NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

ALTERNATE HIGH SPEED NETWORK ACCESS FOR THE LAST MILE

by

Peng Joo Lee

December 2002

Thesis Advisor:	Bert Lundy
Second Reader:	Mike Tatom

Approved for public release; distribution is unlimited

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.			
1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** December 2002	**3. REPORT TYPE AND DATES COVERED** Master's Thesis	
4. TITLE AND SUBTITLE: Alternate High Speed Network Access for the Last Mile			**5. FUNDING NUMBERS**
6. AUTHOR(S) Peng Joo Lee			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited			**12b. DISTRIBUTION CODE**

13. ABSTRACT *(maximum 200 words)*

Existing copper wire infrastructure no longer provides the required bandwidth for today's bandwidth-intense Internet applications. Homes and businesses in the last mile require the same access speeds offer by fiber optic cables. It is however, economically infeasible to bring fiber optic cable to each and every house and business in the last mile.

Free Space Optics and IEEE 802.11 are two technologies that offer high-speed capability and are potential last mile network access option. Free Space Optics uses lasers and IEEE 802.11 uses radio waves to send large amounts of data from one place to another. Both are wireless and uses license-free frequency band for transmission. Both are quickly deployable, easily scalable and cheaper to install and upgrade compared to wired infrastructures. These characteristics support applications that require high bandwidth and high degree of mobility, which are common in the military and civil networks.

This thesis addresses the last mile problem and the current available access technologies which are unable to provide a high speed solution. Free Space Optics and IEEE 802.11 wireless technologies are explored and applied to a fictitious city for an economic analysis as possible high-speed network access method.

14. SUBJECT TERMS Free Space Optics, IEEE 802.11b, IEEE 802.11a, IEEE 802.11g, Wireless Networking, Radio Frequency, Network Infrastructure			**15. NUMBER OF PAGES** 148
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release; distribution is unlimited

ALTERNATE HIGH SPEED NETWORK ACCESS FOR THE LAST MILE

Peng Joo Lee
Captain, Singapore Army
BSc(Hons), University of Bath (UK), 1998

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN COMPUTER SCIENCE

from the

NAVAL POSTGRADUATE SCHOOL
December 2002

Author: Peng Joo Lee

Approved by: Bert Lundy
Thesis Advisor

Mike Tatom
Second Reader

Peter Denning, Chairman
Department of Computer Science

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

Existing copper wire infrastructure no longer provides the required bandwidth for today's bandwidth-intense Internet applications. Homes and businesses in the last mile require the same access speeds offer by fiber optic cables. It is however, economically infeasible to bring fiber optic cable to each and every house and business in the last mile.

Free Space Optics and IEEE 802.11 are two technologies that offer high-speed capability and are potential last mile network access option. Free Space Optics uses lasers and IEEE 802.11 uses radio waves to send large amounts of data from one place to another. Both are wireless and uses license-free frequency band for transmission. Both are quickly deployable, easily scalable and cheaper to install and upgrade compared to wired infrastructures. These characteristics support applications that require high bandwidth and high degree of mobility, which are common in the military and civil networks.

This thesis addresses the last mile problem and the current available access technologies which are unable to provide a high speed solution. Free Space Optics and IEEE 802.11 wireless technologies are explored and applied to a fictitious city for an economic analysis as possible high-speed network access method.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF ABBREVIATIONS, ACRONYMS & SYMBOLS

ATM	Asynchronous Transfer Mode
CSMA/CA	Carrier Sense Multiple Access / Collision Avoidance
DBS	Direct Broadcast Satellite
DES	Data Encryption Standard
DOCSIS	Data Over Cable System Interface Specification
DSL	Digital Subscriber Line
DSSS	Direct Sequence Spread Spectrum
EAP	Extensible Authentication Protocol
FCC	Federal Communication Committee
FFT	Fast Fourier Transform
FHSS	Frequency Hopping Spread Spec trum
FSO	Free Space Optics
FTTC	Fiber To The Curb
HFC	Hybrid Fiber Coax
IEEE	Institute of Electrical and Electronics Engineer
IP	Internet Protocol
IR	Infra-Red
IRED	Infra-Red Emitting Diode
IS	Information System
ISDN	Integrated Services Digital Network
ISI	Inter-Symbol Interference
ISM	Industrial, Scientific and Medical
ISP	Internet Service Provider
IT	Information Technology
IV	Initialization Vector
LAN	Local Area Network
LED	Light Emitting Diode

MAC	Media Access Control
NIC	Network Interface Card
NOS	Network Operating System
OFDM	Orthogonal Frequency Division Multiplexing
PPP	Point-to-Point Protocol
QoS	Quality of Service
RF	Radio Frequency
RFC	Request For Comment
SOHO	Small Office Home Office
TKIP	Temporal Key Integrity Protocol
UNII	Unlicensed National Information Infrastructure
VoIP	Voice over Internet Protocol
VVD	Voice, Video and Data
WAN	Wide Area Network
WEP	Wired Equivalency Protocol
WLAN	Wireless Local Area Network

ACKNOWLEDGMENTS

The author would like to express his sincere thanks and appreciation to the following for their kind advice, assistance, support, guidance and contribution to the success and completion of this thesis:

Dr Bert Lundy

Mr. Mike Tatom

THIS PAGE INTENTIONALL Y LEFT BLANK

I. INTRODUCTION

A. OVERVIEW

Try to imagine a city water distribution system that does not deliver water to buildings and homes well enough because its pipes are simply too thin. Water serving the homes comes in trickle, even if the taps are the most expensive of its kind. This leaves one wondering why pay water bills when there is no steady flow of water. Moreover, as more taps are turned on, the lesser the drips...

This is very much of the same situation in the Internet, in the world today. The increasing speed of technology and innovation of computing and networking are revolutionizing the way businesses are conducted around the world. In the beginning, the commercial Internet was used mostly as a test message exchange mean or small file transfer. Since the introduction of E-commerce and more recently voice over IP (VoIP) and streaming video and audio, the Internet has taken the driver seat in many aspects of daily life. Bandwidth intensive graphics, video and audio applications are increasing popular among the younger generations[1]. Television, movies, music and other applications are in demands that were not at all expected when the Internet was first started. The desire for instant access to information at the fingertips has never been so resounding. The Internet is more than just an entertainment delivery system. The military is embracing the Internet in support of its network-centric warfare and using web-based applications for things ranging from operational issues to distance learning.

Networks are hence fast becoming the backbone of many businesses, but the technology behind them is probably the most complex and least understood information technology (IT) subject. It is not enough to have a particular network in place – data flowing from site to site and to and from the Internet at adequate speed must be

1 Free Space Optics and Wireless Broadband RF Technology: Bringing Highspeed Network Access to the Last Mile – John W.Sprague, NPS, Mar 2002 [01]

maintained[2]. Most of the world is now in the information age and due to this, information delivery has become more and more important to everyone.

Billions of dollars were spent on building the optical fibers backbone so as to deliver true high performance multimedia services within and across countries and nations. These services were in great demand but most users could not actually benefit from it. The services are often, running short of its true capability by just a mile.

A mile before, the capability of the Internet on high-speed access is unleashed. With the wide bandwidth, it is the desired digital world. Delay-free web browsing and data library access, instantaneous electronic commerce for trading and banking, uninterrupted streaming of audio and video for exciting entertainment, video on demand, video conferencing, real-time medical image transfer, enterprise networking and work-sharing capabilities, as well as numerous business-to-business transactions are all just a mile away.

Connecting to these services has been relatively simple for many like higher educational institutes and big businesses which are well-funded. However, the last mile to consumer households, small and medium enterprises and offices are still often limited and slow. Those desired services of the digital world still lies over the horizon. But in fact, these services are limited by what was buried under local streets and sidewalks.

Speed, cost and reliability are all very important factors creating the many ways to access the global information structure. Since the turn of the 20th century, copper wire has brought telecommunication into the homes and offices around the world. It has also served as the major link form of communications for most of the century. Traditional copper wires and co-axial cables connecting buildings to telephone and cable television

[2] Emerging High Speed Access Technologies - D. Cuffie, K.Biesecker & C.Kain, IT Pro Mar/Apr 1999 [02]

system simply do not process the giga-bit per second (Gbps) capacity necessary to carry advanced bandwidth-intense services and applications. While there are means to carry these data using optical fiber, using optical fiber to connect millions of users to the high-speed backbone would cost too much to install. Microwave transmitter and satellite transmitter have changed the world dramatically. Originally set up to send 2-way voice communication and broadcast television signals, these tools are now being used to send all kinds of data at high speed to all across the world.

It is noted that nearly 12 million home web users accessed the Internet with a high-speed connection in Dec 2000, as compared to just 5 million in 1999[3]. Though cable and DSL took up most of the market, it does imply that high-speed connection is indeed in demand.

Technical solutions will only be successful if they can meet the demanding requirements of the users, as well as the operators. Users want a service that is convenient to use (always on), reliable and at a price that does not present a disincentive to use. Operators have even more exacting requirements, all, ultimately, linked to the need to earn a speedy and secure return on the inevitable up-front investment. Their prime requirement is for an access technology that is simple, quick and economic to deploy – ensuring the minimum of delay between starting to build the network and generating income from paying customers. The technology must also be scalable, i.e. it must generate profit even when customer take-up is difficult to predict, and continue to deliver a satisfactory grade of service as customer number grows.

B. MOTIVATION

While computing power and computing memory are exploding their capabilities as anticipated by Morse's Law, bandwidth for the last mile remains stagnant. While large

3 Why Go Wireless? – Michael R. Anderson, 802.11 Wireless LAN ISP -Planet 2001 [03]

companies, corporations and educational institutes around the world have relatively fast access speeds, users at home are not. The fast access speeds are usually at least 10 times faster than what is currently available at home. This large difference in network access speed is making some web page applications offer text only versions to download at home so as to compensate for the slower downloading time. Conversely, at work with the faster access speed, web pages can be viewed in their truest form, with graphics, video and audio. With the recent emerging trend of Small Office Home Office (SOHO) working concept, the demand for faster access from home is on the rise. The problem lies here, in the last mile, where the pipes leading to the homes and offices were never upgraded. While the consumers are not given high-speed Internet, demands for many applications and services that require high-bandwidth were put on hold. Progresses for applications and services to offer even more exciting services are hence a thought that is still skeptical among the developers.

This has been so over the past few decades. The copper wires that were laid underneath the sidewalks decades ago are still the same set of copper wires today. While there are no changes to the medium, the content that the wires are carrying changes dramatically. Demands for bandwidth are often left unattended. So what are the uses of mighty computing if data are too slowly fed to them?

How then could these high-speed bandwidth-intense services and applications that could bring much more excitement and business opportunities be ever brought directly to the home and offices?

What are the strengths and weaknesses of these available means if they were to be used to bridge the last mile?

What could possibly be the optimal choice/means of bridging the last mile such that it is most economical for the service provider and most cost-beneficial to the subscribers?

This thesis aims to answer these questions by providing a study of the current technologies that could possibly minimize, if not, eliminate the last mile problem by the following steps:

a. Identifying the last mile problem.

b. Considering current technologies that could be used for last mile implementation.

c. Proposing possible solutions that could enable homes and offices to have high-speed access.

C. THESIS ORGANIZATION

The thesis is organized in the following manner: Chapter II will elaborate on the problem of the last mile. The problem will be explained so as to highlight the need to solve it. Chapter III discusses briefly the technologies that are currently used in the last mile. The pros and cons of each technology will be study and compared. Chapter IV will introduce one of the new technologies that could possibly be used to broaden the bandwidth bottleneck, if not eliminate the last mile problem: Free Space Optics. Chapter V explores the other technology: IEEE 802.11, which is currently used in wireless LANs. With its increasing popularity and expanded bandwidth capacity, it has position itself to be one of the candidates for solving the last mile problem. Chapter VI proposes possible solutions and study into the pros and cons of these proposed solutions. Chapter VII extends the application of these solutions other than using them for the last mile. Similar concept of employing the solution could be applied to other areas where instant, uninterrupted speedy data transfer in a network is required. Chapter VIII provides the concluding remarks and suggestions for further researches.

II. THE LAST MILE PROBLEM

A. OVERVIEW

In today's high-paced and dynamic society, information delivery is crucial to business, trading, banking, education and entertainment. Even in the military, the need for situation awareness and intelligence gathering in the digitized battlefield relies centrally on the information delivery technologies. The demand for instant delivery of critical information is key to many successes in today's society. While transfer-medium technologies[4] advance for higher bandwidth accommodation capability, not many of the users could justify the cost of having a high-bandwidth connection. Much of the Internet and many larger networks however, could enjoy much faster access because most large businesses find high-bandwidth connection worth the investment. The returns of their businesses outweigh their capital cost. The speed to homes, many small and medium-sized business and small office home office (SOHO) are however limited to the speed of phone lines and analog modems. Fundamentally, the limitation is the access means to these places and the cost benefits of each access means.

B. THE LAST MILE

This barrier that stands in the way of low-cost high-speed network is called the "last mile". The last mile consists of the local loop that connects a house or office to a phone company's central office. Figure 2.1 shows what is meant by the last mile. It denotes that the last mile is the portion of the telecommunication network that starts from the phone in the house to the local central office. As shown in the figure, the utilized bandwidth is only 4 KHz (as specified by Shannon's Law for analog voice modulation), and allows digital transmission at a maximum rate of 56 Kbps.

[4] Digital data transfer started from copper wires, coax-cables and now fiber optic cables.

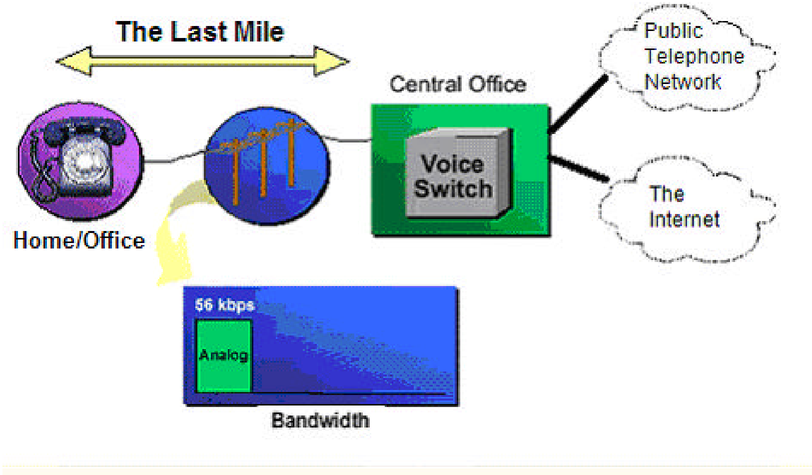


Figure 2.1 – The Last Mile. [From: 04]

Telephone calls made from homes are connected to the central office switching system. This is where the copper wires from each individual house and office are connected to a system that will handle the call, either within the same switch, handing it off to another switch in the same building, passing it to a nearby switch in the loc al area, or passing it on to the toll network. At the destination, the call will go through another central office and then, to the destination number[5].

These central offices are also known as switching stations. From these switching stations, optical fib ers are used to connect to the Internet (core network), where data are riding on giga-bit fast speed. For the case of the Internet Access, most providers are themselves, the telephone companies and hence, able to have connection to the core network. Other Internet service providers would have to lease services to access the core network, via the optical fibers own by the telephone companies.

5 Telephone World – Local Central Office System, www.dmine.com/phworld/network/office.htm [04]

Figure 2.2 shows the telecommunication network system in a wider scope. Phones from the house and payphones are connected to the central office (CO). Similarly for the mobile phones, the base stations (as in cells) are connected to the central office. The central offices are connected to the main exchange (ME) and the main exchanges are interconnected in a mesh topolo gy using optical fiber cables. This portion is also known as the backbone of the telecommunication system where data are transferred at giga -bits per second. Countries are then link via the international exchanges using satellite or undersea cables.

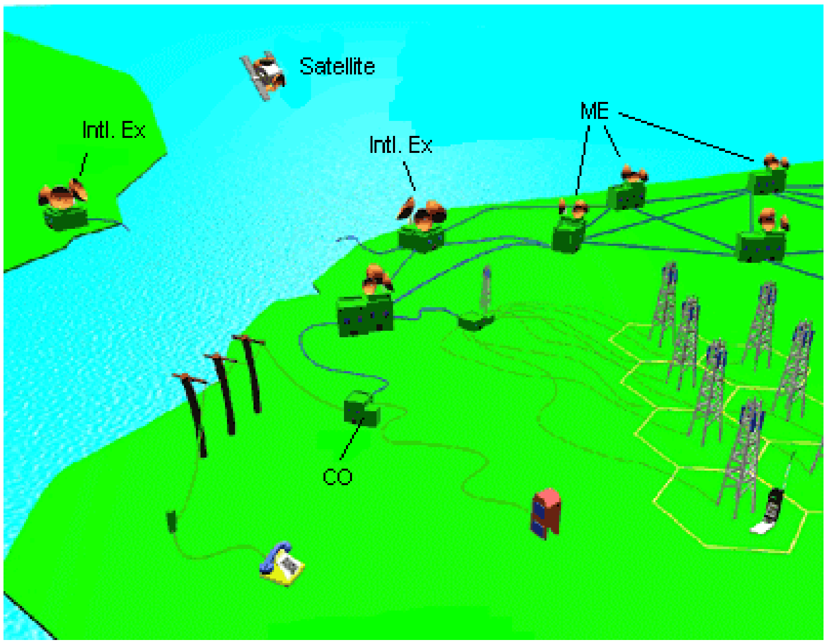


Figure 2.2 – The Telecommunication System. [From: 05]

As illustrated above, high-speed data transfer takes place at one end of the central office; while only a small fraction of the speed is available at the other end, which is leading to the homes and offic es.

C. ACCESS OVER THE LAST MILE

Connection at the homes and offices varies, depending on the needs and requirements of the Internet usage. Though there are many more options for the users in accessing the Internet than a couple of decades ago, these options too can only offer to a certain speed – a speed that is still insufficient to obtain very good Quality of Service (QoS) in today's bandwidth-intense applications and services. Furthermore, access options differ from cities to cities, nations to nations. Generally, the access options are over the phone lines, TV cable and satellite.

Today's large business operations have tended to rely on dedicated-service access, such as T1 (at 1.544 Mbps), T3 (at 44.7 Mbps) and sometimes Asynchronous Transfer Mode (ATM) which supports at least 155 Mbps. These options generally too expensive for the homes and SOHO environment[6]. They also won't work for the increasing number of off-sites and traveling employees for whom the corporate Information System (IS) managers must provide.

The telephone companies provide reasonably low-priced access services over the same copper lines that provide ordinary telephone service. These services use just the voice frequency band (0 to 4 KHz) on the wire, which does lead to some limitations in representing digital data. Remember that the frequency band is meant for analog voice. Still, analog lines are sufficient to support dial-up modems that deliver speeds of up to 56 Kbps. Note that this connection speed is not guaranteed. The connection speed depends on the location of access. Other limitations to good connection speed depend largely on the electrical noise and other interferences on the copper wires.

For the cost of a phone line, users can connect to the Internet or to a company network from a remote site. Note that this includes the subscription fees for the Internet

[6] Emerging High Speed Access Technologies - D. Cuffie, K.Biesecker & C.Kain, IT Pro Mar/Apr 1999 [02]

Service Provider (ISP). For most households, there is only 1 phone line and hence, once users get on-line, their telephone service is disabled. Nevertheless, this method of accessing the Internet is most common and most widely used around the world today.

For those who require faster access, Integrated Services Digital Network Basic Rate Interface (ISDN - BRI) is also widely available. The BRI which runs at 128 Kbps usually requires the purchase and installation of special hardware in the home or office. The hardware is usually purchased from a local telephone company for about $30 per month (for 20 hours with an additional $20 for Internet service)[7].

For even higher access speed, Digital Subscriber Line (DSL), cable modem and broadcast satellite are used. These services are of even higher subscription cost and in many times, users are unable to get connected to the advertised speed as promised. In many areas, these services are not even available. With the mentioned access technologies, the connection speed seldom reaches 1 Mbps throughput.

Of course, if fiber optic cables could be used for the last mile, the last mile problem would be solved completely. Giga-bits of data could flow directly to and from the homes and offices. The problem is the very high cost and time needed in digging up the sidewalks, roads, junctions, buildings, just to lay fiber optic cables to each and every house and office. Disturbing the earth for a mile of fiber optic cable can cost more than $100 per meter – noting that the fiber optic cable from the central office to a residence is not a straight line[8]. Operators will not take on this challenge, until laying and maintaining the fiber optic cables are cheap enough.

---

[7] From ISP2K.com – Premium Internet Service for 128Kbps ISDN

D. IT IS A REAL PROBLEM

In today's fast paced dynamic Internet world that offers many exciting applications and services, having fast connection speed would do wonders and show-case the power of the Internet. The true power of the Internet could only be unleashed if the users can have what they want on-line rapidly.

Imagine the use of Internet for buying/selling of stocks and shares. Stock and share prices changes every possible second and the golden opportunity to sell or buy could be missed because of the slow connection. Worse would be the case where the stock counter is overseas. Internet traffic is already experiencing delays when routing between continents. More delays are added and in terms of distance, the delays added could be 100% or more.

One view is that the more people who join the on-line world, the slower the Internet becomes for everyone due to the inevitable increase in traffic in a phone system, which is already straining at the seams.

If the Internet is to realize its full potential as a new medium for distance learning, e-commerce and entertainment, these issues of connection speed and cost are going to have to be overcome. Though in America, local calls are usually free – no cost in calling the ISP access number; this is not the case for other countries. Every second spent on-line is costing money.

The Internet does not all run at the snail's pace that the average home user's machine seems to crawl around the cyberspace. There are a variety of high-speed links available today to anyone who prepared to pay. The prices for subscribing to these higher-speed access methods are still high and for most of the home and small office

[8] Fiber – Can't Find Its Way Home? By Rob Kirby, Network Magazine, Sep 2001 [06]

users, the payment for these access methods does not make much dollar sense or the desired access methods are not at all available to their location. Most users would in fact purchase more computing power, hoping that the faster computing and mega-bits of memory could speedup the access. However, the equipment ironically, is not the heart of the problem. Most PCs/Macs are easily capable of handling the multimedia content the Internet would provide; the problem is receiving the huge amount of data.

At the crux of the question of Internet connection speeds is the telephone network itself, which is simply not designed for this purpose. When Bell designed the telephone, his vision stopped at people in different physical locations talking to one another in real time, which meant that the phone networks have been based largely on that premise[9]. Voice communication requires considerably less bandwidth and can cope with much greater signal degradation than data communication, and the biggest problem lies between the exchange and the house. The telecommunication companies have, over the years upgraded the exchanges to digital ones, giving subscribers' access to such innovations as caller line identification, exchange based answering services, touch tone dialing, etc., but the line between the house and the telecommunication companies is still a twisted copper.

E. SUMMARY

The last mile problem is a real problem that is limiting the Internet from reaching its full potential and it is affecting people everywhere in the world today. There is a serious need to solve this problem.

[9] The Last Mile Problem – Cybersavvy UK, 2001 [07]

THIS PAGE INTENTIONALLY LEFT BLANK

III. CURRENT AVAILABLE TECHNOLOGIES FOR LAST MILE ACCESS

A. OVERVIEW

Having elaborated the problem in the last mile, in this chapter, the current available technologies that are used to access the last mile will be discussed. Other than the dial-up method, there are several more options available for higher connection speed. The Digital Subscriber Line (DSL) and cable modem technologies will be discussed due to their increasing popularity and each is currently well positioned to serve almost all users in the near future who have access to telephone or cable services. Direct broadcast satellite will also be discussed as it could become a big player in the Internet access market. While exploring each of the access technologies, their pros and cons will also be discussed.

B. ACCESS OVER PHONE LINES

Most people are connected to the Internet using 56Kbps modem – The dial-up access method. Other than using the 56Kbps modem dial-up access over the last mile, there are also other means of getting connected to the Internet at a faster rate, at a higher cost. There are dedicated service access, such as T1 (at 1.544Mbps), T3 (44.7Mbps), and sometimes ATM (155Mbps). These options are generally too expensive for the home and Small Office Home Office (SOHO) environment. It also does not make economical sense for the ISP to offer these services to the millions of home and SOHO users.

According to the report, 80% of the Internet users around the world today are still accessing the Internet using the 56Kbps dial-up access method. It is by no means a surprise as the telephone lines and networks, also known as the Plain Old Telephone System (POTS) are already well established in many parts of the world even before computers were introduced. The telephone companies provide reasonably priced access services over the same copper wires that provide ordinary telephone service. These services use just the voice frequency band (0 – 4 KHz) on the wire, which does lead to some limitations in representing digital data. Still, analog lines are sufficient to support dial-up modems that deliver speeds of up to 56 Kbps. They are also the cheapest means of accessing the Internet.

Table 1 shows some of the current 56 Kbps modem dial-up plan available in the US. Note that the price ranges from $8.95 to $21.95 per month, with the lower priced having pop-up advertisement. Such pop-up advertisement could not trade off the lower fees as AOL has reported that they have more than 33 million subscribers[10] as of Dec 2001 while MSN attracted about 8 million[11].

ISP	Price/Month	Setup Fees	Internet	Coverage
AT&T	$21.95	Nil	Unlimited	Nation-wide
Juno.net	$9.95	Nil	Unlimited with pop-up ads	Nation-wide
ISP.com	$8.95	Nil	Unlimited with pop-up ads	Nation-wide
MSN	$21.95	Nil	Unlimited	Nation-wide
AOL	$23.95	Nil	Unlimited	Nation-wide
Earthlink	$21.95	Nil	Unlimited	Nation-wide

Table 1. Comparison of dial-up plan in the United States.

Note that with the pricing, the highest connection speed is 56Kbps (theoretically). More often than not, the average access connection speed is about 48Kbps. For homes and offices with only 1 telephone line, no telephone calls can be made once the line is used to connect to the Internet. It is important to note that the subscription for the telephone services do not halt while connected to the Internet.

10 Taken from www.informationweek.com [08]

11 Taken from www.adage.com – MSN continues struggle to catch up to AOL, Mar 2002 [09]

This access method is generally sufficient for light Internet users, whom basically use the Internet for text-form emails and very light web browsing. Accessing videos and audios streaming could be very demoralizing as the connection speed for downloading simply could not match the speed of delivery normal-paced video screening and audio playing. Attempts to access these bandwidth-intense applications could only cost more money as they require long downloading time.

Even for light Internet users, using the Internet to send pictures/images is gaining popularity. In most cases, the images would have to be down-sized so not to take up too much time and cost in uploading and downloading – trading off the clarity and details of the image. Why bother to send the picture in the first place if the delivered image is not the desired?

C. DIGITAL SUBSCRIBER LINES

Today, telephone companies are developing several digital subscriber line (xDSL) technologies. The 'x' denotes a variable that signifies a particular flavor of DSL; collectively these services are known as xDSL.

Essentially, xDSL implements high-speed data services over the existing phone infrastructure. In the case of the last mile, the current infrastructure probably consists of twisted-pair wires laid decades ago. Replacing these infrastructures with current hardware, like fiber optics, is extremely expensive.

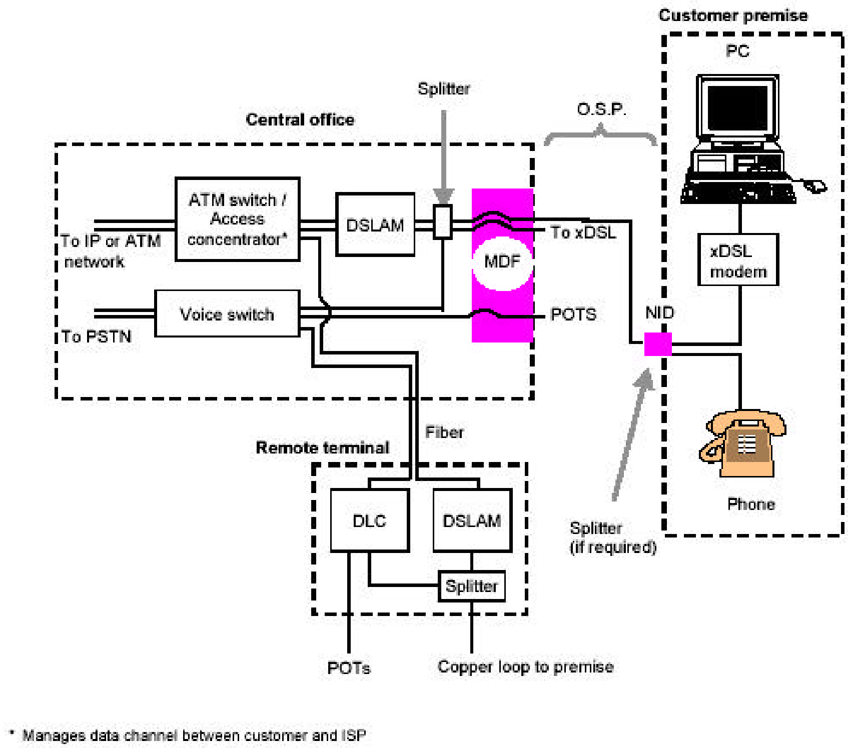


Figure 3.1 – xDSL Network Architecture. [From: 02]

Telephone companies have long been developing other ways to provide new high bandwidth services to the homes and SOHO markets. Technologies like fiber-to-the-curb (FTTC) and hybrid fiber-coax (HFC) are strategies that are not yet practical or economical for individual users, as well to the ISPs themselves. That is why the telephone companies are depending on xDSL for installations.

Subscriber lines are the twisted-pair connections between the home/office and the central office. Individual subscriber lines are combined into feeder cables (some with as many as 3600 pairs) and connected to the central office.

When ordering the xDSL service, the telephone company will provide equipment, which could be given or rented. A basic xDSL system consists of the transceiver unit, POTS splitters, DSL access multiplexer and the transport system. The description of each component is as follows:

a. Transceiver Unit, Remote (TU-R). This device provides an interface (Ethernet, ATM, etc) to the digital subscriber line and it is installed at the local site. Such devices cost about $400 to $600.

b. POTS Splitters. These devices, embedded in the modems permit certain xDSL technologies to simultaneously send high-speed data transmissions and the slow 4 KHz voice signals required for POTS. POTS Splitters are partic ularly attractive to home users as there is no need to install a separate telephone line (so as to have telephone and Internet service as in the dial-up method). New ‘splitterless’ xDSL technologies eliminate the need of this equipment, hence reducing the deployment costs and making xDSL services more attractive and convenient.

c. Digital Subscriber Line Access Multiplexer (DSLAM). This device resides within the central office and concentrates the data traffic from multiple digital subscriber lines onto the local access network.

d. Transport System. These lines are the local access networks that carry data between a network provider and another central office or access point. Typically, these are T1, T3 and optical fiber based lines. Big businesses, ed ucation institutions and government bodies are usually connected to the Internet via these second level central offices.

1. Flavours of xDSL

There are two flavors of xDSL technologies, namely the asymmetric and the symmetric DSL. The demands for each of the xDSL technologies are driven by two markets, which drive the evolution of xDSL technologies: The SOHO market has driven the development of lower cost, asymmetric technologies – those with different capabilities for sending and receiving transmissions. Larger businesses are more likely to pay for the higher speeds that come with symmetric technologies. This section explores the varieties of each technology.

a. Asymmetric

In general, an asymmetric transmission is faster coming downstream (from the ISP to user) than it is going upstream (from the user to the ISP). There are three varieties.

i. Asymmetric DSL (ADSL). ADSL runs on a single twisted pair wire. It supports downstream rates ranging from as slow as 1.544 Mbps (at distances up to 18000 feet) to as fast as 8.448 Mbps (at 9000 feet or less). Upstream rates range from 16 to 640 Kbps. ADSL uses a spectrum well above 4 KHz, leaving the POTS undisturbed. A variation on this is ADSL Lite (also called G.Lite or Splitterless ADSL). As its name implies, ADSL Lite eliminates the need for installing a splitter, but it is slower: downstream at not more than 1.5 Mbps and upstream at 256 Kbps. Targeted at SOHO, ADSL Lite is less expensive and less complex than ADSL.

ii. Rate-Adaptive DSL (RADSL). RADSL also uses a single twisted pair, but its modems can periodically assess the quality of the line and adjust the transmission rate accordingly. Depending on line length and quality, transmission speeds range from 1 to 2 Mbps downstream to 128 Kbps to 1 Mbps upstream.

iii. Very High Bit Rate DSL (VDSL). VDSL is used to transmit 30-51 Mbps downstream over very short distances – usually less than 1000 feet. Some newer variants of VDSL support symmetric rates ranging from 2 to 4 Mbps over much longer distances.

b. Symmetric

Symmetric technologies are slightly more expensive but offer the same capabilities downstream and upstream. They are thus better able to support interactive, real-time applications like video conferencing or LAN extensions. On the other hand, most of the symmetric technologies use a part of the spectrum that overlaps the voice frequency (0 – 4 KHz). The same telephone line cannot be used to simultaneously support POTS or voice-grade modems. These technologies therefore usually require dedicated twisted-pair lines.

i. High Bit Rate DSL (HDSL). One of the first DSL technologies that is fielded, HDSL is now the most widely used, with nearly a half-million installations. HDSL can be run over long distance and at high speeds – symmetric data rates of 1.544 Mbps up to 12000 feet. It is noted that two twisted pair wires are required, needing a second line. Telecommunication companies use it primarily for installing T1 and ISDN lines.

ii. Single Pair HDSL (S-HDSL). This is used by telecommunication companies in their infrastructure. It uses only a single twisted pair and the data rate is limited to 768 Kbps.

iii. Symmetric DSL (SDSL). SDSL represents a family of symmetric rate lines (384, 768, 1544 and 2048 Kbps) that are implemented over a single twisted pair line. Telephone companies intended this technology to support symmetric services such as frame relay and two-way video conferencing. At a T1 rate (1.544 Mbps), SDSL can reach distances beyond 10000 feet.

iv. HDSL Version 2 (HDSL2). HDSL2 has the same data rate as HDSL, but uses a single twisted pair line. This DSL technology has new features designed to simplify implementation of telecommunications company infrastructure.

2. xDSL Implementation Issues

There have been many complaints from DSL customers that they rarely get the advertised connection speed. While service providers are continuing their effort in getting customers, by stating their connection speed – hence allowing more potential for bandwidth intense services and applications, the connection speeds are often 50% less.

The Public Switched Telephone Network (PSTN) was designed for voice transmissions that were limited to frequencies below 4 KHz. To achieve the dramatic increase in data rates provided by xDSL technologies, xDSL providers are using the available spectrum above 4 KHz. Higher frequency operations comes with a penalty: higher attenuation and increased crosstalk.

Both attenuation and crosstalk are caused by the physical properties of copper wires. Attenuation is the natural decrease in a signal's strength as the signal travels further from its source. At higher frequencies, the loss of strength is more pronounced. Crosstalk is the transfer of energy from one wire to another. As twisted pair is bundled into large cables containing up to several thousand wires, it is not difficult for data or voice in one wire to interfere with data in another wire. The twisting in the wire itself serves as an anti-interference feature but with thousand of such wires, there is still a probability that interference will occur.

In addition, the maximum data rates and distances quoted for xDSL technologies are often based on continuous runs of good quality copper wires. Unfortunately, this is not usually the case. For example, the connection from a residence to a central office can involve three distinct types of cables: feeder, distribution and drop wires.

A feeder cable connects the central office to a concentrated customer area. It may contain thousands of individual twisted-pairs and if the duct space leading to the central office is crowded, the telephone company will often use higher gauge (thinner) wire. Thinner wires have their drawback in that they are more susceptible to cross talk than lower gauge (thicker) wire.

A distribution cable connects these concentrated customer areas to potential customer sites. They are sized to serve existing customers as well as future requests for service and anticipated growth. Therefore, some distribution cables remain temporarily unused, resulting in bridged taps. A bridged tap is simple a loop segment that is not in the direct path between the central office and the customer’s equipment. Bridged taps can induce signal changes that reduce both effective data rate and distance.

A drop wire connects the concentrated customer areas to individual residences. Longer drop wires may use lower gauge wires because the lower gauge wires have less resistance per unit distance. Think about it as a larger water pipe.

There is also the potential for loading coils, which telephone companies use in some cases to condition a voice line. These coils severely attenuate frequencies, directly interfering with the way xDSL encodes digital data. AM radio interference can also impair xDSL performance. The AM radio band falls in the same frequency range used by the xDSL downstream channels, and radios close to a cable can inject interference.

All of these impairments will result in either shorter distances or lower data rates for xDSL services. Due to the distance limitation problems, xDSL is only available in metropolitan areas and their surrounding suburbs.

3. DSL Modulation

DSL must employ modulation to convert digital data (bits) into analog data (just like a waveform) that a telephone line can carry. Note that the telephone line was meant to carry analog signals. Products that implement xDSL will incorporate one of two modulation techniques (also called line codes). These line codes are competing standards, so it is important to understand which technology each access method implies.

a. Carrierless Amplitude and Phase (CAP). CAP modulation is a version of Quadrature Amplitude Modulation (QAM). The important characteristic is that it converts digital data into an analogue signal that a single carrier can transmit down a telephone line.

b. Discrete Multitone (DMT). DMT is a version of multi-carrier modulation. Incoming data is collected and then distributed over a large number of sub-carriers, each of which uses a form of QAM. DMT modems divide the downstream bandwidth into 256 channels of 4 KHz each, and can transmit up to 15 bits/Hz in each channel. The DMT modem can adapt to different impairments in different lines by evaluation the signal to noise ratio (S/N) in each channel and sending more data in the higher quality channels.

Both CAP and DMT have advantages, but many observers feel that the differences are not overwhelming and that a market shakedown may ensue.

4. DSL Standards

Like most modern technologies, xDSL is subject to standards conflicts. The American National Standards Institute (ANSI) has been publishing standards for xDSL technologies through its T1E1.4 Committee. DMT was the first technique developed for ADSL service and the first to receive ANSI support. The committee thus selected it as the offic ial ADSL standard (T1E1.4).

ANSI has since been asked to standardize the CAP modulation. CAP has the backing of several telephone companies, was deployed first, and is used more than DMT. Some argue that these facts effectively make CAP the de facto stand ard for ADSL.

The ANSI committee has also established a working group to develop an RADSL standard. This standard would focus on data services instead of bit synchronous services, the ADSL standard's focus. The group is still considering recommendations, and they are also updating the original DMT standard.

Similarly, most other xDSL technologies are based on variations of the tow coding techniques and have yet to be standardized. Several standards bodies are now considering an HDSL2 standard. ADSL Lite w as just recently approved by the International Standards Organization (ISO).

D. CABLE MODEMS

The telephone companies are not the only entities competing for data communication dollars. Telecommunications and cable service providers – the same companies that provide cable TV – are seriously investigating cable modems as a viable last mile access technology. The potential for access to 113 million connected homes and

73 million paying subscribers in North America alone presents a strong impetus for them to deploy cable modems.

And these vendors have a leg up on the telephone companies in terms of infrastructure. The home's network for cable TV may have initially been deployed as coaxial cable but many cable networks are already upgrading to Hybrid Fiber Coax (HFC) system which deliver more channels and capabilities. The immediate increase in bandwidth and bidirectional communications has telecommunications and cable service providers thinking: Cable technologies is a viable means of providing high-speed access to the Internet and to corporate Intranets for voice, video and data (VVD) services.

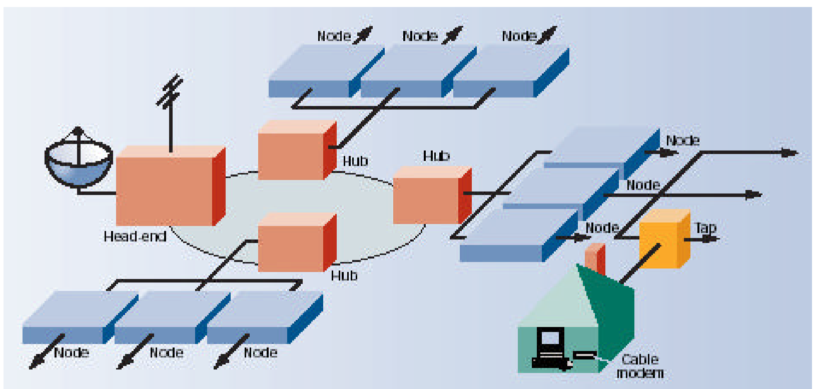


Figure 3.2 – Hybrid Fiber Coax System Architecture. [From: 02]

Figure 3.2 shows a typical HFC system architecture. Businesses and homes tap into the hybrid network by tapping into the fiber or coaxial lines coming from nodes – local concentration and information distribution centers. Nodes in turn, come together at the hubs, which finally join to the head-ends. The head-ends supply information downstream to the user and receive information via a separate path upstream (from the user). Therefore, the head-end is the end of the line for all transmissions. It is the location of the information source (server) or the Internet connection. Hubs simply serve to concentrate and distribute information flowing to and from locations that are interconnected through the nodes.

1. Cable Modem Technology

A cable modem is a device that allows high-speed data access via the cable television network. It is a true modulator-demodulator in the classic sense of the meaning of ‘modem’. Cable modems, however, actually operate more as a last mile interface between the user’s site and the cable company. Coaxial cable can be stretched; it is not restricted to 18000 feet like ISDN and ADSL.

A cable modem communicates with a cable modem termination system (CMTS), located at the cable company. The CMTS terminates cable connections from users and aggregates those signals into outputs to the cable providers’ network distribution equipment.

The CMTS is also an integral member of the head-end. The head-end consists of several servers, gateways, and routers that together provide services via the Internet. These services include data/video transmission, satellite channel reception and normal radio frequency broadcast reception.

Cable companies may also have the equipment to provide advanced networking capabilities. They may employ Web cache servers to store the contents of frequently accessed web sites.

Cable modems provide network access via separate channels for downstream and upstream communications, but these channels are asymmetric. The downstream channel has a higher capacity and throughput than the upstream channel. Cable companies focus on delivering content data to users. There is less demand placed on the upstream channel

– upstream transmission typically involves keyboard inputs and mouse/cursors moves. The concept of network access is similar to their cable TV services. No subscribers would be pumping huge data to the cable TV providers – other than channels programming selections.

Traditional coaxial CATV networks operate with 330 or 450 MHz of capacity. Newer HFC systems operate with 750 MHz. each channel normally occupies 6MHz of the frequency. Therefore, a 400 MHz cable system can deliver approximately 60 channels, and a system with 700 MHz can deliver up to 110 channels.

Each 6 MHz channel can deliver up to 40 Mbps of throughput on the downstream frequency. Upstream throughput ranges from 500 Kbps to 10 Mbps. The maximum throughput to a PC from a cable modem is currently 10 Mbps, due to the cable modem's 10Base T Ethernet interface.

The cable modem standard DOCSIS (Data Over Cable System Interface Specification) specifies that a cable network should be able to sustain a maximum throughput of 36 Mbps. But it is unlikely that this speed can be achieved because the entire cable network handles shared media. Most likely, sustained data rates will be about 400 Kbps to 3 Mbps. This throughput depends completely on how the network has been segmented and loaded in terms of the number of user sites per segment. The general rule of thumb is: the lower the number of sites per node, the greater the bandwidth for customers on that segment. Typically, the cable industry loads 125 to 2000 sites on to each segment.

2. Cable Modem Standards

There are two competing cable modem standards, DOCSIS and the Digital Video Broadcasting/Digital Audio-Visual Council (DVB/DAVIC).

DOCSIS was introduced by a coalition of companies in the US and Canada as an initiative of the Multimedia Cable Network System (MCNS) consortium. The MCNS services 85% of the US subscribers and 75% of the Canadian subscribers ("Cable Modem Standards and Specifications", Cable DataCom News, Kinetic Strategies Inc.).

The European Cable Modem Coalition also supports DOCSIS. This organization includes companies like Cisco Systems, Motorola, and 3Com ("Dueling Cable Modem Standards", Computer).

The DVB/DAVIC Interoperability Consortium also has support from big players – companies like Alcatel, Hughes Network Systems, and Thomson SA. In addition, it has backing from Euro-Cable Labs., the European Cable Communications Association's technical arm.

At the moment, DOCSIS cable modems are widely available in the US; there are many vendors and the subscriptions are relatively inexpensive. Costs range from $30 to $60 and include the cable modem rental, unlimited access to the Internet and email. DOCSIS modems may have an edge because of higher volumes and lower prices.

However DVB modems from several vendors are also becoming available. They may have an advantage in that they fit into existing European network architectures and they work efficiently with European video-broadcast standards. This situation can decrease deployment and management costs and possibly offset the equipment cost savings that DOCSIS may offer.

Meantime, manufacturers have bypassed the Institute of Electrical and Electronics Engineers (IEEE) standard. They are using less stringent but more easily agreed to

DOCSIS and DVB/DAVIC interim solutions. Because of this situation, it appears that the IEEE has lost the first round in the cable modem standardization. However, IEEE 802.14 standard (Cable TV Media Access Control and Physical Protocol) is set up to serve the next generation standard for data access over cable. DOCSIS and IEEE 802.14 have similar specifications for error correction, encryption and radio frequency (RF) transmissions at the physical layer.

3. Cable Modems Implementation Issues

Cable modems broadcast noise on the upstream channel and because channels are shared, this noise is further aggregated by all the nodes on each segment connected to the CMTS. Noise has been known to interfere with adjacent channels and is sometimes influenced by such things as ham and citizen band radios. Vendors have developed silicon chips designed specifically for removing upstream noise.

The biggest concern that users have over cable modems is security. Similarly, it is due to the shared nature of cable modems that creates the concern. The thought of private information passing by every modem on the sender's network segment immediately raises questions about security.

Several elements of cable modem systems address this concern. Firstly, all DOCSIS-compliant systems must meet Baseline Privacy Specifications, which enable true end-to-end secure communications for business applications. In addition to those specifications, cable modems communicate with CMTS using the Data Encryption Standard (DES) 40 and 56 bits encryption keys. The IEEE 802.14 standard includes DES and Triple-DES, 128-bit encryption algorithms. In contrast, DSL does not have a security specification for encryption.

Finally, there are long standing concerns about cable network reliability. CATV networks are notorious for delivering spotty service during heavy storms and for experiencing periodic outages without explanations. In areas where cable providers are upgrading, HFC will greatly increase capacity and improve the quality of service (QoS) to consumers. These new HFC networks will have to deliver services according to contracts that specify service levels.

Competition should increase as large telecommunication equipment manufacturers – such as Cisco, Motorola and Nortel – deliver cable modems, which should result in better quality at lower cost.

E. DIRECT BROADCAST SATELLITE

Direct broadcast satellite (DBS) service brings subscription TV and video programs to remote or rural locations worldwide. It has been especially effective in locations where it is too expensive or difficult to deploy other high-speed services.

There are different access technologies in DBS, as shown in figure 3.3. Offered by different vendors, each has their own band of access satellites but generally, the working concept is similar.

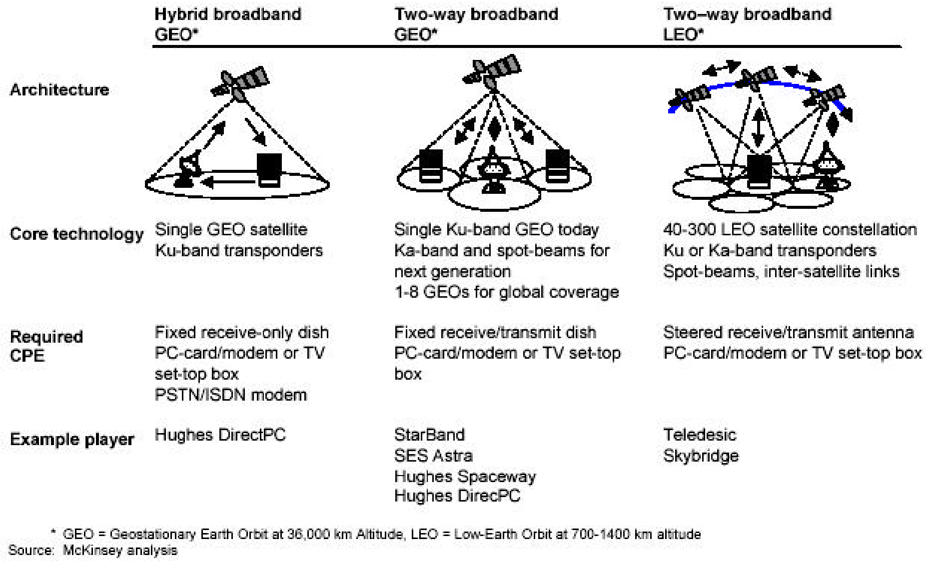


Figure 3.3 – Broadband Satellite Access Technologies. [From: 10]

The promise of DBS is the deployment of an information gateway capable of showering the earth with high-speed Internet services. Although it is relatively easy and natural for satellite services to broadcast information to homes and offices, high bandwidth return links (transmission from users) are more expensive and difficult. This concept is also similar to that of cable modems as the broadcast satellites were meant for receiving TV signals – large downstream traffic compared to upstream traffic.

For bidirectional Internet access, DBS is best used in combination with wired communication and modems. The satellite provides low cost, high bandwidth broadcast from the network, while lower speed dial-up modems across telephone lines carry transmissions from the users. In other words, the telephone lines will be busy once connected to the Internet – just like using the 56 Kbps dial-up access method.

This situation could not support video conferencing, but would suffice for most of today's Internet applications, which generally need high-speed data from service providers to the users.

Currently, DBS services are provided by DirecTV (also known as DirecPC), USSB, DISH Network, Primestar and many others as shown in figure 3.3. Although the DBS satellite broadcast rate is 12 Mbps, the vendors allot each user up to 400Kbps.

Subscribers to DirecPC, for example, once supplied with the hardware (a 24-inch satellite antenna) and software, get high-speed access from the Internet only, as well as DirecPC sports, news and financial information. This service costs about $500 (a one time investment) and a monthly fee of about $25 to $130, depending on access time. Communications from the user to the Internet must be via a technology other than the DBS, however. Other installation inconveniences include selection of position for the satellite dish, the cabling installation from the satellite dish to the modem, etc.

A bidirectional satellite connection now costs users from several hundreds to several thousand of dollars per month. At least two companies are working on technologies that will let many more users share a single satellite and thus, driving down the cost.

F. COMPARISON OF ACCESS TECHNOLOGIES

The table below summarizes the discussed access technologies. Each of the access technology is compared against another based on the availability, coverage area, start-up cost, monthly fees, downloading and uploading speed. Note that these are the currently available access technologies and the limitations are clear.

Characteristic	Dial-up lines and modems	ISDN BRI	xDSL	Cable modem	Direct broadcast satellite
Availability	Now	Now	Limited	Limited	Limited
Geographic coverage area	Widespread	Widespread	Limited	Limited	Widespread (CONUS)
One-time cost to user	Under $100	Minimal	Starts at about $600	$150	$500 or more
Monthly charge	$10 to $30	$100	$40 to $70	$30 to $60	$20 to $130
Download speed (Kbps)	Less than or equal to 56	128	ADSL: 1,544 to (at up to 18,000 feet) 8,448 (at less than 9,000 feet) Other forms of DSL have faster/slower speeds and shorter/further distances.	400 to 14,000	400
Upload speed (Kbps)	Less than or equal to 56	128	ADSL: 640 (other forms can provide up to 2,000)	400	Less than 56

Figure 3.4 – Common Network Access Technologies. [From: 02]

For any of these technologies to be the leading technology for the last mile, not only must they can meet the demanding requirements of the users, they must also meet that of the operators. Users want a service that is convenient to use (always on), reliable and at a price that does not present a disincentive to use. Operators have even more exacting requirements, all, ultimately, linked to the need to earn a speedy and secure return on the inevitable up-front investment. Their prime requirement is for an access technology that is simple, quick and economic to deploy – ensuring the minimum of delay between starting to build the network and generating income from paying customers. The technology must also be scalable, i.e. it must generate profit even when customer take-up is difficult to predict, and continue to deliver a satisfactory grade of service as customer number grows.

G. SUMMARY

Overall, the impact of these new access offerings should be improved performance and lower prices to the consumer for all service arrangements. It is a fact that these technologies do help support the growing multimedia usage of the Internet by all users, in SOHOs and big business alike, making Internet services and applications even more popular and attractive. Competition does work but bearing the advantages and disadvantages of these access methods, none of them offers the ideal all-in-one solution for the last mile.

THIS PAGE INTENTIONALLY LEFT BLANK

IV. FREE SPACE OPTICS TECHNOLOGY

A. OVERVIEW

The invention and application of fiber optics has significantly changed the course of telecommunications around the world. Fiber optic cables connect all major countries and continents around the world, enabling the ultra high-speed transfer of data voice, video signals and of course the Internet. Fiber optic cables are also used in all telecommunication switches, i.e. the central office. What is lacking, as discussed in the previous chapters, is the high-speed communication line between these central offices and the homes. Today, about 5% of the commercial buildings in the US are connected to fiber optics for high bandwidth services, and the percentages are even smaller in Asia and other parts of the world.

Free space optics (FSO), also known as free space photonics, is the technology whereby the voice, video and data can be transmitted through the atmosphere using modulated visible or infrared beams. Laser beams are generally used, although non-lasing sources such as Light Emitting Diodes (LEDs) or InfraRed Emitting Diodes (IREDs) will serve the purpose.

Through the use of free space optics, broadband communication can be achieved, just like fiber optics transmission. The difference is that free space optics uses air as the transmission medium instead of fiber or glass. At the source, the visible or infrared energy is modulated with the data to be transmitted. While at the destination, the beam is received by a photo-detector, the data is extracted from the visible or IR beam (demodulated), and the resulting signal is amplified and sent to the hardware.

Free space optics requires line of sight (visual[12]) between the source and the destination. In cases where by there is no line of sight, strategically positioned mirrors can be used to reflect the energy. The beams can pass through glass windows with little or no attenuation (as long as the windows are clean). Depending on the type of source used and the visibility condition of the atmosphere, free space optics systems can function over distances of several kilometers.

Nowadays, free space optics is becoming more and more popular, as free space optics equipment is being deployed for a variety of applications, including last-mile connections to buildings, mobile networks assist, network backup and emergency relief. Marketing experts estimated that global equipment revenues in the free space optics market are projected to reach $2 billion in year 2005, up from less than $100 million in year 2000. With its increasing popularity and known advantages, the potential of implementing FSO as a mean to resolve the last mile problem seems high.

B. BRIEF HISTORY OF FREE SPACE OPTICS

Free Space Optics (FSO) uses lasers to transmit data, voice and video communications through the air, allowing optical connectivity without laying fiber or securing spectrum licenses.

The idea of using lasers to transmit data through the air first attracted widespread interest in the 1960s, when scientists started developing applications for the military. With the Cold War in full bloom, physicists on both sides of the Iron Curtain were looking for ways to offer secure, high-speed communications. The properties of light – its ability to carry information great distances at high speeds with little degradation of the signal – also intrigued scientists developing communications for space exploration. These laser-based FSO communications had potential benefits well beyond other wireless technologies – including security levels and data rates beyond those that could be

12 Not radio line of sight.

obtained using existing radio frequency (RF) solutions. However, many of these programs did not full materialize due to funding cuts and changing priorities.

However, after Corning researchers Robert Maurer, Donald Keck and Peter Shultz developed the first optical fiber capable of transmitting information over long distances, physicists began focusing more on the properties of optical cable. The study of optical transmissions through the air continued, but the industry focused more on developing land-based fiber optics.

By the early 1990s, researchers again started focusing on FSO technology. Developments in optics and lasers drove down the price of components, making FSO a cost-effective approach to addressing the skyrocketing demand for broadband services.

Recent developments in the technology have advanced it from a short-term solution for short-haul bridges to a viable alternative for helping service providers deliver the promise of optical networks. The increasing demand for high bandwidth "now" in the metro networks - as service providers clamor for a wide range of applications, including metro network extension, enterprise LAN-to-LAN connectivity, wireless backhaul and LMDS supplement - has caused an imbalance, a "connectivity bottleneck". Service providers are faced with a need to turn up services quickly and cost effectively, at a time when capital expenditures are restrained.

As an optical technology, FSO is a natural extension of the metro optical core. FSOs bring optical capacity to the edge of the network, allowing end users to connect with technology that is cost-effective, reliable and quickly installed.

C. HOW FSO WORKS

Free space optics is a technology similar to fiber optic cable infrastructure except that no cable is involved. The light pulses are transmitted through the atmosphere in a small conical shaped beam by the means of low powered lasers or LED's. It is hence a point-to-point, line of sight method for delivering high data rate through optical signals, using the free space as a medium. Instead of focusing the output of a laser into a strand of optical fiber, the output is broadcast in a thin beam across the sky, at the receiving unit.

1. Operating Frequency Band

FSO equipment usually operates in two ranges of wavelength – one is between 780 nanometers (nm) to 900nm and the other is between 1500nm to 1600nm.

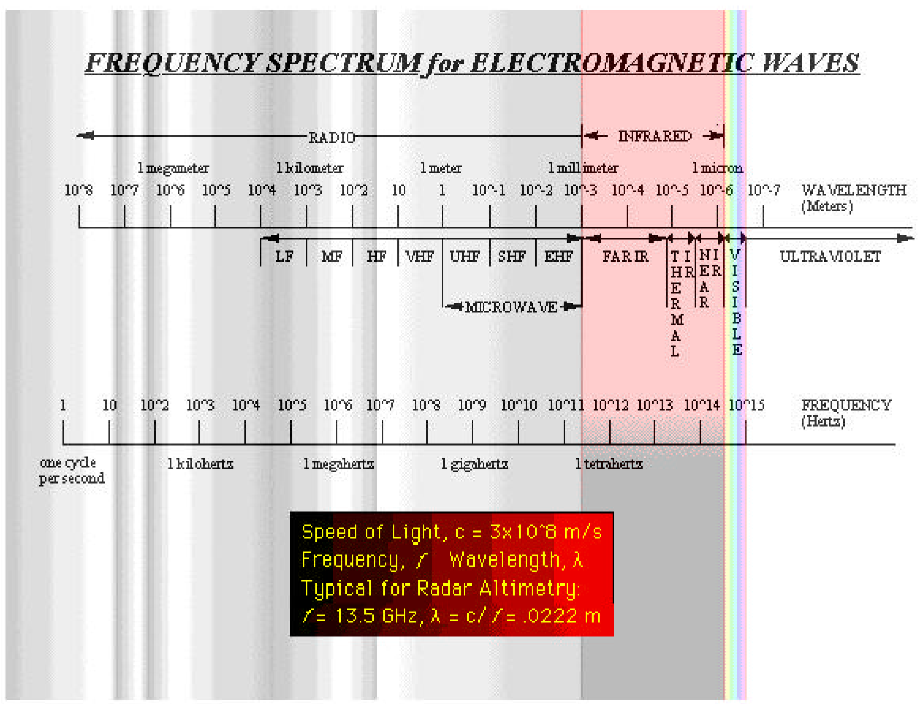


Figure 4.1 – Frequency Spectrum. [From: 11]

Most FSO vendors do not use the 1300nm window, which is used in fiber optics because it has poor transmission characteristics through atmospheric conditions. Of the two operating frequency range, the 1500nm laser would be better in terms of power, distance and eye safety. IR radiation at 1500nm tends not to reach the retina of the eye, being mostly absorbed by the cornea. Regulations accordingly allow these longer wavelength beams to operate at higher power than the 800nm beams, by about two orders of magnitude. With this increase in power, it can boost the link lengths by a factor of at least five while maintaining sufficient signal strength for proper link operation.

Alternatively, it would be able to boost data rate considerably over the same length of link. So for high data rates, long distances, poor propagation conditions, or combination of these conditions, the 1550nm operating frequency range can be rather attractive, but of course, it is at the expense of the cost of equipment, which is much more expensive than those operating at 800 nm. The smaller wavelength (850nm) is about one-tenth the price of the larger (1550nm) wavelength to manufacture.

Why then not just operate at the 850nm wavelength? It is due to the larger wavelength allows for much greater power to travel over a greater distance at a very high data rate. A recent example has an 850nm laser costing about $5000 dollars with a data rate of about 10Mbps over a few hundred yards while a 1550nm laser that costs about $50000 could get data rate up in the giga-bits per second range over a few kilometers.

2. Description of the Transceiver

Normally, an FSO link refers to a pair of free space transceivers that are called link heads, aiming beam at one another and creating a full-duplex communication link. The figure (Figure 4.2) below shows a typical link head.

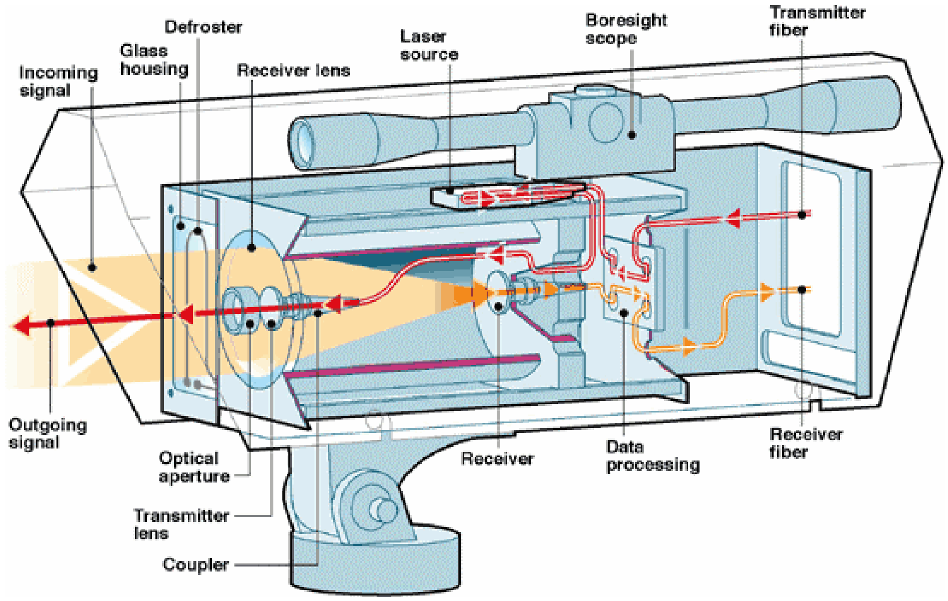


Figure 4.2 - A typical link head for FSO. [From: 12]

The functions of each component in a link head is summarized in the figure 4.3. The block diagram is based on a simulation that transmits voice data over FSO. In this description, only the main functional block will be described. It follows from the interface card through the transmission path to the TX lens. The receive path indicates the incoming beam from the remote unit following it through the receiver back to the interface card and completing the loop.

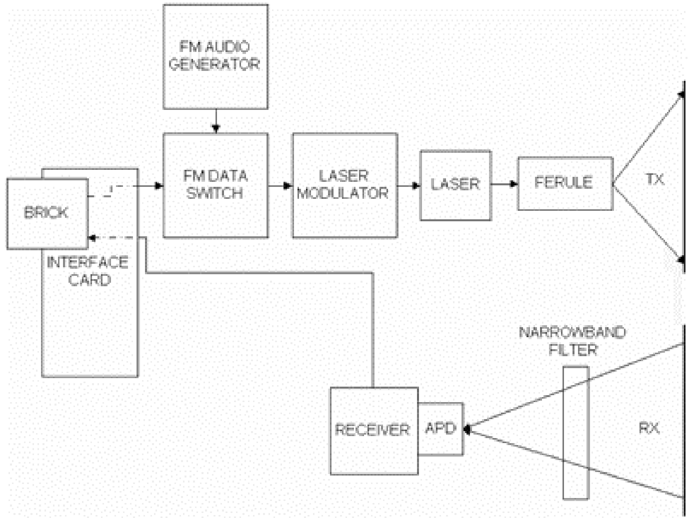


Figure 4.3 - Block Diagram of the Transceiver. [From: 13]

a. Interface Card.The interface card connects the link head with the external network in standard interface types - Fiber (SC or ST), UTP and BNC. The interface also specifies the data rate of the link and is the only change required when upgrading to higher data rates.

b. FM / Data Switch. The FM Data switch allows the unit to be switched into FM mode via the alignment module (FM audio generator), allowing duplex voice communication across the link. Communication between the ends of the link is vital for correct alignment and installation. When the alignment module is removed the system automatically switches into data mode.

c. LASER Modulator. The LASER modulator converts the incoming data into a signal that modulates the laser at the data rate set by the interface card. This process is achieved by modulating the current through the laser, as it is the current that controls the output power of the laser, the higher the current the higher the output power.

d. Laser. This transmits an infrared beam at a set wavelength. Depending on the bandwidth requirements and distance of the link, the type and number of lasers will change. For higher data rates Gigabit and some 622 systems 785nm lasers are used, which are visible. For longer distance links i.e. 1000M, 2000M, 4000M, 980nm Lasers are used which are not visible. The Laser is coupled into a fiber and the beam is launched directly from the fiber.

e. Narrow Band Optical Filter. A narrowband optical filter is placed over the front of the APD, which passes wavelengths ±35nm either side of the operating wavelength. The 785nm and 980nm systems have filters specific to these wavelengths.

f. APD and Receiver. A photodiode is a device that converts light (photons) into electrical signals, the higher the number of photons arriving, the higher the output current of the photodiode. The incoming modulated beam that varies in optical power as described in the LASER modulator section, induces the correct level of electrical signal from the APD. The type of APD varies depending on the data rate but all are wide area to give maximum signal output and low BER at high bandwidths. It is the APD that sets the dynamic range and hence the fade margin for the entire system.

D. FSO IMPLEMENTATION ISSUES

As mentioned, a strict line-of-sight needs to be maintained within the link at all times for optimal operation in FSO. As such, a thorough pre-installation site evaluation must be done to ensure that the paths between the Free-Space Optic units are clear and will remain so for a number of years. One of the main issues with the technology is that fog and severe weather can have a detrimental impact on the performance of the Free-Space Optic systems. The main factor is fog, with rain and snow also contributing to the maximum distances that can be achieved.

When planning a Free-Space Optic system, it is recommended that someone review the city's fog table and the anticipated distance of the connection. The vendor's product specifications should be used to ensure that the product would perform in a satisfactory manner for the connection. One other factor involved in limiting the distance of the connections is the atmosphere itself. As the beam goes through small pockets of differing variations in air temperature and wind speed the light can be refracted off course. Since these variations are physically very small, most vendors will use multiple lasers in parallel on the Free-Space Optic system to compensate, especially on units designed for longer distances.

The following table (Table 2) is taken from a white paper on the Optical Access web site and is representative of the impact of fog and bad weather on the operational distance of a Free-Space Optic system. The table shows also the distance achieved and signal loss ratio based on the fog condition and visibility.

Weather condition		Precipitation	mm/hr	Visibility	dB loss/ km	TerraLink 8-155 Range
Dense fog				0 m		
				50 m	-315.0	140 m
Thick fog				200 m	-75.3	460 m
Moderate fog				500 m	-28.9	980 m
Light fog		Cloudburst	100	770 m	-18.3	1.38 km
				1 km	-13.8	1.68 km
Thin fog	Snow	Heavy rain	25	1.9 km	-6.9	2.39 km
				2 km	-6.6	2.79 km
Haze		Medium rain	12.5	2.8 km	-4.6	3.50 km
				4 km	-3.1	4.38 km
Light Haze		Light rain	2.5	5.9 km	-2.0	5.44 km
				10 km	-1.1	6.89 km
Clear		Drizzle	0.25	18.1 km	-0.6	8.00 km
				20 km	-0.54	8.22 km
Very Clear				23 km	-0.47	8.33 km
				50 km	-0.19	9.15 km

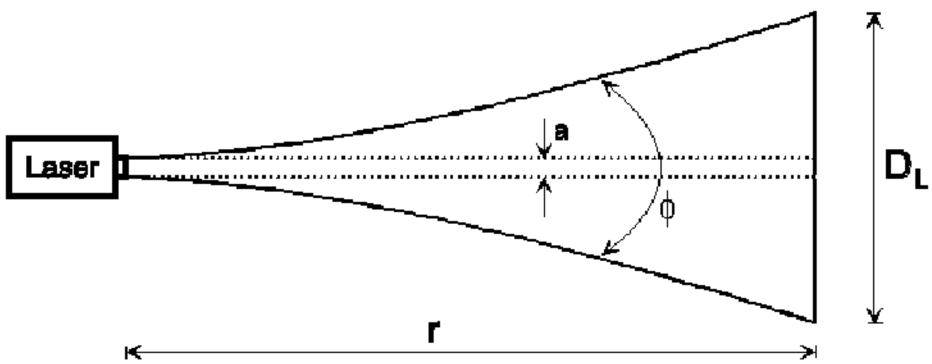
Table 2. Impact of fog and bad weather on the operational distance of a Free-Space Optic system. [From: 01]

Since RF (radio frequency) wireless systems like the ones based on the 802.11b standard are not affected so much by fog, some manufacturers are using these as a redundant system and have incorporated them into their Free Space Optic systems. The growth of trees and the construction of buildings need to be considered along with any aesthetic issues and required permits. The units can be mounted on building tops, sides and even behind windows. Speeds range from single T-1 and 10Mbps to 2.5Gbps on currently available products. 40Gbps has been successfully tested in laboratories; speeds could potentially be able to reach into the Terabit range.

E. COUNTERING DIFFICULTIES

Another common difficulty that arises when deploying free space optics links on tall buildings or towers is sway due to wind or seismic activity. Both storms and earthquakes can cause buildings to move enough to affect beam aiming. The problem can be dealt with in two complementary ways: through beam divergence and active tracking.

With beam divergence, the transmitted beam is purposely allowed to diverge, or spread, so that by the time it arrives at the receiving link head, it forms a fairly large optical cone.



$$D_L = \sqrt{a^2 + r^2\phi^2}$$

where

D_L: Beam Diameter

a: Beam Waist (beam diameter at the exit)

r: Range

F: Beam Divergence

Figure 4.4 – Beam Divergence. [From: 01]

As shown in figure 4.4, the beam divergence can be calculated based on the given formula. The result will be able to give FSO network designers a fairly good estimate. Depending on product design, the typical free space optics light beam subtends an angle of 3-6 milli-radians (10-20 minutes of arc) and will have a diameter of 3-6 meters after traveling for 1 km. If the receiver is initially positioned at the center of the beam, divergence alone can deal with many perturbations. This inexpensive approach to maintaining system alignment has been used quite successfully by the FSO vendors.

If however, the link heads are mounted on the tops of extremely tall build ings or towers, an active tracking system may be required. More sophisticated and costly than beam divergence, active tracking is based on movable mirrors that control the direction in which the beams are launched. A feedback mechanism continuously adjusts the mirrors so that the beams stay on target. These closed loop systems are also valuable for high-speed links than span long distances. In those applications, beam divergence is not a good approach. By its very nature, it reduces the beam power density just when receivers, being less sensitive at high data rates, need all the power they can get.

F. FREE SPACE OPTICS SECURITY

Even though Free-Space Optics is a wireless technology it is unlike other wireless technology that has omni-directional transmission. Instead, FSO transmits a very high frequency narrow beam of light to a specific destination, i.e. point-to-point transmission. In order for an individual to intercept the beamed signal they would somehow have to wiretap the beam - beamtap and beamtapping to describe the process or equipment used in trying to garner data from a beam of light transmitted by a Free-Space Optic system. As this technology is quite new to the marketplace, little information was found on the security of Free-Space Optics. The three following quotes were taken directly from the vendors' web sites.

a. "To ensure high security, Terabeam's optical stream is directional and limited to a small diameter, so only Terabeam's site equipment can receive data sent from the Terabeam network."[13]

b. "In addition, because the OPTera Metro 2400 is laser-based, it is much more secure than other wireless solutions—its narrow laser beam is not accessible unless viewed directly on the transmission path. Therefore, it is virtually impossible to intercept its signal without being detected."[14]

In both quotes, it is observed that the beam of a FSO transceiver is narrow and precise. Hence, the communication link is almost impossible for an intruder to intercept. The vendors have a good position. FSO is far superior to other comparable technologies, e.g. an 802.11b wireless system, as there is no broadcasting of data. As stated by the vendors, it would be difficult for an individual to beamtap without physically exposing himself and his equipment without interrupting the communication link. The Free-Space Optic systems are normally installed as high as possible so that passing cars; trucks or other moving things do not interfere with the beam. A bird can disrupt communication but it is only momentary and the system will very quickly recover. By contrast, beamtapping would require that a mirror or other device remain in the beam path for extended periods of time. Care would need to be taken by the intruder to not disrupt either beam because if one beam is interrupted the other beam would automatically go into failure recovery mode and would not transmit any data of interest to the intruder.

It was mentioned earlier that the Free-Space Optics systems transmit a conical shaped beam of light with the beam expanding more and more as it leaves the laser and goes through the atmosphere. The conical shapes differ from one another in size; some designs send a very narrow beam and other designs send a wider beam. The reason for

13 http://www.terabeam.com/our/our_gen.com [14]

14 http://www.nortelnetworks.com/products/library/collateral/56328.02-06-01.pdf [15]

this difference is the fact that tall buildings will sway back and forth due to strong winds and earthquakes. Since the systems are usually installed at the top of buildings the units can move in and out of the beam of light when the building sways, losing synchronization with one another.

Beam size is important to securing the connection. The larger the beam, the easier it would be for someone to find the beam and to place a mirror or receiver in the beam and not disrupt either connection. If an individual wanted transmitted data from both ends of the connection simultaneously, the beamtapping device would need to be placed approximately equidistant between the Free-Space Optic units. The closer the beamtapping device is placed toward one end or the other, one of the conical shaped beams would become smaller and the likelihood of disrupting the beam would be greatly increased thus stopping the connection. Admittedly, placing a beamtapping device between Free-Space Optic units would be difficult to do in most circumstances. The beam is very small, would be difficult to locate and is generally very high and not close to anything. The chance of being discovered is real, because by blocking one of the beams, the company when investigating the problem could discover the intrusion attempt. Since the beam needs to be line of sight, surveillance cameras could easily be used to monitor the installation and beam path to detect any suspicious activity.

A greater concern is the beam extending past the Free-Space Optic equipment for a few kilometers. The Free-Space Optic equipment takes around a square foot or less of the beam, so in most scenarios the majority of the beam extends past the intended target. Only one side of the data conversation could be beamtapped in this case, but that could easily be the part of the data stream of interest to the individual. The beamtapping would probably never be detected and could continue for years.

The solution here is to determine the size of the beam at the receiving point by using the distance of the connection and the vendor specific beam dispersion formula.

Once the diameter of the beam is determined plan the installation so that the Free-Space Optic equipment has a wall or similar non-reflective surface directly behind it to block the remaining remnants of the beam. A wall could be built to block the beam if required. Physically monitoring the installation would be recommended to ensure that a beamtapping device was not mounted on the wall or somewhere near the Free-Space Optic equipment.

Encryption equipment could also be used on each end to encrypt and decrypt data. It would be very difficult to find encryption devices that could support the speeds that Free-Space Optics are capable of, but it is an alternative. In doing research for this paper an interesting technology was discovered that is currently under development. It involves applying a varying analog input to a laser and the laser responding by transmitting a digital chaotic output. The theory is that if the receiving end had a similar analog input the chaotic signal could be decrypted. Any device intercepting the signal would view it as being chaotic and could not discern a pattern or be able to crack an encryption algorithm. This technology could potentially be used on Free-Space Optic equipment making encrypted high-speed connections a reality.

G. ADVANTAGES OF USING FREE SPACE OPTICS

Free-space optical wireless has relatively more than just cost-effectiveness to offer the world of networking. Many of the benefits are experienced through better, faster, more ubiquitous service. With the ability to create links quickly and economically, optical wireless complements existing services including cable, DSL, radio and microwave.

The lower initial outlays also allow service providers to build out their networks at unprecedented speeds and extend them to isolated areas. In sparsely populated locales, few providers can justify bringing fiber close enough to offer high-speed services. But optical wireless complements these services by taking the place of fiber, making it economical to extend service areas and making it possible to cross previously difficult terrain.

And optical wireless also allows service provider to pay off the initial expense in a matter of months with no licensing or leasing fees. Easy, fast deployment and lower link costs for service providers spell better service to homes and businesses. Optical wireless is also known as "free space" optics. This is the part of the electro-magnetic spectrum not regulated by government agencies. A free space optical link transmits information through the atmosphere on beams of light created by lasers. The beams of light are similar to those created by the TV remote and are perfectly safe to the skin and eyes.

a. High Speed Broadband Access. Free space optics (FSO) utilizes advanced wireless optical technologies to bridge the last-mile in carrier networks and makes high-speed broadband access a reality. Based on optical technology, it provides levels of bandwidth comparable to fiber optic cable. With current availability of up to 1.25 Gbps, throughputs of hundreds of Gbps are possible in the future.

b. Low Cost Bypass of Copper Infrastructure. FSO solutions enable service providers to dramatically lower their cost of providing high-speed broadband access to end-users compared to other commercially available last-mile solutions. This is because it does not involve the expensive process of obtaining rights-of-way, licenses, or permits from governments, digging the ground to lay cable, or charges for spectrum rights. All that while maintaining costs that are lower than traditional infrastructure. FSO offers a return on investment of weeks or a couple of months, versus the years it takes for other solutions. An example of implementing FSO in bypassing the copper wire infrastructure is as shown in figure 4.5.

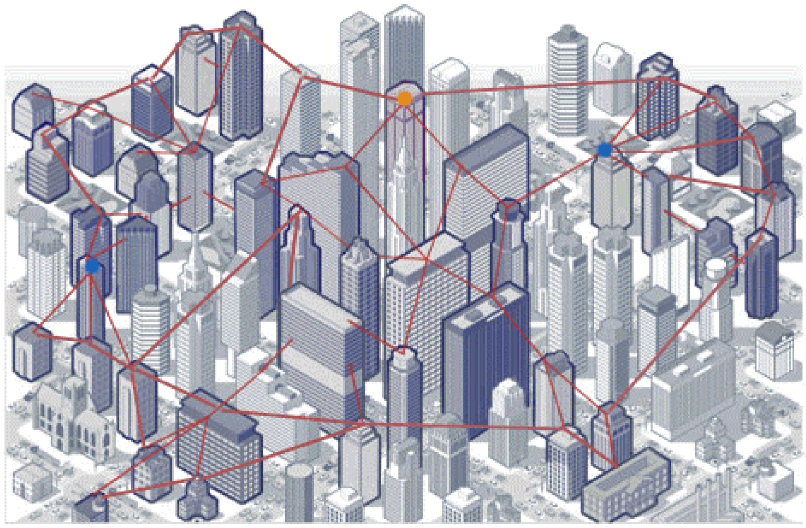


Figure 4.5 – Bypassing Copper Wire Infrastructure. [From: 16]

c. Rapid Deployment and Service Provisioning. FSO optical wireless products enable service providers to avoid time-consuming processes, such as obtaining rights-of-way, and other governmental licenses, or the labor-intensive process of digging and installing cables in the ground. As a result, FSO can be installed and made operational in a few hours. Using available Network Management Systems, service providers can efficiently and cost-effectively perform provisioning from a central location through a point-and-click graphical user interface, thus eliminating time-consuming onsite service calls or "truck-rolls".

d. Improved Availability and Reliability. FSO can be deployed to operate over an optical mesh architecture that allows transmission between any two points on the network and enables full traffic re-routing around a failed link. The short mesh configuration enables the wireless link to remain connected in all types of weather.

e. Improved Scalability and Flexibility. An FSO solution can be designed to scale efficiently as demand for bandwidth and new services grow, therefore initial deployment is also cost effective.

f. Creation of New Revenue Opportunities for Service Providers and Carriers. Service providers and carriers are able to rapidly introduce new upgrades, thanks to available software and system based products. Features include new service level agreements, Quality of Service enhancements, dedicated wavelengths to the end-user, and bandwidth on demand, without significant hardware changes or additions.

Depending on the bandwidth requirements, FSO may be the lowest cost technology. One way to view the cost advantage of FSO is to compare it to leased line costs[15].

[15] Leased line costs are from www.telcoexchange.com [17]

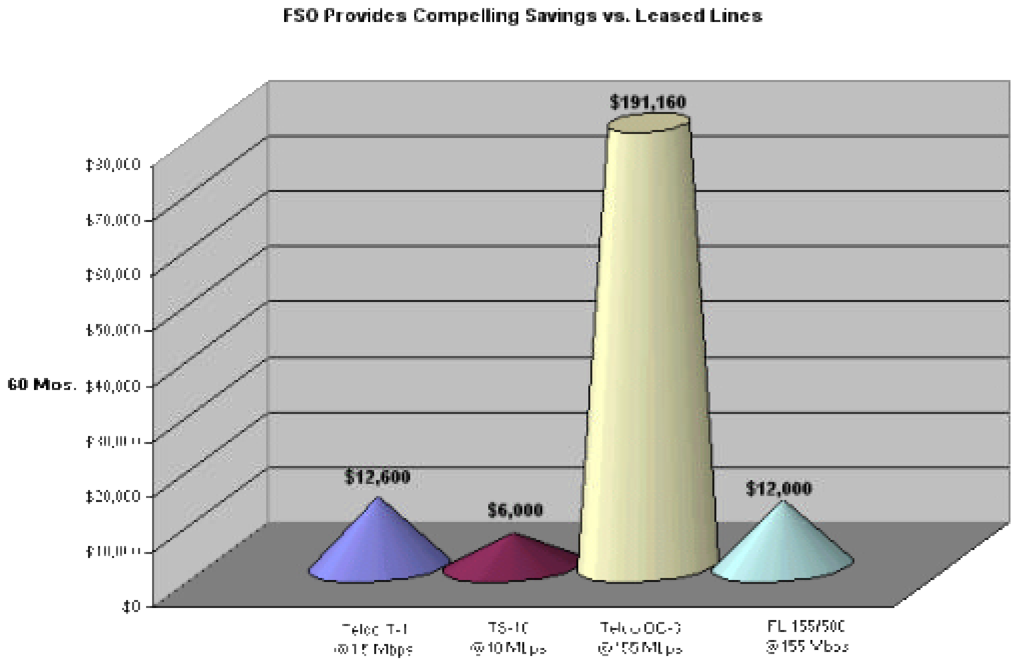


Figure 4.6 - Comparison Chart (FSO vs Leased Line). [From: 17]

The above chart (Figure 4.6) compares the 60 month cost of a Telco T-1 to the approximate installed cost of an Optical Access Model TS-10. At 10 Mbps the FSO solution delivers almost 7 times the throughput for half the cost. It also compares the 60 month cost of a Telco OC-3 to the approximate installed cost of a LightPointe Model FL 155/500. At equal throughput (OC3, or 3-DS3's), the FSO solution is less than 1/16th the cost.

Another valid comparison of costs is to break the information in the above chart down into cost per Mbps per month.

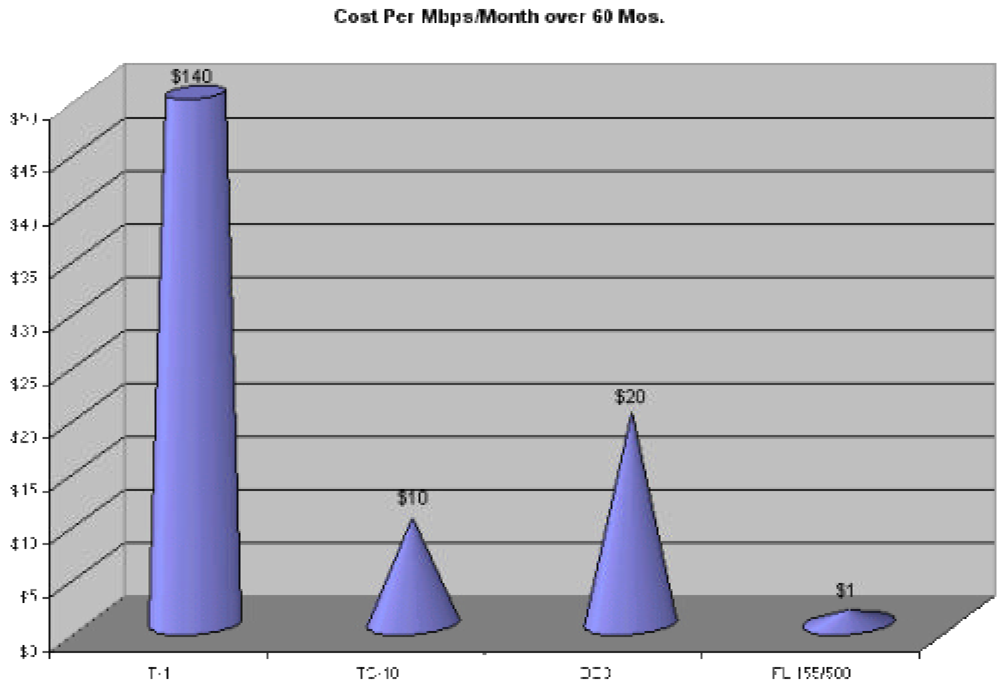


Figure 4.7 - Comparison Chart (Cost per Mbps/Month). [From: 17]

The above chart (Figure 4.7) assumes a 60 month write-off of FSO equipment. It shows that the 10 Mbps TS-10 provides its throughput for 7% of lease line cost, and the 155 Mbps FL 155/500 for 6% of lease line cost.

For comparison purposes, the following table (Table 3) shows the approximate FSO link costs at various throughput rates. There are several factors that can increase and/or decrease costs such as distance, etc.

10 Mbps	$6k-$25k
25 Mbps	$8k-$30k
155 Mbps	$12k-$35k
622-1250 Mbps	$35k-$50k

Table 3. FSO Link Cost at Various Throughput Rates.

H. LIMITATIONS OF FREE SPACE OPTICS

For free-space optics, challenges to achieving this level of performance take the shape of environmental phenomena that vary widely from one micrometeorological area to another. Included here is scintillation, scattering, beam spread, and beam wanders.

Scintillation is best defined as the temporal and spatial variations in light intensity caused by atmospheric turbulence. Such turbulence is caused by wind and temperature gradients that create pockets of air with rapidly varying densities and therefore fast-changing indices of optical refraction. These air pockets act like prisms and lenses with time-varying properties. Their action is readily observed in the twinkling of stars in the night sky and the shimmering of the horizon on a hot day.

FSO communications systems deal with scintillation by sending the same information from several separate laser transmitters. These are mounted in the same housing, or link head, but separated from one another by distances of about 200 mm. It is unlikely that in traveling to the receiver, all the parallel beams will encounter the same pocket of turbulence since the scintillation pockets are usually quite small. Most probably, at least one of the beams will arrive at the target node with adequate strength to be properly received. This approach is called spatial diversity, because it exploits multiple regions of space. In addition, it is highly effective in overcoming any scintillation that may occur near windows. In conjunction with a design that uses multiple and spatially separated large-aperture receive lenses, this multi-beam approach is even more effective.

Dealing with fog, more formally known as Mie scattering, is largely a matter of boosting the transmitted power, although spatial diversity also helps to some extent. In areas with frequent heavy fogs, it is often necessary to choose 1550nm lasers because of the higher power permitted at that wavelength. Also, there seems to be some evidence that Mie scattering is slightly lower at 1550nm than at 850nm. However, this assumption has recently been challenged, with some studies implying that scattering is independent of the wavelength under heavy fog conditions. Nevertheless, to ensure carrier-class availability for a single FSO link in most non-desert environments, the link length should be limited to 200-500 meters. Other atmospheric disturbances, like snow and especially rain, are less of a problem for free space optics than fog.

I. SUMMARY

FSO is discussed in this chapter and its benefits clearly position itself as one of the potential means for eliminating the last mile problem. In very near future, it is likely to make this technology cheaper and smaller in order to provide high bandwidth for individual homes and small offices, hence solving the last mile problem. The initial research shows that it might be difficult today to achieve a pure FSO link to each home in the last mile. The technology however, works well for buildings (with fiber optic cables already laid) to be connected to the central office. The implementation is likely to happen in major cities, but solutions and smaller devices would need to be made available at a low cost for this to be optimal in the true last mile. As this technology and its applications mature further, FSO will become a viable solution for serving individual homes and small businesses in the last mile.

V. IEEE 802.11 WIRELESS TECHNOLOGIES

A. OVERVIEW

The previous chapter discussed Free Space Optics, a wireless technology which could be a candidate for solving the last mile problem. This chapter discusses yet another wireless technology that could also be used for the last mile application: IEEE 802.11.

IEEE 802.11[16] is the general standard on which wireless local area networking (wireless LAN) exists today, and products that employ the technology support a broad range of uses for enterprises and home users. The standard discards the wires from a wired local area network, allowing the nodes in the local area network to have mobility. Presently, wireless networking is on the rise. From its humble beginning with a data rate of 1Mbps, it has increased to a rate of 54 Mbps at the present day. With its increasing high bandwidth capacity, wireless technology today is a strong competitor for high-speed Internet, particularly in the last mile application. It is often compared against wide band or even ultra-wideband. It is therefore reasonable to consider wireless networking as a potential solution for the last mile.

With the wireless standard operating in the license-free band, namely the Industrial, Scientific and Medical (ISM) and the Unlicensed National Information Infrastructure (UNII) frequency bands[17], the equipment makers are not bound by any federal regulations. This translates to lower cost in the equipment, as well as the services.

[16] A standard for wireless networking was developed, so as to allow different equipment and devices to interoperate. IEEE established the standard from the famous Ethernet, IEEE 802.3, naming it IEEE 802.11

[17] Referring to the 2.4 – 2.483 GHz and 5.2 GHz range, which are the standard frequency ranges for wireless LAN.

Studies have shown wireless Internet is the next big wave for future high-speed data services[18].

While it shall be discussed that wireless Internet access has several advantages such as mobility, roaming capability and flexibility in network management over comparable DSL, cable and satellite services, does that imply that wireless Internet access is a viable solution for delivering high-speed Internet access to the subscribers?

B. BRIEF HISTORY OF IEEE 802.11

IEEE 802.11 is an IEEE (Institute of Electrical and Electronics Engineering) standard for wireless networking by adding new physical and data-link layers to the ISO model to provide Ethernet over a radio frequency (RF). Though the concept started in the mid-1990s, the standard was only established in 1999.

Reference to the ISO's OSI model (shown in figure 5.1), the IEEE 802.11 standard is similar to the Ethernet IEEE 802.3, except that the physical and data layers are different.

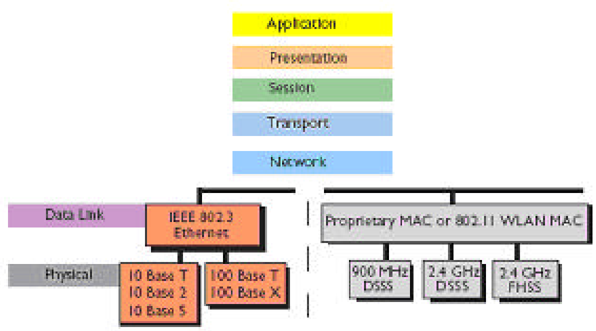


Figure 5.1 – Wired and wireless protocols in the ISO model. IEEE 802.11 uses a different physical and data-link layer. [18]

---

18 Why Go Wireless? – Michael R. Anderson, 802.11 Wireless LAN ISP -Planet 2001 [03]

Generally, the IEEE 802.11 standard employs the CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance) protocol at the Media Access Control (MAC)/data link layer and there are four radio techniques at the physical layer:

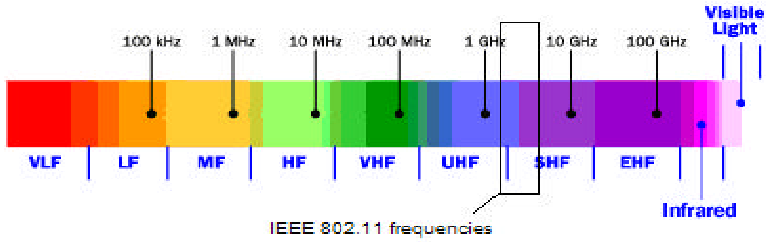
a. A direct sequence spread spectrum (DSSS) 2.4 GHz radio that uses complementary code keying (CCK) modulation;

b. A frequency hopping spread spectrum (FHSS) 2.4 GHz radio that also uses CCK;

c. An orthogonal frequency division multiplexing (OFDM) 2.4 GHz and 5 GHz radio;

d. An infra-red (IR) technique that is largely unused in networking.

To ensure a cooperative operation of the standard, the FCC specifies that IEEE 802.11 standard equipment will operate in the unlicensed frequency band called the instrument, scientific and medical (ISM) band that ranges from 2.4 to 2.4835 GHz and the Unlicensed National Information Infrastructure (UNII) 5.2 GHz. It is important to note that household equipment like the microwave ovens and some cordless telephones are also operating in the 2.4 GHz band, which means there is a potential interference problem. Figure 5.2 shows the radio frequency spectrum and the frequency characteristics.



a. The radio frequency spectrum.

Frequency Band	Frequency Range	Wavelength (meters)	Energy (eV)	Region	Propagation Models	Characteristics
ELF	< 3kHz	> 100 KM	$< 10^{-5}$	Radio	Surface Wave	Worldwide, military and submarine
VLF	3-30 kHz	100-10 KM			Ionosphere	Worldwide, military and navigation
LF	30-300 kHz	10 - 1 KM			Surface Wave	Stable signal, distance up to 1500 KM
MF	300kHz – 3MHz	1KM-100 Meters			Surface wave (Short)/Sky wave (Long)	Radio broadcasting. Long distance sky-wave signals subject to fading
HF	3-30 MHz	100 - 10 Meters			Sky wave but very limited	3-6 MHz continental, 6-30 MHz Intercontinental, Land and ship-to-shore comms
VHF	30-300 MHz	10 - 1 Meters		TV	Space Waves	Close to line of sight over short distances, Broadcasting and land mobile
UHF	300 MHz - 3 GHz	1Meter-1cm			Space Waves	Essentially line of sight over short distances, Broadcasting and land mobile
SHF	3-30 GHz	1cm - 100cm	10^{-5} - 0.01	Microwave	Space Waves	The "workhorse" microwave band. LOS. Terrestrial and satellite relay links
EHF	30-300 GHz	100cm - 1mm			Space Waves	Line of sight millimeter waves. Space to space links, military uses, and possible future uses
	300GHz - 430 NHz	1mm - 700 nm	0.01 - 2	Infrared		
	430-750 NHz	700-400 nm		Visible		
	750-3000 NHz	400 - 1 nm	3 - 10^{3}	Ultraviolet		
	3000 - $3x10^{19}$	10^{-9} - 10^{-11}	10^{3} - 10^{5}	X-Rays		
	> $3x10^{19}$	< 10^{-11}	> 10^{5}	Gamma Rays		
10^{-9} - Nano	10^{3} - Kilo	Wavelength = Speed of Light / Frequency in hertz (where speed of light = 3 X 10^{8} m/sec)				
10^{-6} - Micro	10^{6} - Mega					
10^{-3} - Milli	10^{9} - Giga					
10^{-2} - Centi	10^{12} - Nano					

[Derived from multiple sources]

b. Characteristics of the frequency spectrum.

Figure 5.2 – The radio frequency spectrum and the frequency characteristics. [From: 19]

The standard will allow unconnected (not physically connected using wires) client devices to communicate with an Ethernet network through a radio frequency (RF) transmitter that is physically connected to the wired network. As long as the client is within the transmitter's range, the client is connected (associated) to the network and hence, able to send and receive data.

The motivation of IEEE 802.11 is to allow mobility of network hosts in a network. Compared to a wired network, the hosts need not be fixed or specifically located at or near network ports. The hosts can be everywhere within the transmitter's range. Being mobile would incur flexibility in the network topology and hence making the network architecture less dependent of building structure. With IEEE 802.11, extending an existing network is easy. New network hosts can be added as long as the wireless network interface card (NIC) is able to pick up the signal from the access point.

C. THE WIRELESS STANDARDS

With the establishment of the IEEE 802.11, several different specifications were developed. As briefly described, the 802.11 works in different transmission technologies (i.e. IR, DSSS and FHSS), and hence, there is a need for a more precise standard. It leads to the introduction of IEEE 802.11b, which works only in the DSSS modes and it offers a throughput rate up to 11 Mbps. As the predominant standard currently, it is widely supported by vendors such as Cisco, Lucent, Apple, etc. Since then, more specifications were developed as technology mature, particularly IEEE 802.11a and IEEE 802.11g.

1. IEEE 802.11b

The IEEE 802.11b standard operates in the 2.4 GHz ISM band and utilizes Direct Sequence Spread Spectrum (DSSS). The standard delivers 11 Mbps of raw data at indoor distances from several dozen to several hundred feet and outdoor distances about 8 – 10 miles (assuming LOS)[19]. The distance depends on impediments, materials and line of sight. While there are 11 channels available for use, only three are completely non-overlapping. This may seem as a limitation in a large-scale deployment or applications where an all time 11 Mbps coverage requirement exists but with an in-depth understanding of channel spacing and separation, this hurdle can be overcome. In fact, the technology can lend itself to deliver up to an aggregated 33 Mbps within one coverage area[20]. IEEE 802.11b started to appear in commercial form in mid 1999, with Apple Computer's introduction of its AirPort components, manufactured in conjunction with Lucent's WaveLAN division[21].

Recent surveys have shown that functionality and robustness of products based on the IEEE 802.11b standard are more suitable to satisfy the majority of enterprise type applications in the areas of quick network establishment, easy network extension and network infrastructure changes, etc. Whether it be an infrastructure supplement, like building to building bridging or an application enabler within a CRM process, organizations large and small have all benefited from this wireless LAN standard.

2. IEEE 802.11a

The next wave of wireless products is based on the IEEE 802.11a standard. IEEE 802.11a uses same the MAC layer as 802.11b (including CSMA/CA). The main differences are that the 802.11a standard operates at a higher frequency band and uses a different encoding scheme. The standard operates at the 5 GHz UNII (Unlicensed National Information Infrastructure) band and the total bandwidth is broken into three "domains" for a total of 300 MHz as shown in Table 4.

---

[19] Broadband Access Platforms – Stagg Newman, McKinsey and Company, Apr 2002 [10]

[20] This uses 3 co-located access points. Note that this is the theoretical maximum aggregation due to 3 non-overlapping channels.

[21] The division changed its name to Orinoco and was spun off to the newly formed Agere Corporation with a variety of other Lucent assets in early 2001.

Frequency	Max Power Output Allowed
5.15 MHz - 5.25 MHz	50mW
5.25 MHz - 5.35 MHz	250mW
5.725 MHz - 5.825 MHz	1W (outdoor only)

Table 4. Frequencies and power output in the UNII 5.2 GHz.

Given the same radiated power and encoding scheme used in IEEE 802.11b, transmission in higher frequencies results in shorter reception distances, about 3 – 5 miles[22]. With the higher frequencies, the transmitted signal is more susceptible to multi-path fading. To counter this, 802.11a uses frequency division multiplexing instead of the spread spectrum encoding that 802.11b requires.

The encoding is done with "coded OFDM", which was developed specifically for indoor wireless use. COFDM breaks a single 20 MHz channel of a high-speed data carrier into 52 lower-speed sub-carriers. Each sub-channel is approx 300 KHz wide. These sub-channels are then transmitted in parallel. COFDM uses 48 of these sub-channels for data and the remaining four for error correction.

The 802.11a standard specifies that all vendor products must support 6Mbps, 12Mbps, and 24Mbps. Higher data rates are allowed, but not explicitly discussed in the standard. However, the de-facto vendor standard is turning out to be 54 Mbps.

The 54Mbps data rate is achieved by using 64QAM (64-level Quadrature Amplitude Modulation). This allows for up to 1.125Mbps per 300 KHz sub-channel. With 48 channels the result is a 54Mbps data rate.

[22] Broadband Access Platform – Stagg Newman, McKinsey and Company, Apr 2002 [10]

At lower speeds, binary phase shift keying (BPSK) is used to encode 125Kbps per sub-channel, resulting in 6Mbps. Using Quadrature Phase Shift Keying (QPSK), the data rate doubles to 12Mbps. Using 16-level Quadrature Amplitude Modulation (encoding 4 bits per hertz), yields 24Mbps.

Many proponents of this technology feel that, not only does it provide for greater scalability, it also operates in a much cleaner RF band with less interference than the 2.4 GHz band. However, there are still some issues to consider before worldwide adoption of this new standard. While the UNII band is relatively unpopulated in the United S tates, the same is not true in other parts of the world.

In Europe, the ETSI (European Telecommunications Standards Institute) is requiring DFS (Dynamic Frequency Selection) and TPC (Transmit Power Control) functionality before allowing unlicensed applications to use the 5 GHz band. These two protocols will allow a client to dynamically change channels and/or use lower power modulation if it sees interference, thus giving existing signals on the band first priority.

In Japan, only the lower 100 MHz of the FCC's UNII band is available. This means that users in Japan will only have 5 channels to choose from instead of the 10 that will be available in the United States and Europe[23].

3. IEEE 802.11g

The latest wireless LAN standard to be ratified is the IEEE 802.11g standard, which also operates within the 2.4GHz band, however utilizes an OFDM modulation scheme. This standard is for the most part a consolidation of the IEEE 802.11b and 802.11a standards.

[23] http://www.stanford.edu/group/networking/NetConsult/wireless/80211a.html [20]

IEEE 802.11g is an extension to IEEE 802.11b, the basis of the majority of wireless LANs in existence today. Because of backward compatibility, an IEEE 802.11b radio card will interface directly with an IEEE 802.11g access point (and vice versa) at 11 Mbps or lower depending on range.

Similar to the IEEE 802.11b, IEEE 802.11g operates in the 2.4 GHz band, and the transmitted signal uses approximately 30 MHz, which is one third of the band. This limits the number of non-overlapping IEEE 802.11g access points to three, which is the same as IEEE 802.11b.

A big issue with IEEE 802.11g, which also applies to IEEE 802.11b, is considerable RF interference from other 2.4 GHz devices, such as the newer cordless phones. This is due to the fact that the 2.4 GHz ISM band is already used by many devices. A summary of the above standards is shown in Table 5.

	IEEE 802.11b	IEEE 802.11g	IEEE 802.11a
Time Table	Standard in 1997, Products in 2000	Standard in 2001, products in 2002	Standard in 2001, products in 2002
Frequency Band and bandwidth	Transmit at 2.4 GHz	2.4 GHz	5 GHz
Speed	11 Mbps (Effective speed - half of rated speed)	22 Mbps (Effective speed – half of rated speed)	54 Mbps (Effective speed - 50% rated speed)
Modulation Technique	Spread Spectrum (Direct Sequence Spread Spectrum)	OFDM (Orthogonal Frequenc y Division Multiplexing)	OFDM (Orthogonal Frequency Division Multiplexing)
Max Distance Coverage	8-10 miles[24]	8-10 miles	3-5 miles
Number of access points required	Every 200 feet in each direction	Every 200 feet in each direction	Every 50 feet;
Maturity	More matured products	Less matured but progressing fast	Less matured but progressing fast
Market Penetration	Quite widespread	Just starting in 2002	Just starting in 2002
Interference with other devices	Band is more polluted - significant interference here	Band is more polluted – significant interference	Less interference because of few devices in this band
Interoperability	Current problems expected to be resolved in future	Current problems expected to be resolved in near future	Problems now but expect resolution soon
Cost	Cheaper - $100 for access point and $75 for adapter	No available in press time	More expensive - $350 for access point and $200 for adapter

Table 5. Summary of the IEEE 802.11 wireless standards.

Over an above the physical standards, ther e are a number of sub-committees of the IEEE working on functionality such as Quality of Service (QoS), Security, Mobility, and European/Global approvals. It should be noted that most of these advancements will be backward compatible with the current insta ll base of wireless products.

[24] Broadband Access Platform – Stagg Newman, McKinsey and Company, Apr 2002 [10]

D. HOW DOES IT WORK

Wireless LAN configurations vary from simple, independent, peer-to-peer connections between a set of PCs, to more complex, intra-building infrastructure networks. There are also point-to-point and point-to-multipoint wireless solutions. A point-to-point solution is used to bridge between two local area networks, and to provide an alternative to cable between two geographically distant locations (up to 30 miles). Point-to-multipoint solutions connect several, separate locations to one single location or building. In a typical wireless LAN infrastructure configuration, there are two basic components:

a. Access Point. An access point or base station connects to a LAN by means of Ethernet cable or RJ-11 (standard twisted pair port). Usually installed in the ceiling, access points receive, buffer, and transmit data between the wireless LAN and the wired network infrastructure. A single access point supports on average twenty users and has a coverage varying from 20 meters in areas with obstacles (walls, stairways, elevators) and up to 100 meters in areas with clear line of sight[25]. A building may require several access points to provide complete coverage and allow users to roam seamlessly between access points. The access point can essentially be mounted anywhere that is practical as long as the desired radio coverage is obtained. The coverage concept is similar to that of a cell coverage (that is used in the mobile phone technology).

b. Wireless Client Adapter. A wireless adapter connects users via an access point to the rest of the LAN. A wireless adapter can be a PC card in a laptop, an ISA or PCI adapter in a desktop computer, or can be fully integrated within a handheld device. The adapters provide an interface between the client network operating system

[25] Distance quoted is based on built-in antennas. With custom antenna, e.g. yagi antenna, the distance can reach a couple of miles in outdoor with clear LOS.

(NOS) and the airwaves (via an antenna). The nature of the wireless connection is transparent to the NOS.

With understandings of the basic components, the basic wireless LAN architecture is as shown in figure 5.3.

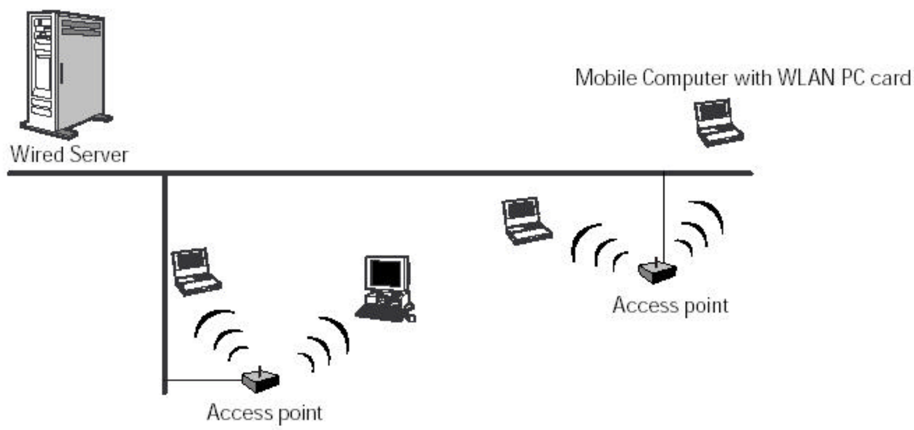


Figure 5.3 – Typical Wireless LAN Configuration. [21]

Wireless LAN uses electromagnetic airwaves (radio and IR) to communicate information from one point to another without relying on any physical connection. Radio waves are often referred to as radio carriers because they simply perform the function of delivering energy to a remote receiver. The data being transmitted is superimposed on the radio carrier so that it can be accurately extracted at the receiving end. This is generally referred to as modulation of the carrier by the information being transmitted. Once data is superimposed (modulated) onto the radio carrier, the radio signal occupies more than a single frequency, since the frequency or bit rate of modulating information adds to the carrier.

Multiple radio carriers can exist in a same space at the same time without inferring with each other if the radio waves are transmitted on different radio frequencies.

To extract data, a radio receiver tunes in (or selects) one radio frequency while rejecting all other radio signals on different frequencies.

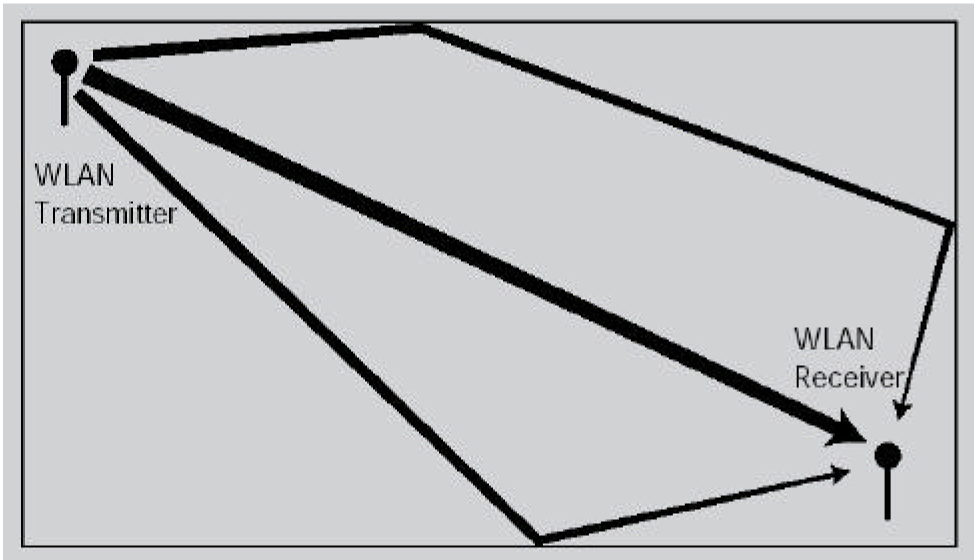


Figure 5.4 – Radio signals traveling over different paths. [From: 22]

Each radio carrier signal can travel from the transmitter to the receiver in many paths, especially when there are buildings, walls, trees, etc. Figure 5.4 illustrates the many paths that can be taken by the same radio signal, resulting in different arriving time at the receiver. The time difference can be crucial as it will cause a phase shift in each of the arrived signal. This phenomenon is known as the multi-path effect. If a signal arrived in phase at the receiver together with another signal (having taken another path) that arrived out of phase at the receiver, the signal will be cancelled, resulting in total signal loss[26]. OFDM is used to combat this multi-fading effect, hence enhancing the signals' transmission and reducing the bit error rate. OFDM will be discussed in greater details in the later sections.

26 Note that a total signal loss will occur if both signals are of the same amplitude (power). If one signal is stronger than the other, the result is just a weaker signal.

E. WIRELESS LAN CONFIGURATIONS

Having gone through the basics of a wireless LAN system and understanding the way radio waves travel, this section discuss the various configurations of the wireless LAN.

1. Independent Wireless LANs

The simplest wireless LAN configuration is an independent (or peer-to-peer) wireless LAN that connects a set of PCs with wireless adapters. Any time two or more wireless adapters are within range of each other, they can set up an independent network. These on demand networks typically require no administration or pre-configuration.

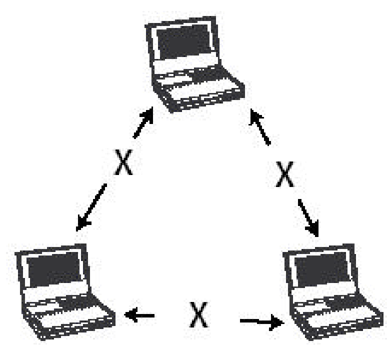


Figure 5.5 – Independent Wireless LAN Configuration. [From: 21]

By introducing an access point to the independent network, the access point literally acts as a repeater, effectively doubling the distance between wireless PCs.

2. Infrastructure Wireless LANs

In the infrastructure wireless LANs, multiple access points link the wireless LAN to a wired network and allow users to efficiently share network resources. The access points not only provide communication with the wired network but also mediate wireles s network traffic in the immediate neighborhood. Multiple access points can provide wireless coverage for an entire building or campus.

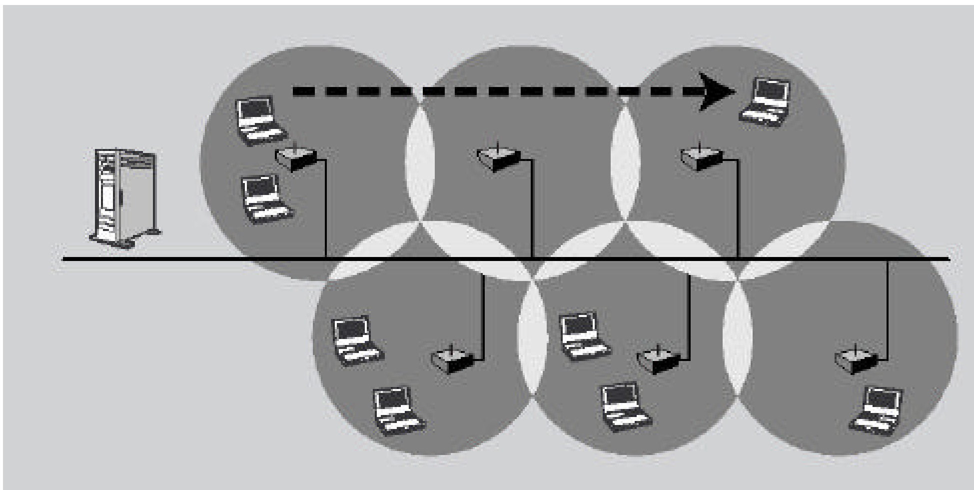


Figure 5.6 – Infrastructure Wireless LAN Configuration. [From: 21]

3. Microcells and Roaming

Wireless communication is limited by how far signals carry for the given power output. Wireless LAN uses cells, called microcells, which is similar to the cellular telephone system to extend the range of wireless connectivity. At any point in time, a mobile PC equipped with a w ireless LAN adapter is associated with a single access point and its microcells, or area of coverage. Individual microcells overlap to allow continuous communication within the wired network, as illustrated in the figure below. The microcells handle low power signals and 'hand off' users as they roam through a given geographic area.

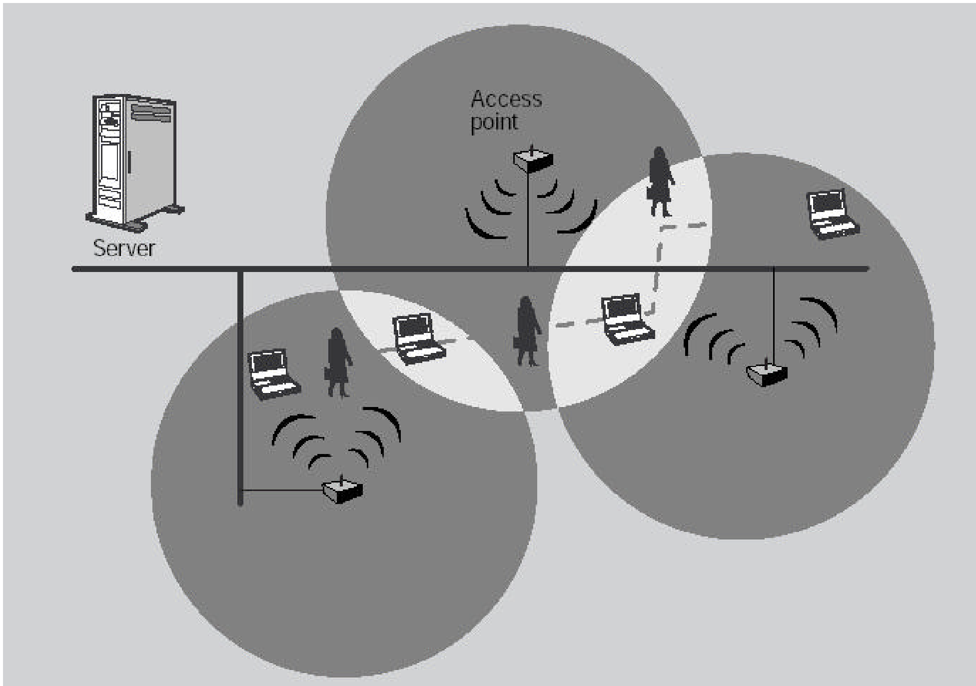


Figure 5.7 – Handing off between Access Points. [From: 21]

F. WIRELESS LAN TECHNOLOGY OPTIONS

Manufacturers of wireless LAN have a range of technologies to choose from when designing a wireless LAN solution. Each technology comes with its own set of advantages and limitations.

Most wireless LAN system use spread spectrum technology, which is a wideband radio frequency technique originally developed by the military for use in reliable, secure, mission-critical communication systems. Spread spectrum is designed to trade off bandwidth efficiency for reliability, integrity and security. In other words, more bandwidth is consumed than in the case of a narrowband transmission, but the tradeoff produces a signal that, in effect, louder and thus easier to detect, provided that the receiver knows the parameters of the spread spectrum signal being broadcasted. If a receiver is not tuned to the right frequency, a spread spectrum signal looks like background noise. When observed via an oscilloscope, the signal is of no difference with the white noise. By using a wider frequency spectrum, the probability that the data be corrupted or jammed is significantly reduced. Any narrowband jamming will thus affect only a small part of the information falling into the narrowband signal's frequency. The peak power of a spread spectrum signal is also low, hence, making spread spectrum a good choice for wireless technology transmission. There are two types of spread spectrum radio, namely frequency hopping and direct sequence.

1. Frequency Hopping Spread Spectrum

Frequency hopping spread spectrum (FHSS) uses a narrowband carrier that changes frequency in a pattern known to both transmitter and receiver. Properly synchronized, the net effect is to maintain a single logical channel. To an unintended receiver, FHSS appears to be short duration impulse noise.

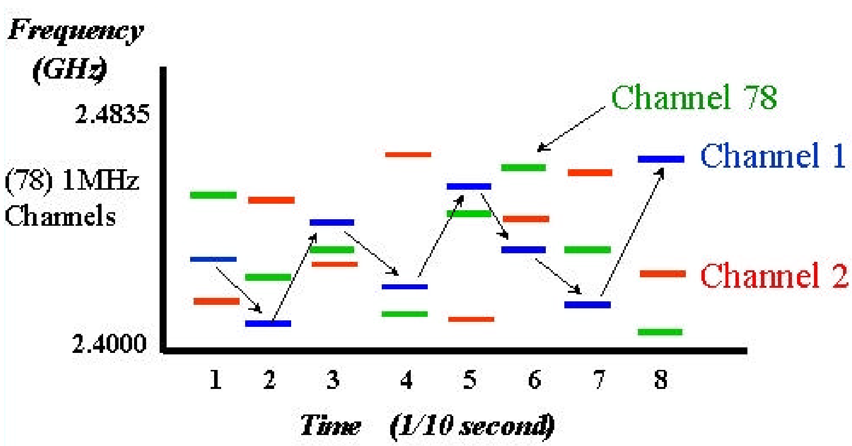


Figure 5.8 – Frequency Hopping Spread Spectrum. [From: 23]

Figure 5.8 shows the working concept of a frequency hopping spread spectrum system. The carrier frequency hops at every time interval based on a synchronized code that is shared by all the intended radios. The code is a list of several frequencies which the carrier will hop at specified time intervals before repeating the sequence. The transmitter uses this hop sequence to select its transmission frequencies. The carrier will remain at a certain frequency for a specified time (known as the dwell time), and then use a small amount of time to hop to the next frequency (hop time). When the list of frequencies has been exhausted, the transmitter will repeat the sequence.

The IEEE 802.11 standard specifies data rates of 1 Mbps and 2 Mbps. In order for a frequency hopping system to be 802.11 compliant, it must operate in the 2.4 GHz ISM band (which is defined by the FCC as being from 2.4 GHz to 2.4835 GHz). Based on the ISM band of 2.4 GHz, the spread of frequency for FHSS is 83.5 MHz and thus, allowing a theoretical maximum of 79 channels.

2. Direct Sequence Spread Spectrum

Direct sequence spread spectrum (DSSS) is very widely known and the most used of the spread spectrum types, owing most of its popularity to its ease of implementation and high data rates. The majority of wireless LAN equipment on the market today uses DSSS technology. DSSS is a method of sending data in which the transmitting and receiving systems are both on a 22 MHz-wide set of frequencies. The wide channel enables devices to transmit more information at a higher data rate than the FHSS systems.

DSSS generates a redundant bit pattern for each bit to be transmitted. This bit pattern is called a chip (or chipping code or processing gain [27]). The longer the chip, the greater the probability that the original data can be recovered (of course, the more

[27] The IEEE 802.11 working group has set their minimum processing gain requirements at 11.

bandwidth required) and the signal's resistance to interference also increases. Even if one or more bits in the chip are damaged during transmission, statistical techniques embedded in the radio can recover the original data without the need for re-transmission. To the unintended receiver, DSSS appears as low-power wideband noise and is rejected (ignored) by most narrowband receivers. Figure 5.9 shows the working concept of a DSSS system.

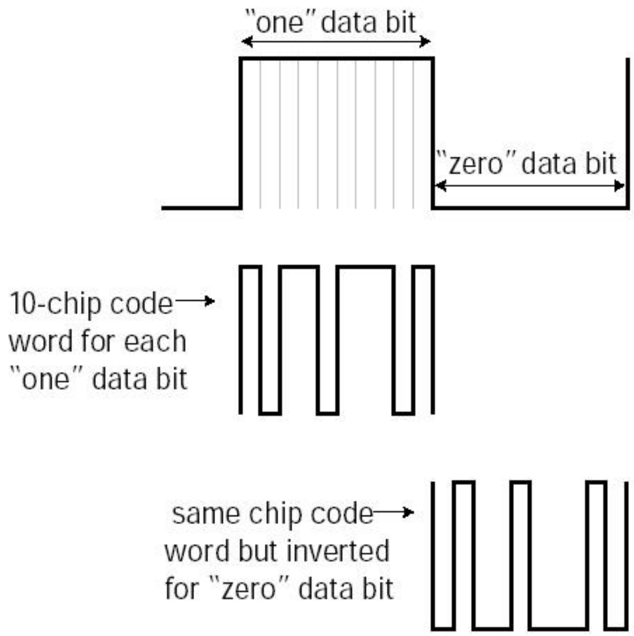


Figure 5.9 – Direct Sequence Spread Spectrum. [From: 23]

In the 2.4 GHz ISM band, the IEEE specifies the use of DSSS at a data rate of 1 or 2 Mbps under the 802.11 standard. Under the 802.11b standard, data rates of 5.5 and 11 Mbps are specified. Equipment of the latter standard are able to communicate with the former as the standard provides for backward compatibility. Users employing 802.11 devices do not need to upgrade their entire wireless LAN in order to use 802.11b devices.

A recent addition of the list of devices using DSSS technology is the IEEE 802.11a standard, which specifies units that can operate up to 54 Mbps. This standard is not backward compatible because it does not use the 2.4 GHz band, but instead uses the 5 GHz UNII band. The 802.11g standard also offers data rate up to 54 Mbps but it has backward compatibility as it works on the same frequency band as the 802.11 and 802.11b.

Unlike frequency hopping systems that use hop sequences to define the channels, DSSS use a more conventional definition of channels. Each channel is a contiguous band of frequencies 22 MHz wide and 1 MHz carrier frequencies are used, similar to the FHSS.

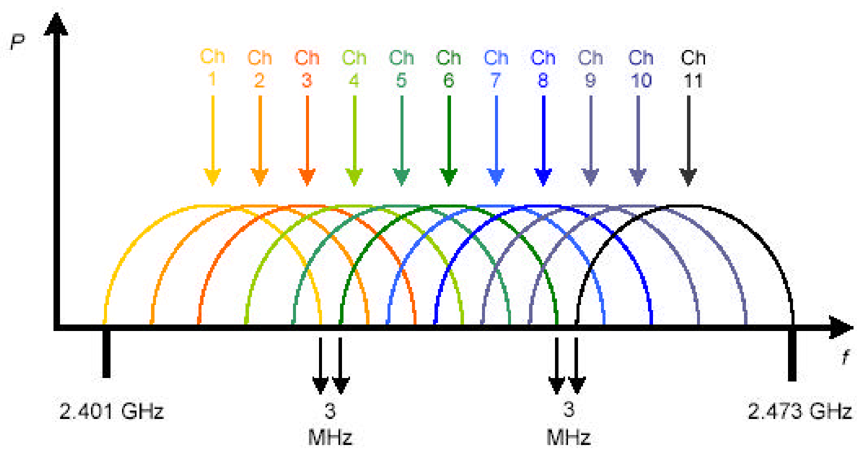


Figure 5.10 – Channels allocation and Spectral relationship of the DSSS system. [From: 23]

Figure 5.10 shows a complete list of channels used in the US and Europe. The FCC specifies only 11 channels and there are significant overlaps. This implies that DSSS systems with overlapping channels should not be co-located because there will almost always be a drastic or complete reduction in throughput. Because the center frequencies are 5 MHz apart and the channels are 22 MHz wide, channels should be co-located only if the channel numbers are at least 5 apart: Channels 1, 6 and 11 are the only theoretically non-overlapping channels.

3. Orthogonal Frequency Division Multiplexing

Typically, OFDM, a spread-spectrum technology that gives wireless networking a new physical layer, is implemented in embedded chipsets made up of radio transceivers, Fast Fourier Transform (FFT) processors, system input/output (I/O), serial to parallel and back again translators and OFDM logic.

In practice, the OFDM chipset bundles data over narrowband carriers transmitted in parallel at different frequencies. High bandwidth is achieved by using these parall el sub-channels (aka sub-carriers) that areas closely spaced as possible in frequency without overlapping/interfering[28]. By being orthogonal, they have no overlap, and thus do not interfere at all with each other. Orthogonal means that they are perpendicula r, but in a mathematical, rather than a spatial, sense. As shown in figure 5.11, OFDM allows the spectrum of each tone to overlap, and because they are orthogonal, they do not interfere with each other. By allowing the tones to overlap, the overall amount of spectrum required is reduced.

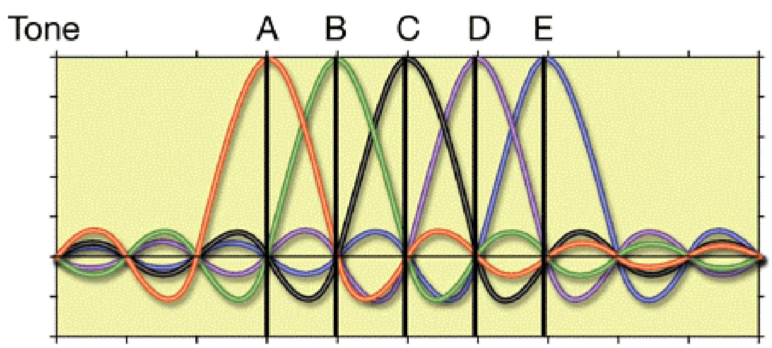


Figure 5.11 – OFDM overlapping tones. [From: 24]

[28] R. W. Chang, "Orthogonal Frequency Division Multiplexing Data Transmission System", U.S. Patent 3,488,445, filed Nov 14, 1966, issued Jan 6, 1970 [25]

This differs from the traditional analog modulation by transmitting a digital signal that is determined; by the use of the Fast Fourier Transform (FFT) algorithm. It can be better because it allows precise control of all those multiple simultaneous frequencies (carriers) used to simultaneously carry many data bits in paralle l on different frequencies. With the use of the FFT on both transmitter and receiver, an OFDM system, naturally and efficiently spaces the frequencies such that they are as close together as is possible and yet are orthogonal, hence, resulting in maximum bandwidth with no interference between sub-channels.

In addition, to getting even better performance, OFDM deployments typically protect against inter-symbol interference (ISI) by using a redundant symbol extension, the guard interval. Typically, ISI comes from multi-path delays. This is the result of receiving not one, but several copies of the signal, due to multiple reflections (i.e., multipath) of the transmitted signal. Since the reflections travel a longer distance to get to the receiver antenna, they are delayed, hence resulting in multipath delay spread. The simple guard interval performs error correction from multipath distortion without requiring complex error correction.

Though, OFDM defeats multipath distortion, the transmission technique combats it by transmitting bits in parallel, with each bit being transmitted rather slowly. For e.g. to transmit 1,000,000 bits per second; the bits could be transmitted one at a time, each taking one microsecond to send. Any delay spread longer than one microsecond would cause delayed reflections from multipath to overlap the direct signal for the next bit, thus causing ISI. If instead 1000 bits are transmitted in parallel at a time on 1000 separate OFDM sub-channels, the transmission will take 1000 times slower ; i.e. one millisecond to send them. A multipath delay spread of 1 microsecond would only overlap 1/1000th of the transmission interval for any given bit, thus causing any significant interference[29].

[29] Orthogonal Frequency Division Multiplexing Signal Generation – PJ Lee, University of Bath, UK, 1998 [24]

G. SECURITY IN WIRELESS LAN

Wireless LANs are not inherently secure; however, if no precautions or configurations for defenses are taken with wired LAN, they are not secure either. The security solution used in wireless LAN is known as Wired Equivalency Protocol (WEP) as specified by IEEE 802.11.

Wired Equivalent Privacy (WEP) is an encryption algorithm used by the Shared Key authentication process for authenticating users and for encrypting data payloads over only the wireless segment of the LAN.

WEP is a simple algorithm that utilizes a pseudorandom number generator (PRNG) and the RC4 stream cipher. The RC4 stream cipher is fast to decrypt and encrypt which saves on CPU cycles, and is also simple enough for most software developers to code it into software.

When WEP is referred to as being simple, it means that it is weak. The RC4 algorithm was inappropriately implemented in WEP, yielding a less-than-adequate security solution for 802.11 networks. Both 64-bit and 128-bit WEP (the two available types) have the same weak implementation of a 24-bit Initialization Vector (IV) and use the same flawed process of encryption. The flawed process is that most implementation of WEP initializes hardware using an IV of 0 – thereafter incrementing the IV by 1 for each packet sent. For a busy network, statistical analysis shows that all possible IVs (2^{24}) would be exhausted in half a day, meaning that IV would be re-initialized starting at zero at least once a day. This scenario creates an open door for determined hackers. When WEP is used, the IV is transmitted in the clear with each encrypted packet.

All is not lost with the known weakness as new strengthen security solutions are sought to replace WEP for 802.11 standards. New security standard like 802.1x with EAP is already in consideration to be taken as the security solution for IEEE 802.11.

The 802.1x standard provides specifications for port-based network access control and has been incorporated into many wireless LAN systems, has become almost a standard practice among many vendors. With combined with extensible authentication protocol (EAP), 802.1x can provide a very secure and flexible environment based on various authentication schemes. EAP, which was first defined for the point-to-point protocol (PPP), is a protocol for negotiating an authentication method. EAP is defined in RFC 2284 and defines the characteristics of the authentication method including the required user credentials (password, certificate, etc), the protocol to be used, support of key generation and support of mutual authentication.

More information about IEEE 802.1x with EAP and other security solutions for wireless LAN such as AES Based solutions, Temporal Key Integrity Protocol (TKIP) are discussed in the Certified Wireless Network Administrator official study guide[30].

H. CONSIDERATIONS FOR WIRELESS NETWORKING

Compared with wired LANs, wireless LANs provide installation and configuration flexibility and the freedom inherent in the network mobility. The following issues should be considered when implementing a wireless network.

a. Range and Coverage. The distance over which the RF waves can communicate is a function of product design (including transmitted power and receiver design) and the propagation path, especially in indoor environment. Interactions with typical building objects, including walls, metal and even people can affect how energy

[30] Certified Wireless Network Administrator Official Study Guide –Planet3 Wireless [23]

propagates, and thus what range and coverage a particular system achieves. Most wireless LAN system uses RF because radio waves can penetrate many indoor walls and surfaces. The range or radius of coverage for a typical wireless LAN system varies from under 100 feet to more than 500 feet. Coverage can be extended, and true freedom of mobility via roaming, provided through microcells can be achieved.

b. Throughput. As with wired LAN systems, actual throughput in wireless LANs is dependent on product and equipment/device set-up. Factors that affect throughput include airwaves congestion (number of users), propagation factors such as range and multipath, the type of wireless LAN system uses and the latency and bottlenecks on the wired portions of the wireless LAN. Typical data rates range from 1 to 11 Mbps. With the introduction of IEEE 802.11g and 802.11a, data rates are extended to 54 Mbps. Users of traditional Ethernet LANs generally experience little difference in performance when using a wireless LAN and can expect similar latency behavior. Wireless LANs provide throughout sufficient for the most common LAN-based office applications, including electronic mail exchange, access to shared peripherals, and access to multi-user databases and applications. With the extended data rates, more bandwidth-intense applications could also go on the wireless means.

c. Integrity and Reliability. Wireless data technologies have been proven through more than fifty years of wireless application in both commercial and military systems. While radio interference can cause degradation in throughput, such interference is rare in the workplace. Robust designs of proven wireless LAN technology and the limited distance over which signals travel in connections that are far more robust than cellular phone connections and provide data integrity performance equal to or better than wired networking.

d. Interoperability with Wired Infrastructure. Most wireless LAN systems provide industry-standard interconnection with wired systems, including

Ethernet (IEEE 802.3) and the Token Ring (IEEE 802.5). Standard-based interoperability makes the wireless portions of a network completely transparent to the rest of the network. Wireless LAN nodes are supported by network operating systems in the same way as any other LAN node drivers. Once installed, the NOS treats wireless nodes like any other component of the network.

e. Interoperability with Wireless Infrastructure. There are several types of interoperability that are possible between wireless LANs. This will depend both on technology choice and on the specific vendor's implementation. Products from different vendors employing the same technology and the same implementation typically allow for the interchange of adapters and access points. The goal of industry standards, such as the IEEE 802.11 specifications is to allow compliant products to interoperate without explicit collaboration between vendors.

f. Interference and Coexistence. The unlicensed nature of radio-based wireless LANs means that other products that transmit energy in the same frequency spectrum can potentially provide some measure of interference to a WLAN system. Microwave ovens are a potential concern, but most WLAN manufacturers design their products to account for microwave interference. Another concern is the co-location of multiple WLAN systems. While co-located WLANs from different vendors may interfere with each other, others co-exist without interference.

g. Simplicity and Ease of Use. Users need very little new information to take advantage of wireless LANs. This is because the wireless nature of a WLAN is transparent to a user's Network Operating System (NOS), applications work the same as they do on the wired LANs. WLAN products incorporate a variety of diagnostic tools to address issues associated with the wireless elements of the system; however, products are designed so that most uses rarely need them. WLAN simplifies many of the installation and configuration issues that plague network managers. Since only the access points of

WLANs require cabling, network managers are freed from pulling cables for WLAN end users. Lack of cabling also make moves, adds and changes trivial operations on WLANs. Finally, the portable nature of WLANs lets network managers pre-configure and troubleshoot entire networks before installing them at remote locations. Once configured, WLANs can be moved from place to place with little or no modifications.

h. Security. Because wireless technology has roots in military applications, security has long been a design criterion for wireless devices. Security provisions are typically built into wireless LANs as in the transmission techniques of using FHSS and DSSS. While the new security solution is yet to be formalized by IEEE, it is certain the chosen solution would be much stronger than WEP but in general, individual nodes must be security-enabled before they are allowed to participate in network traffic.

i. Cost. A wireless LAN implementation includes both infrastructure costs, for the wireless access points, and user costs, for the wireless LAN adapters. Infrastructure costs depend primarily on the number of access points deployed. Access points range in the price from $800 to $2000. The number of access points typically depends on the required coverage region and the number and type of users to be serviced. The coverage area is proportional to the square of the product range. Wireless LAN adapters are required for standard computer platforms, and range in price from $100 to $500. The cost of installing the maintaining a wireless LAN generally is lower than the cost of installing and maintaining a traditional wired LAN, for two reasons. First, a wireless LAN eliminates the direct costs of cabling and the labor associated with installing and repairing it. Second, because wireless LANs simplify moves, adds and changes, it greatly reduces the indirect costs of user downtime and administrative overhead.

j. Scalability. Wireless networks can be designed to be extremely simple or quite complex. Wireless networks can support large number of nodes and large physical areas by adding access points to boost or extend coverage.

k. Battery Life for Mobile Platform. End user wireless products are capable of being completed unethered and run off the battery power form their host notebook or handheld computer. Wireless LAN vendors typically employ special design techniques to maximize the host computer's energy usage and battery life.

l. Safety. The output power of wireless LAN systems is very low, much less than that of a handheld cellular phone. Since radio waves fade rapidly over distance, very little exposure to RF energy is provided to those in the area of a wireless LAN system. Wireless LAN must meet stringent government[31] and industry regulations for safety. No adverse health effects have ever been attributed to wireless LANs.

I. SUMMARY

This chapter discussed the IEEE 802.11 wireless technologies and its standards. It is observed that with the flexibility and mobility features of IEEE 802.11, the LANs can be effectively extended and can offer many attractive alternatives to wired networks. There is no longer a physical constraint of the wire in setting up a network. IEEE 802.11 configurations include independent networks, suitable for small or temporary peer-to-peer configurations and infrastructure networks, offering fully distributed data connectivity via microcells and roaming. In addition, wireless LANs enables portable networks, allowing LANs to move with the knowledge workers that need them.

With the understanding of the wireless technology, there is a possibility that the concept of wireless networking be applied to the last mile problem. Relatively, each

[31] Rules set by the FCC and the IEEE.

home and office is deemed as a PC that needs to be connected to each other and be connected to the service provider (i.e. the access point). Of the discussed wireless standards, it is observed that 802.11g could be the likely candidate for last mile implementation due to its offered data rate and coverage distance.

THIS PAGE INTENTIONALLY LEFT BLANK

VI. PROPOSED SOLUTIONS FOR THE LAST MILE

A. OVERVIEW

Chapter II discussed the problem of the last mile, in terms of Internet access. The technologies that are currently offered and us ed for Internet access as discussed in Chapter III, are studied and reviewed. Through reviewing the access methods, it is clear that the last mile problem is still not solved. Though there are ways to obtain constant high-speed Internet access at gigabit per second, the monthly fees would prevent users from having them. Subsequent chapters discuss technologies that could be used for high-speed data transfer, at a lower price. Free Space Optics (FSO) and 802.11 (wireless technology) are fresh technologies in the market, offering potential solutions for the last mile problem.

While it may not be economical to have fiber optical cables laid to every individual house and office around the world (even though the access speed is the desired speed), having to live with the current copper wires for 56 Kbps dial-up access is also not a viable option. Even xDSL, cable modem and Direct Broadcast Satellites (DBS) have limitations.

This chapter will discuss and compare two technologies: Free Space Optics and IEEE 802.11, on how they may be used to provide high-speed access to the Internet at a cheaper price that is both economical for the service provider as well as the users. The services that are provided by a generic high-speed network and all of the decision factors will remain constant for all three options. In order to compare the three options, a generic template was created for the network. Though there are unique circumstances in various part of the world, the underlying assumptions need to be made in order to c reate a basis on which these comparisons can be made.

B. APPROACH FOR COMPARISON ANALYSIS

The general approach towards making the comparison is done by first defining a city where the technologies discussed will be implemented. Once the city is defined, FSO and IEEE 802.11 technologies will each be considered for comparison.

A high-speed access network to last mile homes and businesses will package together many of the services provided by various vendors using various different transmission mediums, all charging fees for the use of their service. In some cases, these companies have monopolies in certain areas and the home user has no real alternatives to choose from. If a high-speed access network is provided to each and every home and business in the last mile, then the applications that can be developed are endless and the door can be opened wider to the free market. The following services will utilize this high-speed network and the current costs associated with them can therefore be eliminated or at least significantly reduced (assuming a cost to activate certain services through the Internet arises):

High Speed Internet

Television

Telephony

Long Distance Telephone (both voice and video)

Music and Movies on Demand

Image and Photo Sharing

Sports Broadcast

Banking and E-Commerce

Appliance software updates

Information based operation

Numerous other services possible

C. THE CITY DEFINED

It is important to diagram the hypothetical city to be used as a template so as to compare the options on a common bas is. The city will have a population of 1 million people[32]. It will consist of 500 neighborhoods, each containing about 400 users (both homes and businesses) for a total of 200,000 last mile end nodes. Each end node will require some type of home equipment based on the alternative being considered. The topology of the city is illustrated in figure 6.1 and will be round or oval shaped approximately 16 kilometers (km) in diameter. Each neighborhood will consist of two streets of 200 homes or businesses and each home lot will be about 25 m^2. There is a ring around the center of the city, similar to the fiber optic ring found in the U.S. cities today, with spokes emanating out from the ring to each of the 500 neighborhoods. The backbone ring around the center of the city will be 25 km in length and each spoke to the neighborhood will be an average of 2 km in length.

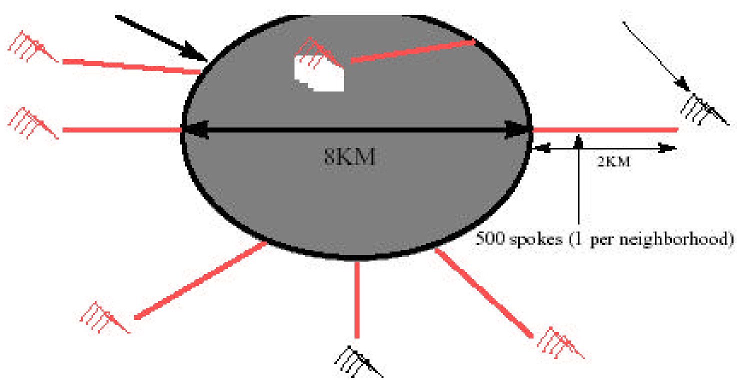


Figure 6.1 – Hypothetical City. [From: 26]

32 Lundy Bert, Business Plan for Telecommunication in Mexico, unpublished, 2001 [26]

The following summarizes all the options that will apply to all three alternatives:

a. City is comprised on one million people, with an average home size of five people, yields 200,000 homes.

b. City is round or slightly oval shaped, 16 km in diameter.

c. The entire network will be constructed from scratch, not utilizing any existing infrastructure. In addition, each home and business will have access to the high-speed network.

d. The center ring around the city is approximately 8 km in diameter by 4 km in height, so that the total ring around the city (8 km x 2 top and bottom plus 4 km x 2 for each side) is 24 km. This will be rounded up to 25 km for the center ring.

e. There will be spokes from the center ring to each neighborhood with an average length of 2 km per spoke. Each neighborhood has 400 homes or business and there are exactly 500 neighborhoods, yielding a total of 200,000 homes and businesses.

f. Each home will require some type of equipment based on the access technology implemented.

Table 6 summarizes the assumptions that will apply to all three access technologies.

Population	One million people
Average Household	5 people
Total Homes/Businesses	200,000
Backbone center ring	25 km
Spokes	500 spokes
Neighborhood	500
Homes/Business per neighborhood	400

Table 6. Summary of the hypothetical city.

D. NETWORK DESIGN ALTERNATIVES

In this section, each implementation of access technology namely, FSO, IEEE 802.11 and FSO/IEEE 802.11 will be discussed. Other assumptions will be made for each option but the general assumptions made above will remain unchanged. The advantages and disadvantages of each option will be explored.

1. All FSO Option

Having seen the benefits of FSO and its quick deployable, expandable nature, FSO could be used entirely for the last mile. There are various alternatives available from many different vendors; however, for the purpose of this research, products from LightPointe[33] will be used. LightPointe's Flight Spectrum[34] works with a maximum data rate of 2.5 Gbps and a maximum distance of 4000 meters[35] will be used in the design implementation. LightPointe's Flight Spectrum will be used as the network nodes and be sufficiently installed to create a mesh network. Each node will have four Flight Spectrum link heads, each pointing to other link heads to create a mesh network. Each node will be

33 www.lightpointe.com [27]

34 Flight Spectrum Link Head [27]

35 Max distance but supporting only 1.5 Mbps

placed 500 meters apart and hence, the distance for each FSO link will similarly be 500 meters. The backbone ring comprises of fifty FSO nodes and each spoke comprises of four FSO nodes. This closeness allows high data rate and will enhance the transmission's effect from bad/poor weather in most areas of the world, such as scintillation, scattering and beam spread as discussed in Chapter IV.

For the homes and offices, the LightPointe's Flight Lite link head [36] will be used. Each Flight Lite link head can support up a maximum data rate of 155 Mbps and a maximum distance of 1000 meters. Though this link head is generally not meant for individual home and office user, it is the best available product in the market today that can be exploited for the end node implementation. This data rate is deemed more than sufficient for high-speed Internet access as the wired Ethernet currently supports up to 100 Mbps.

Figure 6.2 shows the graphical view of the all FSO option. The mesh topology allows temporary node-to-node link disruptions while maintaining the overall network operability and reliability as traffic is automatically re-routed through other operational links. New nodes could also be added by simply pointing the new FSO node to the existing network's edge node. This advantage allows instant addition of nodes and expansion of the network as demand increases.

[36] Flight Lite Link Head [27]

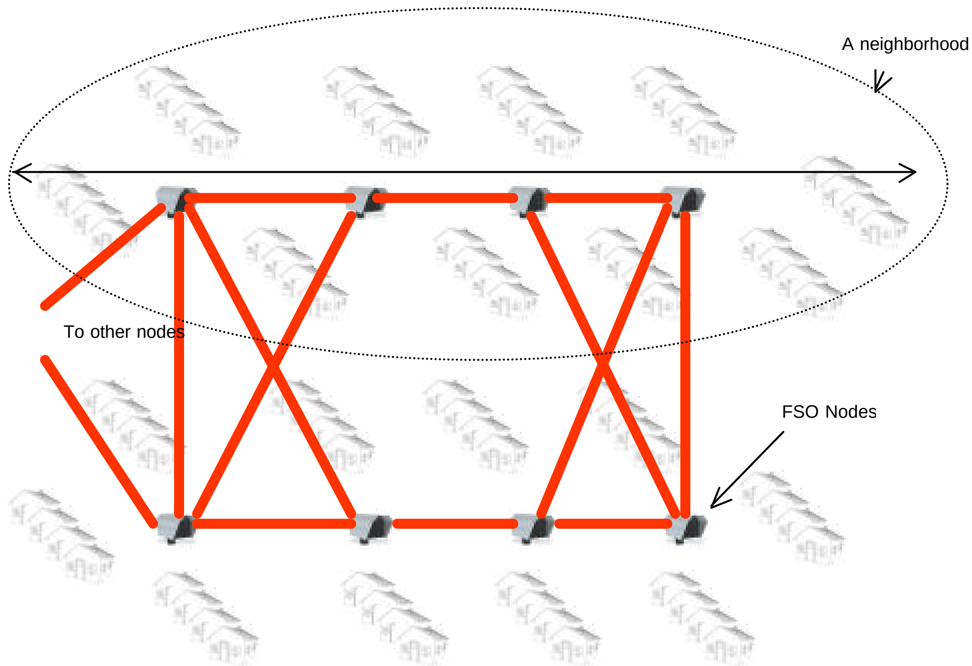


Figure 6.2 – All FSO graphical illustration.

In the case where business or office grows and experience organizational expansion such that the bandwidth required is higher than 155Mbps, either additional link heads are added or LightPointe's Flight Path link head can be used. The Flight Path link head currently supports a maximum data rate of 1.25 Gbps and a maximum distance of 600 meters. It is believed that as the technology matures, high bandwidth capability per node is possible without compromising the distance. At present, 2 Flight Lite link heads can be used to provide a cumulated bandwidth of 310 Mbps.

Currently, the vendor does not have any lower cost FSO link heads that also provides a lower bandwidth, which can be used particularly for the homes as it is unlikely that home usage requires higher than 100 Mbps (based on fast Ethernet technology). There is also no FSO product that has multi-beams that provide near omni-directional link orientation. If there such a product exists, it could be used in the network nodes, so as to reduce the number of link heads (as currently 4 link heads are used in each node). Therefore, the overall cost could still be high. The full detailed specifications of each LightPointe's equipment are attached in the appendix.

2. All Wireless Option

The option of using all wireless is using the concept that is similar to the cellular phone system. Access points will be co-located with the base stations to provide a complete coverage of the city. For the purpose of this design implementation, LinkSys [37] wireless system will be used. The LinkSys Wireless-G Access Point[38] which could provide a data rate of 54 Mbps operates on the IEEE 802.11g standard. The maximum outdoor distance covered as per specification is 350 m. Based on the hypothetical city, 8 access points are needed to provide a complete coverage for every home and office in a neighborhood. In addition, each house is deemed to have a lower end access point and each terminal in the house or office is to be equipped with the wireless network card. The LinkSys Wireless-G PC Card that operates on IEEE 802.11g standard offers a maximum data rate of 54 Mbps and a maximum outdoor coverage distance of 457 m. For extended distance up to more than 500 m, the yagi antenna is used in conjunction with the access point.

To provide a complete coverage for each neighborhood, a total of 8 access points are required and a total number of network cards needed are 400, assuming that there is an average of 1 computer per household or offices.

Figure 6.3 shows the graphical view of the implementation for a neighborhood. The mesh connectivity will provide the reliability and survivability of the network.

37 www.linksys.com

38 http://www.linksys.com/press/press.asp?prid=94&cyear=2002 [28]

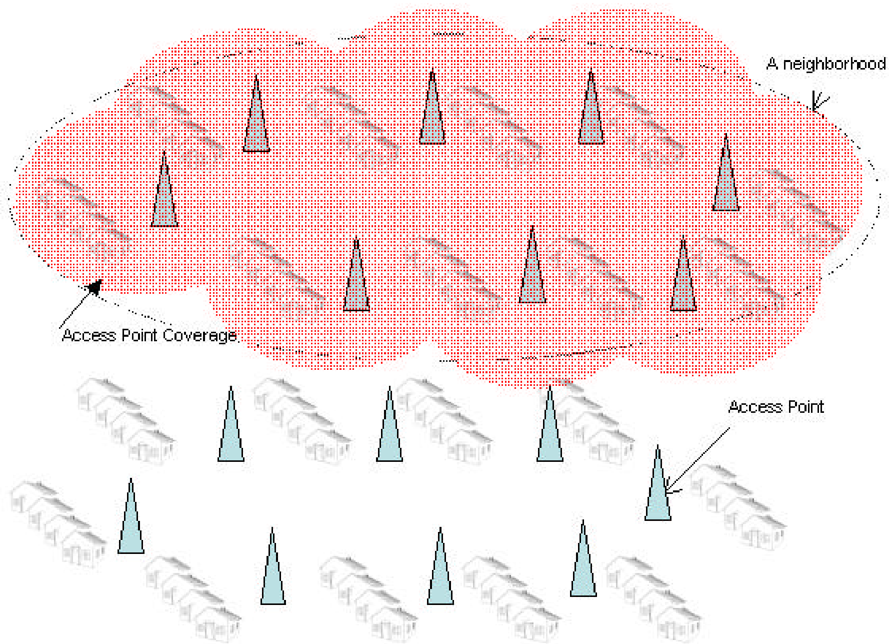


Figure 6.3 – Graphical illustration of the All Wireless option.

Of course, the subscribers are required to register their network card's MAC address with the service provider, in order to use the network. The service provider will then issue the Wired Equivalency Protocol (WEP) key so that only the register Network Interface Card (NIC) can be used to access the network. The security issue of the IEEE 802.11 is discussed in Chapter V. The operating concept of this full wireless network is similar to the cellular phone system. Once the (Media Access Control) MAC address is registered, the user of the network card would be able to access the network, regardless of the terminal used.

Any addition of subscribers to a particular cell or coverage area, especially at the edge could be easily added, simply by using the established access point or connecting an additional access point which will double the number of channels, hence, allowing more users.

The network manager would need to have an updated subscriber list and their connecting access points. For each access point, a 20% redundancy is catered for roaming users and access points in business and crowded areas will provide 40% redundancy. This effort would allow seamless connectivity of wireless Internet access for people on the move, taking advantage of the microcells operating concept for wireless roaming as discussed in Chapter V.

The main disadvantage of this implementation is that the mesh network traffic i.e. the trunk links, is limited to just 54 Mbps. The trunk bandwidth is insufficient in today's high bandwidth intense application and the result of having just 54 Mbps is many congestions and bottlenecks at the network nodes. Having a higher bandwidth on the trunk link would certainly enhance the reliability and speed of the data traffic.

3. Hybrid FSO-Wireless Option

Acknowledging the disadvantages of using the full FSO and the full wireless option, a combinational effort of the two technologies could reduce the effect of their weakness. While understanding the current FSO provides a good trunk link, rather than the edge links and the IEEE 802.11g provides good edge links, the hybrid FSO/IEEE 802.11g system could bring out the best of both technologies.

Figure 6.4 shows the graphical implementation of the hybrid system for a neighborhood. The concept is to have both the FSO link heads and IEEE 802.11g access points at the network nodes, and IEEE 802.11g network interface cards for each subscriber. Compared to the all-wireless option, the network would be enhanced using FSO to allow super high-bandwidth trunk links, while maintaining the complete wireless coverage for roaming users. Compared to the all-FSO option, the equipment cost for each household will be significantly reduced.

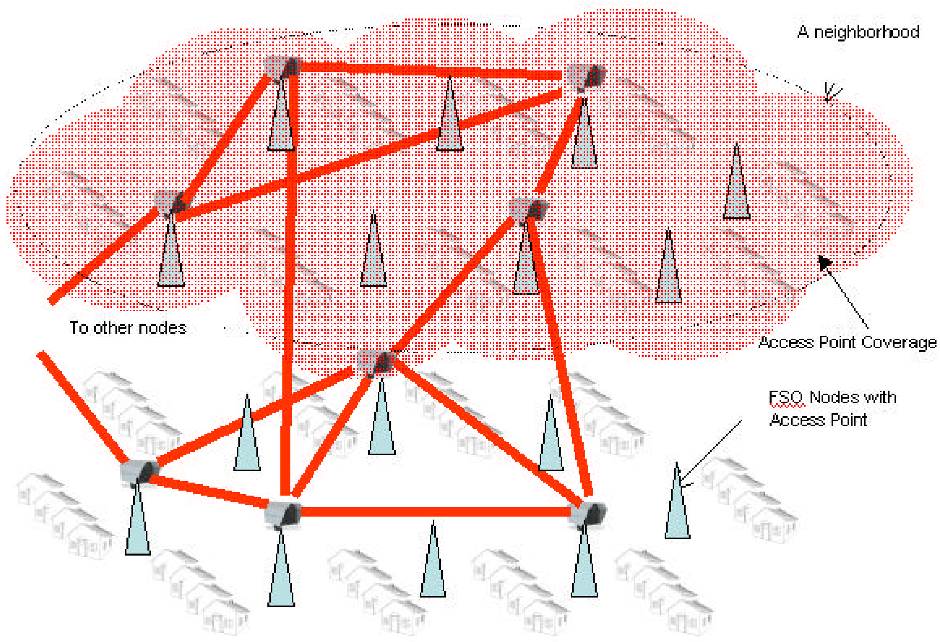


Figure 6.4 – Graphical illustration of the Hybrid FSO-IEEE 802.11 option.

With this implementation, the overall implementation cost would be generally reduced due to the reduced number of FSO link heads required in the homes and offices. While understanding that some larger businesses would required that amount of bandwidth, the number of link heads for the edge is reduced to 15%, compared to the full FSO option.

E. COMPARING ALL

Perhaps cost is the most influential variable in all three options. It can be the best equipment providing the best bandwidth with the best reliability and operability but be too expansive for each home or business to afford in the last mile. It is therefore vital to not only look at the best technologies and products available, but also the best product for the lowest cost. All costs included here are the best estimated costs (in U.S. dollars) at the time of printing. Many corporations and carriers are sensitive to providing cost estimates because there are too many variables that can change the cost including the amount purchased, the contract length, age of the technology, location, etc.

The analysis assumes the entire network is being constructed from scratch. However, in practice, it would be wise to use existing infrastructure such as established conduits from power companies, natural gas lines, sewers, subways, etc . This analysis also assumes that all homes and businesses will have access to the network. In practice, there might not be a need to construct a section of the network in areas where subscription rate is lower or where there is simply no demand for networ k access. Practical implementation in such areas could result n operational and financial loss. In such cases, the network edge of such areas can be installed with redundancy so as to provide instant network access availability as and when needed.

1. All FSO Option

The first cost analysis to be examined is the all Free Space Optics option. To be implemented in the hypothetical city, each neighborhood will need 4 network nodes (i.e. 4 Flight Spectrum per node), and each house will need 1 Flight Lite link head, yielding a total of 16 Flight Spectrums and 400 Flight Lites per neighborhood. The computation is as shown:

Each network nodes = 4 Flight Spectrum Link Heads

Each neighborhood = 4 network nodes

Flight Spectrum link head per neighborhood = 16

Each hous e = 1 Flight Lite Link Head

Flight Lite link head per neighborhood = 400

The entire mesh network would need 8000 Flight Spectrums and 200,000 Flight Lites link heads:

Total Neighborhood = 500

Total Flight Spectrum Link Heads: 500 x 16 = 8000

Total Flight Lite Link Heads: 500 x 400 = 200,000

In the all FSO option, the total number of link heads required and the corresponding cost are as tabulated:

Equipment	Quantity	Cost per link head[39]	Total Cost
Link Head for network nodes	8000	$30,000	$240 million
Link Head for home	200,000	$5,000	$1,000 million
Total Cost			**$1.24 billion**

Table 7. Cost for the all FSO option.

The above costing does not include the labor, operational and maintenance cost in running this system. Only the cost of the equipment and installation is considered. There are no sources for the exact cost for the link heads but the cost is made from a conservative and educated quote.

The main disadvantage of having an all FSO city is the unavailability of a small and inexpensive FSO link head for the homes. As stated in the previous chapter on FSO, this application of FSO technology is still in its infancy and now only reaches large buildings just outside the fiber optic backbone within most cities. As the demand for home use rises, companies may begin to offer an affordable solution for individual home and offices in the last mile. The other disadvantage of this option is that the FSO link

39 http://www.antennasystems.com/broadband.html [29]

works on LOS and hence, to create a mesh network, more links (i.e. link heads) are required. This will escalate the equipment cost.

The advantages of this option are that everyone in the city will get high-speed and reliable network access. Any expansion of the network can be easily implemented and there are no worries for future cost involved in digging up sidewalks and roads, merely to bring high-speed data to a new building.

2. All Wireless Option

The next cost analysis is that of utilizing IEEE 802.11g wireless technology. Based on the design implementation, each neighborhood will require 8 access points and each house needs 1 Network card, yielding a total of 8 access points and 400 network cards per neighborhood:

Access Points per neighborhood = 8

NIC per neighborhood = 400

To implement on the entire city, a total of 4000 access points and 200,000 network cards:

Total Access Points: 500 x 8 = 4000

Total NIC: 500 x 400 = 200,000

The total number of access points and wireless network cards, together with the corresponding cost are tabulated in table 8:

Equipment	Quantity	Cost per equipment	Total Cost
Access Point	4000	$140	$560,000
Wireless NIC	200,000	$90	$18 million
Total Cost			**$18.56 million**

Table 8. Cost for the all Wireless option.

The above costing does not include the labor, operational and maintenance cost in running this system. Only the cost of the equipment is considered. It is assumed that the home users are capable in installing the NICs.

Though the cost is only a small fraction compared to the all FSO option, this option will not be able to provide a true high-speed network access as the core of the network has only a maximum data transfer rate of 54 Mbps. This amount of data rate will create many bottlenecks in the network, resulting in numerous data traffic congestion.

The option is nevertheless studied; so as to be convinced on the results obtain from a low implementation cost.

3. Hybrid FSO-Wireless Option

Since the cost of FSO link heads at $5000 per link head are still expensive for the last mile homes and offices, this study would be incomplete without trying to obtain a current way to use wireless technology to the home, thereby eliminating the high cost of home link heads. This last option uses a hybrid of the FSO technology discussed in Chapter IV and the IEEE 802.11 technology discussed in Chapter V. Similar to the above presented options, the LightPointe's Flight Spectrum link heads will be used for setting up the city's mesh network. The access equipment from the homes and offices will be similar to those used in the wireless option. The tabulated cost for the equipment used is as shown:

Each network nodes = 4 Flight Spectrum Link Heads

Each neighborhood = 4 network nodes

Flight Spectrum link head per neighborhood = 16

Access Points per neighborhood = 8

NIC per neighborhood = 400

Total Flight Spectrum Link Heads: 500 x 16 = 8000

Total Access Points: 500 x 8 = 4000

Total NIC: 500 x 400 = 200,000

Equipment	Quantity	Cost per equipment	Total Cost
Link Head for network	8000	$30,000	$240 million
Access Point	4000	$140	$560,000
Wireless NIC	200,000	$90	$18 million
Total Cost			**$258.56 million**

Table 9. Cost for the hybrid FSO-Wireless option.

In this option, the true savings is seen in the access equipment cost from the homes and the offices. NICs at $90 per piece are used instead of the link heads that cost $5000 per piece. Though the option does not offer as much bandwidth as what was offered in the all FSO option, the cost of the access equipment is more affordable. Technically speaking, the bandwidth offered is still greater than what is offered today via telephone lines (be it modem dial-up, xDSL) and cable modems. A respectable 54 Mbps, obtained from the home at an affordable cost could well be the cardinal selling point.

It is also important to note that by implementing this option, users are able to roam while maintaining connection to the services. This is particularly useful in areas like the business districts and campus. There is no need for additional access points as the Virtual Private Network (VPN) concept can be implemented as well.

Note that this option is already a savings compared to an all fiber optics cable option. The all fiber optics cable option would cost an estimated $920 million dollars to be implemented in this hypothetical city[40]. The implementation cost is simply too high based on today's market and to generate a profit (as a service provider's point of view) would be far fetched.

F. INCOME VS COST

Now that the costs of the three options have been discussed, it is critical to look at the potential income home users could save or the maximum price they would be willing to pay for the high-speed network. Assuming that the high-speed network access can provide the following services:

Internet access

Mobile telephone

Local telephone

Long distance telephone

Cable TV

Radio

40 Free Space Optics and Wireless Broadband Radio Frequency Technology: Bringing High Speed Network Access to the last mile – John W.Sprague, March 2002 [01]

This high-speed access network would then eliminate the current costs associated with these services. Assuming that a typical home user has the following monthly costs associated with these services, shown in the table below.

Services	Cost per month	Remarks
Internet access	$40	Based on xDSL or cable modem for relative comparison.
Local telephone	$10	By Pacific Bell
Long distance telephone	$10	By AT&T
Cable TV	$40	By AT&T
Radio	Free	
Total Cost	**$100**	

Table 10. Services and average associated cost per household per month.

It is conceivable that the home user would pay 50% of this cost for all their services combined into one. A charge of $50 per month is certainly reasonable for access to the high-speed network.

If the typical home user pays approximately $100 for the above services monthly and for the new access network, the user pays only $50 for the access network that is able to provide similar services, there would be an average of 50% savings in monthly subscriptions.

With the charge of $50 per home or office, the 200,000 homes in the city will yield a potential income of 10 million dollars per month or 120 million dollars per year.

If this is the case and home equipment is provided free, then it could potentially take 2.13 years to make back the capital investment for the hybrid FSO-Wireless option and 10.3 years for the all FSO option.

G. SUMMARY

This chapter discussed the network design and analysis of a city of one million people. It discussed the potential services that can be provided by a high-speed network access to homes and offices in the last mile. The chapter looked at three different options and discussed the approximate cost associated with each. The all FSO option provided high-speed access but at a cost ranging about $1.24 billion dollars due to the high end-user equipment cost. The technology is still in its infancy and smaller FSO link heads for the home and offices are not yet available. It is believed that the cost of implementation will drop as the technology matures. The second option utilized the IEEE 802.11g. Though it can be implemented with a much lower cost, the traffic between the trunk nodes are however limited to just 54 Mbps and hence, data congestion might be high and frequent. The option is simply unstable for a high-speed network. The final option utilized the advantages of both technologies, creating the hybrid FSO-wireless option. Though the last mile bandwidth is much lower compared to the all FSO option, the equipment cost and the supported bandwidth is much more affordable and feasible for home users. An estimated cost of $259 million dollars would be needed to start up this system and the returns of the capital investment would take about 2.13 years. Though it requires a high start up cost, the benefits after implementation of this system is rich. There is no need to worry about high cost involved in equipment upgrading. This low-cost network access implementation utilizing FSO and IEEE 802.11g appears to be the best solution in solving the last mile problem.

THIS PAGE INTENTIONALLY LEFT BLANK

VII. APPLICATIONS OF FREE SPACE OPTICS AND IEEE 802.11 TECHNOLOGIES

A. OVERVIEW

In the previous chapter, implementation using Free Space Optics (FSO) and IEEE 802.11 wireless technologies in the network access shows that the hybrid system can be a viable last mile answer to the bandwidth-shortage last mile problem. Having understood the fundamentals of both technologies, as discussed in Chapter IV and Chapter V, the combination of the two technologies does not limit its application to the last mile. There are other areas of networking where this combination of technologies can be used to enhance and overcome the network setup speed requirement, the desired bandwidth requirement and space and geographical area constraints requirements. In this chapter, the market demands for the two technologies are studied and other areas concerning networking and telecommunication where the combination system of both FSO and IEEE 802.11 could be applied are conceptually explored.

B. DEMANDS FOR FSO

Free space optics (FSO), a tec hnology that transports data from point to point and multipoint via laser technology, will grow from a nascent technology to a strong niche player in the broadband market in the next five years, according to a study by The Strategist Group. The study, "Free Space Optics: Fixed Wireless Broadband," estimated that global equipment revenues in the FSO market are projected to reach $2 billion in 2005, up from less than $100 million in 2000.

While the technology is progressively maturing, with the increasing popularity of the technology, there is a definite place in the market for it. With its benefits, such as quick deployment time and high-capacity links, FSO should have strong appeal for both new and established carriers. Carriers, like Allied Riser and XO Communications, may use FSO in conjunction with other technologies to expand their current networks, while others, such as Terabeam, see the technology as a means to break into the broadband market.

FSO Equipment Revenue, 1999-2005							
Year	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**
Revenue (millions)	$1.7	$51.4	$111.7	$199.8	$354.1	$579.2	$864.9
Source: The Strategist Group							

Figure 7.1 – FSO Market Forecast. [From: 30]

FSO equipment currently is being deployed for a variety of applications, including last-mile connections to buildings, mobile networks assist, and network backup and emergency relief. Last-mile access provides the greatest opportunity because FSO provides the high-speed links customers need without the costs of laying fiber to the end user. In 2005, last-mile access will represent more than two-thirds of the total FSO equipment market, according to The Strategist Group.

Simply on using FSO, there are numerous applications where the technology has edge out the competition against fiber optical cables. Applications like Fiber Backup, Ethernet Access, Network Backhaul, LAN-to-LAN Building Connectivity, DS3 Services and SONET Ring Closure are typical areas of networking and communication where FSO can be applied. Based on the studies[41] done, solely using FSO has cut down the cost by a significant amount compared to using fiber optical cables.

[41] Free Space Optics, Applications and Economic Analysis – www.lightpointe.com, 2000 [30]

C. DEMANDS FOR IEEE 802.11

Wireless networking has also been gaining large market share in the present years. The growing wireless market will grow from about 170 million subscribers worldwide in 2000 to greater than 1.3 billion in 2004, with the number of wireless messages sent each month surpassing 244 billion by December 2004[42]. Analysis also reveals that this wireless industry generated revenues of $4.6 billion in 2000 and is projected to increase to $15.6 billion by 2007[43]. Most businesses, educational institutes and government ministries are employing wireless networking today as the management does see the benefits of having mobility and flexibility built into their networks. Extension of existing network could be done more easily with wireless, at a reduced cost. These factors are generally the driving motivations in the increasing wireless market.

Instat/MDR, a leading market research firm, recently reported that 38% of the existing home networks have a wireless LAN to share files, printers, Internet access and play games. By the end of 2004 more than 17 million homes in the US will have some form of home network. The launch of 54 Mbps 2.4 GHz products changes the dynamics of the industry, as it opens the door to very high speed, affordable wireless networking in the 2.4 GHz band[44].

There are many applications where IEEE 802.11 wireless technology can be applied. Though its bandwidth is currently limited to 54 Mbps, there are high hopes that the bandwidth will be increased as the technology matures. Also, the wireless network can be faster and easily deployed compared to the wired network. Wireless networking sees its application to network backup, network extension, home networking and campus

---

42 Cahner's In-Stat (CIS) Group, Scottsdale, AZ [31]

43 Michael Pastore, "Big Years Ahead for WLAN Market", [http://cyberatlas.internet.com/markets/wireless/article/0,,10094_974711,00.html], Feb 2002. [32]

44 http://www.linksys.com/press/press.asp?prid=94&cyear=2002 [28]

networking. The wireless networking concept has also been used in the military in today's digital and information world.

D. AREAS OF APPLICATION

Having briefly seen the areas of networking and communication where each of technology is bring applied; this section explores areas where both technologies when used in hybrid, can be applied. The following applications will be conceptually discussed:

1. Network - Backup and Extension

Information delivery today is critical in many aspects of our daily lives. Any disruption in the information traffic could cause delays that could severely affect businesses, banking, ecommerce and the economy. It is pertinent that the network providers provide not only uninterrupted services, but confidence level in information delivery. FSO could be used as backup link for backbone traffic, assuming that the main transmission is via fiber optical cable. This backup will provide sufficient bandwidth, just like what the fiber can offer. Figure 7.2 shows the illustration of this backup application.

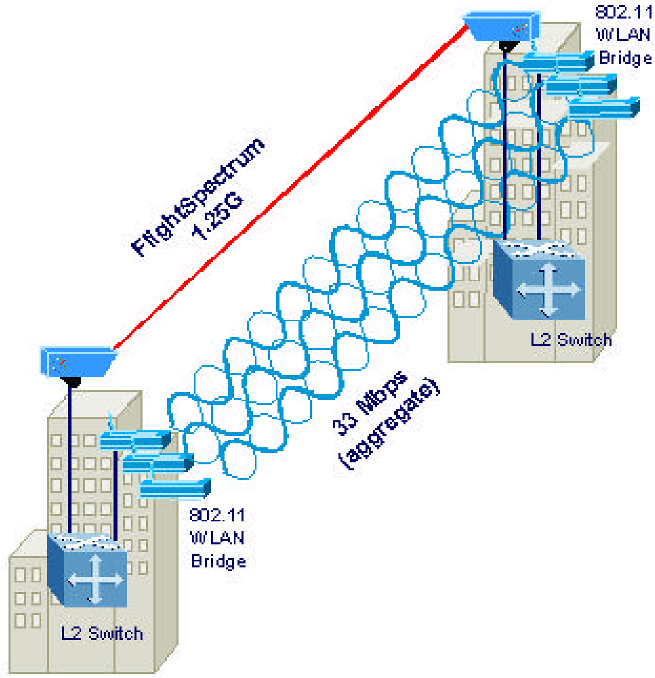


Figure 7.2 – Network backup using the hybrid system. [From: 27]

While there are reports that state that it is sufficient just by using FSO as the backup means, it is studied that FSO is affected by fog and other atmospheric factors. The small moisture particles scatter the light beam, thereby interrupting the optical transmission. Birds could also cause a temporary disruption to the laser beam. In this application illustration, the IEEE 802.11 wireless technology provides the third layer of redundancy in the back up system. Disruptions to the laser beam will be taken care of by the wireless transmission. In this case, the network reliability and confidence level is said to have the true 'five nines' – i.e. 99.999%.

FSO is also used to complement existing networks to increase their range and capacity. There is reasonable interoperability between major FSO equipment vendors, including RAD, Lightpointe, Terabeam, Optical Access, fSONA and Canobeam.

It could be in the case of a campus where new buildings are erected due to campus expansion. This could also likely in big establishments like Microsoft, Cisco, NASA, etc. In such a situation, the hybrid system could be used at a lower cost compared to laying fiber optical cable to the new buildings. The concept is illustrated in figure 7.3 as shown:

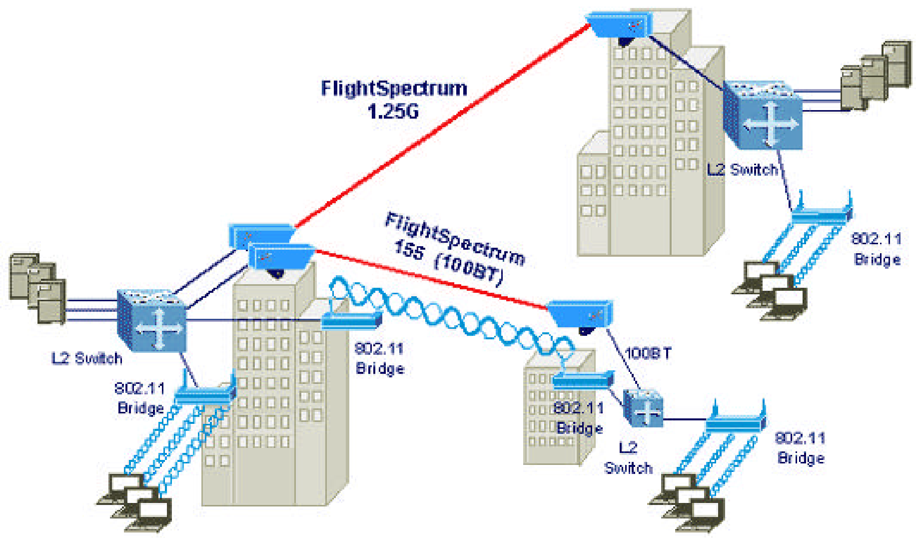


Figure 7.3 – Network extension using the hybrid system. [From: 27]

With the implementation of the hybrid system, the networking service includes also wireless networking, which is highly popular in campus type establishment. Not only there is mobility for the staff, information could also be retrieved anywhere, anytime.

With the demand for both fixed and mobile wireless services growing at a rapid pace, along with new services in the areas of voice, data and multimedia, the application extends to ISP and network providers. As wireless service providers develop networks to meet this growing demand and seek to deliver new services, particularly with 2.5G, 3G, and 802.11 network roll-outs, they must address increasing demand for network back-haul, where FSO has taken care of.

2. Disaster Recovery

As discussed earlier, FSO can be used as the main infrastructure or as a backup path in case the fiber network is cut or damaged in some way. An important application for FSO is disaster recovery, as evidenced in the aftermath of the September 11 tragedy. When the fiber infrastructure was knocked out, many businesses employed FSO to connect their offices to the networks in buildings in their line-of-sight. Rockefeller Group Telecommunications Services, for example, used FSO connected to RAD's IPmux TDM over IP gateway, to provide fast telephone connectivity to relocated users over Ethernet, connecting them to a working PBX in another building. Note that FSO merely provides the continuation of information traffic at the backbone level. This transmitted information could not have reached to the end users, if the communication lines to the end-users are damaged as well. In this case, the application of IEEE 802.11 could be effective. End-users could continue to communicate using wireless networking means while recovery of the main communication lines takes place. During the recovery phase, high bandwidth is still available, hence, minimizing the network handicap[45]. In today's vulnerable situation were terrorism could happen anywhere, the need and availability of a quickly-deployable backup system for critical networks cannot be emphasized enough.

3. Homeland Security

The hybrid system could also be used in homeland security. As in any mission or operation, communication is critical to the success. Though homeland security plans are likely to rely on the country's communication line, it is very possible that these communication assets are prime targets of the aggressor. What if the communication stations and assets are bombed and damaged? The destruction of the primary lines of

45 Note that in most cases, the backup system only provides about 30% of the primary bandwidth and networking equipment.

communication could severely damage the defense operation and the result could be chaotic. With the hybrid system, the communication network could be deployed quickly, and the communication could be re-established in the event when the main and primary communication lines are disabled.

4. Military Operations

Application to military operations is similar to what was discussed in homeland security. Communication is key to any operation's success. While most military are embarking to network centric operation, the reliance of computers and networking are increasing important. Communication is no longer simply voice communication, but data communication. As such, having a networking system that is high bandwidth, reliable, flexible, easy-deployable and robust could multiply the combat effectiveness of the force. Real time information could be sent and share among those in need, creating situation awareness among the peers. Note that information is knowledge and knowledge translates to power in military terms. From the real time information, better decisions can be made by the respective commanders, hence, resulting in a higher possibility of winning the battle. It is important to note that the decisions made will also be transmitted real time, minimizing confusions and latency. Of course, the security issues for the hybrid system must be addressed as security is critical in the military.

While fiber optical cables could be used in establishing a network in the field, it can be quite a load to carry the amount of optical fiber cables. There is also a need to maintain the cables regularly as having subjected to harsh environments, the cables would be stained, soiled and the rubber shielding of the optical cable could be easily worn. In addition, the space needed to store and transport the cables is definitely more than using the hybrid system. At the same time, more manpower is needed for the above tasks. The table (Table 11) below summarizes the comparison between using the fiber optical cables and the hybrid system, if used in the military.

Factors	Optical Fiber Cable System	Hybrid System
Security	Very secure.	Less Secure.
Load	Heavy.	Light.
Storage	Large space needed.	Less space need.
Maintenance	High and regular.	Less needed.
Deployment	Slow and requires more manpower	Fast and quick. Less manpower.
Reach	Backbone system only.	Backbone and End Users.
Bandwidth	High	High

Table 11. Comparison of existing optical fiber system and the hybrid system.

E. SUMMARY

This chapter discussed the current market share and the market forecast of the Free Space Optics and IEEE 802.11 wireless technologies. From the studies shown, these technologies are indeed in great demand and there are many areas of networking and communication where each of these technologies can be applied. As in the previous chapter, a comparison has been made and it was observed that a hybrid system utilizin g both technologies can prove a better result; areas of networking and communications where both technologies can be applied in hybrid are also discussed. Particularly in the network backup and extension, the hybrid system could provide a true level of reliability i.e. 99.999%. In addition, the speed, freedom, mobility, scalability and flexibility factors further highlights the benefits achieved from the system. Also discussed in this chapter, the hybrid system can also be applicable in the disaster recover y, homeland security program and operations in the military.

As only the concept of applying both technologies are explored in this chapter, more detailed studies should be carried out in the proposed applications as there are many areas of concern that are not discussed. Nonetheless, this chapter provides a wide perception on applying the technologies, which is hoped to initiate deeper ideas.

VIII. CONCLUSION

A. SUMMARY

The last mile problem is one of the most important in telecommunications and the Internet today. It is getting a lot of attention by companies looking to take advantage of the possibilities that exist. The current infrastructure of twisted pair is at its upper limit, so new and innovative ways are required to reach last mile homes and offices with access to high-speed networks. Though fiber optic cable is the most mature high-speed alternative available, the cost of implementation, operation and maintenance is a major obstacle. Once fiber optic cables are installed, the problem of scalability and replacing old cables when newer high-speed fiber becomes difficult and the same problem occur again. There is no flexibility in upgrading the fiber cable system without involving high cost, time and resources.

Wireless optical and RF technologies are gaining significant momentum today in helping to solve the last mile problem. Both the FSO and the IEEE 802.11 are two emerging technologies aimed at improving network access to last mile homes and offices. FSO, utilizing laser technology, provides high-speed network access but is still in its infancy and only now affordable by large corporations or multi-units dwellings close to the backbone ring. FSO also needs to be relatively precise and distances are relatively limited in support for true high bandwidth capability. Weather and atmospheric conditions can also adversely affect it. IEEE 802.11, on the other hand, uses the radio frequency spectrum. RF can go distances without being affected much by weather and atmospherics, but the access speeds are relatively slower.

The goal of this thesis was to present various options available to help solve the last mile problem. Areas in the U.S. as well as areas around the world are quite different and different solutions may be better for various part of the world. For example, if fog is a common place in an area, then FSO technology may not be the best solution for that area. Whatever technology that is to be implemented, a thorough ground survey of the technology implementation must be carried out so as to better obtain the decision of implementing the best system. The best available technology might not be suitable for certain areas due to other problems. Once the cost and benefits are weighted and compared, a better justification can hence be made for the proposed system to be implemented.

Besides physically implementing the system, the services that can ride on it play a role in consideration as well. The aim was to wrap up Internet access, phone access, long distance access and cable access into one network, link to the home, thereby eliminating the services of each individual provider and their associated cost. In this way, there is a more attractive package deal for consumers so that they can seriously consider taking up the services. Marketing the services is thus, also critical in gaining ground in the consumer market.

B. CASE STUDY

The best solution today for the hypothetical city in this case study seems to be the hybrid FSO-IEEE 802.11 system. By benefiting the strengths of both the wireless technologies, a system that can achieve the providence of high bandwidth in the last mile and yet, not indulging high amount of investment cost can hence be constructed. The cost of implementation is also more feasible in today's telecommunication and networking market. It is also important to note that current existing infrastructures can be made used of in the system implementation; hence cutting more cost. Different cities in the U.S and the rest of the world offer different implementation difficulties; therefore, it is pertinent that a city that has the potentials (infrastructural, market and demand) be selected for implementation.

It is also important to realize that the cost of equipment today will depreciate as technologies mature and better and cheaper equipment are produced. It is also important to note that the cost estimated for each of the options does not reflect on the labor, installation, implementation and system operational costs. The total cost needed for each option to be implemented is computed solely on the cost of the hardware today. A more detailed accounting study hence needs to be carried out to really obtain the investment break-even time frame. The market forecast of the each technology must be obtained and studied so as to better appreciate the investment. The time frame and market forecast provided in this thesis is an academic estimate that does not consider about various market and economy inflations and deflations.

The production of newer and more powerful equipment will enhance the current proposed system. As discussed in Chapter VI, the availability of low cost link heads could well position the all FSO option as the optimal solution to provide true high bandwidth to the homes and offices in the last mile. Note that the main contrib ution to the high cost in the all FSO option is from the consumer's equipment.

Meanwhile, based on the current technology today, this all FSO option proves too high a cost for implementation thus, the hybrid system seems to be the most economical and beneficial option, while understanding that bandwidth is lower in the last mile. The benefits are applicable to both the service providers and the end consumers. Noting that the lowered bandwidth is still many times faster than what dial up, xDSL and cable modem are offering.

C. FURTHER RESEARCH

While this thesis's concentration is on the possibility of using the hybrid system for the last mile, there are other areas of networking and telecommunication where a smaller scale of this option can be used. It was discussed that such a hybrid system could provide a true reliable network that provides 99.999% in the areas of network backup and extension. The application of the hybrid system extends to the end consumers while most backup systems available in the mar ket today are only applicable to the network's backbone system. As was discussed that the hybrid system could be used in disaster recovery, homeland security and areas in the military, there are further areas where the hybrid system could also be applied. It is hope that what was discussed could initiate new ideas so as to improve on the robustness of networking in today's vulnerable world.

In today's high tech military system, information delivery is critical in the success of many campaigns and missions, especially in the growing area of information warfare. Further studies can also be carried out in the implementation of such system to be used in the battlefield.

LIST OF REFERENCES

[01] John W. Sprague, Free Space Optics and Wireless Broadband Radio Fr equency Technology: Bringing High Speed Network Access to the last mile, Master's Thesis, Naval Postgraduate School, Monterey, California, Mar 2002.

[02] Darren Cuffie, Keith Biesecker, Carl Kain, Giles Charleston and John Ma, "Emerging High Speed Access Technologies", IT Pro, Mar/Apr 1999.

[03] Michael R. Anderson, "Why Go Wireless?", ISP-Planet, Feb 2001.

[04] Telephone World – Local Central Office System, [www.dmine.com/phworld/network/office.htm].

[05] How Stuff Works – Telecommunication System, [www.howstuffworks.com].

[06] Rob Kirby, "Fiber – Can't Find Its Way Home?", Network Magazine, [http://www.networkmagazine.com/article/NMG20010823S0014], Sep 2001.

[07] *The Last Mile Problem*, Cybersavvy UK, Jan 2000.

[08] www.informationweek.com, accessed on 8 Oct 2002.

[09] www.adage.com – MSN continues struggle to catch up to AOL, Mar 2002, accessed on 8 Oct 2002.

[10] Stagg Newmann, *Broadband Access Platform – FCC Tutorial for Communications Networks and Services*, McKinsey and Company, Apr 2002.

[11] Michael J. Riezenman, "The Rebirth of Radio", IEEE Spectrum, Jan 2001.

[12] LightPointe Communication Inc, *Free Space Optics, White Paper*, LightPointe, 200

[13] Heinz A Willebrand, "New Roles for Free Space Optics", Broadband Wireless Online Article, vol. 3, no. 2, Feb 2002.

[14] http://www.terabeam.com/our/our_gen.com, accessed on 10 Oct 2002.

[15] http://www.nortelnetworks.com/products/library/collateral/56328.02 -06-01.pdf, accessed on 10 Oct 2002.

[16] James Harris, "The Last Mile: Wired or Wireless", Term Project, University of Washington, Seattle, Washington, Dec 2001.

[17] www.telcoexchange.com, accessed on 10 Oct 2002.

[18] Ramiro Jordan, Chaouki T. Abdallah, "Wireless Communications and Networking: An Overview", IEEE Antenna's and Propagation Magazine, vol. 44, no. 1, p. 185-193, Feb 2002.

[19] Leonidas Fountanas, *An Assessment of Emerging Wireless Broadband Technologies*, Master's Thesis, Naval Postgraduate School, Monterey, California, Dec 2001.

[20] http://www.stanford.edu/group/networking/NetConsult/wireless/80211a.html, accessed on 12 Oct 2002.

[21] *Introduction to Wireless LANs*, The Wireless LAN Alliance, [http://www.wlana.com], 1999.

[22] Steve Kapp, "802.11: Leaving the Wire Behind", IEEE Internet Computing, [http;//computer.org/internet/], Jan/Feb 2002.

[23] Certified Wireless Network Administrator Official Study Guide –Planet3 Wireless

[24] Peng J. Lee, *Orthogonal Frequency Division Multiplexing Signal Generation*, BSc's Thesis, University of Bath, Bath, UK, 1998.

[25] R. W. Chang, "Orthogonal Frequency Division Multiplexing Data Transmission System", U.S. Patent 3,488,445, filed Nov 14, 1966, issued Jan 6, 1970

[26] Lundy Bert, Business Plan for Telecommunication in Mexico, unpublished, 2001

[27] LightPointe Communication Inc, *Free Space Optics: A Viable Last Mile Alternative, White Paper*, LightPointe, 2002.

[28] http://www.linksys.com/press/press.asp?prid=94&cyear=2002, accessed on 15 Oct 2002.

[29] http://www.antennasystems.com/broadband.html, accessed on 15 Oct 2002.

[30] Free Space Optics, Applications and Economic Analysis – www.lightpointe.com, 2000

[31] Cahner's In-Stat (CIS) Group, Scottsdale, AZ

[32] Michael Pastore, “Big Years Ahead for WLAN Market”, [http://cyberatlas.internet.com/markets/wireless/article/0,,10094_974711,00.html], Feb 2002.

[33] D. J. Heartly, et al, “Optical Wireless: The story so far”, IEEE Communications Magazine, vol. 36, no. 12, p. 72, Dec 1998.

[34] Doug Allen, “The Second Coming of Free Space Optics”, Network Magazine, [http://www.networkmagazine.com/article/NMG20010226S0007], Mar, 2001.

[35] Andy Dornan, “Wireless Optics: Fiber is Cheap, But Space is Free”, Network Magazine, [http://www.networkmagazine.com/article/NMG20020826S0003], Sep 2002.

[36] Mark Steege, “Free-Space Optics: A Viable, Secure Last Mile Solution?”, Jan 2002.

[37] Anthony Acampora, “Last Mile by Laser”, Jun 2002.

[38] Joe McGarvey, “802.11g: Ready or Not?”, 802.11 Planet, [http://www.80211-planet.com/columns/article.php/1380571], Jul 2002.

[39] *802.11a: Wait Until Next Year*, 802.11 Planet, [http://www.80211-planet.com/columns/article.php/1465111], Sep 2002.

THIS PAGE INTENTIONALLY LEFT BLANK

INITIAL DISTRIBUTION LIST

1. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California

2. Dr Bert Lundy
   Department of Computer Science
   Naval Postgraduate School
   Monterey, CA

3. Mike Tatom
   Telecommunication Executive, USWEST
   Lone Tree, CO

4. CPT Peng J. Lee
   Ministry of Defense, Singapore

THIS PAGE INTENTIONALLY LEFT BLANK