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THESIS

EFFECTIVE DISTRIBUTION OF HIGH BANDWIDTH TO THE LAST MILE

by

Kwok Vi-Keng David

December 2003

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13. ABSTRACT (maximum 200 words)

Since the mid 1990s, Internet is revolutionizing the way business is conducted around the globe. Bandwidth-intensive graphics, video and audio applications are becoming more popular and the desire for fast access to information places a huge demand on high bandwidth in metro networks. The primary bottleneck in the quest for delivering high bandwidth to the customers is the last mile. The last-mile of today primarily relies on infrastructures that were not designed for the transport of digital data. The current infrastructure of twisted pair is very close to its upper limits. As a result, consumers are unable to enjoy the full potential of the Internet and generally do not have access to enhanced services such as enriched multimedia services, converged voice, video, and data services and high-speed Web browsing.

This thesis assesses a broad spectrum of wired and wireless last mile technologies available - Optical Fiber Technology, Digital Subscriber Lines, Free Space Optics, Wireless Local Loop, Wireless LAN and Cellular Technology. Besides discussing the basic concepts and principles, it highlights the current limitations of these technologies for last mile implementation. An innovative and state-of-the-art methodology for linking building with optical fiber to achieve high bandwidth through sewer systems is presented.

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TABLE OF CONTENTS

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LIST OF FIGURES

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LIST OF TABLES

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I. INTRODUCTION

A. OVERVIEW

In the information age, the amount of data being created and consumed has increased tremendously. Increasingly, information has become a vital resource of the government, businesses and individuals. More so now than any other era of modern history, organizations reply on timely, accurate and complete information for efficient operation, growth and survival. From military operation viewpoint, the need for situation awareness and intelligence gathering in the digitized battlefield places a demand on advanced information delivery technologies.

Over the past decade, computer networks have played an important role in the transportation of this digitized information. As government agencies, private organizations and the individual man in the street seek for faster and greater access to critical information, the demand on high bandwidth increases exponentially. To meet this demand, countries all over the world has developed the infrastructure of the core global network backbone consisting of optical fiber cable links between major cities and countries. The core network bandwidth is of the order of gigabits per seconds and there is little doubt that terabits per second is a possibility today. This dramatic increase in bandwidth capability and data rate is due primarily to advances in optical fibers technologies.

B. WHAT IS THE LAST MILE?

While the current technological capability is able to meet the high bandwidth requirement of the metropolitan network (WAN) using optical fiber trucking, the major problem faced today is the delivering of this high bandwidth down to the individual in the household or small businesses. This is defined as the local access loop or the *last mile* of the Internet. It is the portion of the Internet or telecommunication network that connects Internet Service Providers

(ISPs) and the consumers. As shown in Figure 1, the *last mile* is that portion beginning from the phone in the house and ending at the local central office. The utilized bandwidth is only 4KHz (Shannon's Law for analog voice modulation) and allows digital transmission at a maximum rate of 56kps.

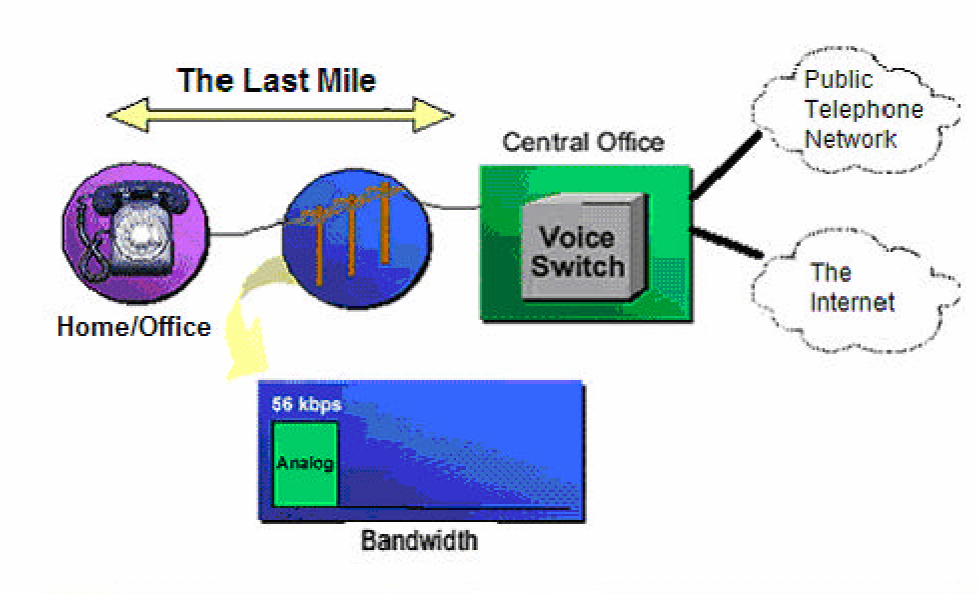

Figure 1. The Last Mile (From [Tele2003])

Telephone calls made from homes are connected to the central office switching system. Using copper wires, each individual homes and office are connected to a system that 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 local area or passing it to the toll network. At the destination, the call will go through another central office and then to the destination number.

These central offices are also known as switching stations. From these switching stations, optical fibers are used to connect to the Internet and long distance networks (core network), where data are riding on gigabit data rates. 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.

The current delivery infrastructure for residential and small office home office (SOHO) bandwidth access is inadequate, as it does not provide sufficient data rate meet customers needs. The majority of Internet users in the world still using 56kps modems to access the Internet via dial-up. While the theoretical limit is 56kps, these users typically do not obtain information faster than 50kps, some going as low as 20kps. The inadequacy of the local assess loop is stark when compared to dense-wave division multiple (DWDM) systems where the data rate is of the order of 1.6Tbps.

The issue at hand is whether consumers really require such high bandwidth. This can be analyzed by examining the potential bandwidth demand of common applications such as file transfer, high quality web surfing and high – definition TV.

Applications	Bandwidth Requirements (Mbps)	Number of Sessions	Total Bandwidth Requirements (Mbps)
High Definition TV	20	2	40
Quality Web Surfing	5	2	10
Online Gambling	2	1	2
Telephone	0.64	4	2.56
File Transfer	10	1	10
Total Bandwidth			**62.256**

Table 1. Projected Residential Bandwidth Requirements (From [Schw2002])

It is clear from Table 1 that the access network of today which primarily provides bandwidth of the order of kilobits/sec is not able to meet the projected bandwidth needs. The push for residential broadband access comes from many fronts, the information technology (IT) industry, the government, consumer demands and the emergence of new applications. Consumers with broadband Internet access have the potential to reap the benefits of applications such as high-definition television (HDTV), video telecommuting, tele-education, video-on-demand, online video games, interactive shopping and yet to be determined applications. The possibilities are unlimited.

The Federal Communications Commission (FCC) defines *broadband* as having a transmission rate of at least 200kbps [Gatt2002]. Broadband access can be more accurately described as high-speed Internet access that is capable of delivering voice, data and video services to one's home or SOHO. Specifically, true broadband Internet access should be in the range of 10Mbps to 100Mbps. This data rate meets the needs described in Table 1, while providing spare capacity for unforeseen applications and services.

C. CHALLENGES OF THE LAST MILE

Connection at the homes and offices varies, depending on the needs and requirements of the Internet usage. Although there are more options for the users in accessing the Internet than a couple of decades ago, these options 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 tend 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. They also would not 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 leads 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. 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 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) [Isp2003]. 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 users are often 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.

The challenge of the last mile problem is to provide high speed broadband to the masses at an affordable cost. Of course, if fiber optic cables, instead of copper wires, 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. Operators will not take on this challenge, until laying and maintaining the fiber optic cables are cheap enough.

D. THESIS ORGANIZATION

This thesis discusses a broad range of technologies available to address the last mile problem. The benefits and limitations of these various last mile technologies are examined. We will start off with a discussion on Optical Fiber systems, commonly used to support the backbone of modern telecommunication systems and Internet. In Chapter III, Digital Subscriber Line (DSL) technologies will be explained, focusing on Asymmetric Digital Subscriber Lines (ADSL) and Very High Rate Digital Subscriber Lines (VDSL). Wireless technologies are discussed in the subsequent chapters. The principle of Free Space Optics (FSO) is discussed in Chapter IV. The concept of Wireless Local Loop and Wireless 802.11b are covered in Chapter V and Chapter VI respectively. Chapter VII examines the evolution of cellular technologies and discusses the third generation (3G) of mobile communications. Finally, a case study of an innovative method to circumvent the last mile problem using existing sewer network is presented.

II. OPTICAL FIBER TECHNOLOGY

A. INTRODUCTION

A communication system transmits information from one place to another, whether separated by a few kilometers or by transoceanic distances. Information is often carried by an electromagnetic carrier wave whose frequency can vary from a few megahertz to several hundred terahertz. Optical communication systems differ from microwave systems in the frequency range of the carrier wave used to carry the information. The optical carrier frequencies are typically 200 THz, in contrast with the microwave carrier frequencies (1 GHz). Fiber-optic communication systems are lightwave systems that employ optical fibers for information transmission. An increase in the information capacity of optical communication systems over traditional copper infrastructure by a factor of up to 10,000 is possible due to such high carrier frequencies used for lightwave systems.

Optical Fibers are fibers of glass, usually about 120 micrometers in diameter, which are used to carry signals in the form of pulses of light. The purity of today's glass fiber, combined with improved system electronics, enables fiber to transmit digitized light signals well beyond 100 km (60 miles) without amplification. With few transmission losses, low interference, and high bandwidth potential, optical fiber is an almost ideal transmission medium.

The advantages provided by optical fiber systems are the result of a continuous stream of product innovations and process improvements. As the requirements and emerging opportunities of optical fiber systems are better understood, fiber is improved to address them.

B. HISTORY OF FIBER OPTIC

Interest in the use of light as a carrier for information grew in the 1960's with the advent of the laser as a source of coherent light. Initially the transmission distances were very short as manufacturing techniques for very pure glass is primitive.

The first challenge undertaken by scientists was to develop a glass so pure that 99% of light will be transmitted at the end of one kilometer (km), the existing transmission distance for copper-based telephone systems. In terms of attenuation, this one-percent of light retention translated to 20 decibels per kilometer (dB/km) of glass material. Glass researchers all over the world worked on the challenge in the 1960s, but the breakthrough came in 1970, when Corning scientists Drs. Robert Maurer, Donald Keck, and Peter Schultz [Wood2000] created a fiber with a measured attenuation of less than 20 dB per km. It was the purest glass ever made.

The three scientists' work is recognized as the discovery that led the way to the commercialization of optical fiber technology. Since then, the technology has advanced tremendously in terms of performance, quality, consistency, and applications. At the same time, developments in semi-conductor light sources and detectors meant that by 1980 world wide installation of fiber optic communication systems had been achieved. Working closely with customers has made it possible for scientists to understand what modifications are required, to improve the product accordingly through design and manufacturing, and to develop industry-wide standards for fiber.

The commitment to optical fiber technology has spanned more than 30 years and continues today with the endeavor to determine how fiber is currently used and how it can meet the challenges of future applications. As a result of research and development efforts to improve fiber, a high level of glass purity has been achieved. Today, fiber's optical performance is approaching the theoretical limits of silica-based glass materials. This purity, combined with improved system electronics, enables fiber to transmit digitized light signals well beyond 100 km (more than 60 miles) without amplification. When compared with early attenuation levels of 20 dB per km, today's achievable levels of less than 0.35 dB per km at 1310 nanometers (nm) and 0.25 dB per km at 1550 nm, testify to the incredible drive for improvement.

C. PROPAGATION OF LIGHT IN THE FIBER

The operation of an optical fiber is based on the principle of *total internal reflection*. Light reflects (bounces back) or refracts (alters its direction while penetrating a different medium), depending on the angle at which it strikes a surface.

This principle is at the heart of how optical fiber works. Light waves are guided through the core of the optical fiber. The light waves are guided to the other end of the fiber by being reflected within the core. Controlling the angle at which the light waves are transmitted makes it possible to control how efficiently they reach their destination. The composition of the cladding glass relative to the core glass determines the fiber's ability to reflect light. The difference in the index of refraction of the core and the cladding causes practically all of the transmitted light to bounce off the cladding glass and stay within the core.

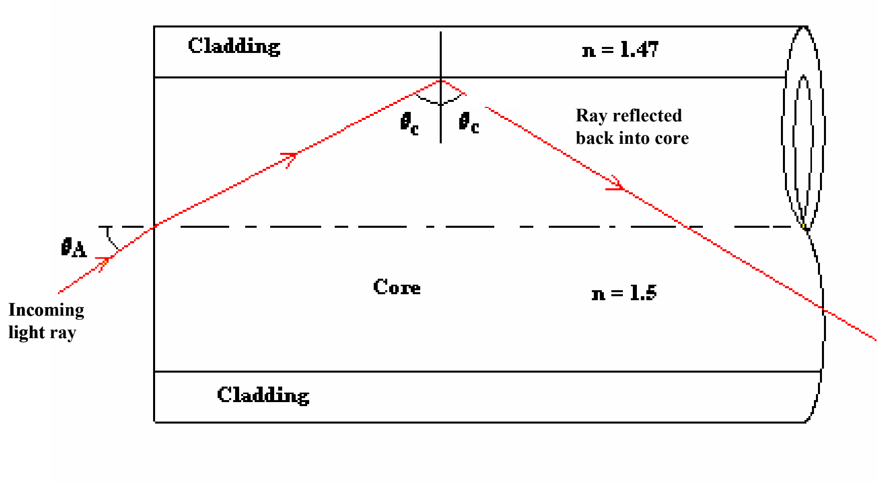

Figure 2. Principle of Total Internal Reflection (TIR)

The angle θ_c in the Figure 2 is called the *Acceptance Angle*. Any light entering the fiber at less than this angle will meet the cladding at an angle greater than θ_c. If light meets the inner surface of the cladding (the core - cladding interface) at greater than or equal to θ_c then Total Internal Reflection (TIR) occurs, causing all the energy in the ray of light is reflected back into the core and none escapes into the cladding. The ray then crosses to the other side of the core and, because the fiber is more or less straight, the ray will meet the cladding on the other side at an angle which again causes TIR. The ray is then reflected back across the core again and the same thing happens. In this way the light zigzags its way along the fiber and it will be transmitted to the end of the fiber.

D. FIBER OPTIC TRANSMISSION SYSTEM

The role of a fiber optic transmission system is to transport optical signal from transmitter to receiver without distorting it. The figure below depicts the main components of a fiber optic system comprising the transmitter, fiber and receiver.

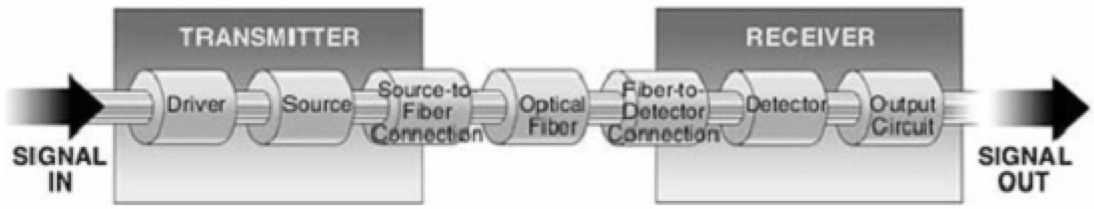

Figure 3. Basic Fiber Optic Link (From [Noll2003])

The "encoding" side of an optical communication system is called the transmitter. This is the place of origin for all data entering the fiber optic system. The transmitter essentially converts coded electrical signals into equivalently coded light pulses. A light-emitting diode (LED) or an injection-laser diode (ILD) is typically the source of the actual light pulses. Using a lens, the light pulses are funneled into the fiber optic connector (or terminus), and transmitted down the line.

Light pulses move easily down the fiber optic line because of the principle of total internal reflection. In the case of optical communications systems, this principle makes it possible to transmit light pulses down a twisting and turning fiber (though there is a limit to the amount of twisting and turning) without losing the light out the sides of the strand.

At the opposite end of the line, the light pulses are channeled into the "decoding" element in the system, known as the optical receiver or detector. Again, the actual fiber to detector connection is accomplished with a specialized fiber optic connector/terminus. The purpose of an optical receiver is to detect the received light incident on it and to convert it to an electrical signal containing the information impressed on the light at the transmitting end. The information is then ready for input into electronic based devices, such as computers, navigation control systems, video monitors and so on.

E. FIBER OPTICS CONSTRUCTION

There are typically five elements that make up the construction of a fiber optic cable: the optic core, optic cladding, buffer, strength member and outer jacket. The optic core is the light-carrying element at the center of the optical fiber. It is commonly made from a combination of highly purified silica and germania.

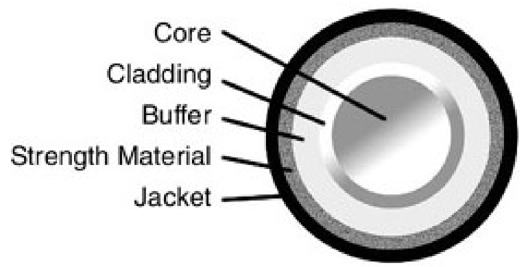

Figure 4. Cross Section of a Fiber Optic Cable (From [Noll2003])

Surrounding the core is the optic cladding made of pure silica. The combination of these materials makes the principle of total internal reflection possible, as the difference in materials used in the core and the cladding creates an extremely reflective surface at the point in which they interface. Light pulses entering the fiber core reflect off the core/cladding interface and thus remain within the core as they move down the line.

Surrounding the cladding is a buffer material which acts as a shock absorber to protect the core and cladding from damage. A strength member, typically Aramid, surrounds the buffer adding critical tensile strength to the cable to prevent damage from pull forces during installation. The outer jacket protects against abrasion and environmental damage. The type of jacket used also defines the cable's duty and flammability rating.

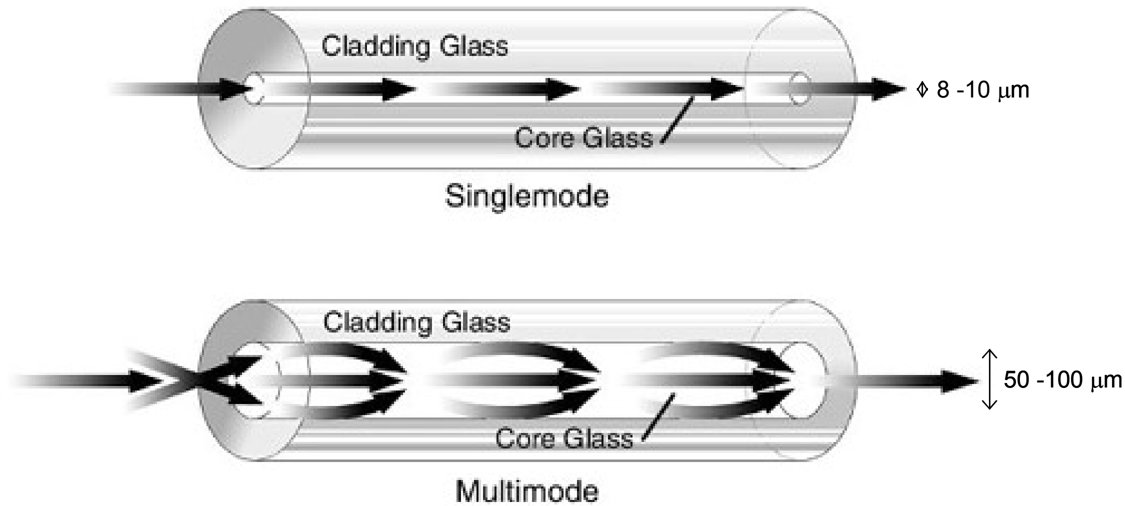

Figure 5. Optical Fiber Core Diameters - Singlemode and Multimode (After [Noll2003])

Rays of light passing through a fiber do not travel randomly. Rather, they are channeled into modes - the thousands of possible paths a light ray may take as it travels down the fiber. A fiber can support as few as one mode and as many as tens of thousands. The number of modes in a fiber is significant because it determines the fiber's bandwidth. Multimode fiber has a much larger core (50 – 100 um in diameter) than single mode fiber, allowing hundreds of rays of light to propagate through the fiber simultaneously. Single mode fiber has a much smaller core (8 – 10 um in diameter), allowing a few modes of light to propagate through the core. The higher the number of modes implies the lower the bandwidth of the cable.

F. PULSE SPREADING

The data which is carried in an optical fiber consists of pulses of light energy following each other rapidly. There is a limit to the highest frequency, i.e. how many pulses per second which can be sent into a fiber and be expected to emerge intact at the other end. This is because of a phenomenon known as pulse spreading which limits the capacity of the fiber.

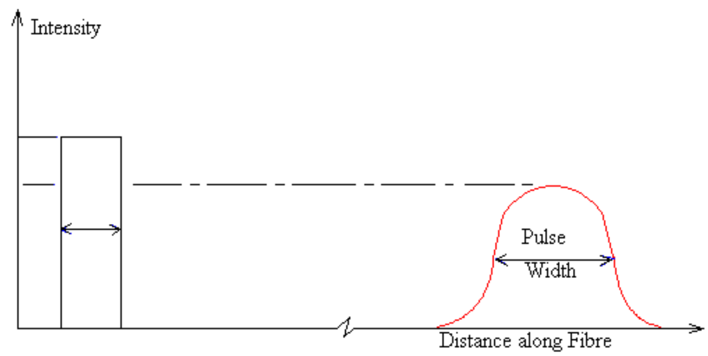

Figure 6. Pulse Spreading in an Optical Fiber

Referring to Figure 6 above, the pulse sets off down the fiber with a nice square wave shape. As it travels along the fiber it gradually gets wider and the peak intensity decreases. The cause of spreading is dispersion. This means that some components of the pulse of light travel at different rates along the fiber. There are three general forms of dispersion: Modal Dispersion and Chromatic (Material) Dispersion and Waveguide Dispersion.

1. Modal Dispersion

Modal Dispersion is caused by the different path lengths followed by light rays as they bounce down the fiber (some rays follow a more direct route down the middle of the fiber, and so arrive at their destination well before those rays which waste their time bouncing back and forth against the sides). More oblique rays (lower order modes) travel a shorter distance. These correspond to rays traveling almost parallel to the centre line of the fiber and reach the end of fiber sooner. The more zigzag rays (higher order modes) take a longer route as they pass along the fiber and so reach the end of the fiber later. Modal Dispersion occurs in multimode fibers and is minimized by using graded-index.

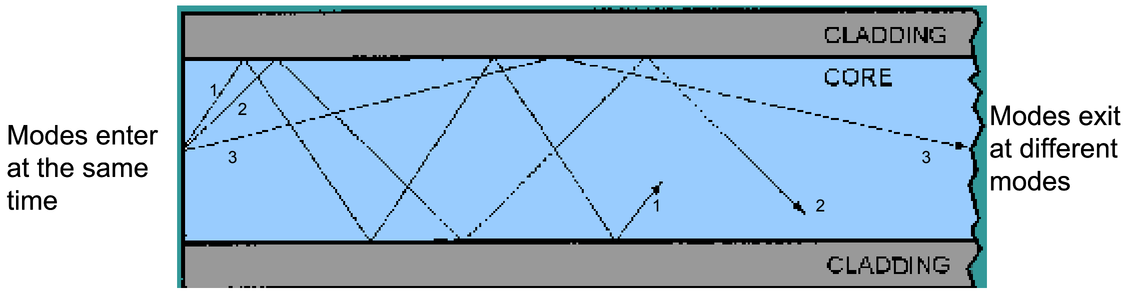

Figure 7. Modal Dispersion

2. Chromatic (Material) Dispersion

Chromatic Dispersion, also known as Material Dispersion, is the variation of refractive index with the wavelength (or the frequency) of the light. Each wavelength of light travels through the same material at its own particular speed that is different from the speed of other wavelengths. This can occurs in both singlemode and multimode fibers.

An analogy is when white light passes through a prism. Some wavelengths of light bend more than others because their refractive index is higher. This is what gives us the "Spectrum" of white light. The "red' and "orange" lights bend the least while the "violet" and "blue" bent most as white light travel through the prism. All the other colors lie in between.

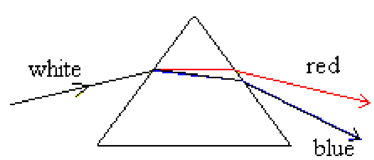

Figure 8. Dispersion of Light through a Prism

This phenomenon implies that different wavelengths traveling through an optical fiber also travel at different speeds.

3. Waveguide Dispersion

Wavelength Dispersion, which occurs in single-mode fibers, is caused by the dependence of the phase and group velocities on core radius, numerical aperture, and wavelength. For instance, in the case of circular waveguides, the dependence is on the ratio of the core radius and the wavelength. In practice, the problem of waveguide and chromatic dispersion can be circumvented by the proper design of single-mode fibers so that material dispersion and waveguide dispersion cancel one another at the wavelength of interest.

The total dispersion is the sum total of modal dispersion, chromatic dispersion and waveguide dispersion. For various reasons some components of a pulse of light traveling along an optical fiber move faster and other components move slower. So, a pulse which starts off as a narrow burst of light gets wider because some components race ahead while other components lag behind, rather like the runners in a marathon race.

4. Consequences of Pulse Spreading

Now that we understand the causes of pulse spreading, it is timely to examine the consequences of pulse spreading on optical fiber systems and its impact on communication effectiveness.

a. Limits on Data Rate

The further the pulse travels in the fiber the worse the spreading gets. This is demonstrated in Figure 9.

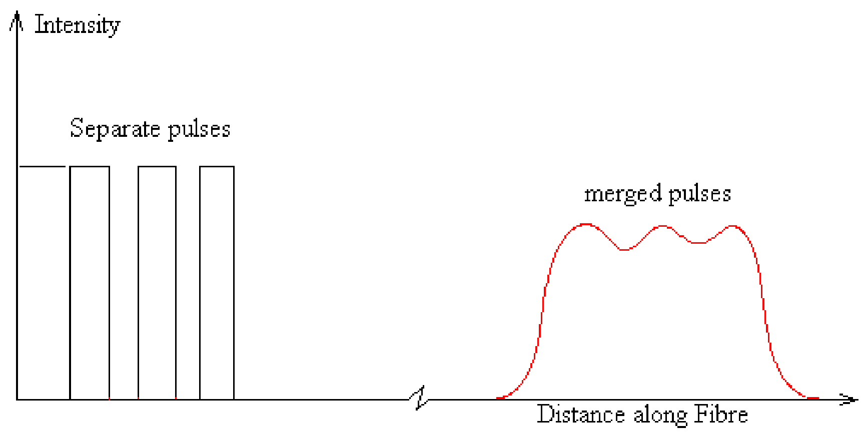

Figure 9. Merging of Pulses in a Fiber.

Pulse spreading limits the maximum data rate which can be sent along a fiber. If signal pulses follow each other too fast then by the time they reach the end fiber they will have merged together and become indistinguishable. This is unacceptable for digital systems which depend on the precise sequence of pulses as a code for information.

b. Limits on Distance

A given length of fiber, as explained above has a maximum data rate which can be sent along it. If we want to increase the data rate for the same type of fiber we can achieve this by decreasing the length of the fiber. Another way of saying this is that for a given data rate there is a maximum distance which the data can be sent.

c. Bandwidth Distance Product (BDP)

We can combine the two ideas above into a single term called the *bandwidth distance product (BDP).* It is the bandwidth of a fiber multiplied by the length of the fiber. The BDP is the bandwidth of a kilometer of fiber and is a constant for any particular type of fiber. For example, suppose a particular type of multimode fiber has a BDP of 20 MHz.km, then 1 km of the fiber would have a bandwidth of 20 MHz, 2 km of the fiber would have a bandwidth of 10 MHz and 5 km of the fiber would have a bandwidth of 4 MHz.

The typical **B.D.P**. of the two types of fibers are as follows:-

Multimode 6 - 25 MHz.km (read as megahertz kilometers)

Single Mode 500 - 1500 MHz.km

G. ADVANTAGES AND DISADVANTAGES OF FIBER OPTICS SYSTEMS

Fiber optic transmission systems offer a wide range of benefits not offered by traditional copper wire or coaxial cable. These include:

- The ability to carry much more information and deliver it with greater fidelity than either copper wire or coaxial cable.
- Fiber optic cable can support much higher data rates, and at greater distances, than coaxial cable, making it ideal for transmission of serial digital data.
- The fiber is immune to virtually all kinds of interference, including lightning, and will not conduct electricity. It can therefore come in direct contact with high voltage electrical equipment and power lines. It will also not create ground loops of any kind.
- As the basic fiber is made of glass, it will not corrode and is unaffected by most chemicals. It can be buried directly in most kinds of soil or exposed to most corrosive atmospheres in chemical plants without significant concern.
- Since the only carrier in the fiber is light, there is no possibility of a spark from a broken fiber. Even in the most explosive of atmospheres, there is no fire hazard, and no danger of electrical shock to personnel repairing broken fibers.
- Fiber optic cables are virtually unaffected by outdoor atmospheric conditions, allowing them to be lashed directly to telephone poles or existing electrical cables without concern for extraneous signal pickup.

- A fiber optic cable, even one that contains many fibers, is usually much smaller and lighter in weight than a wire or coaxial cable with similar information carrying capacity. It is easier to handle and install, and uses less duct space. (It can frequently be installed without ducts.)
- Fiber optic cable is ideal for secure communications systems because it is very difficult to tap but very easy to monitor. In addition, there is absolutely no electrical radiation from a fiber.

Currently, there are 2 chief disadvantages in the deployment of optical fiber systems:

- *Price* - In spite of the fact that the raw material for making optical fibers, sand, is abundant and cheap, optical fibers are still more expensive per meter than copper. In the context of last-mile, the major cost arises from extensive construction works required to replace the current copper wires infrastructures. Having said this, one fiber can carry many more signals than a single copper cable and the large transmission distances mean that fewer expensive repeaters are required.
- *Special Skills* - Optical fibers cannot be joined/spliced together as a easily as copper cable and requires additional training of personnel and expensive precision splicing and measurement equipment

H. AREAS OF APPLICATION

Telecommunication - Optical fibers are now the standard point to point cable link between telephone substations.

Local Area Networks (LAN's) - Multimode fiber is commonly used as the "backbone" to carry signals between the hubs of LAN's from where copper coaxial cable takes the data to the desktop. Fiber links to the desktop, however, are also common.

Cable TV - Domestic cable TV networks use optical fiber because of its very low power consumption.

CCTV - Closed circuit television security systems use optical fiber because of its inherent security.

Optical Fiber Sensors - Many advances have been made in recent years in the use of Optical Fibers as sensors. Gas concentration, chemical concentration, pressure, temperature, and rate of rotation can all be sensed using optical fiber.

I. SUMMARY

In this chapter, the main principle and technology of optical fiber is introduced. Optical Fiber systems are critical components in modern communication as it forms the backbone of Internet. While it is commonly used in MAN and LAN systems, the high cost of replacing existing copper infrastructures wires made it prohibitively difficult to implement optical fiber system in the last miles, thus greatly limiting the bandwidths of SOHO and home users. In a later chapter, we will examine how a company has devised an innovative way to implement optical fiber in the last miles.

III. DIGITAL SUBSCRIBER LINE TECHNOLOGIES

A. INTRODUCTION

A Digital Subscriber Line (DSL) makes use of the current copper infrastructure to supply broadband services. Two modems are required, one at the phone companies' end and one at the subscribers end. DSL technologies have the benefit of transmitting telephone services on the same set of wire as data services. DSL come in many flavors, and are sometimes collectively referred to as xDSL, the x representing the specific type.

For years it has been believed that the upper limit for transmitting data on analog phone lines was 56kb/s. This limit is set using the maximum possible bandwidth. The reason for this limit is that Plain Old Telephone Service (POTS) uses the lower 4 KHz only. The limit imposed by the POTS lines does not take advantage of all the bandwidth available on copper, which is of the order of 1MHz, depending on the distance. The xDSL technologies, on the other hand, take advantage of this difference and use the upper frequencies for data services. Previously this was not possible because of the interference that the data services would cause in the POTS band. Advances in digital signal processing (DSP) have eliminated the near-end crosstalk that results from the use of the upper bandwidth for data. The new DSP technologies allow data and POTS to be transmitted on the same set of copper wires without interfering with each other. DSL technologies were initially tested for use with video on demand (VOD) and interactive television (ITV) services. Lack of a "killer application" for these services and competition from the cable TV industry in these areas forced the telephone companies to look for a different application for their technologies. With the popularity of the World Wide Web and telecommuting on the rise the DSL technologies moved to providing network and phone services to the home.

Other areas where DSL technologies are targeted for are Intranet access, LAN to LAN connections, Frame Relay, ATM Network access, and leased line provisioning.

B. ASYMMETRIC DIGITAL SUBSCRIBER LINE

The most promising of the DSL technologies is ADSL or Asymmetric Digital Subscriber Line. ADSL looks to make the most impact in residential access and the SOHO (Small Office Home Office) market. As the name implies, ADSL is asymmetric, meaning that the downstream bandwidth is higher than the upstream bandwidth. Downstream refers to traffic in the direction towards the subscriber, and upstream refers to data sent from the subscriber back to the network.

Asymmetric Digital Subscriber Line converts existing twisted-pair telephone lines into access paths for multimedia and high-speed data communications. ADSL can transmit up to 6 Mbps to a subscriber, and as much as 832 kbps in both directions. Such rates expand existing access capacity by a factor of 50 or more without new cabling, which is a tremendous advantage. ADSL is literally transforming the existing public information network from one limited to voice, text and low resolution graphics to a powerful, ubiquitous system capable of bringing multimedia, including full motion video, to everyone's home.

1. Capabilities of ADSL

It is forecasted that ADSL will play a crucial role over the next ten or more years as telephone companies, and other service providers, enter new markets for delivering information in video and multimedia formats. New broadband cabling will take decades to reach all prospective subscribers. But success of these new services will depend upon reaching as many subscribers as possible during the first few years. By bringing movies, television, video catalogs, remote

CD-ROMs, corporate LANs, and the Internet into homes and small businesses, ADSL will make these markets viable, and profitable, for telephone companies and application suppliers alike.

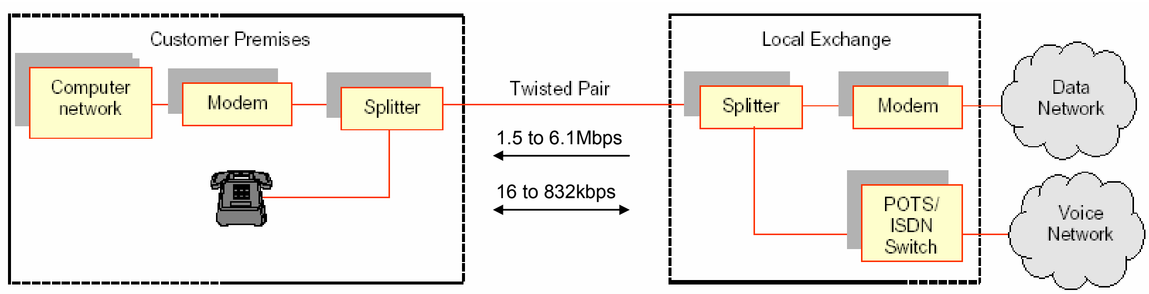

Figure 10. ADSL Configuration (From [Bouy2001])

An ADSL configuration connects an ADSL modem on each end of a twisted-pair telephone line, creating three information channels - a high speed downstream channel, a medium speed duplex channel, depending on the implementation of the ADSL architecture, and a POTS or an Integrated Services Digital Network (ISDN) channel. The POTS/ISDN channel is split off from the digital modem by filters, thus guaranteeing uninterrupted POTS/ISDN, even if ADSL fails. The high speed channel ranges from 1.5 to 6.1 Mbps, while duplex rates range from 16 to 832 kbps. Each channel can be sub-multiplexed to form multiple, lower rate channels, depending on the system.

ADSL modems provide data rates consistent with North American and European digital hierarchies and can be purchased with various speed ranges and capabilities. The minimum configuration provides 1.5 or 2.0 Mbps downstream and a 16 kbps duplex channel; others provide rates of 6.1 Mbps and 64 kbps duplex. Products with downstream rates up to 8 Mbps and duplex rates up to 640 kbps are available today. ADSL modems will accommodate ATM transport with variable rates and compensation for ATM overhead, as well as IP protocols.

Downstream data rates depend on a number of factors, including the length of the copper line, its wire gauge, presence of bridged taps, and cross-coupled interference. Line attenuation increases with line length and frequency, and decreases as wire diameter increases. Ignoring bridged taps, ADSL will perform as follows:

Data Rate	Wire Gauge (Wire Size)	Distance
1.5 to 2 Mbps	24 AWG (0.5mm)	18,000 ft (5.5km)
	26 AWG (0.4mm)	15,000 ft (4.6km)
6.1 Mbps	24 AWG (0.5mm)	12,000 ft (3.7km)
	26 AWG (0.4mm)	9,000 ft (2.7km)

Table 2. ADSL Data Rate and Distances

While the measure varies from provider to provider, these capabilities can cover up to 95% of a loop plant depending on the desired data rate. Customers beyond these distances can be reached with fiber-based Digital Loop Carrier (DLC) systems. As these DLC systems become commercially available, it may not be inconceivable that telephone companies can offer virtually ubiquitous access in a relatively short time.

Many applications enabled by ADSL involve digital compressed video. As a real time signal, digital video cannot use link or network level error control procedures commonly found in data communications systems. ADSL modems therefore incorporate forward error correction that dramatically reduces errors caused by impulse noise. Error correction on a symbol-by-symbol basis also reduces errors caused by continuous noise coupled into a line.

2. ADSL Technology

ADSL depends upon advanced digital signal processing and creative algorithms to squeeze as much information as possible through twisted-pair telephone lines. In addition, many advances have been required in transformers, analog filters, and A/D converters. Long telephone lines may attenuate signals at one megahertz (the outer edge of the band used by ADSL) by as much as 90 dB, forcing analog sections of ADSL modems to work very hard to realize large dynamic ranges, separate channels, and maintain low noise figures.

To create multiple channels, ADSL modems divide the available bandwidth of a telephone line in one of two ways -- Frequency Division Multiplexing (FDM) or Echo Cancellation. FDM is the simultaneous transmission of multiple separate signals through a twisted copper wire by modulating, at the transmitter, the separate signals into separable frequency bands, and adding those results linearly either before transmission or within the medium. While thus combined, all the signals may be amplified, conducted, translated in frequency and routed toward a destination as a single signal, resulting in economies which are the motivation for multiplexing. Apparatus at the receiver separates the multiplexed signals by means of frequency passing or rejecting filters, and demodulates the results individually, each in the manner appropriate for the modulation scheme used for that band or group. FDM assigns one band for upstream data and another band for downstream data. The downstream path is then divided by time division multiplexing into one or more high speed channels and one or more low speed channels. The upstream path is also multiplexed into corresponding low speed channels. Echo Cancellation is a process which removes unwanted echoes from the signal on a telephone line. Echoes are usually caused by impedance mismatches along an analogue line. Echo cancellation assigns the upstream band to over-lap the downstream, and separates the two by means of local echo cancellation, a technique well know in

V.32 and V.34 modems. With either technique, ADSL splits off a 4 kHz region for POTS at the DC end of the band (see Figure 11)

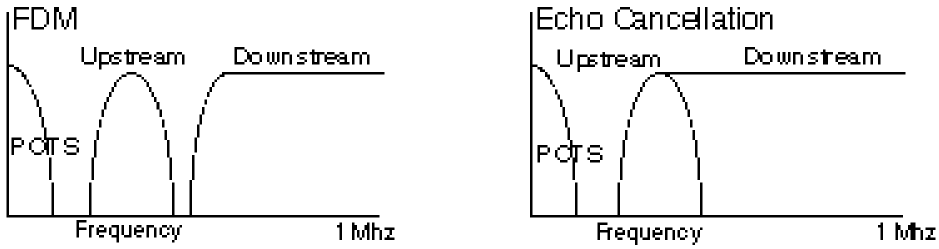

Figure 11. FDM and Echo Cancellation (From [Dsl2001])

An ADSL modem organizes the aggregate data stream created by multiplexing downstream channels, duplex channels, and maintenance channels together into blocks, and attaches an error correction code to each block. The receiver then corrects errors that occur during transmission up to the limits implied by the code and the block length. The unit may, at the users' option, also create super-blocks by interleaving data within sub-blocks; this allows the receiver to correct any combination of errors within a specific span of bits. This allows for effective transmission of both data and video signals alike.

3. ADSL Standards and Associations

The American National Standards Institute (ANSI), working group T1E1.4, approved the first ADSL in 1995. It supported data rates up to 6.1 Mbps (ANSI Standard T1.413). The European Technical Standards Institute (ETSI) contributed an Annex to T1.413 to reflect European requirements. T1.413 (Issue I) was limited to a single terminal interface at the premise end. Issue II (T1.413i2), approved in 2001, expanded the standard to include a multiplexed interface at the premise end, protocols for configuration and network management, and other improvements.

Work towards an Issue III was ultimately submitted to the international standards body, the ITU-T, to develop the international standards for ADSL. The

ITU-T standards for ADSL are most commonly referred to as G.lite (G.992.2) and G.dmt (G.992.1)–both of which are approved in June of 1999. Having an international standard has aided in moving towards vendor interoperability and service provider acceptance, further increasing deployment, and ultimately availability to the consumer. The ATM Forum has recognized ADSL as a physical layer transmission protocol for unshielded twisted pair media.

The DSL Forum was formed in December of 1994 to promote the DSL concept and facilitate development of DSL system architectures, protocols, and interfaces for major DSL applications. The DSL Forum has expanded its efforts to address marketing issues surrounding awareness, and enabling high-speed applications via DSL. The DSL Forum has approximately 340 members representing service providers, equipment manufacturers, and content developers from throughout the world.

C. VERY-HIGH-RATE DIGITAL SUBSCRIBER LINE

One of the enabling technologies for fiber-to-the-neighborhood (FTTN) is Very high rate Digital Subscriber Line, or VDSL. VDSL transmits high speed data over short reaches of twisted-pair copper telephone lines, with a range of speeds depending upon actual line length. The maximum downstream rate under consideration is between 51 and 55 Mbps over lines up to 1000 ft (300 meters) in length (see Figure 12). Downstream speeds as low as 13 Mbps over lengths beyond 4000 ft (1500 meters) are also a possibility. Upstream rates in early models will be asymmetric, just like ADSL, at speeds from 1.6 to 2.3 Mbps. Both data channels will be separated in frequency from bands used for POTS and ISDN, enabling service providers to overlay VDSL on existing services. At present the two high speed channels will also be separated in frequency. As needs arise for higher speed upstream channels or symmetric rates, VDSL systems may need to use echo cancellation.

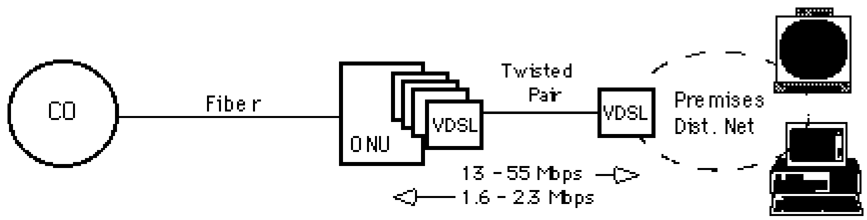

Figure 12. VDSL System (From [Dsl2001])

This section discusses VDSL in terms of projected capabilities, underlying technology, and outstanding issues. It follows with a survey of standards activity and a suggestion that VDSL and ADSL together provide network providers an excellent combination for evolving a full service network while offering virtually ubiquitous access to most PC applications and interactive TV applications as the network develops.

1. VDSL Projected Capabilities

While VDSL has not achieved the degree of definition of ADSL, it has advanced far enough to discuss realizable goals, beginning with data rate and range. Downstream rates derive from submultiples of the Synchronous Optical Network (SONET) and Synchronous Digital Hierarchy (SDH) canonical speed of 155.52 Mbps. Each rate has a corresponding target range:

Data Rate	Range (feet)	Range (meter)
12.96 - 13.8 Mb/s	4500	1500
25.92 - 27.6 Mb/s	3000	1000
51.84 - 55.2 Mb/s	1000	300

Table 3. Proposed Data Rates for VDSL

Upstream rates under discussion fall into three general ranges: 1.6 - 2.3 Mbps, 19.2 Mbps, and equal to downstream rate (symmetric).

Early versions of VDSL will almost certainly incorporate the slower asymmetric rate. Higher upstream and symmetric configurations may only be possible for very short lines. Like ADSL, VDSL must transmit compressed video, a real time signal unsuited to error retransmission schemes used in data communications. To achieve error rates compatible with compressed video, VDSL will have to incorporate Forward Error Correction (FEC) with sufficient interleaving to correct all errors created by impulsive noise events of some specified duration. Interleaving introduces delay, in the order of 40 times the maximum length correctable impulse.

Data in the downstream direction will be broadcast to every customer premises equipment (CPE) in a premise or be transmitted to a logically separated hub that distributes data to addressed CPE based on cell or TDM multiplexing within the data stream itself. Upstream multiplexing is more difficult. Systems using a passive Network Termination (NT) must insert data onto a shared medium, either by a form of TDMA or a form of FDM. TDMA may use a species of token control called cell grants passed in the downstream direction from the Optical Network Unit (ONU) modem, or contention, or both (contention for unrecognized devices, cell grants for recognized devices). FDM gives each CPE its own channel, obviating a MAC protocol, but either limiting data rates available to any one CPE or requiring dynamic allocation of bandwidth and inverse multiplexing at each CPE. Systems using active NT transfer the upstream collection problem to a logically separated hub that would use (typically) Ethernet or ATM protocols for upstream multiplexing.

Migration and inventory considerations dictate VDSL units that can operate at various (preferably all) speeds with automatic recognition of a newly connected device to a line or a change in speed. Passive network interfaces need to have hot insertion, where a new VDSL premises unit can be put on the line without interfering with the operation of other modems.

2. VDSL Technology

VDSL technology will resemble ADSL to a large degree, although ADSL must face much larger dynamic ranges and is considerably more complex as a result. To be commercially viable, VDSL must be lower in cost and consume less power than ADSL, and premises VDSL units may have to implement a physical layer media access control for multiplexing upstream data.

Four line codes have been proposed for VDSL:

a. Carrierless AM/PM (CAP)

CAP is a version of suppressed carrier Quadrature Amplitude Modulation (QAM). For passive NT configurations, CAP would use Quadrature Phase Shift Keying (QPSK) upstream and a type of TDMA for multiplexing (although CAP does not preclude an FDM approach to upstream multiplexing).

b. Discrete Multi-tone (DMT)

DMT is a multi-carrier system using Discrete Fourier Transforms to create and demodulate individual carriers. For passive NT configurations, DMT would use FDM for upstream multiplexing (although DMT does not preclude a TDMA multiplexing strategy).

c. Discrete Wavelet Multi-tone (DWMT)

DWMT is a multi-carrier system using Wavelet Transforms to create and demodulate individual carriers. DWMT also uses FDM for upstream multiplexing, but also allows TDMA.

d. Simple Line Code (SLC)

SLC is a version of four-level base band signaling that filters the based band and restores it at the receiver. For passive NT configurations, SLC would most likely use TDMA for upstream multiplexing, although FDM is possible.

Early versions of VDSL will use frequency division multiplexing to separate downstream from upstream channels and both of them from POTS and ISDN. Echo cancellation may be required for later generation systems featuring symmetric data rates. A rather substantial distance, in frequency, will be maintained between the lowest data channel and POTS to enable very simple and cost-effective POTS splitters. Normal practice would place the downstream channel above the upstream channel. However, the Digital Audio-Visual Council (DAVIC) specification reverses this order to enable premises distribution of VDSL signals over coaxial cable systems.

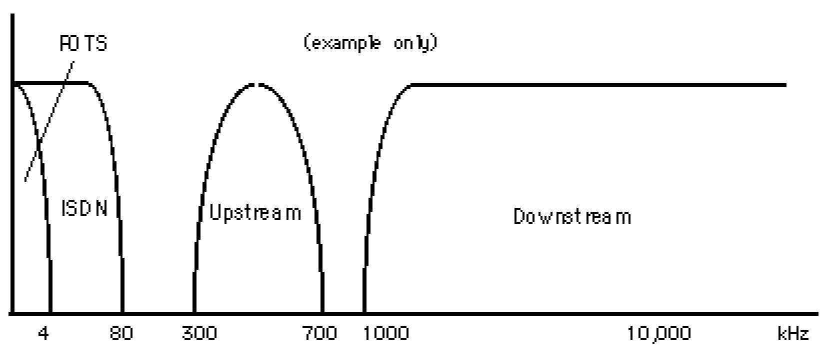

Figure 13. Frequency Division Multiplexing (From [Dsl2001])

Forward Error Control (FEC) may use a form of Reed Solomon[1] coding and optional interleaving to correct bursts of errors caused by impulse noise. An outstanding question is whether FEC overhead (in the range of 8%) will be taken from the payload capacity or added as an out-of-band signal. The former reduces payload capacity but maintains nominal reach, while the latter retains the nominal payload but suffers a small reduction in reach. ADSL puts FEC overhead out of band.

[1]Cyclical method of error correction first published in the June 1960 issue of Journal of the Society for Industrial and Applied Mathematics in a paper titled "Polynomial Codes over Certain Finite Fields" by I.S. Reed and G. Solomon

If the premises VDSL unit comprises the network termination (an active NT, as shown in Figure 14), then the means of multiplexing upstream cells or data channels from more than one CPE into a single upstream becomes the responsibility of the premises network. The VDSL unit simply presents raw data streams in both directions. One type of premises network involves a star connecting each CPE to a switching or multiplexing hub; such a hub could be integral to the premises VDSL unit.

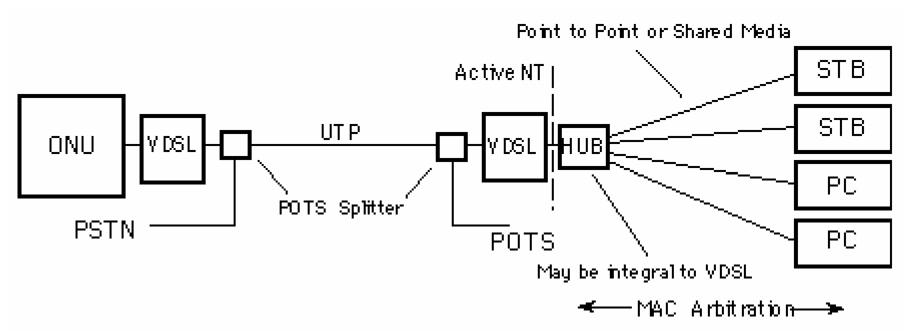

Figure 14. Active Network Termination (From [Dsl2001])

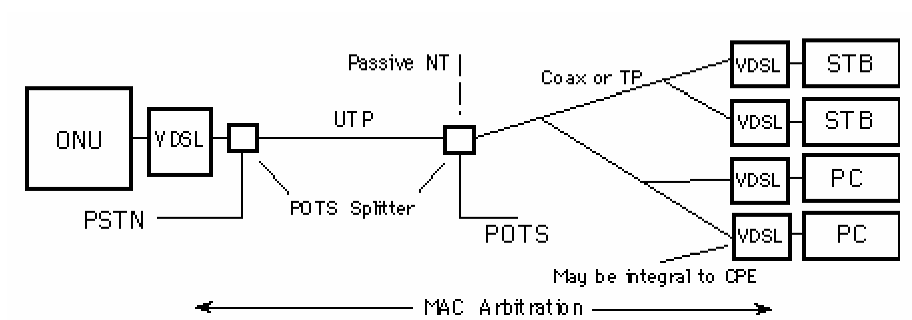

Figure 15. Passive Network Termination (From [Dsl2001])

In a passive NT configuration (Figure 15), each CPE has an associated VDSL unit. (A passive NT does not conceptually preclude multiple CPE per VDSL, but then the question of active versus passive NT becomes a matter of ownership, not a matter of wiring topology and multiplexing strategies.) Now the upstream channels for each CPE must share a common wire. While a collision detection system could be used, the desire for guaranteed bandwidth indicates one of two solutions. One invokes a cell-grant protocol in which downstream frames generated at the ONU or further up the network contain a few bits that grant access to specific CPE during a specified period subsequent to receiving a frame. A granted CPE can send one upstream cell during this period. The transmitter in the CPE must turn on, send a preamble to condition the ONU receiver, send the cell, then turn itself off. The protocol must insert enough silence to let line ringing clear. One construction of this protocol uses 77 octet intervals to transmit a single 53 octet cell. A second method divides the upstream channel into frequency bands and assigns one band to each CPE. This method has the advantage of avoiding any media access control with its associated overhead (although a multiplexor must be built into the ONU), but either restricts the data rate available to any one CPE or imposes a dynamic inverse multiplexing scheme that lets one CPE send more than its share for a period. The latter would look a great deal like a media access control protocol, but without the lost of bandwidth associated with carrier detect and clear for each cell.

3. VDSL Issues

VDSL is still in the definition stage; some preliminary products exist, but not enough is known yet about telephone line characteristics, RFI emissions and susceptibility, upstream multiplexing protocols, and information requirements to frame a set of definitive, standardizable properties. One large unknown is the maximum distance that VDSL can reliably realize for a given data rate. This is unknown because real line characteristics at the frequencies required for VDSL are speculative and items such as short bridged taps or unterminated extension lines in homes, which have no affect on telephony, ISDN or ADSL, may have very detrimental affects on VDSL in certain configurations. Furthermore, VDSL invades the frequency ranges of amateur radio, and every above-ground telephone wire is an antenna that both radiates and attracts energy in amateur radio bands. Balancing low signal levels to prevent emissions that interfere with amateur radio with higher signals needed to combat interference by amateur radio could be the dominant factor in determining line reach.

A second dimension of VDSL that is far from clear is the services environment. It can be assumed that VDSL will carry information in ATM cell format for video and asymmetric data communications, although optimum downstream and upstream data rates have not been ascertained. What is harder to assess is the need for VDSL to carry information in non-ATM formats (such as conventional Plesiochronous Digital Hierarchy - PDH structures) and the need for symmetric channels at broadband rates (above T1/E1). VDSL will not be completely independent of upper layer protocols, particularly in the upstream direction where multiplexing data from more than one CPE may require knowledge of link layer formats (that is, ATM or not).

A third difficult subject is premises distribution and the interface between the telephone network and CPE. Cost considerations favor a passive network interface with premises VDSL installed in CPE and upstream multiplexing handled much like local area network busses. System management, reliability, regulatory constraints, and migration favor an active network termination, just like ADSL and ISDN, which can operate like a hub, with point-to-point or shared media distribution to multiple CPE on premises wiring that is independent and physically isolated from network wiring.

Ultimately, cost is a consideration and cannot be ignored. Small ONUs must spread common equipment costs, such as fiber links, interfaces, and equipment cabinets, over a small number of subscribers compared to Hybrid/Fiber Coax (HFC). VDSL therefore has a much lower cost target than ADSL, which may connect directly from a wiring center, or cable modems, which also have much lower common equipment costs per user. Furthermore, VDSL for passive NTs may (only may) be more expensive than VDSL for active NTs, but the elimination of any other premises network electronics may make it the most cost effective solution, and highly desired, despite the obvious benefits of an active NT.

4. VDSL Standard Status

At present, five standards organizations/forums have begun work on VDSL: ANSI group T1E1.4, ETSI, DAVIC, the ATM Forum, and the ADSL Forum.

T1E1.4 - The U.S. ANSI standards group T1E1.4 has just begun a project for VDSL, making a first attack on system requirements that will evolve into a system and protocol definition.

ETSI - The European Telecommunications Standards Institute (ETSI) has a VDSL standards project, under the title High Speed (metallic) Access Systems (HSAS), and has compiled a list of objective, problems, and requirements. Among its preliminary findings are the need for an active NT and payloads in multiples of SDH Virtual Container VC-12, or 2.3 Mbps. ETSI works very closely with T1E1.4 and The ADSL Forum, with significant overlapping attendees.

DAVIC - The Digital Audio-Visual Council (DAVIC) has taken the earliest position on VDSL. Its first specification, finalized in 1995 defines a line code for downstream data, another for upstream data, and a media access control for upstream multiplexing based on TDMA over shared wiring. DAVIC is only specifying VDSL for a single downstream rate of 51.84 Mbps and a single upstream rate of 1.6 Mbps over 300 meters or less of copper. The proposal assumes, and is driven to a large extent by, a passive NT, and further assumes premises distribution from the NT over new coaxial cable or new copper wiring.

The ATM Forum - The ATM Forum has defined a 51.84 Mbps interface for private network UNIs and a corresponding transmission technology. It has also taken up the question of premises distribution and delivery of ATM all the way to premises over the various access technologies described above.

The ADSL Forum - The ADSL Forum has just begun consideration of VDSL. In keeping with its charter, the Forum will address network, protocol, and architectural aspects of VDSL for all prospective applications, leaving line code and transceiver protocols to T1E1.4 and ETSI and higher layer protocols to organizations such as The ATM Forum and DAVIC.

5. Comparison with ADSL

VDSL has an odd technical resemblance to ADSL. VDSL achieves data rates nearly ten times greater than ADSL, but ADSL is the more complex transmission technology, in large part because ADSL must contend with much larger dynamic ranges than VDSL. However, the two are essentially cut from the same cloth. ADSL employs advanced transmission techniques and forward error correction to realize data rates from 1.5 to 6.1 Mbps over twisted-pair ranging to 18,000 feet; VDSL employs the same advanced transmission techniques and forward error correction to realize data rates from 13 to 55 Mbps over twisted pair ranging to 4500 feet. Indeed, the two can be considered a continuum, a set of transmission tools that delivers about as much data as theoretically possible over varying distances of existing telephone wiring.

VDSL is clearly a technology suitable for a full service network (assuming "full service" does not imply more than two high definition televisions - HDTV channels over the highest rate VDSL). It is equally clear that telephone companies cannot deploy ONUs overnight, even if all the technology were available. ADSL may not be a "full service network" technology, but it has the singular advantage of offering service over lines that exist today, and ADSL products are closer in time than VDSL. Many new services being contemplated today can be delivered at speeds at or below T1/E1 rates -- video conferencing, Internet access, video on demand, remote LAN access. For such services, ADSL/VDSL provides an ideal combination for network evolution. On the longest lines, ADSL delivers a single channel. As line length shrinks, either from natural proximity to a central office or deployment of fiber-based access nodes, ADSL and VDSL simply offer more channels, and capacity for services that require rates above T1/E1 (such as digital live television or virtual CD-ROM access).

D. HIGH-DATA-RATE DIGITAL SUBSCRIBER LINE

HDSL, one of the earliest forms of DSL, is used for wideband digital transmission within a corporate site and between the telephone company and a customer. The main characteristic of HDSL is that it is symmetrical: an equal amount of bandwidth is available in both directions. HDSL can carry as much on a single wire of twisted-pair cable as can be carried on a T1 line (up to 1.544 Mbps) in North America or an E1 line (up to 2.048 Mbps) in Europe over a somewhat longer range than DSL and is considered an alternative to a T1 or E1 connection. HDSL's operating range is about 12,000 feet, and it is possible to extend that by using repeaters along the line to the customer. HDSL is mostly used to deploy PBX network connections, inter-exchange POP's (Point Of Presence), and directly connecting servers to the Internet. HDSL has its place in that market while ADSL can provide a better service to homes and small business that use the web and client server technologies.

E. SINGLE-LINE DIGITAL SUBSCRIBER LINE

Similar to HDSL, Single-line Digital Subscriber Line (also know as Symmetric Digital Subscriber Line or SDSL) delivers the same 1.544 Mb/s, but it does it on a single set of twisted pair of copper. This feature limits SDSL reach to 10,000 feet. SDSL could take hold in niche markets like residential video conferencing or connecting LAN's over short distances.

F. RATE ADAPTIVE DIGITAL SUBSCRIBER LINE

RADSL is derived from ADSL technologies with some added features. RADSL automatically adjusts line speed based on the condition of the line. In areas where there is a large variance in the distance between the central office and the subscribers RADSL helps to provide a more consistent service for it's subscribers by taking the uncertainties of line conditions out of the equation when setting up a DSL connection. RADSL can adjust line speed based on the gauge of the wire, the distance between subscriber and the central office, and the condition of the line. It also takes care of fluctuations that the weather can induce into the line.

G. SUMMARY

Table 4 shows the characteristics of various DSL Technologies and highlights the key differences in terms of bandwidth (upstream and downstream), range, media and symmetry.

DSL	Upstream Bandwidth	Downstream Bandwidth	Range (ft)	Media	Symmetry
ADSL	16 to 832kbps	1.5 to 6.1Mbps	18,000	Single Twisted Pair	Asymmetric
VDSL	1.6 to 2.3Mbps	13 – 55 Mbps	1,000 – 4,500	Single Twisted Pair	Both
HDSL	1.544Mbps	1.544Mbps	12,000	Two Twisted Pairs	Symmetric
SDSL	1.544Mbps	1.544Mbps	10,000	Single Twisted Pair	Symmetric
RADSL	Varies within ADSL range	Varies within ADSL range	18,000	Single Twisted Pair	Asymmetric

Table 4. xDSL Comparison (From [Saba2000])

Spurned by Internet growth and the convergence of television with the personal computer, high bandwidth data services are in high demand in homes everywhere. DSL technologies look to be an economically promising alternative to today's current 56 kb/s modems that promise to bring much higher data rates to the home. Two industries race for the business of the data hunger consumer, the telephone companies and cable companies. Phone companies will make use of their existing copper and more recent transition to digital networks as a way to leverage their current infrastructure to meet the high speed demands of their customers. In the near future, it is not inconceivable that broadband services may become as commonplace and necessary as today's telephone service.

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IV. FREE SPACE OPTICS

A. INTRODUCTION

Free Space Optics (FSO) is a technology extensively researched to provide broadband to homes and SOHO. While fiber-optic communication has gained wide acceptance in the telecommunications industry, FSO communication is still relatively new. FSO enables similar bandwidth transmission abilities as fiber optics, using similar optical transmitters and receivers and even enabling WDM-like technologies to operate through free space. Instead of radio waves, FSO uses light pulses to send packetized data through air to provide optical bandwidth connections. Currently, Free Space Optics are capable of up to 2.5 Gbps of data, voice and video communications through the air, allowing optical connectivity without requiring fiber-optic cable or securing spectrum licenses. Free Space Optics (FSO) requires light, which can be focused by using either light emitting diodes (LEDs) or lasers (light amplification by stimulated emission of radiation). The use of lasers is a simple concept similar to optical transmissions using fiber-optic cables; the only difference is the medium. Because light travels through air at a higher speed than it does through glass, FSO has often been dubbed as optical communications technology at the speed of light.

The technology behind Free Space Optics (FSO) is relatively simple. It is based on line–of-sight connectivity between FSO units, each consisting of an optical transceiver with a laser transmitter and a receiver to provide full duplex (bi-directional) capability. These devices may be mounted on the rooftops, wall or even windows of buildings. Each FSO unit uses a high-power optical source (i.e. laser), plus a lens that transmits light through the atmosphere to another lens receiving the information. The receiving lens connects to a high-sensitivity receiver via optical fiber. FSO technology requires no spectrum licensing. FSO is easily upgradeable, and its open interfaces support equipment from a variety of vendors, which helps service providers protect their investment in embedded telecommunications infrastructures.

B. HISTORY OF FREE SPACE OPTICS

Originally used by the military and NASA, FSO has been used for more than 30 years to provide fast communication links in remote locations. The idea behind 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 through 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 obtained using existing radio frequency (RF) solutions. However, many of these programs did not full materialize due to funding cuts and changing priorities.

The prominence placed on FSO research diminishes somewhat when Corning researchers Robert Maurer, Donald Keck and Peter Shultz developed the first optical fiber capable of transmitting information over long distances. This prompted physicists to focus more on the properties of optical cable. While the study of optical transmissions through the air continued, the attention of 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. FSO 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. OPERATION OF FSO

FSO involves the optical transmission of voice, video, and data using air as the medium of transmission as opposed to fiber optic cable. 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 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. While the 1300nm frequency is commonly used in fiber optics, it is not popular in FSO as it has poor transmission characteristics through atmospheric conditions. Of the two operating frequency range, the 1500nm laser is better in terms of power, distance and eye safety. Infrared (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.

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 850 nm. The smaller wavelength (850nm) is about one tenth the price of the larger (1550nm) wavelength to manufacture. For this cost reason, the 850nm frequency range is still in use.

2. FSO Transceiver

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. Figure 16 below shows a typical link head.

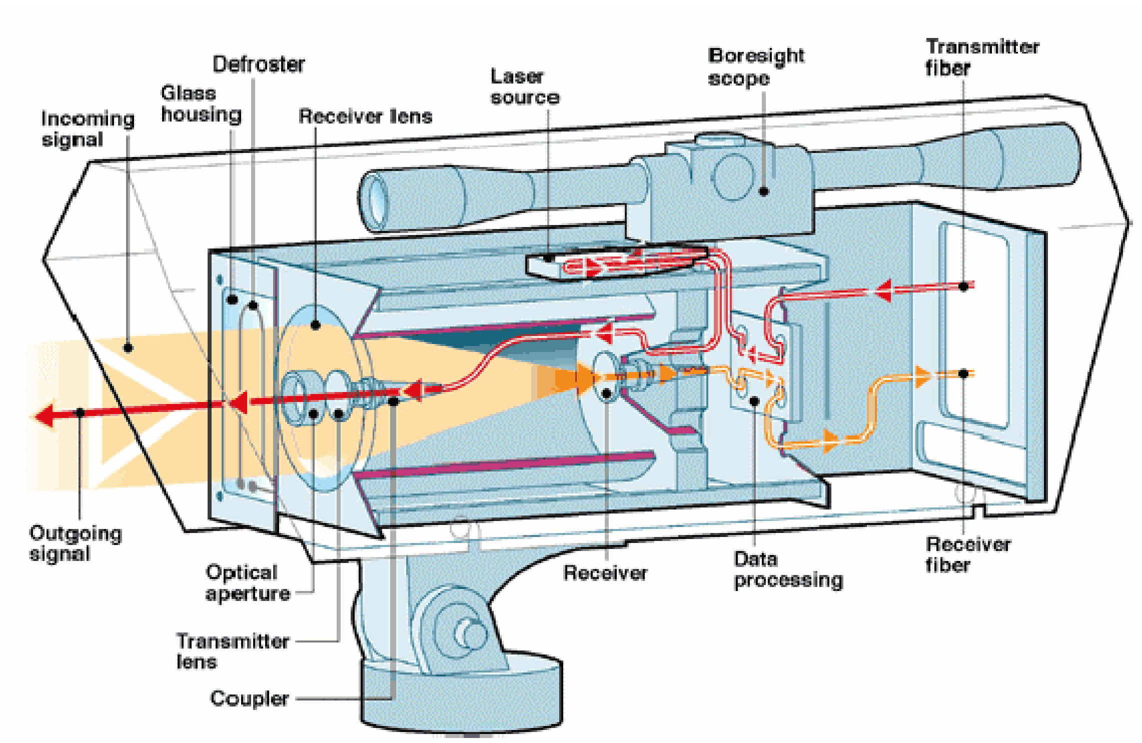

Figure 16. A typical link head for FSO (From [Ligh2003])

The functions of each component in a link head is summarized in the Figure 17. 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.

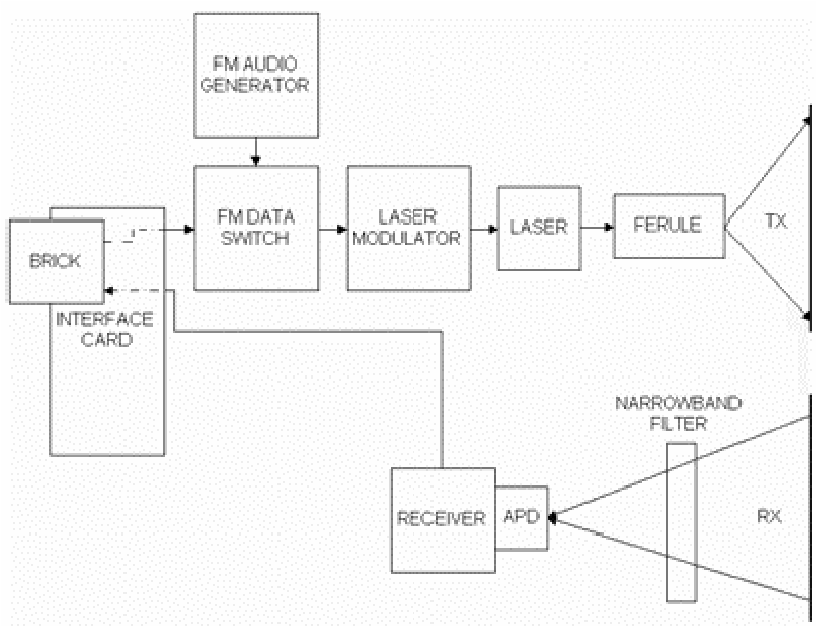

Figure 17. Block Diagram of the Transceiver (From [Will2002])

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.

FM/Data Switch - The FM Data switch allows the unit to be switched into FM mode via the alignment module (FM audio generator), all owing 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.

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.

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 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.

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.

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. ADVANTAGES OF USING FSO

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.

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. FSO utilizes 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.

High Speed Broadband Access - 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 1.25Gbps, throughputs of hundreds of Giga-bit per second are possible in the future.

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 18.

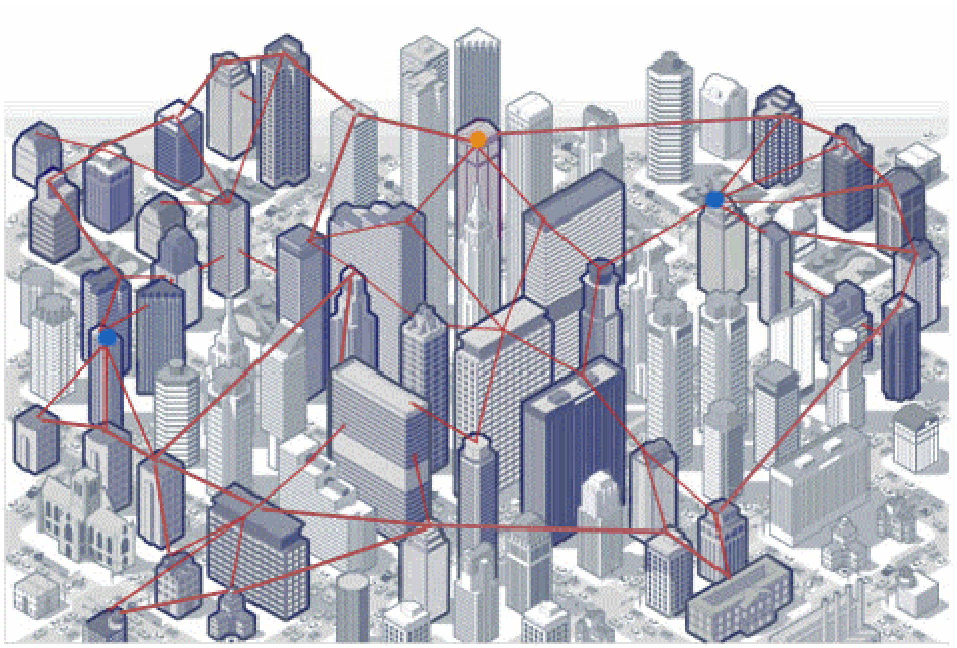

Figure 18. Bypassing Copper Wire Infrastructure (From [Harr2001])

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 on-site service calls or "truck-rolls".

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. CHALLENGES OF FSO IMPLEMENTATION

Fiber-optic cable and FSO share many similarities. However, there is a difference in how each technology transmits information. While fiber uses a relatively predictable medium that is subject to outside disturbances from wayward construction backhoes, gnawing rodents and even sharks when deployed under sea, FSO uses an open medium (the atmosphere) that is subject to its own potential outside disturbances. Networks with FSO must be designed to counter the atmosphere, which can affect an FSO system's capacity. FSO is also a line-of-sight technology and interconnecting points must be free from physical obstruction and able to "see" each other. Despite the advantages offered by FSO technology, all potential disturbances must be addressed through appropriate network design and planning.

Fog - The major challenge to FSO communications is fog. Rain and snow have little effect on FSO, but fog is different. Fog is vapor composed of water droplets, which are only a few hundred microns in diameter but can modify light characteristics or completely hinder the passage of light through a combination of absorption, scattering and reflection. The primary way to counter fog when deploying FSO is via a network design which shortens FSO link distances and adds network redundancies. FSO installations in foggy cities such as San Francisco have successfully achieved carrier-class reliability. The following table (Table 5) 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 5. Impact of Fog and Bad Weather on the Operational Distance of a Free Space Optic System. (From [Spra2002])

Absorption - Absorption occurs when suspended water molecules in the terrestrial atmosphere extinguish photons. This causes a decrease in the power density (attenuation) of the FSO beam and directly affects the availability of a system. Absorption occurs more readily at some wavelengths than others. However, the use of appropriate power, based on atmospheric conditions, and use of spatial diversity (multiple beams within an FSO unit) helps maintain the required level of network availability.

Scattering - Scattering is caused when the wavelength collides with the scatterer. The physical size of the scatterer determines the type of scattering. When the scatterer is smaller than the wavelength, this is known as Rayleigh scattering. When the scatterer is of comparable size to the wavelength, this is known as Mie scattering. When the scatterer is much larger than the wavelength, this is known as non-selective scattering. Unlike absorption, there is no loss of energy in scattering, only a directional redistribution of energy that may have significant reduction in beam intensity for longer distances.

Physical obstructions - Flying birds can temporarily block a single beam, but this tends to cause only short interruptions, and transmissions are easily and automatically resumed. Multi-beam systems (spatial diversity) can be employed to address this issue, as well as other atmospheric conditions, to provide for greater availability.

Building sway/seismic activity - The movement of buildings can upset receiver and transmitter alignment.

Scintillation: Heated air rising from the earth or man-made devices such as heating ducts creates temperature variations among different air pockets. This can cause fluctuations in signal amplitude which leads to "image dancing" at the FSO receiver end.

Refractive turbulence: Refractive turbulence causes two primary effects on optical beams, namely Bean wander and Beam spreading. Beam wander is caused by turbulent eddies that are larger than the beam, while beam spreading occurs as light propagates through the atmosphere.

Safety - To those unfamiliar with FSO, safety is often a concern because the technology uses lasers for transmission. This concern, however, is based on perception more than reality. The proper use and safety of lasers have been discussed since FSO devices first appeared in laboratories more than two decades ago. The two major concerns involve human exposure to laser beams (which present much more danger to the eyes than any other part of the human body) and high voltages within the laser systems and their power supplies. Standards have been set for laser safety and performance.

F. SUMMARY

Free Space Optics is a promising technology that has the potential of solving the last mile problem. The primary focus now is getting high-bandwidth to office buildings close to where fiber optic cables are already laid. This new technology changes the business model from “sell then build” to “build then sell”, representing a paradigm shift and a fundamental shift in the mindset. High-bandwidth wireless optical networks provide high availability with short automatic tracking links and sometimes multiple paths to customers. It is fast and easy to deploy compared to other technologies available. Recalibration is not usually required since there is a tracking system built in the nodes, but if any link fails the nodes may need to be investigated. There is no additional planned or scheduled maintenance for most systems except battery replacement every few years. It may be possible to make this technology cheaper and smaller in order to provide a solution for individual homes and smaller businesses in the last mile. Nodes use all the current technologies and come in many varying topologies. The initial research shows that it might be difficult today to achieve a FSO link to each home in the last mile. These technologies work well for buildings close to fiber optic cables, usually 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 application mature, FSO may become a viable solution for serving individual homes and businesses in the last mile.

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V. WIRELESS LOCAL LOOP

A. INTRODUCTION

Traditionally the provision of voice and data communications to the end user over the local loop (subscriber loop) has been provided by wired systems. For residential subscribers, twisted copper pair had been and continues to be the standard means of connection. As subscribers demand greater capacity, particularly to support Internet use, traditional twisted pair technology has become inadequate. In recent years there has been increasing interest shown in wireless technologies for subscriber access, as an alternative to traditional twisted-pair local loop. These approaches are generally referred to as wireless local loop (WLL), or fixed-wireless access. Also known as radio in the loop (RITL) or fixed-radio access (FRA), WLL is a system that connects subscribers to the public switched telephone network (PSTN) using radio signals as a substitute for copper for all or part of the connection between the subscriber and the switch. This includes cordless access systems, proprietary fixed radio access, and fixed cellular systems. In this chapter, we examine some of the issue confronting WLL technologies and an evolving standard for WLL known as IEEE 802.16.

B. WLL CONFIGURATION

Figure 19 illustrates a simple Wireless Local Loop configuration [Stal2002]. A WLL provider services one of more cells. Each cell includes a base station antenna, mounted on top of a tall building or tower. Individual subscribes have a fixed antenna mounted on a building or pole that has an unobstructed line of sight to the base station antennas. From the base station, there is a link, which may be either wired or wireless, to a switching centre. The switching center is typically a telephone company local office, which provides connections to the local and long distance telephone networks. An internet service provider (ISP) may be collocated at the switch or connected to the switch by a high speed link.

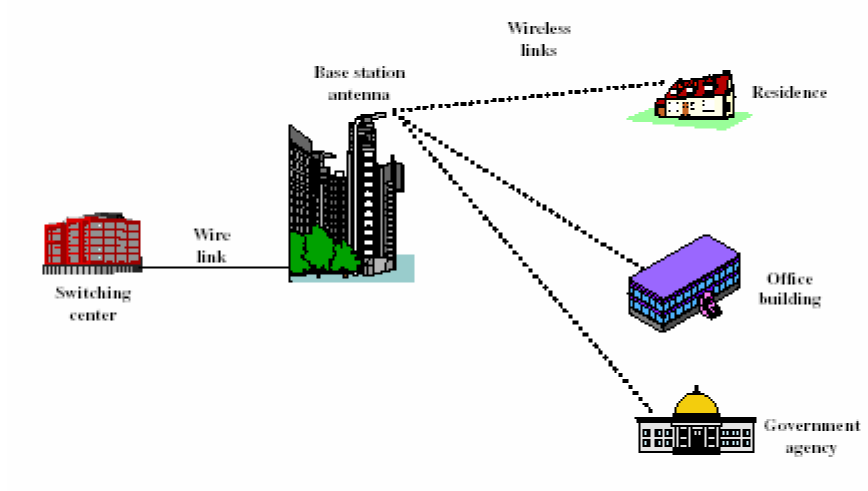

Figure 19. WLL Configuration (From [Stall2002])

Figure 19 depicts a two-level hierarchy. More complex configurations have also been implemented, in which a base station may serve a number of sub-ordinates base station antennas, each of which supports a number of subscribers.

C. IEEE 802.16 STANDARD

With the growing interest in WLL services, a need was recognized within the industry to develop standards for this service. To provide a standardized approach to WLL, the IEEE 802 committee set up the IEEE802.16 working group in 1999 to develop broadband wireless standards. An IEEE802.16 wireless service provides a communications path between a subscriber site and a core network (the network to which 802.16 is providing access). Examples of a core network are the public telephone network and the Internet.

IEEE 802.16 standards are concerned with the air interface between a subscriber's transceiver station and a base transceiver station. IEEE 802.16 standardizes the air interface and related functions associated with WLL [Stal2002]. Three working groups have been chartered to produce standards that:

- Use wireless links with microwave or millimeter wave radios
- Use licensed spectrum (typically)
- Are metropolitan in scale
- Provide public network service to fee-paying customers (typically)
- Use point-to-multipoint architecture with stationary rooftop or tower mounted antennas
- Provide efficient transport of heterogeneous traffic supporting quality of service (QoS)
- Are capable of broadband transmissions (> 2 Mbps)

1. IEEE 802.16.1

This standard species the physical layer and media access control layer of the air interface of interoperable fixed point-to multipoint broadband wireless access systems. The specification enables transport of data, video, and voice services. It applies to systems operating in the vicinity of 30GHz but is broadly applicable to systems operating between 10GHz to 66 GHz.

a. Physical Layer

The lowest layer, the physical layer, specifies the frequency band, the modulation scheme, error-correction techniques, synchronization between transmitter and receiver, data rate and the time-division multiplexing (TDM) structure.

For transmission from subscribers to a base station, the standard uses the Demand Assignment Multiple Access-Time Division Multiple Access (DAMA-TDMA) technique. DAMA is a capacity assignment technique that adapts as needed to respond to demand changes among multiple stations. TDMA is the technique of dividing time on a channel into a sequence of frames, each consisting of a number of slots, and allocating one or more slots per frame to form a logical channel.

With DAMA-TDMA, the assignment of slots to channels varies dynamically. For transmission from a base station to subscribers, the standard specifies two modes of operation, one targeted to support a continuous transmission stream (mode A), such as audio or video, and one targeted to support a burst transmission stream (mode B), such as IP-based traffic. Both are TDM schemes.

b. MAC Layer

Above the physical layer are the functions associated with providing service to subscribers. These functions include transmitting data in frames and controlling access to the shared wireless medium, and are grouped into a media access control (MAC) layer. The MAC protocol defines how and when a base station or subscriber station may initiate transmission on the channel. Because some of the layers above the MAC layer, such as ATM, require quality of service, the MAC protocol must be able to allocate radio channel capacity to satisfy service demands.

In the downstream direction (base station to subscriber stations), there is only one transmitter, and the MAC protocol is relatively simple. In the upstream direction, multiple subscriber stations compete for access, resulting in a more complex MAC protocol. In both directions, a TDMA technique is used, in which the data stream is divided into a number of time slots.

The sequence of time slots across multiple TDMA frames that is dedicated to one subscriber forms a logical channel, and MAC frames are transmitted over that logical channel. IEEE 801.16.1 is intended to support individual channel data rates of from 2M to 155M bit/sec.

c. Above MAC Layer

Above the MAC Layer is a convergence layer that provides functions specific to the service being provided. For IEEE 802.16.1, bearer services include digital audio/video multicast, digital telephony, ATM, Internet access, wireless trunks in telephone networks and frame relay.

2. IEEE 802.16.2

This standard covers development of a Recommended Practice for the design and coordinated deployment of broadband wireless access (BWA) systems to minimize interferences so as to maximize system performance and /or service quality. This practice will provide for coexistence using frequency and spatial separation and will cover three areas.

First, it will recommend limits of in-band and out-of-band emissions from BWA transmitters through parameters including radiated power, spectral masks and antenna patterns. Second, it recommends receiver tolerance parameters, including noise floor degradation and blocking performance, for interference received from other BWA systems as well as from other terrestrial and satellite systems. Third, it will provide coordination parameters, including band plans, separation distances, and power flux density limits, to enable successful deployment of BWA systems with tolerable interference. The scope includes interferences between systems deployed across geographical boundaries in the same frequency band and systems deployed in the same geographical area in different frequency bands (including different systems deployed by a single license-holder in sub-bands of the licensees authorized bandwidth.

3 IEEE 802.16.3

This standard specifies the physical layer and media access control of the air interface of interoperable fixed point-to-multipoint broadband wireless access systems. The specification enables access to data, video, and voice services with a specified quality of service in licensed bands designated for public network access. It applies to systems operating between 2 and 11GHz.

D. IEEE802.16 SERVICES

Requirements for the IEEE 802.16 standards are defined in terms of bearer services that the 802.16 systems must support. A bearer service refers to the type of traffic generated by a subscriber network. The work of 802.16.1 is the farthest along, and it's likely that it will generate the most interest in the industry, as it is targeted at available frequency bands. The following services are supported:

Digital audio/video multicast – Transports one-way digital audio/video streams to subscribers. The principal example of this service is a broadcast radio and video similar to digital broadcast cable TV and digital satellite TV. A special case of this service is two-way video such as in teleconferencing. In this latter case, delay requirements are stringent because of the interactivity involved.

Digital Telephony – Supports multiplexed digital telephony streams. This service is a classic WLL service that provides a replacement for wired access to public telephone network.

ATM – Provides a communications link that supports the transfer of ATM cells as part of an overall ATM network. The 802.16 link must support the various QoS services defined for ATM.

Internet Protocol – Supports the transfer of IP datagrams. The 802.16 link must provide efficient timely service. In addition, a variety of QoS service are now defined for IP-based networks, and 802.16 should support these.

Bridged LAN – Similar to the IP-based support. A bridge LAN service enables transfer of data between two LANs with switching at the MAC layer.

Back-haul – For cellular or digital wireless telephone networks. An 802.16 system may be a convenient means to provide wireless trunks for wireless telephony base stations.

E ADVANTAGES OF WLL

In comparison to wireline, WLL possesses several key attributes which make it attractive to deploy, especially in low tele-density areas. These include:

Reduced cost of deploying longer or difficult loops: With wireless technology, the cost of connecting a customer is, within certain limits, independent of the distance to the exchange. In areas where the cost of cabling is high (e.g. remote areas, rugged terrain), WLL is more cost effective.

Modularity: WLL systems have a low ratio of fixed to incremental costs. A significant part of the total investment lies in the terminal equipment at the subscriber premise, which is only required when connecting the subscriber. The ability to add to the network incrementally with demand lowers the risk of oversizing or undersizing the network.

Rapid deployment: WLL systems can be quickly deployed since there are no streets to dig or copper wires to lay. As systems can be easily implemented in less than six months (compared to copper wire which could take years), operators can rapidly roll out service and begin earning payback revenue.

Security: Copper wires are prone to breaks and theft, especially in lower income countries. A significant part of the infrastructure costs for WLL are in towers, which are more easily guarded.

F. SUMMARY

In this chapter, we have examined the technology of Wireless Local Loop. The potential benefits are widely recognized and has prompted the industry to develop IEEE standards to facilitate deployment of this technology in the last mile. There are clear market opportunities in emerging economies for the deployment of WLL, as well as an enormous potential upside in developed economies. WLL is emerging as a viable alternative to copper wires in providing last mile access. In developing regions where basic services are absent, WLL is well positioned to capture a significant share of the access market. It is predicted that WLL deployment will increase significantly, particularly in areas with low tele-density. However, in markets where most subscribers already have telephony, success of WLL will depend on the ability to provide a level service that is at least equivalent to alternative access technologies.

VI. WIRELESS LANS AND IEEE 802.11

A. INTRODUCTION

Over recent years, the market for wireless communications has enjoyed tremendous growth. Hundreds of millions of people exchange information every day using pagers, cellular telephones, and other wireless communication products. With tremendous success of wireless telephony and messaging services, it is hardly surprising that wireless communication is beginning to be applied to the realm of personal and business computing. No longer bound by the harnesses of wired networks, people will be able to access and share information on a global scale nearly anywhere they venture.

B. TRANSMISSION MEDIA FUNDAMENTALS

In a data transmission system, the *transmission medium* is defined as the physical path between transmitter and receiver. Transmission media can be classified as *guided* and *unguided*. In both cases communication is in the form of electromagnetic waves. With guided media, the waves are guided along a solid medium such as *copper twisted pair* or *optical fiber*. The atmosphere and outer space are examples of unguided media, which provide a means of transmitting electromagnetic signals but do not guide them. This form of transmission is commonly referred to as *wireless transmission*.

The characteristics and quality of a data transmission are determined both by the characteristics of the medium and the characteristics of the signal. In the case of the guided media, the medium itself is more important in determining the limitations of transmission. For unguided media, the bandwidth of the signal produced by the transmitting antenna is more important than the medium in determining transmission characteristics. One key property of signals transmitted by antenna is *directionality*. In general, signals at lower frequencies are *omni-*

directional, that is, the signal propagates in all directions from the antenna. At higher frequencies, it is possible to focus the signal into a directional beam.

Figure 20 depicts the electromagnetic spectrum and indicates the frequencies at which various guided media and unguided transmission techniques operate.

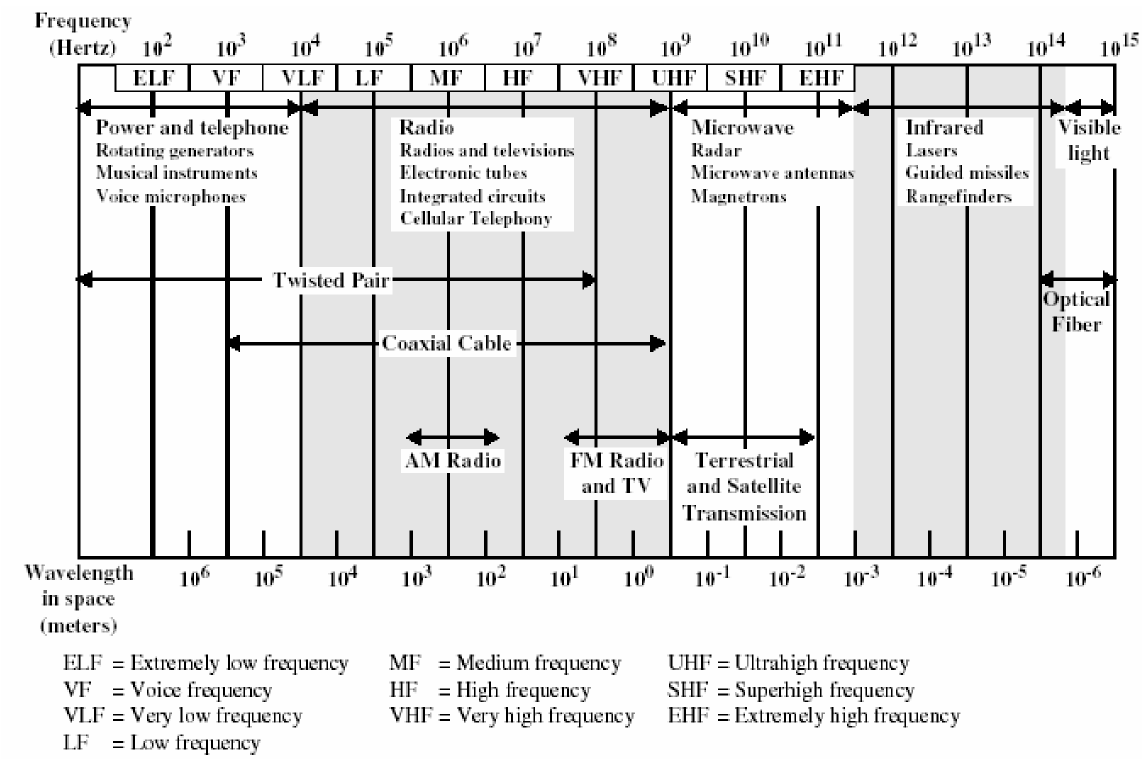

Figure 20. Electromagnetic Spectrum for Telecommunications (From [Stal2002])

For unguided media, transmission and reception are achieved by means of an antenna. For transmission, the antenna radiates electromagnetic energy into the medium (usually air), and for reception, the antenna picks up electromagnetic waves from the surrounding medium. There are basically two types of configurations for wireless transmission: *directiona*l and *omni-directional*. For the directional configuration, the transmitting antenna puts out a focused electromagnetic beam: the transmitting and receiving antennas must therefore be carefully aligned. In the omni-directional case, the transmitted signal spreads out in all directions and can be received by many antennas.

For wireless transmission, three general ranges of frequencies are of interest. Frequencies in the range of about 1 GHz to 40 GHz are referred to as *microwave frequencies*. At these frequencies, highly directional beams are possible, and microwave is suitable for point-to-point transmission and satellite communications. Frequencies in the range of 30 MHz to 1 GH are the *radio range* and are suitable for omni-directional applications. Another important frequency range is the *infrared* portion of the spectrum, 3×10^{11} to 2×10^{14} Hz which is used in local point-to-point and multipoint applications within confined areas, such as a single room.

C. WIRELESS APPLICATIONS

Since the success of the Ethernet project at Xerox's Palo Alto Research Center in the early 1970's and other similar digital protocols, the basic technology has been in place for local area networks (LANs) to blossom in both the public and private sectors. Standard LAN protocols, such as Ethernet, that operate at fairly high speeds with inexpensive connection hardware can bring digital networking to almost any computer. Today, organizations of every size access and share information over a digital network; the power of networking and collaborative, distributed computing is beginning to be realized. However, until recently, LANs were limited to the physical, hard-wired infrastructure of the building. Even with phone dial-ups, network nodes were limited to access through wired, land line connections. Many network users, especially mobile users in businesses, the medical profession, factories, and universities, to name a few, find benefit from the added capabilities of wireless LANs.

The major motivation and benefit from wireless LANs is increased mobility: network users can move about almost without restriction and access LANs from nearly anywhere. Examples of the practical uses for wireless network access are limited only by the imagination of the application designer. Medical professionals can obtain not only patient records, but real-time vital signs and other reference data at the patient bedside without relying on reams of paper charts and physical paper handling. Factory floor workers can access part and process specifications without impractical or impossible wired network connections. Wireless connections with real-time sensing allow a remote engineer to diagnose and maintain the health and welfare of manufacturing equipment, even on an environmentally-hostile factory floor. Warehouse inventories can be carried out and verified quickly and effectively with wireless scanners connected to the main inventory database. Even wireless "smart" price tags, complete with liquid crystal display (LCD) readouts, allow merchants to virtually eliminate discrepancies between stock-point pricing and scanned prices at the checkout lane. The list of possibilities is almost endless.

In addition to increased mobility, wireless LANs offer increased flexibility. One can visualize without too much difficulty a meeting in which employees use small computers and wireless links to share and discuss future design plans and products. This "ad hoc" network can be brought up and torn down in a very short time as needed, either around the conference table and/or around the world. Some car rental establishments already use wireless networks to help facilitate check-ins. Traders on Wall Street are able to use wireless terminals to make market trades. Even students of university campuses have been known to access lecture notes and other course materials while wandering about campus.

Sometimes it is more economical to use a wireless LAN. For instance, in old buildings, the cost of asbestos cleanup or removal outweighs the cost of installing a wireless LAN solution. In other situations, such as a factory floor, it may not be feasible to run a traditional wired LAN. Wireless LANs offer the connectivity and the convenience of wired LANs without the need for expensive wiring or rewiring.

D. MOBILE IP

Mobile IP was suggested as a means to attain wireless networking. It focuses its attention at the Network Layer, working with Internet Protocol. In this protocol, the IP address of the mobile machine does not change when it moves from a home network to a foreign network. In order to maintain connections between the mobile node and the rest of the network, a forwarding routine is implemented.

When a person in the physical world moves, they let their home post office know to which remote post office their mail should be forwarded. When the person arrives at their new residence, they register with the new post office. This same operation happens in Mobile IP. When the mobile agent moves from its home network to a foreign (visited) network, the mobile agent tells a home agent on the home network to which foreign agent their packets should be forwarded. In addition, the mobile agent registers itself with that foreign agent on the foreign network. Thus, all packets intended for the mobile agent are forwarded by the home agent to the foreign agent which sends them to the mobile agent on the foreign network. When the mobile agent returns to its original network, it informs both agents (home and foreign) that the original configuration has been restored. No one on the outside networks need to know that the mobile agent moved.

This configuration works, but it has some drawbacks. Depending on how far the mobile agent moves, there may need to be some store and forwarding of packets while the mobile agent is on neither the home nor the foreign network.

E. WIRELESS LAN ARCHITECTURES

In IEEE's proposed standard for wireless LANs (IEEE 802.11), there are two different ways to configure a network: ad-hoc and infrastructure. In the ad-hoc network, computers are brought together to form a network "on the fly." As shown in Figure 21, there is no structure to the network; there are no fixed points;

and usually every node is able to communicate with every other node. A good example of this is the aforementioned meeting where employees bring laptop computers together to communicate and share design or financial information. Although it seems that order would be difficult to maintain in this type of network, algorithms such as the spokesman election algorithm (SEA) have been designed to "elect" one machine as the base station (master) of the network with the others being slaves. Another algorithm in ad-hoc network architectures uses a broadcast and flooding method to all other nodes to establish who's who.

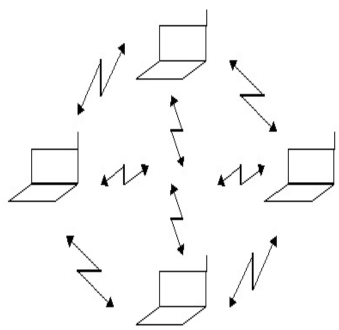

Figure 21. Ad-Hoc Network (From [Loug2000])

As shown in Figure 22, the second type of network structure used in wireless LANs is the infrastructure. This architecture uses fixed network access points with which mobile nodes can communicate. These network access points are sometime connected to landlines to widen the LAN's capability by bridging wireless nodes to other wired nodes. If service areas overlap, handoffs can occur. This structure is very similar to the present day cellular networks around the world.

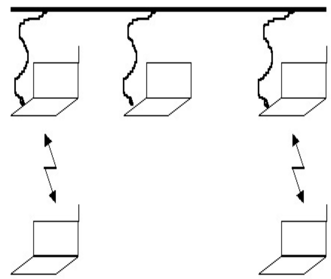

Figure 22. Infrastructure Network (From [Loug2000])

F. IEEE 802.11 STANDARD

In 1997, the Institute of Electrical and Electronics Engineers (IEEE) approved the 802.11 WLAN Standard, establishing a global standard for implementing and deploying WLANs [Nede2001]. The throughput for 802.11 was 2Mbps, which was well below the IEEE 802.3 Ethernet counterpart. Late in 1999, the IEEE approved the 802.11b standard extension, which raised the throughput to 11 Mbps, making this extension more comparable to the wired networks. The 802.11b also supports the 2 Mbps data rate and operates on a 2.4GHz band radio frequency for high-speed data communications.

As with any of the other 802 networking standards (Ethernet, Token Ring, etc.), this 802.11 specification affects the lower layers of the Open Systems Interconnect (OSI) reference model, and the Physical and Data Link layers as shown in Figure 23. The Physical Layer defines how data is transmitted over the physical medium. The IEEE assigned 802.11 two transmission methods for Radio Frequency (RF) and one for Infrared (IR). The two RF methods are Frequency Hopping Spread-Spectrum (FHSS), which operates within the Unlicensed National Information Infrastructure (UNII) and Direct Sequence Spread-Spectrum (DSSS), which operates within the ISM (Industrial, Scientific, and Medical) 2.4 GHz band for unlicensed use. Other devices that operate on this band include remote phones and microwave ovens.

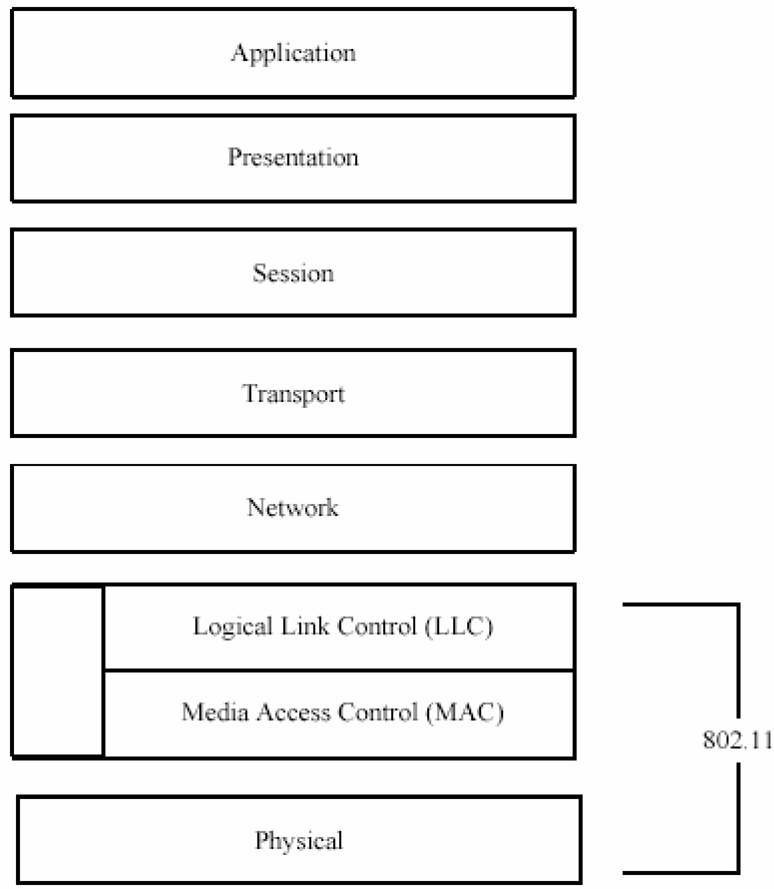

Figure 23. Open Systems Interconnect (OSI) Reference Model (From [Vine2002])

Both FHSS and DSSS are different techniques to transmit data over radio waves. For FHSS, a simple frequency hopping technique is used to navigate the 2.4GHz band, which is divided into 75 sub-channels of 1MHz each. The sender and receiver negotiate a sequence pattern over the sub-channels. On the other hand, DSSS utilizes the same channel for the duration of the transmission by dividing the 2.4 GHz band into 14 channels at 22MHz each with 11 channels, which have eight overlapping and three non-overlapping channels. To compensate for noise and interference, DSSS uses a technique called "chipping," where each data bit is converted into redundant patterns called "chips." The Data Link layer is made up of two sub-layers, the MAC layer and the Logical Link Control (LLC) layer. The Data Link layer determines how transmitted data is packaged, addressed and managed within the network. The LLC sub-layer uses the identical 48-bit addressing found in Ethernet, where the MAC sub-layer uses a unique mechanism called Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). This mechanism is similar to the Carrier Sense Multiple Access Collision Detect (CSMA/CD) used in Ethernet, with a few major differences. As opposed to Ethernet, which detects collisions, CSMA/CA senses the airwaves for activity and sends out a signal when the airwaves appear to be free of transmissions. If the sender detects conflicting signals, it will wait for a random period plus a period proportional to the existing traffic before retrying transmission.

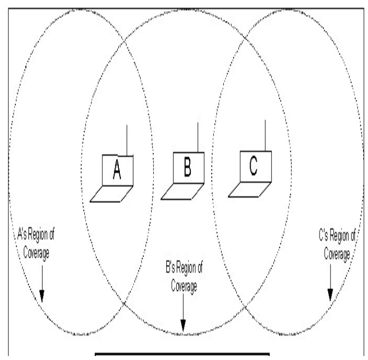

Figure 24. The Hidden Node Problem (From [Loug2000])

The 802.11 standard includes the RTS/CTS (Request To Send/ Clear To Send) function as an optional feature to solve the hidden node problem, in which two stations on opposite sides of an Access Point (AP) can both hear activity from an AP but not from each other. Although the first station may sense the channel to be clear, the second station may in fact be transmitting to the AP. Therefore the collision may occur. This problem occurs when a wall and other structures create obscure radio coverage areas. When this feature is in use, a sending station transmits an RTS packet and waits for a reply from the AP with a CTS packet. Since all stations in the network can hear the AP, the CTS packet causes them to delay any intended transmissions. This allows the sending station to transmit and receive a packet acknowledgement without any chance of collision. However, the RTS/CTS packet adds additional overhead to the 802.11, especially at small packet sizes. It is typically used only on the largest-sized packets, for which retransmission would be expensive from a bandwidth standpoint. In addition, the 802.11 MAC sub-layer provides other robustness features, Cyclic Redundancy Check (CRC) checksum and packet fragmentation: a CRC checksum is calculated for each packet to ensure that the data was not corrupted in transit. Packet fragmentation makes it possible to split large packets into smaller packets before transmitting over the air. This is useful on a crowded transmission, since large packets are more easily corrupted; it also reduces the need to send packets again and increases the throughput of the network.

IEEE802.11a - The 802.11a extension operates on a different physical layer specification than the 802.11b. The 802.11a extension operates at 5GHz and supports data rates up to 54Mbps. The Federal Communication Commission (FCC) has allocated 300Mz of the RF spectrum for unlicensed operation in the 5GHz range. Although 802.11a supports much higher data rates, the effective distance of transmission is much shorter than 802.11b. Additionally 802.11a is not compatible with 802.11b equipment and, in its current state, is usable only in the United States. However, several vendors have embraced the 802.11a standard, and some have dual band support AP devices and network cards.

IEEE802.11b - The 802.11b extension is currently the de facto standard for WLANs; it raises the data rate from 2Mbps to 11Mbps by using the 2.4 GHz frequency band, but the actual throughput is much less. The increased data rate from 2Mbps to 11Mbps is achieved by utilizing an advanced encoding technique called Complementary Code Keying (CCK). The CCK uses Quadrature Phase Shift Keying (QPSK) for modulation to achieve the higher data rates.

IEEE802.11c - The 802.11c extension provides required information to ensure proper bridge operations by using 802.11 APs to bridge across networks within relatively short distances from each other. This project has been completed with related procedures as part of the IEEE 802.11c standard. Product developers utilize this standard when developing APs.

IEEE802.11d - The 802.11d extension was introduced to facilitate the worldwide use of 802.11. It has an ongoing charter to define PHY requirements that satisfy regulatory requirements within additional countries. This extension allows APs to communicate on the permissible radio channels with acceptable power levels for user devices. Since the 802.11 standards are not legal in some countries, the purpose of 802.11d is to add features and restrictions that allow WLANs to operate within the rules of these countries. In countries where the physical layer radio requirements are different from those in North America, the use of WLANs is lagging behind. Moreover, since equipment manufacturers do not want to produce a wide variety of country-specific products and mobile users do not want to carry full country-specific WLAN PC cards, the result is country-specific firmware solutions. The standard was completed in 1999.

IEEE802.11e - The 802.11e extension is a supplement to the MAC layer that provides Quality of Service (QoS) support for LAN applications. This extension will apply to 802.11 physical standards a, b and g. The purpose of this extension is to provide classes of service with managed levels of QoS for data, voice and video applications. Many WLAN manufacturers have targeted QoS as a feature that differentiates their products from others. Therefore many proprietary offerings will be available before 802.11e is complete, which is still in the developmental stage.

IEEE802.11f - The 802.11f extension is designed to achieve AP interoperability within a multi-vendor WLAN network. This reduces vendor lock-in and allows multi-vendor infrastructures. This standard defines the registration of

APs within a network and the interchange of information between APs when a user is handed over from one AP to another. Like 802.11e, 802.11f is still in the standard developmental stage.

IEEE802.11g - The 802.11g extension offers wireless transmission over relatively short distances at speeds from 20 Mbps up to 54 Mbps. It operates in the 2.4GHz and 5GHz radio band ranges. The 802.11g standard uses Orthogonal Frequency-Division Multiplexing (OFDM) modulation. However, for backward compatibility with 11b, it also supports Complementary Code Keying (CCK) modulation and, as an option for faster link rates, allows Packet Binary Convolutional Coding (PBCC) modulation. The 802.11g extension is still in the standard developmental stage.

IEEE802.11h - The 802.11h extension is supplementary to the MAC layer to comply with European regulations for 5GHz WLANs. European radio regulations for the 5GHz band require products to have Transmission Power Control (TPC) and Dynamic Frequency Selection (DFS). This feature, TPC, limits the transmitted power to the minimum needed to reach the farthest user while DFS selects the radio channel at the AP to minimize interference with other systems, particularly radar. This extension is still in the standard developmental stage.

IEEE802.11i - This extension focuses on enhancing WLAN security and on authenticating the 802.11, which includes Remote Authentication Dial-In User Service (RADIUS), Kerberos, and network port authentication (IEEE 802.1x). The 802.11i will apply to 802.11 physical standards a, b and g and will provide an alternative to Wired Equivalent Privacy (WEP), with new encryption methods and authentication procedures. This extension is still in the standard developmental stage.

G. SUMMARY

Wireless technologies are becoming more popular in business and personal life than in the past. Wireless communications offer organizations and users many benefits, such as increased portability, flexibility, and productivity. The Wireless Local Area Network (WLAN) does not replace the wired infrastructure, but complements it and significantly increases its range and flexibility for connecting a wireless device (e.g., laptop, PDA) to a wired LAN. Today, wireless technologies cover a broad range of differing capabilities oriented toward different uses and needs. For instance, WLAN devices allow users to move their laptops from place to place within their office without the need for wires and without losing network connectivity. This results in an increasing number of government agencies, businesses, and home users using, or anticipating the use of wireless technologies in their environments. The use of wireless LANs is expected to increase dramatically in the future as businesses discover the enhanced productivity and the increased mobility that wireless communications can provide in a society that is moving towards more connectionless connections. Wireless LAN and IEEE802.11 technologies are viable solutions to the last mile problem.

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VII. CELLULAR TECHNOLOGIES

A. HISTORY OF CELLULAR TECHNOLOGY

The origins of the mobile telephone can be traced back to two significant technological achievements, the invention of the telephone by Alexander Graham Bell in 1876 and the invention of the radio by Nikolai Tesla in the 1880s. Eventually, telephone and radio technology would converge and the concept of mobile radiotelephone communications became a viable reality.

The United States' involvement in World War II created an urgent need for Frequency Modulation (FM) technology to take the place of Amplitude Modulation (AM) technology for higher quality, two-way mobile radio communications on the battlefield. The strategic value of wireless communication on the battlefield spurred companies like AT&T, Motorola and General Electric to focus on refining mobile and portable communications. Motorola's FM Handie-Talkie and Walkie-Talkie figured prominently among the products developed during the war years and carried over into peacetime use.

In 1946, the first public mobile telephone service was introduced in twenty-five major American cities. Each system used a single, high-powered transmitter and large tower in order to cover distances of over 50 km in a particular market. This early radiotelephone service was a FM push-to-talk system that used 120 kHz of Radio Frequency (RF) bandwidth in a half-duplex mode. The large amount of RF bandwidth was needed because it was difficult to mass-produce tight RF filters and low-noise, front-end receiver amplifiers.

In the 1950s, the Federal Communications Commission (FCC) doubled the number of mobile telephone channels per market, but did not allocate any new spectrum; and technology improvement led to the reduction of channel bandwidth to 60 kHz. In the 1960s, FM channel bandwidth was further reduced to 30 kHz. Also, in the 1950s and 1960s, automatic channel trunking was introduced and implemented under the label Improved Mobile Telephone Service (IMTS). Channel trunking permits a large number of users to share a relatively small number of communication paths - or trunks. With IMTS, telephone companies began offering full duplex, auto dial, auto-trunking phone systems. IMTS quickly became saturated because it did not have the capacity to handle the amount of demand. This resulted in poor services due to call blocking and heavy usage over the few channels.

B. THE EMERGENCE OF CELLULAR CONCEPT

Faced with an ever increasing demand for mobile phone service and a lack of spectrum allocation by the FCC, research efforts focused on restructuring the radiotelephone system to achieve high capacity with limited radio spectrum while at the same time covering large areas. During the 1950s and 1960s, AT&T Bell Laboratories and other telecommunications companies throughout the world developed the theory and techniques of cellular radiotelephony – the concept of breaking a coverage zone (market) into small cells, each of which reuse portions of the spectrum to increase spectrum usage at the expense of greater system infrastructure.

The cellular concept is a system–level idea which calls for replacing a single, high power transmitter (1 very large cell) with many low power transmitters (small cells), each providing coverage to only a small portion of a service area. As shown in Figure 25, large base stations are replaced by many small cells. Each transmitter, or base station, is allocated a portion of the total number of channels available to the entire system, and nearby base stations are assigned different groups of channels so that all the available channels are assigned to a relatively small number of neighboring base stations. Neighboring base stations are assigned different groups of channels so that the interference between base stations (and the mobile users under their control) is minimized. Base stations and their channel groups are systematically spaced throughout a market. This ensures the available channels are distributed throughout the geographic region and can be reused as many times as necessary as long as the interference between co-channel stations is kept below acceptable levels. As the demand for service increases, the number of base stations may be increased to provide additional radio capacity with no additional increase in radio spectrum.

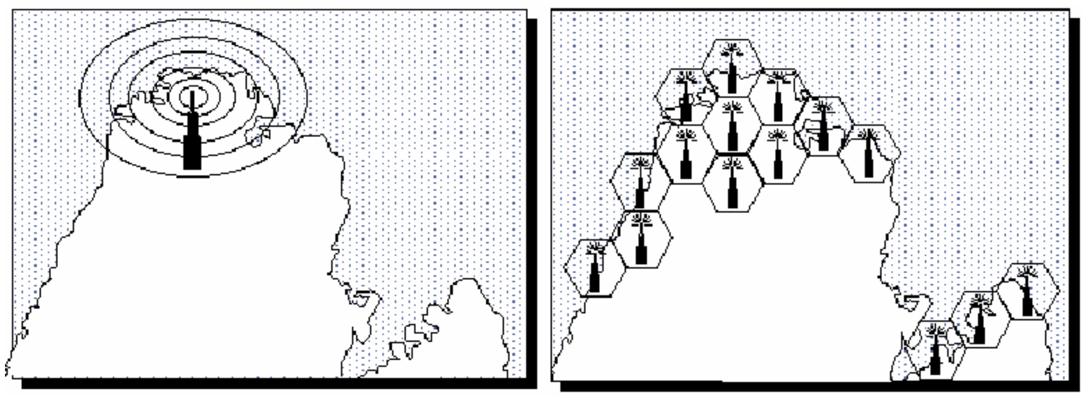

Figure 25. Single Base Station Vs Cellular Concept (From [Inte2003])

Cellular radio systems rely on an intelligent allocation and reuse of channels throughout a coverage region. Each cellular base station is allocated a group of radio channels to be used within a small geographic area called a cell. Base stations in adjacent cells are assigned channel groups which contain completely different channels than neighboring cells. The base station antennas are designed to achieve the desired coverage within the particular cell. By limiting the coverage area to within the boundaries of a cell, the same group of channels may be used to cover different cells that are separated from one another by distances large enough to keep interference levels within tolerable limits. The design process of selecting and allocating channel groups for all of the cellular base stations within a system is called frequency reuse or frequency planning. Figure 26 below illustrates the concept of frequency reuse. Cells with the same letter use the same letter use the same set of frequencies. A cell cluster is outlined in bold and replicated over the coverage area.

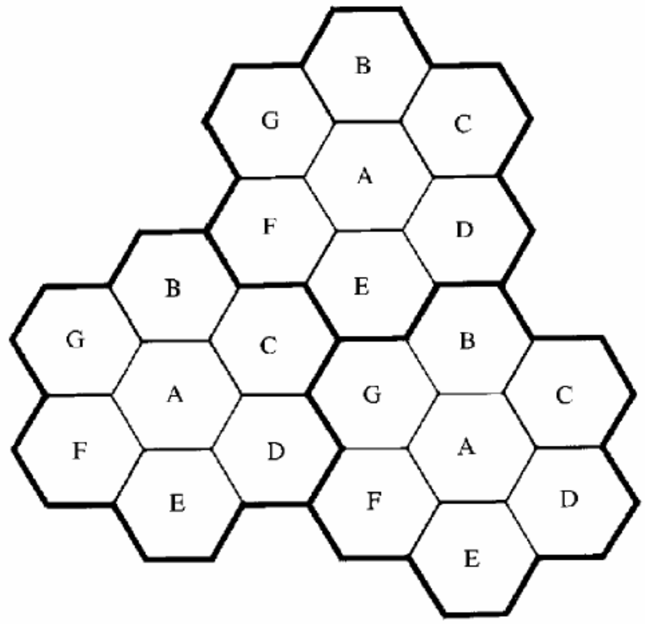

Figure 26. Frequency Reuse (From [Rapp2002])

AT&T proposed the concept of a cellular mobile telephone system to the FCC in 1968, although technology was not available to implement a fully functional cellular telephony system until 1978. In 1983, the FCC finally allocated 666 duplex channels (40 MHz of spectrum in the 800 MHz band, each channel having a one-way bandwidth of 30 kHz for total spectrum occupancy of 60 kHz for each duplex channel) for the U.S. Advanced Mobile Phone System (AMPS).

In late 1991, the first U.S. Digital Cellular (USDC) system hardware was installed in major U.S. cities. The USDC standard, also known as the time division multiple access (TDMA) Interim Standard 54 or TDMA IS-54 and later as IS-136, was developed by the TIA and released in early 1991. This standard used TDMA and allowed cellular operators to gradually replace some single-user analog channels with digital channels that supported three users in the same 30 kHz bandwidth.

A cellular system based on code division multiple access (CDMA) was developed and commercially introduced by Qualcomm, Inc. in 1995. It was later standardized by the TIA as an Interim Standard (IS-95). This system supports a variable number of users in 1.25 MHz wide channels using direct sequence spread spectrum. The first CDMA networks were commercially launched in 1995, and provided roughly 10 times more capacity than analog networks.

C. EVOLUTION OF CELLULAR TECHNOLOGY

Cellular telephone technology has evolved through three generations. These three generations are referred to as first generation (1G), second generation (2G), and third generation (3G). The technology prior to first generation was not technically cellular. This early radiotelephone service was FM push-to-talk, operated in half-duplex mode and used single, high-powered transmitters.

Currently, cellular technology in the United States is primarily 2G. Voice service is the overwhelmingly dominant function used by cellular subscribers. Wireless data capability is seldom used but that is gradually changing. Cellular carriers are currently retrofitting and modifying their 2G digital networks with step phased packet switched technology improvements to enable increases to wireless data performance and always on connections. These phased evolutions are part of a planning roadmap to a 3G level of performance. 3G is a global initiative of the International Telecommunications Union (IMT-2000) and will be based on high-speed wireless packet data transmitting technology that will provide real-time, always connected multimedia applications with streaming audio and video. The major obstacle to implementation of 3G in the U.S. is the lack of available spectrum to implement it.

1. First Generation (1G) Cellular Technology

The first generation of cellular wireless communications was based on analog technology and progressively became available to the consumer during the late 1970s and early 1980s. Since the early 1980s, the most common first generation system in North America has been the Advanced Mobile Phone Service (AMPS).

2. Second Generation (2G) Cellular Technology

First-generation cellular networks, such as AMPS, quickly became highly popular. However, the service on these networks was poor and their capacity was limited. Second generation cellular networks offer higher-quality signals, higher data rates for support of digital services, and greater capacity. Some of the key differences between 1G and 2G are listed below:

Digital traffic channels - First generation systems are almost purely analog, whereas second generation system are digital.

Encryption - Second generation systems encrypt all traffic, whereas first generation systems provide no security.

Error detection and correction - Second generation systems use error detection and correction techniques to provide clear voice reception.

Channel access - In first generation systems, each cell supports a number of channels and only one user is allocated a certain channel at any given time. Second generation systems also provide multiple channels per cell, but each channel is dynamically shared by a number of users using TDMA or CDMA.

3. Third Generation (3G) Cellular Technology

In the early 1990s, the International Telecommunications Union (ITU), which is the standards body for the United Nations, developed a plan to implement a global frequency band in the 2000 MHz range that would support a single, ubiquitous wireless communication standard for all countries throughout the world. This plan, called International Mobile Telecommunication 2000 (IMT-2000), is for a universal, multi-function, globally compatible digital mobile radio system that will integrate paring, cordless, and cellular systems, as well as low earth orbit (LEO) satellites, into one universal mobile system. The technology that will allow the implementation of this plan is known as third generation (3G). The IMT- 2000 initiative has defined the ITU's view of 3G capabilities as follows:

- Voice quality comparable to the public switched telephone network
- 44 kbps data rate available to users in high-speed motor vehicles over large areas
- 384 kbps available to pedestrians standing or moving slowly over small areas
- Support (to be phased in) for 2.048 Mbps for office use
- Symmetrical and asymmetrical data transmission rates
- Support for both packet switched and circuit switched data services
- An adaptive interface to the Internet to reflect efficiently the common asymmetry between inbound and outbound traffic
- More efficient use of available spectrum in general
- Support for a wide variety of mobile equipment
- Flexibility to allow the introduction of new services and technologies

4. 4G and Future Technologies

Even before 3G systems were being deployed, researchers are looking at technologies that may constitute a 4G system. Different modulation technologies, such as Orthogonal Frequency Division Modulation (OFDM) that is used in other wireless systems, such as IEEE802.16 and Digital Video Broadcast (DVB), are being investigated. Other research is taking place on Mesh network technology, where each handset or terminal can be used as a repeater, with the links routed and maintained in a dynamic way.

One technology that is proving interesting is Ultra-Wideband (UWB), as its use has recently been given approval by the FCC in the USA. Formed out of individual discrete pulses, it spreads noise across a very wide frequency band. The noise created has been considered to be sufficiently small that it should not affect other wireless systems. However, more research is being carried out in this area to establish the limits.

D. SUMMARY

In this chapter, the concept of cellular technology is described and the various cellular generations are presented and discussed. Cellular communication technology provides individuals with the ability to connect to others via voice transmission and it is not inconceivable that the technology will advance to a stage in the future where high data rate transmission is possible. If this is achieved, it will fundamentally alter the way people connect to each other, the way businesses are conduct and raise the quality of life.

VIII. OPTICAL FIBER IN SEWER

A. INTRODUCTION

The last mile problem has resulted in severe loss of productivity in businesses and to a certain extent, the quality of life. As more businesses and people are expected to connect globally via Internet, this loss in productivity will become more evident and there is a urgent need to resolve the issue. Over the past couple of years, telecommunication engineers have devised and experimented with innovative ways to circumvent the last mile problems to bring high speed broadband to the masses. At present, the backbone of Internet is supported by optical fiber trunks linking countries and major cities. An optical fiber network is only as fast as its weakest (slowest) link. The so-called fiber glut in the backbone and long haul fiber networks is in large part due to the lack of last mile fiber to provide the final link between the premises and the long haul carriers of data, voice, and video. It has long been known that if we could suddenly replace existing copper wires with optical fibers linking all homes and businesses, we would be able to solve the last mile problem.

However, as any civil engineer would know, deployment of high-speed metropolitan area optical fiber network rings required extensive construction, primarily excavation of city streets. Besides the high cost of construction, these excavations caused pollution, massive traffic hold-ups, economic loss and inconvenience for inhabitants. It is also common that despite repairs, the street conditions are not reinstated to the original state. Due to the inconvenience, mayors in the past are forced to issue moratoriums to shut down construction on last miles projects.

One of the most promising ideas for delivering broadband to the masses is the deployment of robots to lay optical fibers into existing sewers. CityNet Telecommunications is a leader in introducing this unprecedented solution, in which it aims to create true broadband cities all across America and Europe using sewers as the preferred path for building the last mile fiber network. The in-sewer deployment system operates without impact to either the sewer operation or to the streets above. In fact, this process most often leaves the sewer in better condition than before the installation. In addition to its non-invasive advantages, preserving transportation infrastructure with no negative impact on the sewer, the in-sewer deployment process is also efficient and cost effective. This deployment technique is less expensive than traditional fiber network construction, but the major advantage with the last-mile network deployment technique is speed. This chapter discusses the technological advances of building optical fiber networks inside existing sewers.

B. CITYNET'S ROBOT TECHNOLOGY

The idea for CityNet was formed in 1999 and led to the creation of strategic vendor relationships with Alcatel, Ka-te, CableRunner, and Carter & Burgess [City2000]. CityNet Telecommunications will pay lease revenue to the city to use the sewer pipes for delivering the optical fiber cables directly into buildings. This notion of leasing space inside of existing sewers by telecommunications companies has a rather interesting appeal in that owners of existing sewers get to generate a new revenue stream and telecommunication companies could install their optical fiber cables at an attractive cost. As an additional benefit, it is in the interest of CityNet to monitor the condition of the sewers it uses. CityNet will deliver dark optical fiber networks to telecom carriers and network service providers, who will then activate and provide services to building tenants. CityNet uses a small computer-driven robot, shown in Figure 27, called Sewer Access Module (SAM), equipped with CCTV cameras to install alloy rings to support the optical fiber cables inside of the sewer pipes.

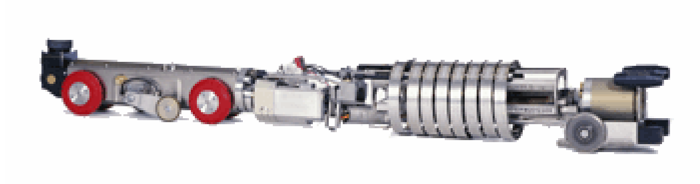

Figure 27. Sewer Access Module (From [City2000])

Developed by Ka-te, SAM's sleek and lean body allows it to access sewers as small as 200mm (8 inches) in diameter. With more than 50 SAMs in its inventory, CityNet has planned or began work at multiple locations in America with contracts in hand with the Cities of Omaha, Indianapolis, St Paul, Scottsdale, Albuquerque, Forth Worth, Pittsburgh, and Dallas. At the same time, CityNet has also secured license agreements in Vienna, Austria and Seville, Spain. The technology used by CityNet telecom is that under the name FAST in Europe.

Depending on the diameter of the sewer pipes, up to 9 optical fiber cables in stainless steel alloy conduits can be installed side by side in a sewer system. These cables are of either 144 fibers, arranged in 6 bundles of 24 each or 72 fibers arranged in 6 bundles with 12 fibers. The outer diameter of these protective conduits, which carry the fiber optic, cables measures on the order of 11.5 to 15.5 mm. The speed of installation is on the order of 150 m/day in non-man entry pipes for anywhere from 1 to 9 cables in the sewers. Because the optical fiber cables are housed inside conduits, if a cable needs to be replaced during the design life either for maintenance or due to significant technological advances occurring in fiber technology, it could be done readily without having to re-construct the network all over again. Work could start rather quickly compared to open-cut work. Most work is done at night when the traffic is low and the flow in the sewer is at its daily minimum. This system can install optical fiber transmission networks in non-man entry sewage pipes with diameters from 200 to 700mm. The Ka-Te special installation robot has been developed for the laying of protective conduits carrying optical fiber cables in non-man entry sewage pipes as shown in Figure 28.

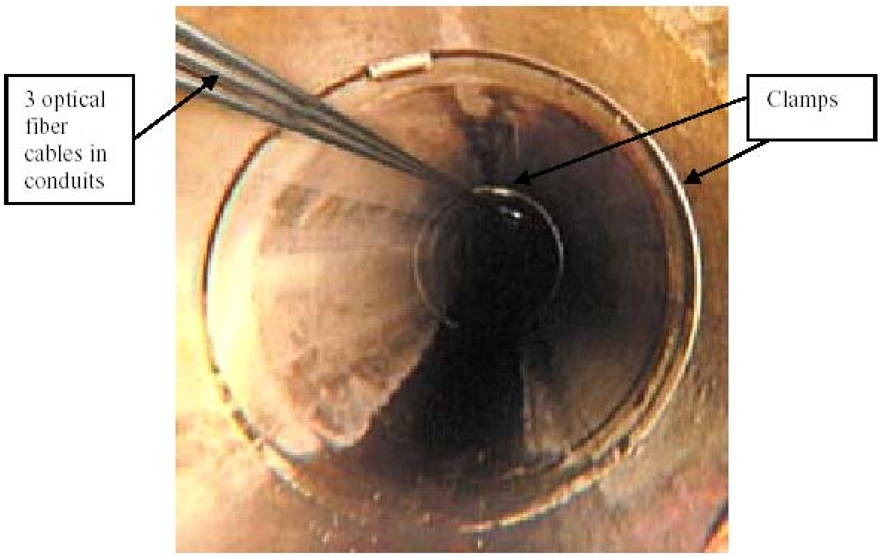

Figure 28. Optical fiber Cables in a Sewer System (From [Jeya2002])

In order to install a clip ring, the spring box on the clip ring is unlocked, so that the ring is snugly pushed against the sewer pipe walls engaging the 4 springs. The cables are tightly fixed to the inside sewer wall without any drilling, cutting or screwing. Depending on the requirements of the communications network, clip rings for sewers with a diameter of 300mm and above can be equipped with up to 9 clips, so that up to 9 protective conduits or 9 optical fiber cables can be mounted. Sewers with a nominal diameter of 200 to 250 mm can be equipped with a maximum of 3 clips. The installation work commences with a CCTV inspection, mapping, and analysis of the sewer line (see Figure 29). Any maintenance work needed is carried out at the onset before installing any cable conduits. In the next step, the clip rings are installed in the sewer by means of the robot. Each ring is fitted with 3 to 9 clips that are used to fasten the steel conduit that will house the single mode optical fiber cable. The rings are loaded into a magazine that is attached to the robot, which then travels through the sewer, using a laser guide to precisely place each ring in its prescribed location within the sewer – approximately every 1.5 m apart. Once all the rings are placed, SAM crawls back out of the sewer and is fitted with another head, which transports the conduit through the sewer. Once again using the laser guides, SAM fastens the conduit to the clips, locking it securely in place. When this part of the process is completed, the conduit is ready to accept the optical fiber cable. Using a push-pull method, the cable is threaded through the conduit, and then terminated to a patch panel inside the building for use by carrier customers. Single mode fiber was selected because it offers the best mix of high bandwidth capability and wide range compatibility with carrier customer systems. Following installation, CityNet then routinely inspects the sewers and provides any necessary cleaning to preserve the integrity of the network and the function of the sewer. Figure 29 depicts the 4-step procedure for installing optical fiber into sewers.

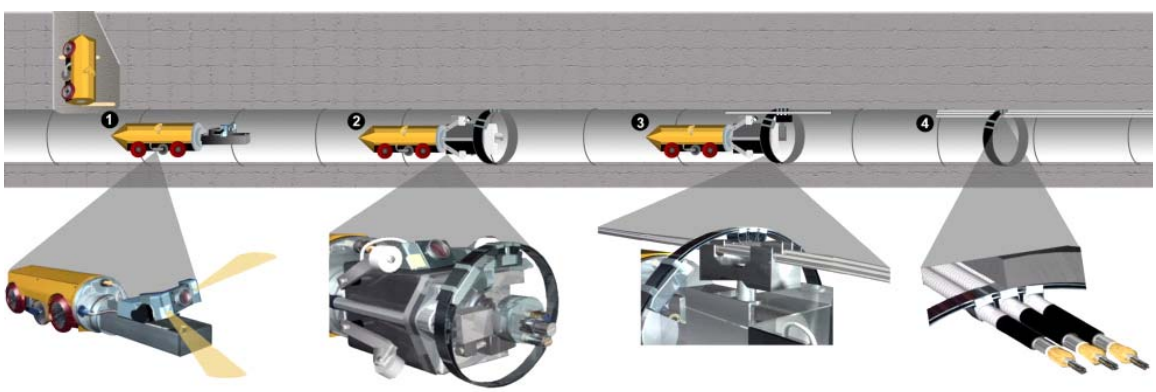

Figure 29. SAM 4-step Installation Procedure (From [City2000])

C MAN-ENTRY TECHNOLOGY

Man-entry sewer pipes are pipes with a diameter of 800mm and above. By means of expansion bolts and nuts, long channels of optical fiber cable trays are bolted to the inside sewer wall, at a desired center to center distance using a small crew-carrying sled. The small tray could hold 2,200 fibers, while the jumbo tray could handle 5,000. Both trays could be used around curves by cutting and installing shorter lengths. Plastic binders are used at the tray joints. For fixing the expansion bolt, a hole must be drilled into the sewer wall, which poses no major structural problems due to the adequate wall thickness in sewers with a 800mm diameter and above. The cables can be added in the future as demand for the fiber count increases. This technology has been in use for over 5 years. In Vienna alone, there is over 300 km of installation in the sewers using a fair amount of Corning cables of 8 of 144 fibers and 4 of 288 fibers.

D. THE ALBUQUERQUE EXPERIENCE

In October 2001, CityNet completed the world's first last-mile fiber optic network of its kind, connecting 19 downtown buildings through the sewers of Albuquerque, New Mexico, with 6 more buildings to be added at a later date [City2000]. The project took 4 months to complete and the first mini-ring is approximately 6,700 m (4 miles) in length. More than 60% of the pipes forming this ring in Albuquerque were storm sewers and the remainder was of sanitary sewers with sizes 200 to 1830 mm requiring man-accessible technology for 30% of the total fiber network.

In this breakthrough project, CityNet successfully connects buildings, which meet certain criteria such as minimum floor area, number of tenants, building owners' needs, type of tenants, existing communication services in the area, etc. A ring topology is used to service the buildings to meet redundancy requirements, optimum bandwidth needs and future expansion needs. The splice points on these mini-rings are located off the main traffic route to provide a safe zone for access for customer connections and for easy Operation & Maintenance (O&M). Connections from the street sewer optical fiber ring to the premises will be through pipes installed for carrying the fiber. These dry connections are sealed with mechanical means to ensure that there is no leak into the sewer and no sewer gas escapes. Often the mini-rings are designed with 2 to 4 aggregation points for the fiber bundles, where all of the fibers in the mini-ring are available for customer connections.

E. SEWER SELECTION CRITERIA

Operating an optical fiber network in the sewers poses its own challenges. Proper civil engineering input is essential for the selection of the suitable sewer system for deployment. [Jeya2002] listed the factors to consider in selecting the right sewer path:

Access to the Sewer: The primary access to the sewer for fiber cable installation using a robot is through the manholes at both ends of the reach. It is desirable that the length of the reach is shorter than 135 m, so that the umbilical cable needed by the robot for the supply of air, electricity, and communications circuits could extend from one end of the reach to the other. If man-accessible pipes were chosen, then this limitation would not apply.

Hydraulics of the Sewer: Although engineers intend not to have any leakage of sewage from the sewers, with aging and inadequate maintenance, most sewers have leaking joints during the design life of the sewer. Given this history of performance, the designers have been able to count on only 85% of the actual flow area to convey the flow, due to a loss of some sewage through leaking joints. An estimate of the flow conditions under the worst possible scenario based on past flow records in that sewer needs to be done before the sewer is considered for optical fiber cable installation. Engineering data used in the evaluation should be based on actual sewer sizes and actual flow conditions rather than those based on original design or as-built drawings. Enough attention needs to be paid to surcharging, slope problems, lack of sewer capacity, and future upsizing of the sewers.

Structural Capacity of the Sewer: An evaluation of the structural capacity of the sewer to carry the soil load, groundwater load, and live load need to be conducted. This is to ensure that the current condition of the sewer is adequate to house the optical fiber network. The decision whether and when to rehabilitate the sewer if the current condition is found to be questionable need to be carefully taken using all necessary engineering data. If the cost and time duration of rehabilitating the sewer would result in a significant delay and added financial burden to either the sewer owner or the optical fiber network owner, an alternate route for the intended optical fiber mini-ring shall be pursued to ensure that the engineering criteria to be met are not relaxed. Sewer Cleaning After Installation of Optical fiber Cable: Sewers need to be cleaned periodically as part of their maintenance. Once optical fiber cables are installed in the sewer, special precautions must be taken in choosing and applying suitable cleaning methods, which would not cause damage either to the sewer wall or the optical fiber cables.

Sewer Inspection after Installation of Optical fiber Cable: Periodic maintenance of the sewer will also involve inspection of the internal condition of the sewer system once the optical fiber cables are installed. Special precautions need to be taken in choosing and applying suitable technology for sewer system inspection in order not to cause damage to either the sewer walls or the optical fiber cables.

Sewer Maintenance after Installation of Optical fiber Cable: Sewers require periodic maintenance involving anything from point repairs, grouting, relining, to total replacement. The current condition of the sewer system and its need for repair or rehabilitation during the design life of the optical fiber network shall be carefully evaluated. The ability of the sewer owner to keep the sewer in serviceable condition and the ability of the sewer owner to be able to do one or more forms of necessary maintenance, repair, or rehabilitation need to be considered in the selection of the suitable components of the sewer system for inclusion in the routes for installing optical fiber networks.

Compatibility of the Sewer Wall: It is not possible to work with certain sewer wall materials depending on the fiber installation technology used. For example, it is not possible to use the drill and dowel method in several pipe wall materials and in old sewers, without having some concern for damage to the pipe wall from structural and hydraulic points of view. The clamp and conduit system on the other hand, can be used in most pipe materials given its non-invasive method of installation.

Presence of Excessive Grease in the Sewer: During the cleaning and inspection process, sufficient grease should be removed to permit inspection of the pipes. Sections of pipe with grease accumulations of over a suitable thickness within one year of cleaning should not be considered candidates for fiber optic system installation until proper remedial action is taken. Remedial action includes tracing source of grease and enacting/enforcing ordnances to require use of grease traps and/or oil separators.

Presence of Excessive Chemical Reagents in the Sewage: Sewage carries many chemical reagents and the longevity of the fiber deployment materials and components in all of such chemicals needs to be tested for compatibility before using. Fiber optic systems should not be deployed in sewers with excessive calcium deposition.

Presence of Joint Separations/Offsets: Joint separations/offsets can lead to both infiltration and exfiltration. Structural damage to the sewer may result from pipe bedding material being transported into the pipe.

Presence of Excessive Root Intrusion: Sewers should be free of excessive root intrusion to be eligible for installation of a fiber optic system. Excessive root intrusion is defined as infestation with roots, which will cause 5% blockage of the sewer within the next 10 years, if left untreated.

Condition of the Manholes: Manholes should be in an acceptable physical condition. Additionally, the portions of the manhole that will receive cable supports should be structurally sound.

Condition and Frequency of Lateral Connections: The condition of the lateral connections to the mainline sewer is important both to the hydraulic functioning of the sewer and to the installation and operation of the fiber optic system. The laterals should connect to the intercepting sewer by means of a wye fitting or transition section approved by the municipality. The joint at the intersection should be watertight and should be able to pass a suitable air test. Cracks or offsets can cause infiltration and/or erosion to pipe bedding materials and eventual structural failure. Cracked or offset lateral connections discovered as a result of CCTV inspection should be repaired by suitable techniques to pass an air test. Laterals that protrude into the sewer (i.e. “break-in” laterals) can hinder both normal operations and maintenance of the sewer and deployment of a fiber optic system. Protrusions over 25 mm should be removed and the joint sealed before installation proceeds. Laterals intersecting the same side of the interceptor sewer should be spaced no closer than a desirable distance on center to center. Laterals intersecting from opposite sides of the interceptor should be spaced no closer than a certain distance on center to center.

F. CHALLENGES IN IMPLEMENTATION

Although CityNet's business model seems logical to most observers, it is not without risk. For the fiber company to succeed, it needs overcome two major hurdles: winning over the support of both the building owners and carriers. CityNet needs permission from each building owners before hooking up their site to a mini-ring. This was not a problem in Albuquerque but this may pose a challenge in larger cities such as New York. Striking a deal with each and every building's owners is a tedious and time consuming process as it depends on how convinced the public is in the benefits of fiber optics to the homes.

Carriers, meanwhile, might prove to be challenging partners - and without their cooperation, CityNet cannot succeed. For one thing, backbone players can refuse CityNet the right to link to its existing metropolitan ring. After all, if the backbone player is already planning a "lateral build" (i.e., connecting its network to a given commercial building) it could actually be against the carrier's interests to let CityNet do the same thing. Without connections to those rings, CityNet's fiber stays dark and unusable, and outside carriers have nothing to lease.

G. SUMMARY

Using existing sewer as optical fiber routes to connect buildings is a novel idea which has great potential for linking up broadband cities in a non-invasive method. The successful deployment of optical fiber using robots in Albuquerque demonstrates a way to cost-effectively close the gap between all of the fiber optic cable put in the ground to date and the paying customer. For the end-user customer, it shows how broadband access can quickly become available, enabling greater speed, fostering competition and delivering on all the communications possibilities promised for so long. For cities, it illustrates how to provide businesses with state-of-the-art communications services to spur economic growth - without destroying a single costly city street or delaying commuter traffic. And, for the federal government and telecom industry overall, the project presents a clear path to the realization of a competitive telecommunications sector promised by the Telecommunications Act of 1996.

VIII. CONCLUSION

Over the past 10 years, the Internet is revolutionizing the way business is conducted around the globe. Bandwidth-intensive graphics, video and audio applications are becoming more and more popular and the desire for fast access to information places a huge demand on high bandwidth in metro networks. The last mile or local access loop is the primary bottleneck in achieving high-speed networking access for the consumer. The last-mile of today primarily relies on systems and infrastructures that were not designed for the transport of digital data. The current infrastructure of twisted pair is very close to its upper limits. As a result, consumers are unable to enjoy the full potential of the Internet and generally do not have access to enhanced services such as enriched multimedia services, converged voice, video, and data services and high-speed Web browsing. New and innovative ways must be explored to provide last mile homes and offices with access to high-speed networks. Service providers are faced with the need to turn up services quickly and cost-effectively at a time when capital expenditures are constrained.

From a technological standpoint, there are several options to address this connectivity bottleneck, which are discussed in this thesis. Unfortunately, there is no one perfect solution and both cost and government regulations make these more difficult. The solutions that are discussed include:

- Optical Fibers
- Radio Frequency (RF) Technology
- Copper-based Technology
- Free Space Optics

The most obvious choice in this dilemma is fiber-optic cable. Without a doubt, fiber is the most reliable means of providing optical communications. However, the digging, delays and associated costs to lay fiber often make it economically prohibitive. While 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. Once fiber is deployed, it becomes a "sunk" cost and cannot be re-deployed if a customer relocates or switches to a competing service provider, making it extremely difficult to recover the investment in a reasonable timeframe.

Another option is radio frequency (RF) technology. RF is a mature technology, but RF-based networks require immense capital investments to acquire spectrum license. Yet, RF technologies cannot scale to optical capacities of 2.5 gigabits. Moreover, RF technology is not suitable for secure communications.

Another alternative is wire and copper based technologies, (such xDSL). Although copper infrastructure is available almost everywhere and the percentage of buildings connected to copper is much higher than fiber, it is still not a viable alternative for solving the connectivity bottleneck. The biggest hurdle is bandwidth scalability. Copper technologies may ease some short-term pain, but the bandwidth limitations of 2 megabits to 3 megabits make them a marginal solution, even on a good day.

Free Space Optics (FSO) is another solution for solving the bottleneck. FSO has many benefits but the transmission is affected significantly by weather and atmospheric conditions. This renders the technology unsuitable for high assurance transmission.

Only 5 percent of the buildings in the United States are connected to fiber-optic infrastructure (backbone), yet 75 percent are within one mile of fiber. In this thesis, the current last mile technologies, applications, benefits and limitations, are examined. We have also discussed how a telecommunication company installs optical fibers through sewers to provide occupants with high bandwidth. Using existing sewer as optical fiber routes to connect buildings is a novel idea that has great potential for linking up broadband cities in a non-invasive method. The successful deployment of optical fiber using robots in Albuquerque, New Mexico demonstrates a way to cost-effectively close the gap between all of the fiber optic cable put in the ground to date and the paying customer. For the end-user customer, the case study shows how broadband access can quickly become available, enabling greater speed, fostering competition and delivering on all the communications possibilities promised for so long. For cities, it illustrates how to provide businesses with state-of-the-art communications services to spur economic growth - without destroying a single costly city street or delaying commuter traffic. This is a promising development that could solve the last mile problem. It is the hope of the author that this method of extending optical fiber to the individuals will be widely accepted and implemented, thus achieving effective distribution of high bandwidth to the last mile.

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LIST OF REFERENCES

[Acam2002] Acampora, A., “Last Mile by Laser”, Scientist American, Jun 2002.

[Agra2002] Agrawal, G.P., “Fiber-Optic Communication Systems”, Third Edition, Wiley-Interscience, 2002

[Bouy2001] Bouy M.C., “Introduction to ADSL” Rev 1.2, NEXTEP Broadband May 2001, http://microboss.com.au/broadband/introduction_to_adsl.pdf, last accessed: Nov 2003

[City2000] CityNet Telecommunications, Inc. (2000) Personal communications, published articles, press releases, www.citynettelecom.com, last accessed: Dec 2003

[Cybe2000] Cybersavvy UK, The Last Mile Problem, Jan 2000 http://www.webpr.co.uk/news/lastmile.asp, last accessed: Nov 2003

[Dsl2001] DSL Forum 2001, published articles, press releases, www.dslforum.org, last accessed: Dec 2003

[Foun2001] Fountanas L., “An Assessment of Emerging Wireless Broadband Technologies”, Masters Thesis, Naval Postgraduate School, Monterey, California, Dec 2001.

[Gatt2002] Gattuso, J., “The Tauzin-Dingell Telecom Bill: Untangling the Confusion.” High-Speed Internet Access, Apr 2002, http://proquest.umi.com, last accessed: Nov 2003

[Glow2003] Glowacki J.P., “Impact of the Telecommunications Acts of 1996 and Spectrum Allocation on Cellular Telephone Technology”, Masters Thesis, Naval Postgraduate School, Monterey, California, Sep 2003.

[Harr2001] Harris, J.,“The Last Mile: Wired or Wireless”, Term Project, University of Washington, Seattle, Washington, Dec 2001.

[Hump1997] Humphrey, M., Freeman, J., Paradyne Corp., "How xDSL supports Broadband Services to the Home", IEEE Network Jan/Feb 1997

[Inte2003] Web ProForum Tutorials, “Cellular Communications”, The International Engineering Consortium, 2003. http://www.iec.org, last accessed: Oct 2003

[Isp2003] Premium Internet Service for 128Kbps ISDN, 2003, http://www.isp2k.com/, last accessed: Dec 2003

[Jand2002] Jander, M., "Fiber to Home: Dream Deferred?" 7 Feb 2002- http://www.lightreading.com, last accessed: Oct 2003

[Jeya2002] Jeyapalan J.K., "Optical Fiber Cables in Sewers 2002: What Do We Know? Where Are We Heading?", Pipeline Engineering Consultant, 2002

[Krim2002] Krim. J., "High-Speed Internet Access Gets White House Spotlight; Bush to Discuss Plans to Promote Availability." The Washington Post, 13 Jun 2002, http:proquest.umi.com, last accessed: Oct 2003

[Lee2001] Lee M., "WLL In Emerging Markets: Key Deployment Issues", 2001 Intelecon Research & Consultancy Ltd, Jan 2001. http://www.inteleconresearch.com/pdf/WLLForum.pdf, last accessed: Oct 2003

[Lee2002] Lee P.J., "Alternative High Speed Network Access for the Last Mile", Masters Thesis, Naval Postgraduate School, Monterey, California, Dec 2002.

[Ligh2002] LightPointe Communication Inc, Free Space Optics, White Paper, LightPointe, 2002.

[Lock2003] Lock J., Kingsley M. & Serin E., "Broadband Robotics Inc – Business Plan" 2003

[Loug2000] Lough, D.L., Blankenship, T.K. & Krizman, K.J., "A Short Tutorial on Wireless LANS and IEEE802.11", Virginia Polytechnic Institute and State University, 2000

[Lund2000] Lundy B., "Business Plan – A New and Modern Network for Mexico" 2000

[Nede2001] Nedeltchev, P.,"Wireless Local Area Networks and the 802.11 Standard", whitepaper, March 2001, http://www.cisco.com/warp/public/84/packet/jul01/pdfs/whitepaper.pdf, last accessed: Nov 2003

[Noll2003] Noll, G.B., "An Introduction to Fiber Optic Concepts and Technologies", Glenair, 2003 http://www.glenair.com/html/intro_to_fiber.htm, last accessed: Oct 2003

[Rapp2002] Rappaport, T.S., “Wireless Communications – Principles and Practice”, Second Edition, Upper Saddle River, NJ: Prentice Hall, 2002

[Saba2000] Sabatino, P., “Digital Subscriber Lines and Cable Modems”, Feb 2000. http://www.cis.ohio-state.edu/~jain/cis788-97/rbb/index.htm, last accessed: Dec 2003

[Schw2002] Schwartz, J.L., “Achieving Last-Mile Broadband Access with Passive Optical Networking Technology” Masters Thesis, Naval Postgraduate School, Monterey, California, Sep 2002.

[Sepp2002] Seppänen, L., “Wireless Local Area Network (WLAN) IEEE 802.11”, whitepaper, 2002, http://trade.hamk.fi/~lseppane/courses/wlan/doc/Material.pdf, last accessed: Oct 2003

[Shap2002] Shapiro, M., “Fiber-to-the-Farm”, 8 Jun 2002. http://www.broadbandmarkets.com/articles/FTTPfarmLTW701.htm, last accessed: Sep 2003

[Spra2002] Sprague, J.W., “Free Space Optics and Wireless Broadband Radio Frequency Technology: Brining High Speed Network Access to the last mile”, Masters Thesis, Naval Postgraduate School, Monterey, California, Mar 2002.

[Stal2002] Stallings, W., “Wireless Communications and Networks”, Upper Saddle River, NJ: Prentice Hall 2002.

[Stee2002] Steege, M., “Free-Space Optics: A Viable Secure Last Mile Solution?”, Jan 2002.

[Tele2003] Telephone World – Local Central Office System www.dmine.com/phworld/network/office.htm, last accessed: Sep 2003

[Vine2002] Vines, R.D., “Wireless Security Essentials”, Wiley Publishing, Inc, 2002.

[Will2002] Willebrand H.A., “New Roles for Free Space Optics”, Broadband Wireless Online Article, vol. 3, no. 2, Feb 2002.

[Wood2000} Woodard K.L., “Profiles in Ceramics: Robert D. Maurer”, The American Ceramic Society Bulletin, 2000. www.ceramicbulletin.org, last accessed: Dec 2003

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