory, there is no guarantee that *TransferBufferMDL* will still be null when the driver is processing the URB in the completion routine [35].

In addition to the URB field information shown in the figure above, a device descriptor is also sent by URB_FUNCTION_CONTROL_TRANSFER. Figure 3-11 shows the device descriptor information captured using USBTrace. In this descriptor, *bcdUSB* is 0x200 indicating that it is a USB 2.0 device. The fields *bDeviceClass*, *bDeviceSubClass*, and *bDeviceProtocol* are used by the operating system to identify a class driver. However, most class specification is determined at the interface level, so these three fields are normally set to 0. The field *bMaxPacketSize0* shows the maximum packet size for endpoint 0. The fields *idVendor*, *idProduct*, and *bcdDevice* are assigned respectively by the USB Implementers Forum, Inc. (see USB.org), the manufacturer (in this case 0x12D1 indicates Huawei Technology), and the device developer (in this case 0x1446 indicates the product is a E1550 or E1750, device 0). The field *bNumConfigurations* specifies how many configurations the device has, and for this device the value is 0x1, so there is only one configuration descriptor. Following packet 48, some URB_FUNCTION_CONTROL_TRANSFER packets continue to show up, these URBs contain

information about the configuration descriptor, interface descriptors, and endpoint descriptors. After receiving these URBs, we know this device has one configuration, two interfaces, and four endpoints.

Device Descriptor	
bLength	0x12
bcdUSB	0x200
bDeviceClass	0x0
bDeviceSubClass	0x0
bDeviceProtocol	0x0
bMaxPacketSize0	0x40
idVendor	0x12D1
idProduct	0x1446
bcdDevice	0x0
iManufacturer	0x2
iProduct	0x1
iSerialNumber	0x0
bNumConfigurations	0x1

Figure 3-11: Device descriptor information

Continuing to watch the enumeration process until packet 92, an unexpected status result appears. As shown in Figure 3-12, the device is removed and the enumeration process restarts again from IRP_MN_QUERY_CAPABILITIES. The reason for this is due to the need for software installation. To surf on the Internet using this dongle, first we need to install the bundled connection control software which is storage in flash memory in the dongle. Although the USB 3G dongle is a modem from the user's perspective, it not only functions as a modem, but in fact it consists of several devices from the point of view of the host OS. In Figure 3-13 we can see there are six USB host controllers in the author's laptop, including two enhanced host controllers specialized for high-speed USB functions. Every USB host controller has an embedded root hub, so in total there are six root hubs. The Huawei USB dongle is controlled by an enhanced host controller 2836 and is recognized as a composite device with two mass storage devices. The connection software is storage in one USB mass storage device; thus avoiding the need to supply the user with a compact disk or digital video disks containing the software that the vendor provides.

This vendor software for managing the modem is automatically installed when the dongle is inserted in the host computer for the first time. After tracing the USB communications before and after the software installation, we found that the device that is removed during enumeration process is a mass storage device which stores the software to be installed. Because the host found that the required software was already installed the driver it performs a SURPRISE_REMOVAL. This means that the first 92 packets were used to detect if the connection control software is installed. Although the check for the mass storage device is performed every time the USB dongle is inserted, it only takes ~3.36 seconds (based upon subtracting time stamp 11.1439s in the 92nd packet from the 7.7823s timestamp of the first packet). The delay is short enough that most users will hardly notice this delay.

Seq	Type	Time	Request	I/O	EndPoint	Device Object	IRP	Status	Buffer Snippet	Buffer Size
82	PNP	7.824856	QUERY_DEVICE_RELATIONS	IN	0	0xD6E1A030	0xDA3F6490	STATUS_SUCCESS		0
83	SYSTE...	7.825131	REGINFO_EX	OUT	0	0xD6E1A030	0xD68A8008	STATUS_NOT_SUPPORTED		0
84	SYSTE...	7.825219	REGINFO_EX	IN	0	0xD6E1A030	0xD68A8008	STATUS_SUCCESS		0
85	PNP	10.5737...	QUERY_DEVICE_RELATIONS	OUT	0	0xD6E1A030	0xDA66D618	STATUS_NOT_SUPPORTED		0
86	PNP	10.5737...	QUERY_DEVICE_RELATIONS	IN	0	0xD6E1A030	0xDA66D618	STATUS_NOT_SUPPORTED		0
87	PNP	10.5737...	QUERY_DEVICE_RELATIONS	OUT	0	0xD6E1A030	0xDA66D618	STATUS_SUCCESS		0
88	PNP	10.5738...	QUERY_DEVICE_RELATIONS	IN	0	0xD6E1A030	0xDA66D618	STATUS_SUCCESS		0
89	PNP	10.7767...	SURPRISE_REMOVAL	OUT	0	0xD6E1A030	0xDA66D618	STATUS_SUCCESS		0
90	PNP	10.7772...	SURPRISE_REMOVAL	IN	0	0xD6E1A030	0xDA66D618	STATUS_SUCCESS		0
91	PNP	11.1439...	REMOVE_DEVICE	OUT	0	0xD6E1A030	0xD6896590	STATUS_NOT_SUPPORTED		0
92	PNP	11.1439...	REMOVE_DEVICE	IN	0	0xD6E1A030	0xD6896590	STATUS_SUCCESS		0
93	PNP	17.4240...	QUERY_CAPABILITIES	OUT	0	0xD684E030	0xD685A008	STATUS_NOT_SUPPORTED		0
94	PNP	17.4240...	QUERY_CAPABILITIES	IN	0	0xD684E030	0xD685A008	STATUS_SUCCESS		0
95	PNP	17.4502...	QUERY_CAPABILITIES	OUT	0	0xD684E030	0xD685A008	STATUS_NOT_SUPPORTED		0
96	PNP	17.4502...	QUERY_CAPABILITIES	IN	0	0xD684E030	0xD685A008	STATUS_SUCCESS		0

Figure 3-12: Mass storage device is removed during the enumeration

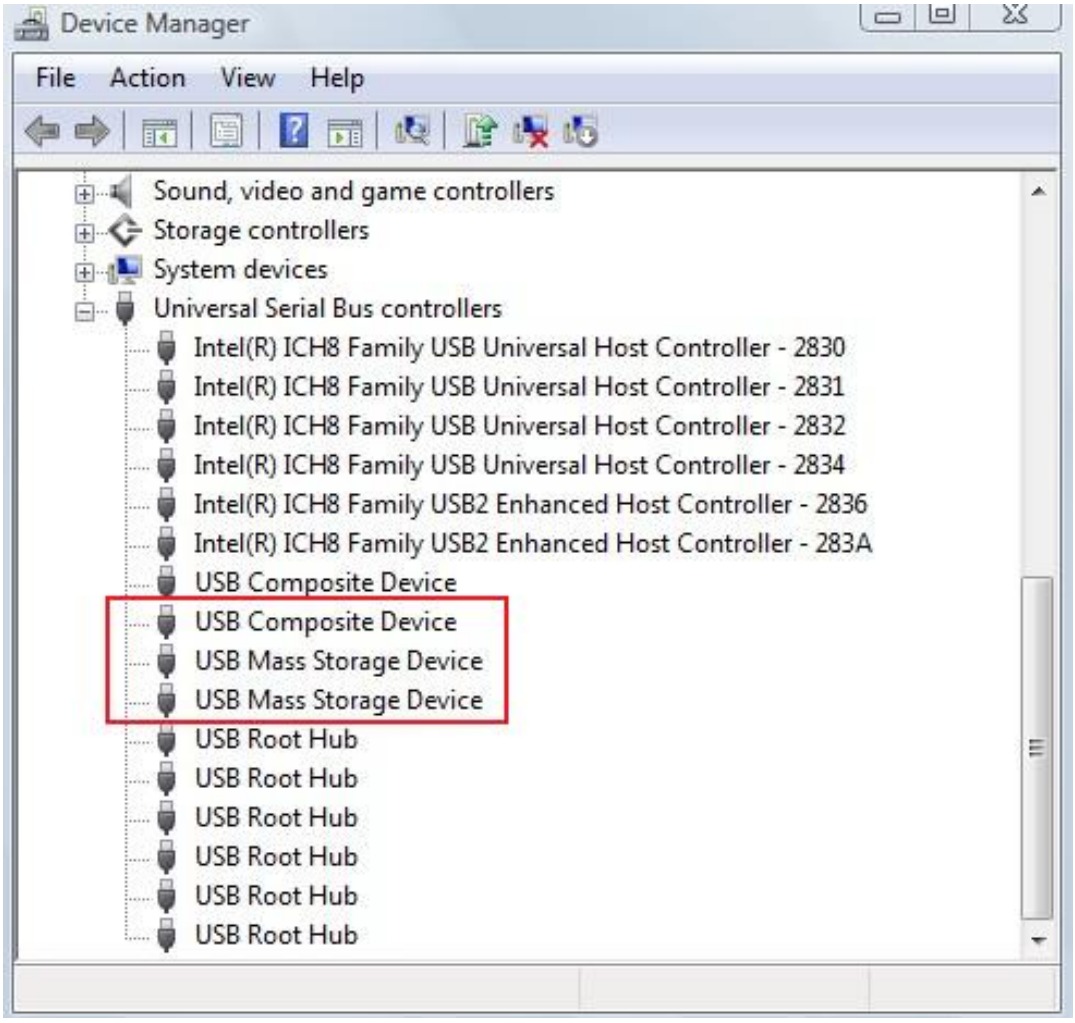

Figure 3-13: The dongle is seen as three devices by the Windows device manager

After the storage device is removed, the PnP manager sends a series of IRP_MJ_PNP requests to gather information about the new composite device, i.e., the modem. This PNP process is very similar to the PnP process that configured and then removed the mass storage device. In the same process as described for the first 45 packets, the PnP IRPs QUERY_INTERFACE, QUERY_ID, and QUERY_DEVICE_TEXT, shown in Figure 3-14 occur for the new device starting with packet 133. Also as before, to learn detailed information about the new device we can click on URB_FUNCTION_CONTROL_TRANSFER (see Appendix B). Examining this URB, we learn that the device has one configuration, five interfaces, and eleven endpoints. After the URB process starts, PnP requests continue. For example, the URB_FUNCTION_GET_DESCRIPTOR_FROM_DEVICE, IRP_MN_QUERY_ID, and URB_FUNCTION_CONTROL_TRANSFER transactions compose a group of requests to retrieve the string descriptor for the device. This group of requests occurs five times, since the device has five interfaces.

Seq	Type	Time	Request	I/O	EndPoint	Device Object	IRP	Status	Buffer Snippet	Buffer Size
127	PNP	17.5722...	QUERY_LEGACY_BUS_INF...	OUT	0	0xD684E030	0xD6865DE0	STATUS_NOT_SUPPORTED		0
128	PNP	17.5722...	QUERY_LEGACY_BUS_INF...	IN	0	0xD684E030	0xD6865DE0	STATUS_NOT_SUPPORTED		0
129	PNP	17.5724...	QUERY_RESOURCE_REQUI...	OUT	0	0xD684E030	0xD6865DE0	STATUS_NOT_SUPPORTED		0
130	PNP	17.5724...	QUERY_RESOURCE_REQUI...	IN	0	0xD684E030	0xD6865DE0	STATUS_NOT_SUPPORTED		0
131	PNP	17.5725...	FILTER_RESOURCE_REQUIR...	OUT	0	0xD684E030	0xD6865DE0	STATUS_NOT_SUPPORTED		0
132	PNP	17.5725...	FILTER_RESOURCE_REQUIR...	IN	0	0xD684E030	0xD6865DE0	STATUS_NOT_SUPPORTED		0
133	PNP	17.5729...	START_DEVICE	OUT	0	0xD684E030	0xD6865DE0	STATUS_SUCCESS		0
134	PNP	17.5736...	START_DEVICE	IN	0	0xD684E030	0xD6865DE0	STATUS_SUCCESS		0
135	PNP	17.5737...	QUERY_INTERFACE	OUT	0	0xD684E030	0xD685A008	STATUS_NOT_SUPPORTED		0
136	PNP	17.5737...	QUERY_INTERFACE	IN	0	0xD684E030	0xD685A008	STATUS_NOT_SUPPORTED		0
137	URB	17.5738...	GET_DESCRIPTOR_FROM_...	OUT	0	0xD684E030	0xD685A008	STATUS_SUCCESS		0
138	URB	17.5738...	GET_DESCRIPTOR_FROM_...	OUT	0	0xD68AD020	0xD685A008	STATUS_SUCCESS		0
139	URB	17.5739...	CONTROL_TRANSFER	IN	0	0xD68AD020	0xD685A008	STATUS_PENDING		0
140	URB	17.5753...	CONTROL_TRANSFER	IN	0	0xD68AD020	0xD685A008	STATUS_SUCCESS	12 01 00 02 0...	18

Figure 3-14: New device starts

Continuing to watch the USB communication, two requests appear many times: SYNC_RESET_PIPE_AND_CLEAR_STALL and BULK_OR_INTERRUPT_TRANSFER. The second request is especially frequent, see Figure 3-15. This seemingly endless process is called a polling transaction. The reason that the BULK_OR_INTERRUPT_TRANSFER repeats steadily is that the IN token from the USB dongle is always pending. However, because the dongle is yet not connected to the Internet no data is actually ready to be provided to the computer. If the request type of the USB device is isochronous or interrupt, (for example a mouse) then there are no repeated attempts to make a data transfer. However, if the request type is a control or bulk transfer, then the polling loop will be repeated again and again. As the 3G USB dongle uses bulk transfer, the device continuously polls until the Internet connection is set up.

Seq	Type	Time	Request	I/O	EndPoint	Device Object	IRP	Status	Buffer Snippet	Buffer Size
301	URB	17.8004...	BULK_OR_INTERRUPT_TRA...	IN	85	0xD6F14B60	0xD685A008	STATUS_SUCCESS	05 80 02 00 3...	36
302	URB	17.8004...	BULK_OR_INTERRUPT_TRA...	OUT	85	0xD684E030	0xD685A008	STATUS_SUCCESS		0
303	URB	17.8004...	BULK_OR_INTERRUPT_TRA...	OUT	85	0xD6F14B60	0xD685A008	STATUS_SUCCESS		0
304	URB	17.8004...	BULK_OR_INTERRUPT_TRA...	IN	85	0xD6F14B60	0xD685A008	STATUS_PENDING		0
305	URB	17.8015...	BULK_OR_INTERRUPT_TRA...	IN	85	0xD6F14B60	0xD685A008	STATUS_SUCCESS	55 53 42 53 0...	13
306	URB	17.8015...	BULK_OR_INTERRUPT_TRA...	OUT	4	0xD684E030	0xD68A8DE0	STATUS_SUCCESS	55 53 42 43 E...	31
307	URB	17.8015...	BULK_OR_INTERRUPT_TRA...	OUT	4	0xD6F14B60	0xD68A8DE0	STATUS_SUCCESS	55 53 42 43 E...	31
308	URB	17.8015...	BULK_OR_INTERRUPT_TRA...	IN	4	0xD6F14B60	0xD68A8DE0	STATUS_PENDING		0
309	URB	17.8023...	BULK_OR_INTERRUPT_TRA...	IN	4	0xD6F14B60	0xD68A8DE0	STATUS_SUCCESS		0
310	URB	17.8023...	BULK_OR_INTERRUPT_TRA...	OUT	85	0xD684E030	0xD68A8DE0	STATUS_SUCCESS		0
311	URB	17.8023...	BULK_OR_INTERRUPT_TRA...	OUT	85	0xD6F14B60	0xD68A8DE0	STATUS_SUCCESS		0
312	URB	17.8023...	BULK_OR_INTERRUPT_TRA...	IN	85	0xD6F14B60	0xD68A8DE0	STATUS_PENDING		0
313	URB	17.8033...	BULK_OR_INTERRUPT_TRA...	IN	85	0xD6F14B60	0xD68A8DE0	STATUS_SUCCESS	05 80 02 00 3...	56
314	URB	17.8033...	BULK_OR_INTERRUPT_TRA...	OUT	85	0xD684E030	0xD68A8DE0	STATUS_SUCCESS		0
315	URB	17.8034...	BULK_OR_INTERRUPT_TRA...	OUT	85	0xD6F14B60	0xD68A8DE0	STATUS_SUCCESS		0

Figure 3-15: Polling transaction

The next step is to connect to the Internet. After watching the communication using USBTrace, we found there are thousands of BULK_OR_INTERRUPT_TRANSFER requests during the communication process, and there is too much irrelevant detail. For this reason, we used the *filter* function in USBTrace to filter out this type of URB, thus this URB will not be displayed. Comparing the traces with/without BULK_OR_INTERRUPT_TRANSFER, we learn that the connection process begins with a continuous series of SYNC_RESET_PIPE_AND_CLEAR_STALL. These URBs do preparation work. They clear and reset all the serial pipes except for isochronous pipes on the host and device in order to perform new transfers without queued URBs. The next several bulk transfers are followed by a series of CLASS_INTERFACE and CONTROL_TRANSFER URBs (see Figure 3-16), these URBs send specific commands to an interface of the device and transfer data from or to a control pipe. The driver initiates the Internet connection during this process, with the main information transferred being control information, not bulk data.

Seq	Type	Time	Request	I/O	EndPoint	Device Object	IRP	Status	Buffer Snippet	Buffer Size
6345	URB	50.137778	BULK_OR_INTERRUPT_TRANSFER	IN	86	0x86BC0440	0x869D5DE0	STATUS_SUCCESS	55 53 42 53 E0 ...	13
6346	URB	50.276780	CLASS_INTERFACE	OUT	0	0xC89CF208	0x86B23338	STATUS_SUCCESS		0
6347	URB	50.276787	CLASS_INTERFACE	OUT	0	0x87658A00	0x86B23338	STATUS_SUCCESS		0
6348	URB	50.276871	CONTROL_TRANSFER	IN	0	0x87658A00	0x86B23338	STATUS_PENDING		0
6349	URB	50.278184	CONTROL_TRANSFER	IN	0	0x87658A00	0x86B23338	STATUS_SUCCESS	00 C2 01 00 00 ...	7
6350	URB	50.278303	CLASS_INTERFACE	OUT	0	0xC89CF208	0x86B23338	STATUS_SUCCESS		0
6351	URB	50.278308	CLASS_INTERFACE	OUT	0	0x87658A00	0x86B23338	STATUS_SUCCESS		0
6352	URB	50.278361	CONTROL_TRANSFER	IN	0	0x87658A00	0x86B23338	STATUS_PENDING		0
6353	URB	50.280206	CONTROL_TRANSFER	IN	0	0x87658A00	0x86B23338	STATUS_SUCCESS	00 C2 01 00 00 ...	7
6354	URB	50.280354	CLASS_INTERFACE	OUT	0	0xC89CF208	0x86B23338	STATUS_SUCCESS		0
6355	URB	50.280360	CLASS_INTERFACE	OUT	0	0x87658A00	0x86B23338	STATUS_SUCCESS		0
6356	URB	50.280417	CONTROL_TRANSFER	IN	0	0x87658A00	0x86B23338	STATUS_PENDING		0
6357	URB	50.282178	CONTROL_TRANSFER	IN	0	0x87658A00	0x86B23338	STATUS_SUCCESS	00 C2 01 00 00 ...	7

Figure 3-16: Connecting to the Internet

After the host computer is connected with the Internet, all of the packets that are transferred are BULK_OR_INTERRUPT_TRANSFER, and this persists until we terminate the connection. During termination, CLASS_INTERFACE and CONTROL_TRANSFER URBs are used for transferring control information. The last step occurs when the user ejects and unplugs the USB dongle by clicking the USB icon in the bottom right of the Windows interface. Note that the USBTrace reveals that there

are bulk transfers even after we virtually unplug the dongle from host, and these transfers continue for about 90 seconds until packet 24266, IOCTL_INTERNAL_USB_SUBMIT_IDLE_NOTIFICATION. The client driver sends this request to the bus driver when a device goes idle. After this the bus driver determines if it is safe to put the device in a low power state by sending a IRP_MN_SET_POWER packet, and finally USBTrace stops detecting communication at packet 24295. At this point we physically unplugged the dongle from the laptop, resulting in a SURPRISE_REMOVAL and a REMOVE_DEVICE URB, see the last 21 packets shown by USBTrace (see Figure 3-17).

Seq	Type	Time	Request	I/O	EndPoint	Device Object	IRP	Status
24292	URB	187.092694	CONTROL_TRANSFER	IN	0	0x87658A00	0xC8E55658	STATUS_UNSUCCESS...
24293	URB	187.109093	BULK_OR_INTERRUPT_TRANSFER	IN	81	0x87658A00	0x8591E570	STATUS_CANCELLED
24294	POWER	187.205966	SET_POWER	OUT	0	0xC89CF208	0xC8E55658	STATUS_NOT_SUPPO...
24295	POWER	187.206279	SET_POWER	IN	0	0xC89CF208	0xC8E55658	STATUS_SUCCESS
24296	INTERNAL_DE...	312.873565	SUBMIT_IDLE_NOTIFICATION	IN	0	0xC89CF208	0xC898AB48	STATUS_CANCELLED
24297	POWER	312.873605	SET_POWER	OUT	0	0xC89CF208	0x855ECE00	STATUS_SUCCESS
24298	POWER	312.873609	SET_POWER	IN	0	0xC89CF208	0x855ECE00	STATUS_SUCCESS
24299	PNP	312.873681	QUERY_DEVICE_RELATIONS	OUT	0	0xC89CF208	0x86D00608	STATUS_NOT_SUPPO...
24300	PNP	312.873684	QUERY_DEVICE_RELATIONS	IN	0	0xC89CF208	0x86D00608	STATUS_NOT_SUPPO...
24301	PNP	312.873734	QUERY_DEVICE_RELATIONS	OUT	0	0xC89CF208	0x86D00608	STATUS_SUCCESS
24302	PNP	312.873737	QUERY_DEVICE_RELATIONS	IN	0	0xC89CF208	0x86D00608	STATUS_SUCCESS
24303	URB	312.873965	CLASS_INTERFACE	OUT	0	0xC89CF208	0x855ECE00	STATUS_SUCCESS
24304	URB	312.873969	CLASS_INTERFACE	IN	0	0xC89CF208	0x855ECE00	STATUS_NO_SUCH_D...
24305	URB	314.873346	BULK_OR_INTERRUPT_TRANSFER	OUT	68	0xC89CF208	0x8591E570	STATUS_SUCCESS
24306	URB	314.873353	BULK_OR_INTERRUPT_TRANSFER	IN	68	0xC89CF208	0x8591E570	STATUS_NO_SUCH_D...
24307	URB	314.873360	SYNC_RESET_PIPE	OUT	68	0xC89CF208	0xB07EE700	STATUS_SUCCESS
24308	URB	314.873363	SYNC_RESET_PIPE	IN	68	0xC89CF208	0xB07EE700	STATUS_NO_SUCH_D...
24309	PNP	316.900560	SURPRISE_REMOVAL	OUT	0	0xC89CF208	0x871A18A0	STATUS_NOT_SUPPO...
24310	PNP	316.900808	SURPRISE_REMOVAL	IN	0	0xC89CF208	0x871A18A0	STATUS_SUCCESS
24311	PNP	317.012519	REMOVE_DEVICE	OUT	0	0xC89CF208	0x871A18A0	STATUS_SUCCESS
24312	PNP	317.012544	REMOVE_DEVICE	IN	0	0xC89CF208	0x871A18A0	STATUS_SUCCESS

Figure 3-17: The last 21 packets watched by USBTrace

3.4 Communication between the laptop and dongle

In this section we descript how the laptop uses the dongle to access a remote access service and then review Microsoft's Remote Network Driver Interface Specification.

3.4.1 Remote Access Service

A traditional USB dongle looks and acts like a serial modem, thus it has to connect to a "terminal server" via PPP, negotiate which protocol family it is going to use, get assigned an IP address, then it can start to encapsulate IP packets and transmit them to the destination. If the connection is lost, then it has to start all over again. This kind of dial up service is supported by Remote Access Service (RAS), a technique which was originally created by Microsoft [36]. RAS connects remote dial up clients to a host computer, known as a remote access server. Via this server, client computers can access to a LAN or the Internet. RAS uses PPP as the client program to establish the connection between the remote client and server. The result is as if the client were connected directly by a serial cable to the server.

PPP is a link layer protocol which can encapsulate and transport multiple network layer protocols over dedicated point to point links between two nodes. It can also provide authentication, configuration, encryption, etc. The general frame format for PPP is shown in Figure 3-18. Each PPP frame has two flag fields to indicate the start and end of a PPP frame. The flag field always has value

"01111110" (or 0x7E in hexadecimal). Since PPP is used for a point to point link, there is actually no need for an address field, so the address field is typically set to the broadcast address "11111111". Similarly the control field has a fixed value "00000011". The reason to keep these unnecessary fields is that PPP frame is based on and follows High-Level Data Link Control (HDLC) framing. The most important fields in PPP are the protocol and information fields. The protocol field identifies the type of encapsulated protocol in the information field. The maximum length of the information field (including possible padding) is 1500 bytes, and this field contains an encapsulated datagram from the network layer. The Frame Check Sequence (FCS) field is used to check whether the frame has errors following its transmission and reception.

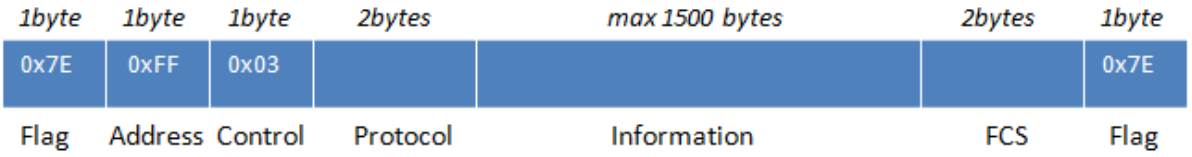

Figure 3-18: General PPP frame format

For a USB dongle in RAS mode, the Hayes command set also know as AT commands ("AT" means attention) is very important. These commands provide the command language used between the laptop computer and USB dongle. From a 3GPP specification [37] we learned that these AT commands involve three parties: Terminal Equipment (TE), Mobile Termination (MT), and Terminal Adaptor (TA). In our case, the TE will be the laptop, MT is the USB dongle, and the TA is integrated within the dongle as the module that processes AT commands. The network setup process is displayed in Figure 3-19, first a user uses the laptop to send AT commands through the serial link to the dongle. The adaptor receives and analyzes these commands, and then transfer control the dongle. The dongle processes the command by interacting with the network and sends the resulting status information back to the laptop through the adapter.

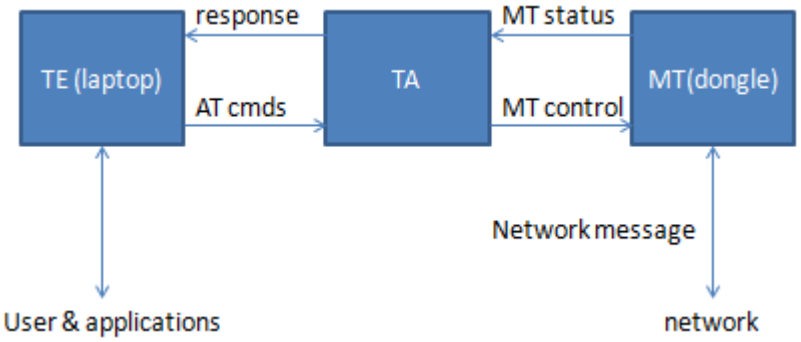

Figure 3-19: AT commands between laptop and dongle

PPP and AT commands are used in a traditional USB dongle to make the dongle work as a serial dial up modem. For this project, our purpose a dongle design in which the dongle can provide multiple heterogeneous network service, for example, the dongle could have interfaces for WLAN, 3G, and 4G. The first step is to recognize that using PPP as the interface between the dongle and laptop is no longer a good idea – as we are not simply trying to look like a dial-up modem, but rather should look like a packet interface.

Furthermore, the interface may need to expose multiple ports as it may want signal quality and status information, while remaining connected with the Internet [38]. Therefore we can see that having a single serial port for PPP communication is not sufficient. Most GSM/UMTS modems have a second AT port; however, most CDMA modems do not [39]. Moreover in RAS mode, IP packets must be encapsulated with headers and trailers to form PPP frames to be sent over a dedicated link. Obviously RAS mode is not efficient. Instead of using a dedicated point to point communication link, if the communication interface between the dongle and laptop were a IEEE 802 network adapter, for

example an Ethernet adapter, then IP data is simply encapsulated as an Ethernet frame for transport. This new network adapter interface is even more appropriate for today's all IP networks.

Before continuing with the next subsection, we need to clarify the two interfaces of a mobile terminal (i.e. USB dongle), and we borrow the names Um and Rm introduce by Sang Woo Park in US Patent 20100074155 [40] to describe these two interfaces. In our case, Um is the air interface between a USB dongle and a base station or WLAN access point. Rm is the physical data communication interface between a dongle and a laptop computer. The two interfaces are illustrated in Figure 3-20. The scope of this thesis focuses on the Rm interface. Despite heterogeneous wireless networks and the need for multiple Um interfaces - such as GSM/3G/4G/WLAN, we only need one Rm interface for these various Um interfaces.

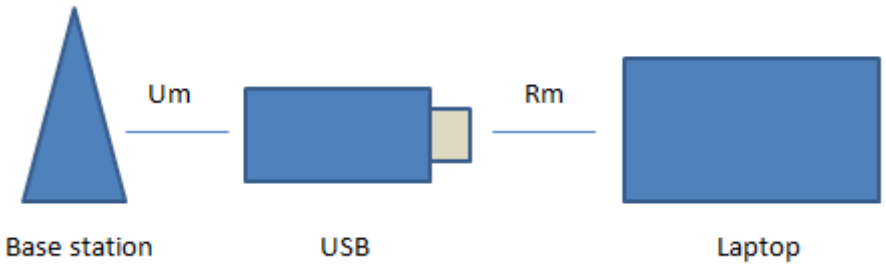

Figure 3-20: Two interfaces of USB dongle

3.4.2 Remote Network Driver Interface Specification

Both academia and industry have realized the deficiency of USB dongle working as a dial up modem, and several protocols to provide Ethernet-style networking over USB have been designed in recent years. The USB Implementers Forum (USB-IF) defined a number of USB Communications Device Class (CDC) protocols to provide this virtual Ethernet functionality, such as CDC ACM (Abstract Control Model) and CDC Network Control Model (NCM). Microsoft defined its proprietary protocol Remote Network Driver Interface Specification (RNDIS) to provide a virtual Ethernet link over USB to most versions of the Windows operating systems. Although RNDIS is not recommend by certain companies, such as MCCI [41], given Microsoft Windows 91.07% market share in desktop and laptop computers operating systems [42], Microsoft Windows still has a dominant position in the market, so we select RNDIS as the protocol to examine in our research. RNDIS is naturally compatible with recent Windows systems which are used by the overwhelming majority of customers. This large number of potential customers leads to greater opportunities for all participants in the value chain. For Apple Mac users, it is also possible to use RNDIS by installing drivers, for example, HoRNDIS [43].

RNDIS is based on NDIS which was developed by Microsoft and 3Com to provide an application programming interface for network adapters in Windows systems. The NDIS interface is located between the physical network adapter and upper layers such as TCP/IP. As shown in Figure 3-21, NDIS contains three types of drivers; from top to bottom, these are a protocol driver, intermediate driver, and miniport driver. The NDIS miniport driver interacts with network adapter, normally this driver varies with the hardware and it is developed by network adapter manufacturers. The NDIS protocol driver is independent of the underlying hardware and it is responsible to handle various upper layer protocols such as TCP/IP and to transport packets to the next lower level. The NDIS intermediate driver is in the middle and it has two different interfaces to communicate with its upper and lower drivers (respectively). The protocol driver looks like an intermediate driver to a miniport driver, whereas the intermediate driver looks like a protocol driver from the miniport driver's view. NDIS can deal with a USB dongle as a network adapter. Modern personal computer operating systems have quite good support for Ethernet and WLAN network adapters, so NDIS mode can have a better performance than RAS mode when carrying TCP/IP traffic. Some vendors have produced USB

dongles with both RAS and NDIS modes [44] [45]. Rather than AT command based communication with modems, NDIS can use non-AT protocols such as Qualcomm MSM Interface (QMI), an interface for communicating with Qualcomm Mobile Station Modems. QMI provides a better service for high data rate mobile broadband, and in practice various Qualcomm chipsets are widely used by USB dongle vendors, for instance, the MDM9x00 [46] which can support 2G/3G/LTE multi-mode service.

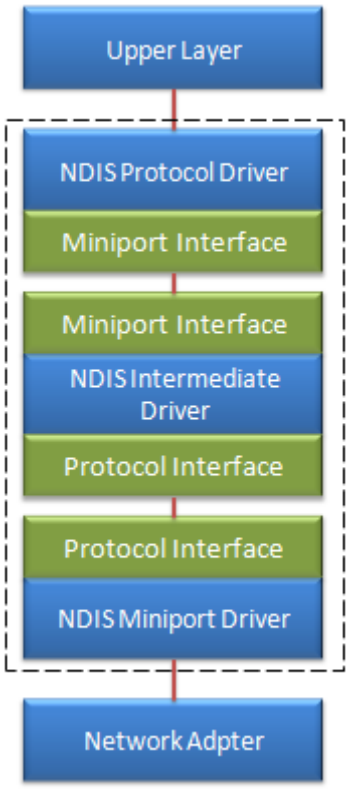

Figure 3-21: NDIS driver architecture

NDIS is a driver architecture which can work with several different types of links, for example, Ethernet, WLAN, and Bluetooth. RNDIS is a USB protocol tightly coupled with NDIS drivers, that provides virtual Ethernet over USB. For the NDIS architecture, network device vendors must develop miniport driver by themselves, and users must install the driver; otherwise the host computer would not recognize the device. RNDIS defines a bus-independent message set and a description of how this message set operates over the USB bus by creating a miniport driver and a USB transport driver in host computer [47].

RNDIS standardized the set of host drivers, so RNDIS can support any number of networking devices attached to the USB bus. The RNDIS solution has two significant advantages [48]. First, the device manufacturers do not need to develop a NDIS miniport driver, they simple need to implement their firmware conforming to the RNDIS protocol, which simplifies the development of the network device. Second, RNDIS eliminates the requirement to install the device driver on the host computer, thus improving the end user's experiences. The RNDIS architecture is illustrated in Figure 3-22. With RNDIS, user does not need to consider driver installation, the user simply plugs the USB dongle into the laptop, and then the user can start to explore the Internet.

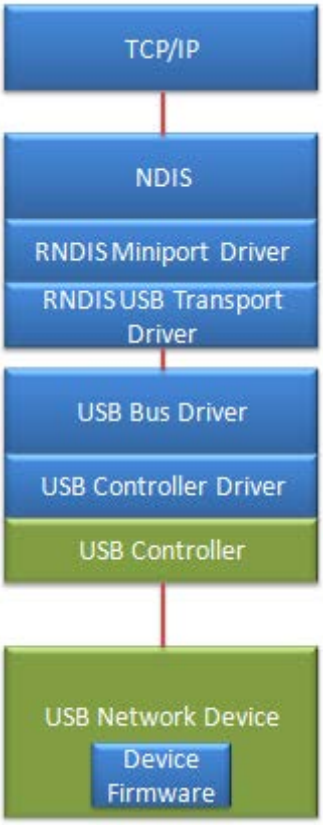

Figure 3-22: RNDIS architecture

3.5 General architecture of the dongle

A comprehensively design of all of the functions of a USB dongle exceeds the scope of a single master's thesis. In this section we briefly describe our design. The general architecture for the proposed USB dongle is illustrated in Figure 3-23. As explained in the previous section, the RNDIS architecture was selected for the Rm interface of the USB dongle. For the Um interface(s), the dongle should be able to support both mobile broadband and WLAN, and the dongle should automatically utilize the best interface to provide the user with the best quality (or personally preferred) network. For this reason, we need interface for both cellular network and WLAN. A policy manager which can manage handoff policy parameters and decide when and how to switch between heterogeneous networks is also required.

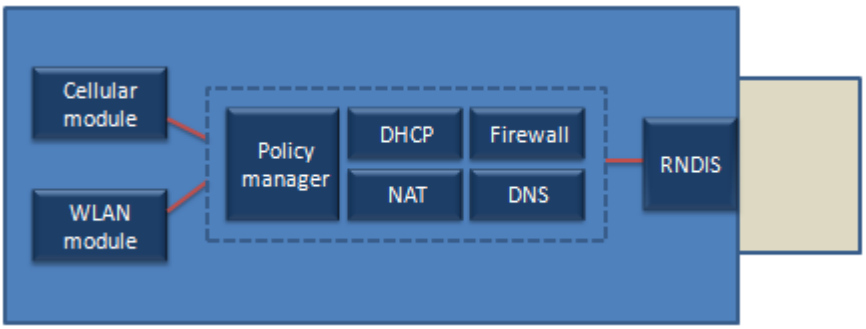

Figure 3-23: USB dongle architecture

The number of laptops and mobile devices such as smartphones and tablets continues to increase. Today many people have more than one mobile node when they are travelling. For this reason it would be great if the USB dongle can work as a wireless access point, thus the user can share their Internet connection with the user's other mobile nodes or with other users. Though some network operators and users may not want to have tethering or virtual Wi-Fi functions due to the substantial increase in network traffic and mobile data, it is still a good idea to provide this service as an optional function of the dongle. For this reason we suggest that tethering as *disabled* by default, but if they would like to have this function, then users could simply turn it on via a configuration interface. This suggests the dongle should have a built-in web server to provide this configuration interface, thus it would be similar to many Wi-Fi APs and Internet routers.

Since several mobile nodes may use the USB dongle at the same time, we need Network Address Translation (NAT), so one public IP address in the dongle can correspond to different private IP addresses in mobile nodes. Additional common network modules which are required for our dongle include: a Dynamic Host Configuration Protocol (DHCP) server, a Domain Name System (DNS) server, and firewall. With a DHCP server the dongle could provide local addresses to other tethered devices. By providing a DNS server (actually a DNS proxy server) all of the local Internet devices would be able to take advantage of the caching gains which this proxy could offer, thus speeding up web browsing and other services. Proving a firewall to all of the local internet devices could reduce the impact of unwanted remote traffic on each of the local devices and their local communication network. Note that this firewall should probably work in conjunction with a firewall service in the different network operators to push filtering to these operators – rather than having this unwanted traffic flow across the Um link(s) to the dongle. However, the details of such a shared and distributed firewall service remain for future work.

Another requirement for the dongle is to support both IPv4 and IPv6. Although IPv6 was designed to replace IPv4, IPv4 is still extensively used in many systems. To enable most customers to use our product, the USB dongle should support both IPv4 and IPv6. This can be implemented by a dual-stack approach. Additionally, the dongle could allow local devices to use IPv4 and it could provide a IPv4 proxy service while actually using IPv6 over each of the Um links.

4 Analysis

In this chapter, we present the detailed analysis for our designed USB dongle. Technical issues such as policy based handoff and configuration interface are discussed. We also review the market changes since USB dongle launched into the market, show the market trend, and give some suggestions and guidance for the product development.

4.1 Technical analysis

Thanks to the rapid development of ICT, today's mobile users can choose a variety of wireless networks such as WLAN, UMTS, LTE and WiMAX. However, the widespread deployment of heterogeneous networks also brings many problems to network users and operators. Users need different devices to connect different networks; operators must think over the integration of heterogeneous networks to provide the best available network depending on users' requirements. There are three important issues we need to consider for heterogeneous networks: security, location management and handoff.

Radio communications networks do not provide physically secure connection paths, but both cellular networks and WLAN have respective security mechanisms about authentication, authorization, privacy, confidentiality, integrity, trust, etc. In heterogeneous networks, however, a communication process may involve networks belonged to several different operators. How to guarantee security issues under different technologies and QoS is a challenge.

Location management is a two-stage process which enables the network to discover the locations of mobile users [49]. The first stage is location registration; the mobile node periodically notifies the network by sending specific signals to inform the network of its current location. The second stage is paging or call delivery; the network is queried about the location of the mobile node based on the registered information, then a connection or a call can be delivered successfully.

As we described in section 2.4, there are two types of handoff: horizontal and vertical. The handoff in heterogeneous networks is vertical handoff. The vertical handoff process may be divided into three phases: network discovery, handoff decision and handoff implementation [50]. In network discovery, the mobile node (or USB dongle in our case) searches for reachable wireless networks and receives the networks' information by activating the dongle's multiple wireless interfaces: WLAN and cellular networks. If the USB dongle always keeps these interfaces on, then the node could find available networks timely. However, it would cost much more battery power by turning the network interfaces always on, and it could seriously reduce the working time of the USB dongle and its connected laptop. To eliminate this problem, one method is to periodically activate the network discovery phase, and find a balance between the system discovery time and power efficiency, but how to set appropriate discovery period in heterogeneous networks is a topic that needs future research. Another method could be Location Service Server (LSS) [51]. LSS collects the wireless network information in its nearby area, so the dongle can get the information from LSS. This method can find nearby available network quickly with relatively less power consumption, but it is quite a challenge to maintain all LSSs in a big heterogeneous network.

Handoff decision is about the ability to decide when to perform the handoff. In homogeneous networks the timing to handoff can be just depending on the signal quality, for handoff in heterogeneous networks, however, many issues should be considered, for example, network bandwidth, cost, security, QoS, or user preferences, so a decision algorithm based on various policies should be designed. Table 4-1 displays the common handoff policy parameters. We use four dimensions to divide these parameters in four groups. The dimensions are: static context, dynamic context, network related, and user related.

Table 4-1: Handoff policy parameters

Policy parameter	Network related	User related
Static context	Operator, network type, bandwidth, network configuration, coverage, latency	User preference, cost, security, application, QoS, mobile node feature
Dynamic context	Signal strength, current data rate, packet loss rate, network traffic	Movement velocity, location, history, priority, mobile node battery

To smoothly perform the handoff implementation, protocols which support the data transfer from old link to new link should be designed. A series of actions such as registration, cancelation, connection and reconnection should be performed. Traditionally the handoff can be controlled entirely by the network or entirely by the mobile node. It is also possible to combine both of these strategies [52]. In this thesis, our aim is to make the USB dongle take charge of the handoff between WLAN and cellular networks. A simple workflow of the dongle is shown in Figure 4-1. We presume that user sets WLAN interface as the priority, so the dongle first tries to search WLAN networks in the vicinity, and the dongle only tries to connect with 3G network if there is no available WLAN in the neighborhood. This is just a very simple example, the real workflow could be much more complex in practice. There may be many WLANs available; the dongle may have the ability to connect to heterogeneous cellular networks such as LTE and 3G; hence the dongle should also decide whether to connect to a WLAN or cellular networks after the signal strength decreases or the connectivity is lost.

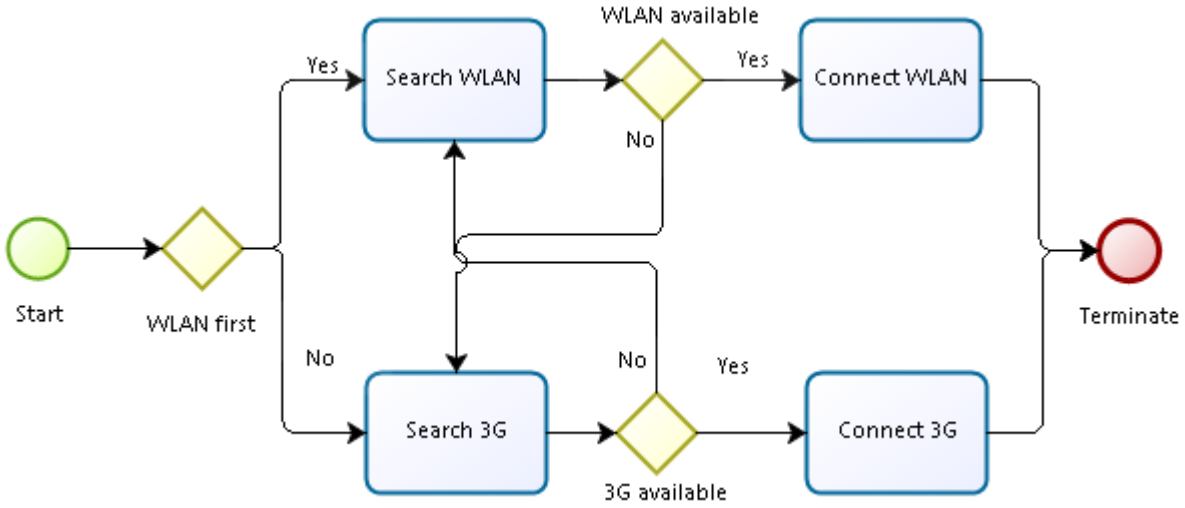

Figure 4-1: A simple workflow of USB dongle

This USB dongle should be able to connect to the Internet automatically without the operation of a user. However, the dongle may need some configurations depending on the user's requirements. Similar to many wireless routers, the dongle should have a built-in web server to provide this configuration interface. Figure 4-2 demonstrates the main functions in the configuration page. There are three groups: network connection, network management and other functions. Each group has sub-groups. In network connection, the user can select to connect the Internet automatically or manually, and the user can set handoff policies. In network management, the user can see statistics about the network traffic, change tethering default, and manually switch to a different network if the user is not satisfied with current network. The USB dongle can also be used as a normal flash drive, so users do not need bring extra flash drives if they have this USB dongle. The dongle is driver free for the current

mainstream Windows operating systems, but the dongle should also provide drivers if the user is using a legacy system, for instance, Windows XP, so the dongle can cover more users by providing drivers.

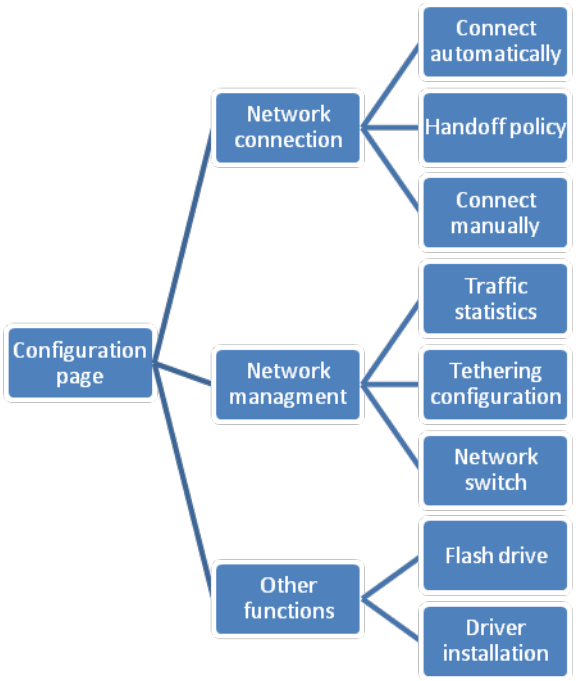

Figure 4-2: Main functions of configuration page

4.2 Market analysis

The ICT industry evolves much faster than other industries. It is argued that the Internet time is seven times more than our real time [53]. When this thesis project was proposed in 2009, the multi-mode USB dongle which provides heterogeneous networks with a Ethernet interface was just an idea. Today, however, there are many similar products in the market. The ICT world has experienced a great deal of changes in the past a few years. Time is probably the best evaluation for a product. Reviewing the changes in market and technology can show us a better overview and assessment of USB dongle, and it can also indicate us the future trend for this product.

The mainstream WLAN standards have moved from IEEE 802.11a/b/g to IEEE 802.11n/ac. WLAN is becoming popular from the beginning of this century, and the old standard, for instance IEEE 802.11b, can provide single user the data rate which is enough for most Internet applications, but the data rate may decrease a lot if too many users share one access point. Due to new techniques such as MIMO and Multi-user MIMO, IEEE 802.11n/ac greatly increase the data rate and transmission range, so one hotspot can provide more users with fast Internet connections. 802.11ac can support up to eight antennas to reach the highest data rate. However, we must note the USB dongle cannot reach the highest theoretical speed because normally a USB device just support 1 or 2 antennas due to cost and space reasons [54].

When USB dongle started to become popular in the market, WCDMA was the most common 3G network worldwide. Then it updated to HSPA and HSPA+. Nowadays 4G networks, especially LTE has been widely deployed in many countries. LTE has the highest data rates in commercial cellular networks, and it was designed based on packet networks, so it is quite appropriate for data applications in all IP networks. Actually USB dongle was the first LTE device when TeliaSonera launched the world first public LTE networks in Oslo and Stockholm in the late of 2009 [55]. With LTE, users can have much better Internet experiences for watching videos, attending webinars, playing online games, etc. However, even though current LTE networks have quite high data rates,

the new WLAN standard such as 802.11ac still has many advantages over LTE, just as 802.11b to WCDMA.

Today USB is the standard connection between personal computers and computer peripherals. The newest USB standard is USB 3.1, and USB Type-C which is a small reversible-plug connector for USB devices. Unlike the half duplex communication mechanism in USB 2.0, USB 3.0 and USB 3.1 use two unidirectional data paths to make the interface as full duplex to be able to receive and send data simultaneously. From USB 3.0, USB ports can provide up to 900 mA, so USB devices are able to consume more power, and the good news is that it does not mean USB devices must consume more power. Because USB 3.0 has better power management, it can conserve power when the USB device is connected to a computer but in idle status. The new USB standards have much faster speed than USB 2.0, so a USB dongle with USB 3.0 interface can better match current fast mobile broadband data rates.

USB dongle has entered the market for around ten years, after 3G networks were widely deployed. Customers were quite surprised when they first found a 3G modem with USB connection [56], and this fancy device was becoming prevalent soon in the whole world. The initial USB dongles, for instance Huawei E220 [57], actually do not look like a USB flash drive, and it needs an extra USB cable to connect to a laptop. User must install driver manually before using the dongle, but it is already a technical advancement since the driver is saved in the flash memory inside the dongle, so the USB dongle vendor does not need ship an extra CD with each device, as other device vendors did ten years ago.

Novatel Wireless introduced a wireless router called MiFi in 2009 [58]. This device can be connected to a cellular network and provide Internet to other mobile nodes as a WLAN access point. Although it is not a USB device, it greatly affected USB dongle manufacturers. Many manufacturers borrowed the idea of mobile WiFi hotspot and even the name MiFi. A USB dongle can not only be a 3G modem with SIM card, but also be a WLAN access point; it receives wireless connections from cellular networks and transmits the signals to other mobile nodes in the hotspot. One example of such USB dongle is ZTE MF70 [59]. This device is a 3G dongle with WiFi router, and it can support up to 10 devices in its hotspot. A special feature is that this device can start to work without setup in a laptop. It just need to be connected to a USB power source, and then it begins to work. Though we are not sure, we suppose ZTE MF70 should support RNDIS or other USB CDC protocols, because supporting these new USB protocols is a consensus view in manufacturers, for example, Huawei 3G modems supports more ECM/NCM/MBIM, rather than PPP [60]. Despite the application of new USB protocols, mobile WiFi is even more popular than USB dongle in current mobile broadband market, because mobile WiFi does not need the physical connection to other host computer or power source. It can support itself with own battery, so it greatly release the power burden of laptop, and laptop users do not need to think about the power share between USB dongles and laptops, which is a very important issue for users. Actually current mobile WiFi can even work as a power bank to provide power to other mobile devices [61], a further improvement to traditional USB dongles.

Today mobile devices are very popular, many people bring more than one mobile device during travelling. That is why it is important for USB dongles be able to create own WiFi hotspot to share cellular networks with other mobile devices. Ten years ago the most common wireless connection scenario is laptop with WLAN, but now smartphone with cellular network is the most popular way. This is a great change. The main two factors to promote the change is the extensive deployment of 3G/4G, and the rapid development of mobile devices, especially devices from Apple. Since Apple released its first generation iPhone in 2007, smartphones with a touchscreen user interface soon became the mainstream mobile phones. The sales of smartphones worldwide topped 1.2 billion in 2014 [62]. Another Apple product, iPad, immediately became the hot cake in market since its first launch in 2010. Gartner predicts that tablet computers sales will finally surpass traditional PCs in 2015 [63]. With the crazy growth of new mobile devices, more and more customers get used to browse the Internet by smartphones and tablet computers, rather than laptop computers. Actually a survey performed in 2011 had shown the declining likelihood for customers to buy a mobile broadband

device [64], and the market proved that the global shipments of mobile broadband devices was indeed continuing decreasing in 2013 and 2014 [65]. Strategy Analytics lists "a number of factors are impacting market growth, such as a declining PC market, carriers bundling tablets with smartphones and offering subsidies or service extras, providing lower cost SIM-only data plans, lengthening modem lifecycles, a healthy 'second-hand' modem market and shared data plan tariffs across multiple devices", but it also points that "mobile hotspot routers continue to be the bright point in an otherwise gloomy market" [65]. We agree mobile WiFi devices still has a quite steady market, especially for multi-mode devices which can support heterogeneous networks such as WLAN, LTE, WiMAx, 3G, and even 2G.

Although mobile WiFi and many current USB dongles combine WLAN and cellular networks, their working methods are still different with our requirements proposed in 2009. Current mobile broadband devices provide users WLAN service by connecting to cellular networks, but our idea is that the dongle should be able to work as a wireless client which can receive signals from other access points, for example wireless routers. Readers may ask why we connect to a WLAN access point by an extra USB dongle instead of the laptop itself, considering almost all laptops have already integrated WLAN modules. Our initial reason is to make the Internet connection as simple as possible. All Internet related operations are moved to the dongle, so users do not need search available WiFi hotspots manually by laptop, they just need simply plug the dongle into laptop, and then all connection works are automatically done by the dongle. Users even do not need to consider what types of networks they are using. Another reason is that most WLAN networks need user authentication, even for public WLANs in airports, libraries, hospitals, etc. Users must get some kinds of passwords and usernames before they can access the WLANs. For most laptop users, this means they are excluded from these WLANs. Fortunately cellular network operators usually deploy a lot of hotspots or have using agreements with other hotspot operators, for example, China Mobile has been built 420,000 WiFi hotspots in China [66]. So if a user subscribes to China Mobile's cellular networks, the user may have the possibility to access that huge amount of hotspots. Then comes to the question how to identify the user is subscribed to China Mobile? We can borrow the idea from WiFi calling [67]. WiFi calling enables cellular network users to make and receive calls and texts over a WiFi connection, so user can access a local WiFi hotspot while there is no or very bad cellular coverage. User uses the same phone number during communication, and the SIM card is checked by an AAA server to authenticate and authorize the user, so the user can use WiFi network as long as the WiFi operator allows the AAA agreement with the cellular operator. Similar to a mobile phone, USB dongle also has a SIM card. We can use the SIM card for WLAN authentication. If the local WiFi hotspot can identify the dongle by its SIM card, then it would allow the user to join the hotspot, so the WiFi client module in a dongle greatly improve the possibility to access the Internet.

Since the prevalence of smartphones and tablet computers, the market for USB dongle is decreasing. Customers can browse the Internet in smaller devices than laptop computers. The good news is that nowadays more and more people need to work on laptops with Internet access, so there is still a steady market for mobile broadband devices. However, USB dongle probably can only share a smaller part in that market, because mobile WiFi has many advantages over USB dongle, and actually vendors have already produced more mobile WiFis than USB dongles. Mobile WiFi is usually expensive than USB dongle, so USB dongle can focus on customers who are sensitive to prices. Another alternative is to embed mobile WiFi or USB dongle functions into laptop, and then customers do not need bring extra network devices, just one laptop is enough.

5 Conclusions and Future work

In the last chapter of this thesis, we conclude our research. Some related researches which are out of the scope of this thesis are suggested as future work. The chapter ends with some reflections on what economic values operators and users can get from our work.

5.1 Conclusions

Ten years ago it was uncommon to see many laptop users surfing on the Internet in public places outside of universities and offices. Today WiFi hotspots are almost a standard as they are deployed in many airports, restaurants, libraries, etc. However, they remain hotspots with limited coverage areas, although the number of hotspots continues to grow rapidly. Fortunately we have an alternative solution, mobile broadband. Despite the relatively lower data rates and higher traffic charges, mobile broadband greatly extends the geographical range of wireless Internet. Users can access the Internet from almost anywhere as long as their device(s) can transmit & receive a sufficiently strong cellular signal. This unique feature made USB dongles quite successful in the initial deployment of 3G/4G networks.

As a pioneer in 3G/4G market, the USB dongle had many advantages. First, normally there is a time lag between mobile devices and network deployment; as the old mobile devices cannot support the new networks very well. For example, 3G networks were widely deployed several years before smartphones became prevalent. As a result a USB dongle was the best solution to provide mobile Internet access during that time interval; as customers did not need wait for new mobile devices, a dongle can help them connect to the Internet via their laptop. Second, the price of a USB dongle is much less than many smartphones. When one considers spending several thousand Swedish kronor to buy a smartphone, many customers would choose a USB dongle costing only several hundred Swedish kronor. Third, a USB dongle is specifically designed for providing Internet connectivity; hence its performance is largely determined by the available network quality. In contrast, other mobile devices such as smartphones and tablet computers have many functions; hence their user's Internet experience will be greatly affected by the quality of devices themselves.

Being a market pioneer, however, also means that its market share decreases after the market becomes mature and stable. Nowadays, more and more customers have smartphones, and they can browse the Internet using these small devices which can put in their pockets. Smaller size is a good feature for a mobile device, but it also brings some deficiencies if it is too small. For example, many customers complain that the keyboards in smartphones are too small and that this results in low input speeds. Additionally, as we have seen the screens of smartphones are becoming bigger, but they are still much smaller than the screens in laptops. Moreover, smaller size constrains the computing ,processing, and battery storage abilities of smartphones. Due to these inherent deficiencies, smartphones or tablets are mainly used for browsing information on the Internet or doing simple office work, for example, checking emails. Today a growing number of office workers and university students need to work on laptops with Internet connection. This group of people are the main customers of mobile broadband devices, especially when they need to work outside of their offices and universities.

The USB dongle was the mainstream mobile broadband device, but now many manufacturers and operators prefer to launch mobile WiFi rather than market USB dongles. However, these two devices can provide the same service, and mobile WiFi does not need to physically connect to a USB host. The main advantage of a USB dongle is probably its low price, so it still remains attractive for customers who are sensitive to price, for example young students. Since many laptop users also have smartphones or tablets, a current USB dongle should have the ability to be a WLAN access point, so that several mobile devices can share the Internet connectivity provided by one dongle. We suggest that the dongle should also be a WLAN client which can connect via other hotspots. If hotspot operators can authenticate USB dongles by SIM cards, then users can easily access a great number of

hotspots. Also as we explained before, the PPP modem solution is too outdated for today's USB dongle, hence manufacturers should update their USB interface to RNDIS or another USB CDC protocols.

5.2 Future work

Section 1.4 indicated that in the case of IPv6 the process of a dongle getting an IP address and sending IPv6 packets was very straight-forward, but did not answer the questions of (1) how the device authenticates itself and (2) how it would be authorized to use the network. These are questions that should be answered in future work. Although these questions might be changed to focus on authentication of the packets and authorization of the packets to be forwarded by the access network – rather than focusing the questions of authentication and access control on the device sending them. This change would be very interesting in the context of Internet of Things (IoT) devices that often only infrequently send data. Meanwhile, existing authentication and authorization protocols, such as IEEE 802.1 could be used. Alternatively, non-binary authentication and authorization protocols might be used [18].

The concept of a shared and distributed firewall service suggested in Section 3.5 should be explored in future work. The ability to have the filtering performed before the traffic flows over the Um link would be a very good added value that network operators could provide. However, there are many open questions that need to be addressed before such a service could be deployed.

As we discussed in Section 4.2, the SIM card authentication for mobile broadband device as a WiFi client need more research. Since some operators have already introduced WiFi calling, a possible research direction could be how to utilize AAA server in WiFi calling for mobile broadband devices. If an operator can launch this service it might greatly increase its market share.

5.3 Reflections

Building one WLAN hotspot is an easy task, whereas the task will become a huge expense as the number of hotspots grows. Deploying ubiquitous cellular networks is theoretically quite possible, however, in practice certain places in buildings may be blind spots for cellular signals, for example, basements. Both WLAN and cellular network have their own advantages and disadvantages, but operators will not wildly deploy more hotspots and cells without limit just to give us better user experiences, because they need to consider their costs and profit. Using the solution proposed in this thesis (with users providing more of the broadband access facilities), operators can provide users better service *without* building more networks, and ease the burden of cellular networks by offloading data to WLAN networks. Users can enjoy "always on" Internet access by using our proposed small low cost device, and users might even cancel their expensive data subscriptions for smartphones and tablets if they can always bring this small device with them. Therefore, this thesis project might offer attractive economic values for both operators and users.

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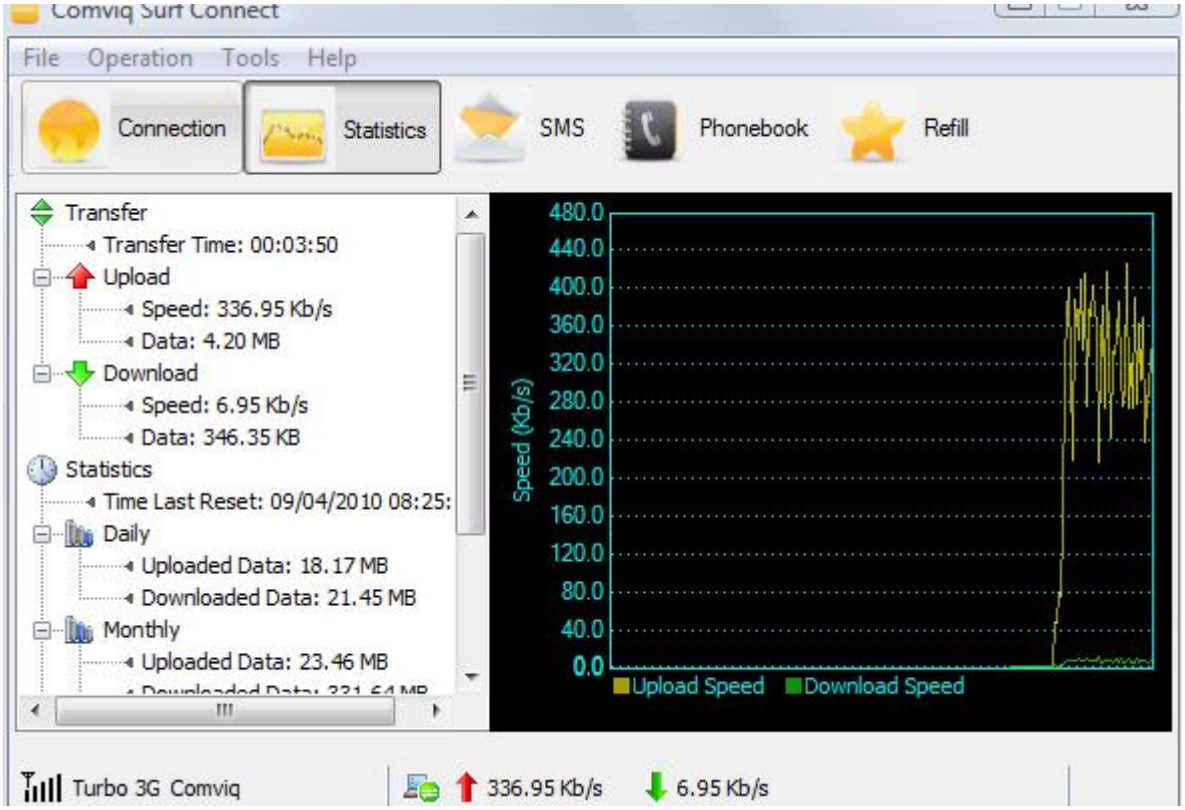
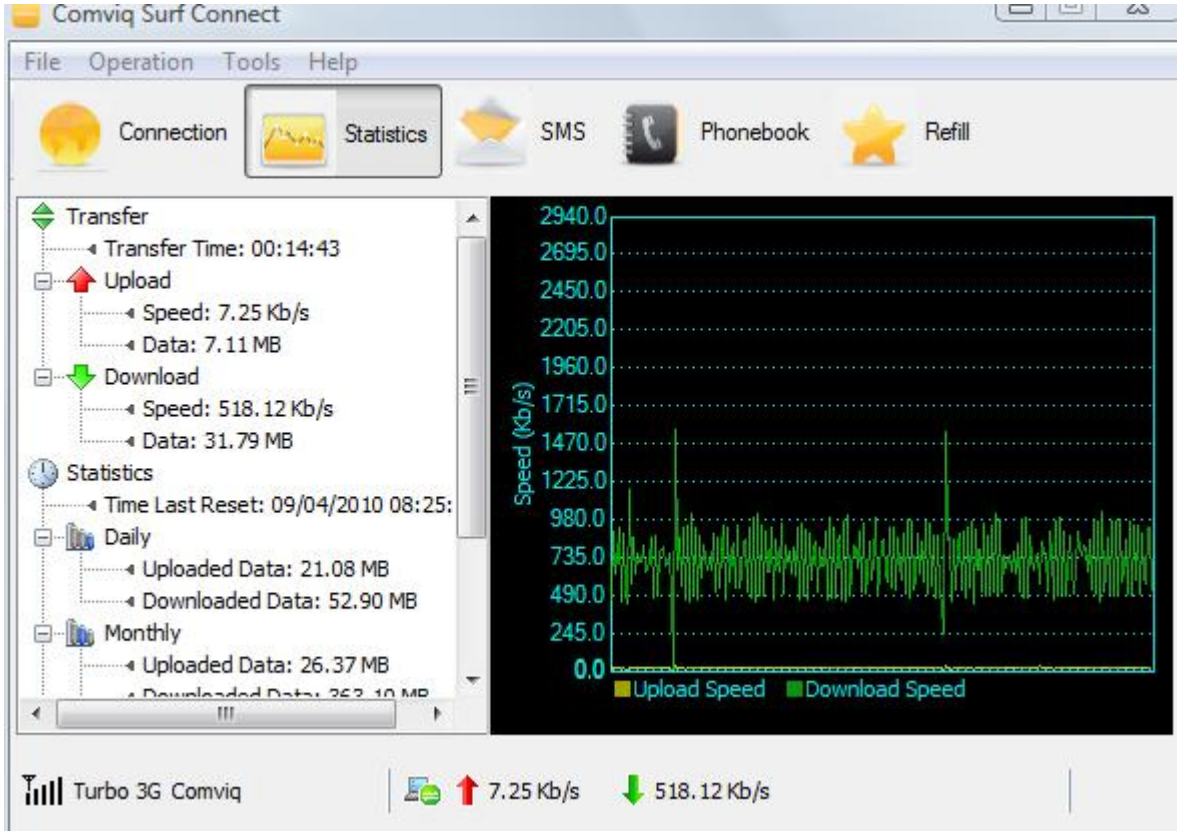
Appendix A

A.1: USB dongle data rate in uploading



A.2: USB dongle data rate in downloading



Appendix B

Information about device descriptors of the USB dongle:

URB_FUNCTION_CONTROL_TRANSFER

Urb Field	Value
Length	0x50
USBD Status	USBD_STATUS_SUCCESS (0x0)
EndpointAddress	0x0
PipeHandle	0x86ADDA5C
TransferFlags	0x86AD563B (USBD_TRANSFER_DIRECTION_IN USBD_SHORT_TRANSFER_OK)
TransferBufferLength	0x83
TransferBuffer	0x86AAB888
TransferBufferMDL	0x88664E50
UrbLink	0x0
SetupPacket	0x80 0x6 0x0 0x2 0x0 0x0 0x83 0x0
RequestType	0x80 (Direction: Device-to-host, Type: Standard, Recipient: Device)
Request	0x6 (GET_DESCRIPTOR)
Value	0x200 (USB_CONFIGURATION_DESCRIPTOR_TYPE)
Index	0x0
Length	0x83
Configuration Descriptor	
bLength	0x9
bDescriptorType	USB_CONFIGURATION_DESCRIPTOR_TYPE
wTotalLength	0x83
bNumInterfaces	0x5
iConfiguration	0x3
bmAttributes	0xE0 (Bus_Powered Self_Powered Remote_Wakeup)
MaxPower	0xFA
Interface Descriptor	
bLength	0x9
bInterfaceNumber	0x0
bAlternateSetting	0x0

Urb Field	Value
bNumEndpoints	0x3
bInterfaceClass	0xFF (Vendor Specific)
bInterfaceSubClass	0xFF
bInterfaceProtocol	0xFF
iInterface	0x0
Endpoint Descriptor	
bLength	0x7
bEndpointAddress	0x81 [IN]
bmAttributes	0x3 (USB_ENDPOINT_TYPE_INTERRUPT)
wMaxPacketSize	0x40
bInterval	0x5
Endpoint Descriptor	
bLength	0x7
bEndpointAddress	0x82 [IN]
bmAttributes	0x2 (USB_ENDPOINT_TYPE_BULK)
wMaxPacketSize	0x200
bInterval	0x20
Endpoint Descriptor	
bLength	0x7
bEndpointAddress	0x1 [OUT]
bmAttributes	0x2 (USB_ENDPOINT_TYPE_BULK)
wMaxPacketSize	0x200
bInterval	0x20
Interface Descriptor	
bLength	0x9
bInterfaceNumber	0x1
bAlternateSetting	0x0
bNumEndpoints	0x2
bInterfaceClass	0xFF (Vendor Specific)
bInterfaceSubClass	0xFF
bInterfaceProtocol	0xFF
iInterface	0x0
Endpoint Descriptor	
bLength	0x7
bEndpointAddress	0x83 [IN]

Urb Field	Value
bmAttributes	0x2 (USB_ENDPOINT_TYPE_BULK)
wMaxPacketSize	0x200
bInterval	0x20
Endpoint Descriptor	
bLength	0x7
bEndpointAddress	0x2 [OUT]
bmAttributes	0x2 (USB_ENDPOINT_TYPE_BULK)
wMaxPacketSize	0x200
bInterval	0x20
Interface Descriptor	
bLength	0x9
bInterfaceNumber	0x2
bAlternateSetting	0x0
bNumEndpoints	0x2
bInterfaceClass	0xFF (Vendor Specific)
bInterfaceSubClass	0xFF
bInterfaceProtocol	0xFF
iInterface	0x0
Endpoint Descriptor	
bLength	0x7
bEndpointAddress	0x84 [IN]
bmAttributes	0x2 (USB_ENDPOINT_TYPE_BULK)
wMaxPacketSize	0x200
bInterval	0x20
Endpoint Descriptor	
bLength	0x7
bEndpointAddress	0x3 [OUT]
bmAttributes	0x2 (USB_ENDPOINT_TYPE_BULK)
wMaxPacketSize	0x200
bInterval	0x20
Interface Descriptor	
bLength	0x9
bInterfaceNumber	0x3
bAlternateSetting	0x0
bNumEndpoints	0x2

Urb Field	Value
bInterfaceClass	0x8 (Mass Storage)
bInterfaceSubClass	0x6 (SCSI Transparent Command Set)
bInterfaceProtocol	0x50 (Bulk-Only Transport)
iInterface	0x0
Endpoint Descriptor	
bLength	0x7
bEndpointAddress	0x85 [IN]
bmAttributes	0x2 (USB_ENDPOINT_TYPE_BULK)
wMaxPacketSize	0x200
bInterval	0x0
Endpoint Descriptor	
bLength	0x7
bEndpointAddress	0x4 [OUT]
bmAttributes	0x2 (USB_ENDPOINT_TYPE_BULK)
wMaxPacketSize	0x200
bInterval	0x0
Interface Descriptor	
bLength	0x9
bInterfaceNumber	0x4
bAlternateSetting	0x0
bNumEndpoints	0x2
bInterfaceClass	0x8 (Mass Storage)
bInterfaceSubClass	0x6 (SCSI Transparent Command Set)
bInterfaceProtocol	0x50 (Bulk-Only Transport)
iInterface	0x0
Endpoint Descriptor	
bLength	0x7
bEndpointAddress	0x5 [OUT]
bmAttributes	0x2 (USB_ENDPOINT_TYPE_BULK)
wMaxPacketSize	0x200
bInterval	0x0
Endpoint Descriptor	
bLength	0x7
bEndpointAddress	0x86 [IN]
bmAttributes	0x2 (USB_ENDPOINT_TYPE_BULK)

Urb Field	Value
wMaxPacketSize	0x200
bInterval	0x0

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