NAVAL POSTGRADUATE SCHOOL

THESIS

HIGH SPEED NETWORK ACCESS TO THE LAST-MILE USING FIXED BROADBAND WIRELESS

by

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March 2004

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REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** March 2004	**3. REPORT TYPE AND DATES COVERED** Master's Thesis

4. TITLE AND SUBTITLE: High Speed Network Access to the Last-mile Using Fixed Broadband Wireless	**5. FUNDING NUMBERS**
6. AUTHOR(S) Nikolaos Fougias	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A	**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release, distribution is unlimited	**12b. DISTRIBUTION CODE**

13. ABSTRACT *(maximum 200 words)*

Despite the increase in the demand for high speed Internet services, the last-mile solutions currently available neither are inexpensive enough to attract the majority of the population, nor are they available in low density populated areas. This thesis examines Fixed Broadband Wireless (FBW) as an alternative technology to the current last-mile solutions. The analysis shows that LMDS and MMDS are the most promising emerging FBW technologies and that they are able, by utilizing microwave radio as their fundamental transport medium and using high modulation schemes, to provide digital two-way voice, data, video and Internet services.

The thesis shows that both technologies are constrained by free space loss and line-of-sight impairments with rain absorption being the most significant cause of attenuation in the LMDS case, while vegetation and multipath fading play a significant role mostly in the MMDS case. Additionally, it is shown that there is a positive association between the data rate achieved and the level of influence due to Additive White Gaussian Noise (AWGN). Based on the analysis and using the coverage areas, the total capacity, the achieved data rates, the weather and line-of-sight limitations as well as the cost as the most important criteria, it is concluded that LMDS is a preferable solution for enterprise end-users in densely populated urban areas outside the reach of fiber networks, while MMDS targets residential end-users in rural or suburban areas that are not able to receive service through high-speed wireline connections.

14. SUBJECT TERMS LMDS, MMDS, OFDM, Line-of-Sight, Fresnel Zones, Additive White Gaussian Noise, Bit Error Rate	**15. NUMBER OF PAGES** 119
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

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

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HIGH SPEED NETWORK ACCESS TO THE LAST-MILE USING FIXED BROADBAND WIRELESS

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Submitted in partial fulfillment of the
requirements for the degrees of

MASTER OF SCIENCE IN INFORMATION TECHNOLOGY MANAGEMENT
and
MASTER OF SCIENCE IN COMPUTER SCIENCE

from the

NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

Despite the increase in the demand for high speed Internet services, the last-mile solutions currently available neither are inexpensive enough to attract the majority of the population, nor are they available in low density populated areas. This thesis examines Fixed Broadband Wireless (FBW) as an alternative technology to the current last-mile solutions. The analysis shows that LMDS and MMDS are the most promising emerging FBW technologies and that they are able, by utilizing microwave radio as their fundamental transport medium and using high modulation schemes, to provide digital two-way voice, data, video and Internet services.

The thesis shows that both technologies are constrained by free space loss and line-of-sight impairments with rain absorption being the most significant cause of attenuation in the LMDS case, while vegetation and multipath fading play a significant role mostly in the MMDS case. Additionally, it is shown that there is a positive association between the data rate achieved and the level of influence due to Additive White Gaussian Noise (AWGN). Based on the analysis and using the coverage areas, the total capacity, the achieved data rates, the weather and line-of-sight limitations as well as the cost as the most important criteria, it is concluded that LMDS is a preferable solution for enterprise end-users in densely populated urban areas outside the reach of fiber networks, while MMDS targets residential end-users in rural or suburban areas that are not able to receive service through high-speed wireline connections.

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ACKNOWLEDGMENTS

This thesis is dedicated to my loving family, my beloved and wonderful wife, Evdokia, and my adorable son, Dimitrios. I am forever indebted to them for their endless love and for enduring my stress during my research here at the Naval Postgraduate School. Without their continuous support, encouragement and patience I would have accomplice nothing.

I also wish to dedicate this thesis to my thoughtful and supportive parents Dimitrios and Aphrodite, who made me believe in myself and taught me the values of education, honor and conscientiousness.

Furthermore, I would like to express my sincere appreciation to my advisors, Professors Bert Lundy and Thomas Housel, whose guidance and supervision made this thesis possible.

In addition, I would like to thank Nancy Sharrock for her valuable help in editing and formatting this thesis.

I would also like to thank my colleague and close friend Aristeidis Dalakos for his advice and assistance in the simulation analysis.

Lastly but not least, I must thank my sponsor, the Hellenic Navy, for providing the opportunity for me to pursue my postgraduate studies at the Naval Postgraduate School.

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I. INTRODUCTION

A. THE LAST-MILE PROBLEM

Prior to 1996, Internet access from home was almost exclusively made via the *Public Switched Telephone Network* (PSTN) with the use of dial-up modems over twisted copper pair[1]. Copper wire provided the link in the local loop between the telephone subscriber and the local exchange. However, the rapid growth of the Internet has let to an extremely high demand for bandwidth. Regardless of the numerous technology innovations that tried to solve the problem, the dilemma of how to support high bandwidth requirements at affordable cost and enable a significant number of dial-up users to adopt broadband, has not yet been resolved.

The Telecommunications At of 1996, which provoked significant changes in the telecommunications industry in the United States, led to the development of several solutions to the last-mile. More precisely, "*Congress directed the Commission and the states, in section 706, to encourage deployment of advanced telecommunications capability in the United States on a reasonable and timely basis*". Most of these solutions (Figure 1), as Asymmetric digital subscriber line (ADSL) technologies, which provide speeds in one direction greater than speeds in the other direction; other wireline technologies including traditional telephone company high-speed services and symmetric DSL services that provide equivalent functionality; coaxial cable, including the typical hybrid fiber-coax (HFC) architecture of upgraded cable TV systems; optical fiber to the subscriber's premises (Fiber-to-the-Home, or FTTH) and satellite wireless systems, which use the radio spectrum to communicate with a radio transmitter at the subscriber's premises[2], have some economical or associated technology drawbacks. A good illustration of that could be the case of DSL, which suffers from distance limitations that typically make it impossible to access areas that are more than 15,000 feet from the Central Office (CO).

[1] Oliver C. Ibe, Fixed Broadband Wireless Access Networks and Services, John Wiley & Sons, Inc., pp. 1-2, 2002.

[2] Federal Communications Commission, Federal Communications Commission Releases Data on High-Speed Services for Internet Access, June 10, 2003.

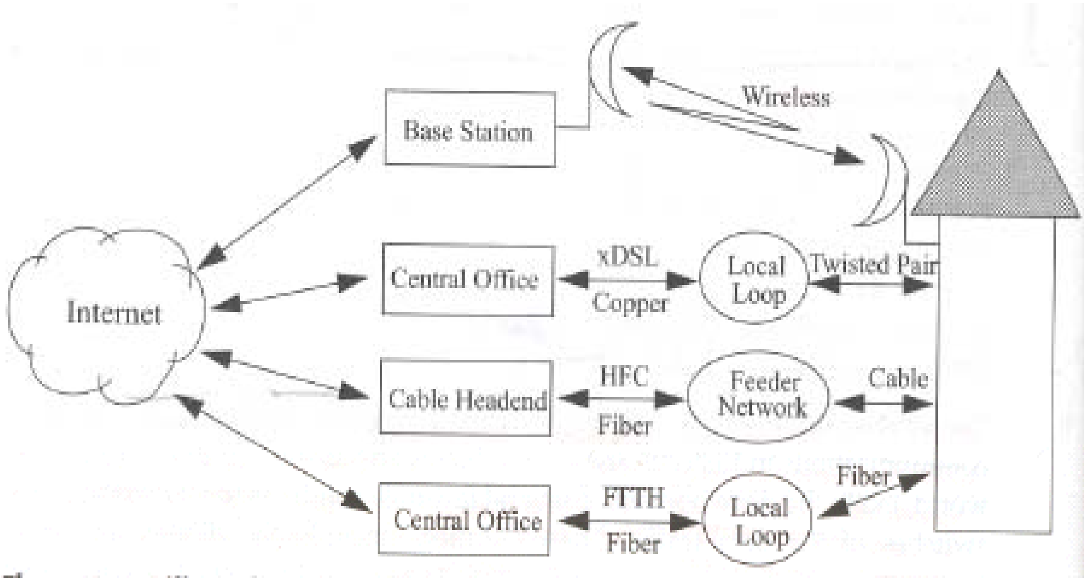

Figure 1. Different Last-Mile Access Technologies. [From: Fixed Broadband Wireless Access Networks and Services, Oliver C. Ibe]

Furthermore, optical fiber may be able to deliver extremely high bandwidth connectivity. However, on the other hand, even in countries with adequate telecommunications backbone infrastructure, it is too expensive and may take months or years to install. The inability of these solutions to fully support high-speed residential and business access needs at affordable prices creates frustration among end users who want inexpensive, reliable and rapidly broadband connectivity. In other words, the consumer does demand a high-speed connection, but on the other hand, is unwilling to pay an unreasonable amount of money to access the Internet. As a result, Fixed Broadband Wireless (FBW) has been projected as an alternative proposition for the last-mile access problems.

Fixed broadband wireless access networks are part of these last-mile solutions. They are extremely well suited for rapidly deploying a broadband connection in many instances and this approach is steadily becoming more popular for providing last-mile broadband local loop access. Using microwave wireless links, they manage to substitute the copper for all or part of the connection between the subscriber and the switch, creating in that way (Figure 2) a Wireless Local Loop (WLL), sometimes called radio in the loop (RITL) or fixed-radio access (FRA), which can be thought of as the "last-mile" of the telecommunication network that resides between the CO and individual homes and businesses in close proximity to the CO[3].

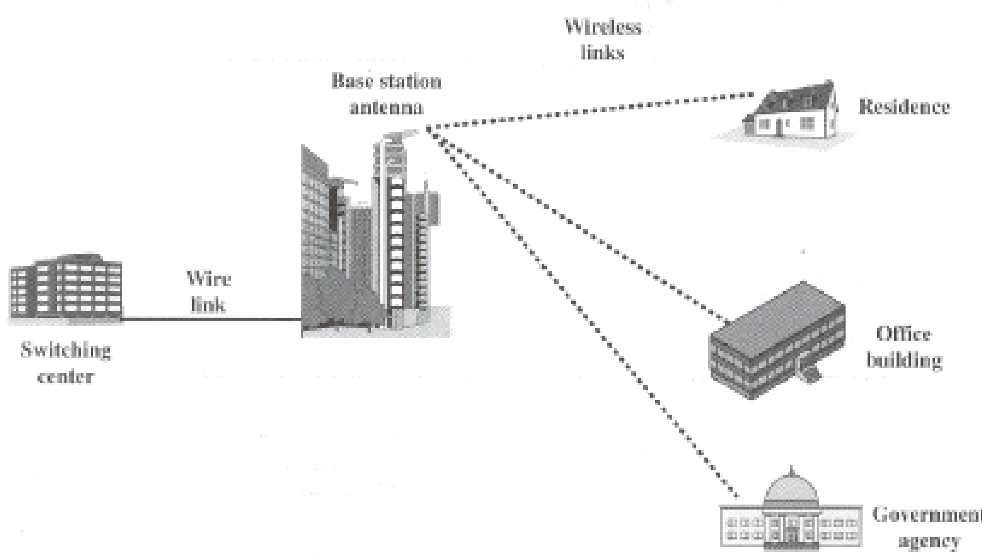

Figure 2. WLL Configuration. [From: Wireless Communications and Networks, William Stalings]

More particularly, FBW networks use *Multichannel Multipoint Distribution Service* (MMDS) and *Local Multipoint Distribution Service* (LMDS) to provide access to the Internet. They significantly differ from mobile wireless networks since the endpoints in this case are stationary, and therefore, less susceptible to the mobile and quality limitations associated with mobile wireless networks. Furthermore, the frequencies used are in the range of GHz, which makes the communication links susceptible to Line-of-Sight impairments.

B. THESIS OBJECTIVES

The purpose of this thesis is first, to discuss the strengths and weaknesses of the current last-mile solution technologies and then to provide a detailed analysis of the FBW access networks. Second, to identify the risks involved and demonstrate their influence in

[3] Theodore S. Rappaport, Wireless Communications Principles and Practices, Second Edition, Prentice Hall, Inc., p. 41, 2002.

the reliability and performance of the network.. More precisely, Chapter II presents the current market trends for high-speed Internet services, the market segmentation and an overview of the existing technologies apart from FBW. Chapter III gives a thorough analysis of the FBW including architecture, design and modulation schemes and also states the benefits of the FBW versus the other available solutions. Chapter IV, using simulation, demonstrates the effects of *Additive White Gaussian Noise* (AWGN) in FBW and shows the different levels of performance depending on the chosen modulation scheme. Chapter V analyses the *Line-of-Sight* (LOS) parameters, including atmospheric absorption, that affect the performance of FBW. Chapter VI illustrates the planning needed, including the risk variables mentioned in the previous chapters, in order to support the decision maker in determining whether FBW is an appropriate solution for a specific set of requirements. Finally, Chapter VII concludes the thesis as well as presents opportunities for future research.

II. MARKET TRENDS – CURRENT SOLUTIONS

A. HIGH SPEED SERVICES MARKET TRENDS

According to a recent report released by the Federal Communications Commission (FCC)[4], high–speed connections to end-users by means of satellite or fixed wireless technologies increased by 25% during the second half of 2002. The total high-speed connections to the Internet increased 23% during the second half of 2002 for a total of 19.9 million lines in service (Table 1). High speed lines increased by 55% for the entire year. For the purposes of the report, *high-speed lines* are defined as those that provide services at speeds exceeding 200 kilobits per second (kbps) in at least one direction.

Types of Technology[2]	Dec 1999	Jun 2000	Dec 2000	Jun 2001	Dec 2001	Jun 2002	Dec 2002	Percent Change	
								Dec 2001 - Jun 2002	Jun 2002 - Dec 2002
ADSL	369,792	951,583	1,977,101	2,693,834	3,947,808	5,101,493	6,471,716	29 %	27 %
Other Wireline	609,909	758,594	1,021,291	1,088,066	1,078,597	1,186,680	1,216,208	10	2
Coaxial Cable	1,411,977	2,284,491	3,582,874	5,184,141	7,059,598	9,172,895	11,369,087	30	24
Fiber	312,204	307,151	376,203	455,593	494,199	520,884	548,471	5	5
Satellite or Fixed Wireless	50,404	65,615	112,405	194,707	212,610	220,588	276,067	4	25
Total Lines	2,754,286	4,367,434	7,069,874	9,616,341	12,792,812	16,202,540	19,881,549	27 %	23 %

Table 1. High Speed Lines. [From: Federal Communications Commission Releases on High-Speed Services for Internet Access, June 10 2002]

Of the above 19.9 million high-speed lines in service, 17.4 million served residential and small business subscribers, a 24% increase from the 14.0 million residential and small businesses high-speed lines reported six months earlier (Table 2). For the full year, high-speed lines for residential and small business subscribers increased by 58%.

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4 Federal Communications Commission, Federal Communications Commission Releases Data on High-Speed Services for Internet Access, June 10, 2003.

Types of Technology [2]	Dec 1999	Jun 2000	Dec 2000	Jun 2001	Dec 2001	Jun 2002	Dec 2002	Percent Change Dec 2001 - Jun 2002	Percent Change Jun 2002 - Dec 2002
ADSL	291,757	772,272	1,594,879	2,490,740	3,615,989	4,395,033	5,529,241	22 %	26 %
Other Wireline	46,856	111,490	176,520	138,307	139,660	223,599	213,489	60	-5
Coaxial Cable	1,402,394	2,215,259	3,294,546	4,998,540	7,050,709	9,157,285	11,342,512	30	24
Fiber	1,023	325	1,994	2,623	4,139	6,120	14,692	NM	NM
Satellite or Fixed Wireless	50,189	64,320	102,432	182,165	194,897	202,251	256,978	4	27
Total Lines	1,792,219	3,163,666	5,170,371	7,812,375	11,005,396	13,984,287	17,356,911	27 %	24 %

Table 2. Residential and Small Business High-Speed Lines. [From: Federal Communications Commission Releases on High-Speed Services for Internet Access, June 10, 2003]

Moreover, the report shows that high population density as well as high median household income has a positive association with reports that high-speed subscribers are present, while on the other hand, low population density and low median household income have an inverse association (Figure 3).

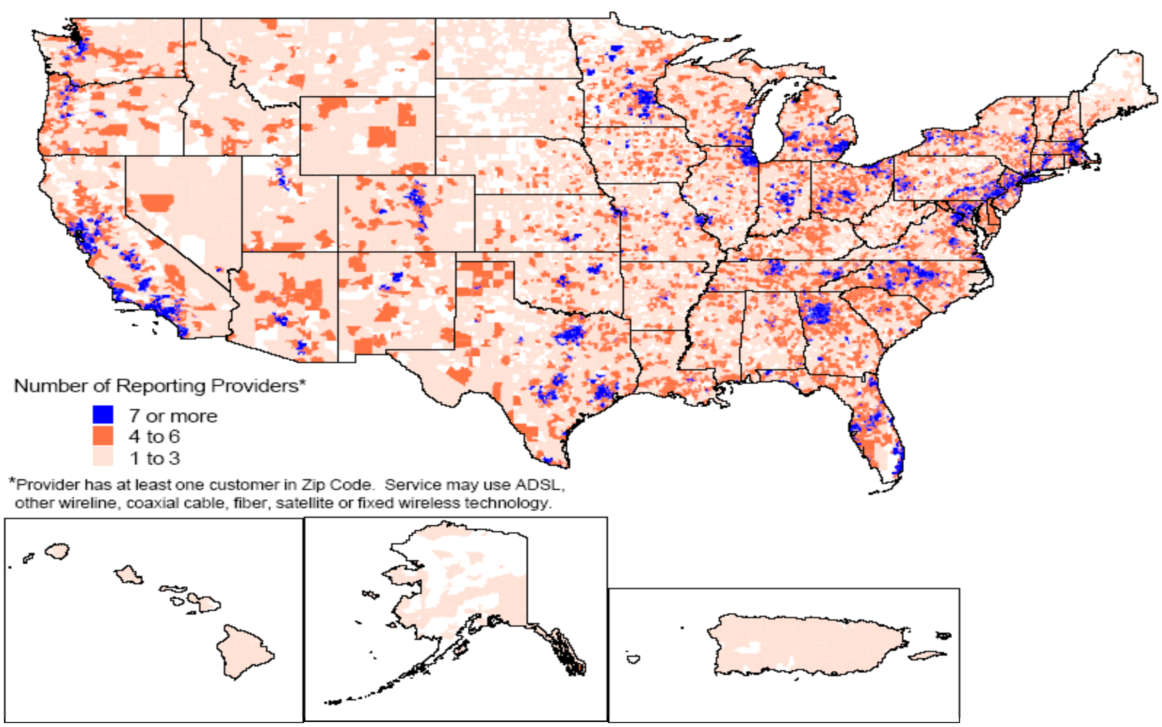

Figure 3. High Speed Providers by Zip Code. [From: Federal Communications Commission Releases on High-Speed Services for Internet Access, June 10, 2003]

To summarize, the report demonstrates a continuous increase in the demand for high speed Internet services, and more importantly, this increase is significantly high for subscribers of Fixed Wireless high-speed lines, compared to the majority of the other solutions. In addition, the report strongly indicates that the last-mile solutions currently available neither are inexpensive enough to attract the majority of the population, nor are they available in low density populated areas since the results definitely have a positive association with areas with a high population density and high median household income.

B. MARKET SEGMENTATION

Last-mile solutions design wired and wireless connectivity solutions for data, voice and video applications. They turn copper wire into fiber quality circuits or point-to-point high-speed wireless connections and increase network speed, capacity and throughput in local loop network environments and even in places where no wire or fiber exists.

The market includes military installations, government facilities, universities, college campuses, corporate campuses, local loop providers, business sites, small offices, individual users and many more. For the purpose of this thesis, the market segmentation is divided into two primary markets: *Residential End-Users* and *Enterprise End-Users*.

As it is shown in Figure 4, **Residential End-Users** include[5] *Home Businesses,* which include either full or part time revenue generating work activity, *Evening Offices,* where the users regularly perform more related activities at home after normal business hours, and *Technologically Advanced Families,* which are higher income families that require fast data speeds for either education or hobbies but nevertheless, are not willing to pay for a professional level of service.

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[5] Broadband Wireless Association, Overview of Point to Multipoint Fixed Wireless Broadband Wireless Access Solutions, [http://www.broadband-wireless.org/overview.html,] February 2004.

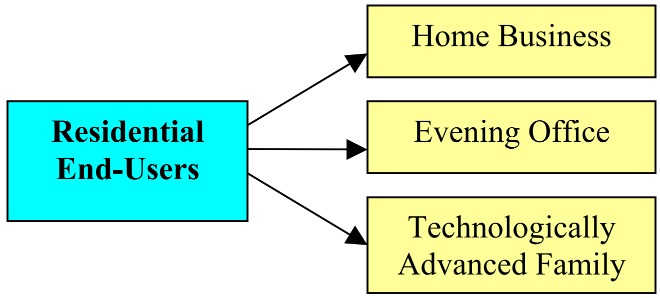

Figure 4. Market Segmentation, Residential End-Users.

Indeed, there are a significant number of users that require fast data speeds when they are at home. Such users include corporate employees, working at home during the evening or weekends, students doing research, as well as professional consultants that need electronic access to clients and collaborators form home to perform a service

On the other hand, as shown in Figure 5, **Enterprise End-Users** include[6] *Branch Offices*, which are branches of multi-site business enterprises with more than 50 employees, *Single Businesses*, considered to be single office sites with less than 50 employees and *Telecommuters*, who are employees of large enterprises working at home many days per week. In this category of end-users, electronic commerce is driving the demand for higher data rates.

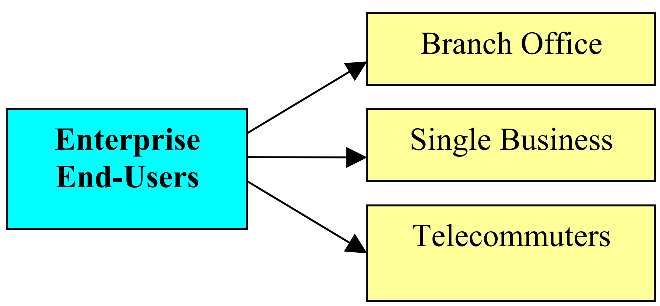

Figure 5. Market Segmentation, Enterprise End-Users.

[6] Ibid.

C. RESIDENTIAL END-USERS

1. Requirements

Even though the needs of each individual are unique, a number of key broadband requirements can be characterized. The most important requirement for broadband for Residential End-Users is *low cost.* That is, affordable access is the most important criterion for most residential customers. Furthermore, residential customers are attracted by providers that feature *ease of installation*. Also, an average speed of *400Kbps-1Mbps* would satisfy most Residential End-Users, since most of them use the Internet mostly for checking e-mail and web-surfing[7].

2. Current Wireline Solutions

Having the above in mind and by not taking into consideration the solutions involving the use of MMDS and LMDS from the Fixed Wireless Broadband arena, various solutions currently available in the marketplace could be mentioned.

a. Twisted Copper Pair (xDSL)

xDSL is the term that describes x-type digital subscriber line technology. It is a copper based broadband technology for the local loop which leverages current telephone infrastructure to deliver high-speed data. There are numerous variants to DSL types, which use different modulation methods to enhance the data throughput capabilities of an existing access line, local loop. The *International Telecommunications Union* (ITU) specifies a maximum speed of 6.1Mbps downstream and 64Kbps upstream for the most popular version that is ADSL. However, 6.1Mbps are possible only for loops up to 9,000 feet going down to 1.5Mbps for loops up to 15,000 feet. The fastest version supports 55Mbps downstream but for only 1,000 feet going down to 13Mbps for 4,500

[7] The Shpigler Group Strategy Management Consulting Services, Opportunities in Last-mile Wireless Access, 2002.

feet[8]. The typical data rates are shown in Table 3. Cisco, Nokia, Lucent, Siemens and Alcatel are the main equipment vendors with SBC, Qwest and Verizon the largest service providers.

x-DSL	Comments	Data Rates
HDSL	Symmetric	1.544Mbps or 2.048Mbps
SDSL	Symmetric	768kbps
ADSL	Asymmetric	1.5 - 8 Mbps downstream / 16 - 640kbps upstream
RDSL	Asymmetric	1.5 - 8 Mbps downstream / 16 - 640kbps upstream
CDSL	Asymmetric	1Mbps downstream / 16 - 128kbps upstream
IDSL	Symmetric	64kbps
VDSL	Asymmetric	13 - 52 Mbps downstream / 1.5 - 6Mbps upstream

Table 3. Typical xDSL data rates [After: LMDS, Clint Smith].

Even though it is a proven technology and uses the current telephone network which is connected to almost every household, the copper part of the loop has to be shorter than 15,000 feet in order to support DSL service. Therefore, and by taking into consideration that higher speed versions require shorter loops, as previously mentioned, it is obvious that a large percentage of Residential End-Users are not yet able to take advantage of xDSL services.

b. Cable Modem

This uses the existing cable TV infrastructure as a local loop technology that delivers data to subscribers and it supports 40Mbps downstream and 10Mbps upstream data channels. It is an alternative solution to xDSL with high customer satisfaction, and in fact, it is the only solution, besides satellite, for urban areas that lack the xDSL service.

8 Stagg Newman, Broadband Access Platforms, pp. 3-5, 2002.

Nevertheless, due to the limitations of RF noise and the shared data channels, the typical available speed is up to 1Mbps downstream and up to 0.5Mbps upstream. Indeed, when many users access the network they might experience low data rates. More precisely, if N subscribers share a single frequency, the amount of capacity available to each individual subscriber can be as little as 1/N[9].

c. Hybrid Fiber/Coax

Hybrid Fiber/Coax (HFC) networks provide two-way communication for data voice and video. The primary access method is physical media, where the connection to the end-user at the end of the line is via coaxial cable. For increased performance, fiber optic cables are part of the cable's network topology. More precisely, HFC uses a combination of optical fiber, for the portion of the network that requires high bandwidth, as well as coax for parts that can tolerate lower capacities. Fiber is used for the central facilities and coax is used for the connections to individual subscribers. Like ADSL, they provide higher data rates downstream than upstream. However, the upstream delivery can be as high as 1.5 to 2Mbps. Regardless of its high potential, cable companies are thus far slowly adopting the technology because they need to replace much of the existing cable wiring and amplifiers. More precisely, in many areas, they need to replace trunk lines with the optical fiber and modify all amplifiers to operate in both directions.

3. Current Wireline Solutions

a. WLAN (IEEE802.11b)

WLANs have a point-to-multipoint architecture and support Internet access to corporate networks through *Virtual Private Networks* (VPN). They do not need to be physically connected to any wired outlet and they enable extreme flexibility for the location as shown in Figure 6. The IEEE Std. 802.11b specification, operating in the 2.4GHz unlicensed band, is the most common WLAN platform with theoretical data rates

[9] Douglas E. Comer, Computer Networks and Internets, Third Edition, Prentice Hall, Inc., p. 189, 2001.

up to 11Mbps. Typically, data rates average 5.5 Mbps shared by many (theoretically 60) users per access point[10] with and outdoor range of 300 feet-to-1 mile, with Lucent, Nokia and Cisco being the largest 802.11b equipment vendors.

802.11b is advantageous for several reasons. The spectrum license is not needed and it is already well proven with many users worldwide. However, due to the WLAN's short-range limits, even though it is applicable almost everywhere, it mostly favors nomadic (e.g. airports) and mobile (e.g. shopping malls) applications. Regardless, power consumption issues delay adoption for mobile applications since WLAN significantly reduces buttery life. Finally, there can be significant RF interference within the 2.4GHz band. Indeed, the growing use of wireless phones and Bluetooth devices may crowd the radio spectrum within a facility and thus, tremendously reduce the performance of the WLAN.

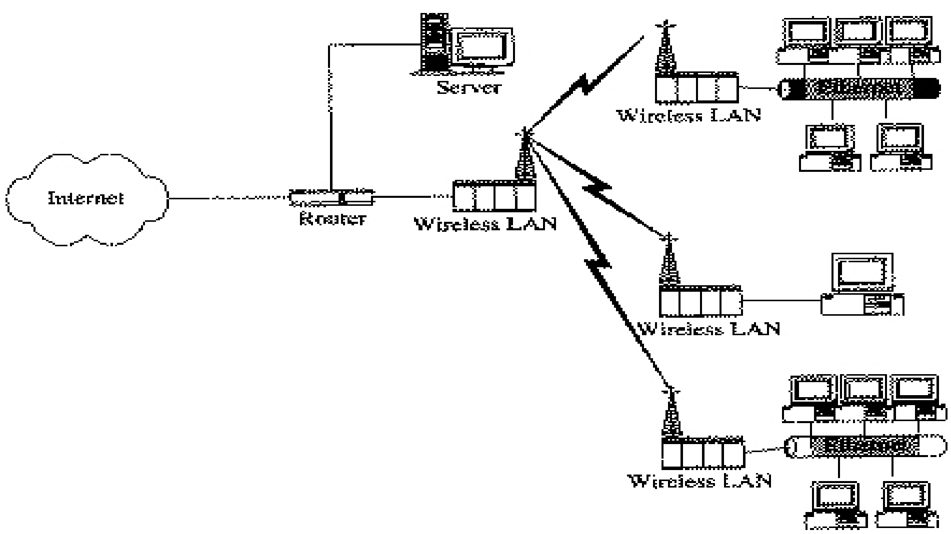

Figure 6. WLAN. [From: LMDS, Clint Smith]

In addition, although IEEE802.11a architectures, with the use of proper modulation schemes, can achieve data rates in the range of the above solutions, the potential is very high, and thus, it is mostly considered a solution for Enterprise End-Users and will be analyzed further.

10 Stagg Newman, Broadband Access Platforms, p. 89, 2002.

b. Satellite

Radio transmissions do not bend around the surface of the earth. However, RF technology can be combined with satellites to provide communication across longer distances. The satellite contains a transponder, which itself contains a radio receiver and transmitter. Satellite transponders typically have 40Mbps shared capacity and are able to serve 10,000 to 20,000 subscribers.

Many important drawbacks must be considered even though a service provider can reach almost the entire United States from a single earth station. First, the previously mentioned transponder capacity is shared by all subscribers and reduces the available bandwidth per customer, especially in the upstream channel. Second, due to high latency, significantly poor performance on interactive (especially voice) services exists. Moreover, like *Free Space Optics* (FSO), the need exists to satisfy Line of Sight (LOS) requirements. Finally, free space loss is another major impairment in satellite communications. In addition, DSL and Cable currently offer higher upstream as well as downstream bandwidth without the problems mentioned above and with lower costs to the end-user. To illustrate the above parameters, a comparison of the current average monthly fees for xDSL, Cable and Satellite are shown in the next table.

Parameters	xDSL	Cable	Satellite
Typical Downstream	0.64-1.54Mbps	0.5-1Mbps	150-400Kbps
Typical Upstream	256-384Kbps	256-500Kbps	40-128Kbps
Monthly Fee	$35-50	$40-70	$70.00

Table 4. Price/Performance Comparison.

D. ENTERPRISE END-USERS

1. Requirements

In an attempt to characterize the most important business requirements for broadband, *high speed* in both directions is identified as the key requirement. Indeed, businesses have a tremendous need for moving increasing amounts of data downstream as well as upstream. Moreover, the ability to conduct *secure transactions* is considered to be extremely important. In addition, *high reliability* is another requirement since enterprises demand 24/7 security regardless of environmental and physical factors. Even though in this case cost is not a key requirement, solutions that have *relatively lower costs* than the current ILEC-provided services are more preferable than others.

2. Current Wireline Solutions

Various current solutions can be demonstrated by keeping in mind the aforementioned requirements and not taking into account again the solutions from the Fixed Wireless Broadband arena.

a. Optical Fiber – Gigabit Ethernet

Gigabit Ethernet is a low cost optical networking platform capable of providing Internet access to large enterprises using dedicated fiber and Ethernet switches. Data rates range from 1Mbps to 1Gbps, it supports almost all applications and it is easily interfaced with Ethernet LANS. Nevertheless, the extremely high cost of laying fiber limits the reach of gigabit Ethernet, which is extremely important when considering that the fiber access network infrastructure is still under development and that it costs at least $10,000 per mile to lay fiber. In fact, *there are roughly 60,000 buildings in the US on or near fiber*[11].

b. Point-to-Point Digital Circuits

Telephone companies lease point-to-point Digital Circuits for a monthly fee. The fee depends on the capacity of the circuit as well as the distance spanned. Since the standards for telephone system digital circuits differ from those used in the computer industry, a device known as Data Service Unit/ Channel Service Unit (DSU/CSU) is

[11] Douglas E. Comer, Computer Networks and Internets, Third Edition, Prentice Hall, Inc., 2001.

needed at each end of the line (Figure 7). The purpose of the DSU/CSU is to perform the "translation" between the digital representation used by the phone companies and the digital representation used by the computer industry.

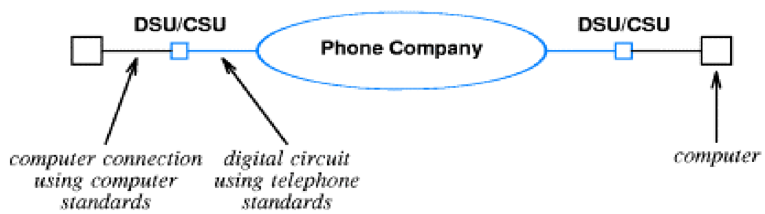

Figure 7. Digital Circuits. [From: Computer Networks and Internets, Douglas E. Comer]

Digital Circuits are classified according to a set of telephone standards as shown in Table 5.

Name	Bit Rate	Voice Circuits	Location
–	0.064 Mbps	1	
T1	1.544 Mbps	24	North America
T2	6.312 Mbps	96	North America
T3	44.736 Mbps	672	North America
E1	2.048 Mbps	30	Europe
E2	8.448 Mbps	120	Europe
E3	34.368 Mbps	480	Europe

Table 5. Data Rates of Popular Digital Circuits. [From: Computer Networks and Internets, Douglas E. Comer]

For enterprises that need higher capacities, a series of standards known as Synchronous Transport Signal (STS) specifies the details for high speed connections, with standards exceeding 1Gbps (Table 6) where OC stands for Optical Carrier. The high data rates require the use of optical fiber as a media.

Standard Name	Optical Name	Bit Rate	Voice Circuits
STS-1	OC-1	51.840 Mbps	810
STS-3	OC-3	155.520 Mbps	2430
STS-12	OC-12	622.080 Mbps	9720
STS-24	OC-24	1,244.160 Mbps	19440
STS-48	OC-48	2,488.320 Mbps	38880

Table 6. Data Rates According to the STS Standards [From: Computer Networks and Internets, Douglas E. Comer]

Regardless of the extreme high data rates, the cost of such a solution, especially in the T3 and OC range, is considerably high. However, for companies seeking intermediate capacities, e.g. more than T1, but much less than T3 with the use of *inverse multiplexity*, they could implement a lower cost solution, as shown in Figure 8. This is achieved by leasing multiple T1 circuits between two points and using them as a single higher-capacity circuit.

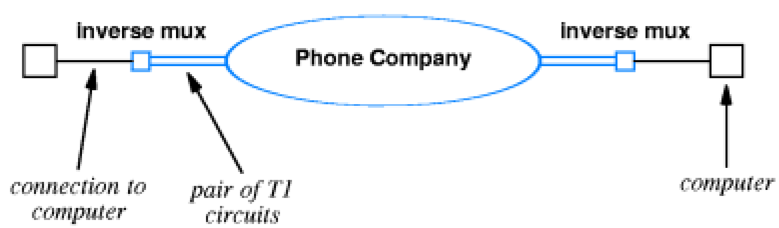

Figure 8. An Inverse Mux Using Two T1 Circuits to Provide a Connection with Twice the Capacity. [From: Computer Networks and Internets, Douglas E. Comer]

3. Current Wireless Solutions

a. WLAN (802.11a)

The IEEE 802.11a specification makes use of the 5GHz band to deliver broadband solutions. By using *Orthogonal Frequency Division Multiplexing* (OFDM), to be analyzed in Chapter IV, and depending on the modulation scheme data, rates vary from 6 to 54Mbps. It has been widely deployed for corporate and campus networking. However, given the higher frequency, the coverage range is very limited. A good illustration is that the effective range is 500 feet with 802.11b, but drops to 60 feet with 802.11a,. As a result, the cost of such an installation is considerably higher because a large number of access points are required to cover a facility, especially for large, sparsely populated enterprises.

b. Free Space Optics (FSO)

FSO is an optical wireless platform providing point-to-point connections. Providers utilize lasers to deliver fiber-like data rates. More precisely, information is transmitted over beams of infrared laser light traveling through open air. Due to the high frequencies of lasers, the speeds delivered are in the range of 100Mbps to 1.25Gbps[12]. Apart from the significantly high capacity, a spectrum license is not needed. Furthermore, since the laser transmission travels directly to the receiver with a minimum beam diverge, FSO becomes a very attractive solution for enterprises that value security as the most important intangible factor.

However, compared to other wireless solutions, FSO suffer from strict LOS requirements, which means that buildings and foliage may totally block the signal. Moreover, due to the extremely small wavelengths of FSO, weather patterns such as snow, rain, extreme heat and especially fog, may severely disrupt the signal. Finally, the various atmospheric gases analyzed in Chapter IV provoke scattering, and thus absorption, which also significantly affects performance.

[12] Stagg Newman, Broadband Access Platforms, pp. 61-62, 2002.

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III. FIXED BROADBAND WIRELESS TECHNOLOGY

A. OVERVIEW

Until approximately 1996, wired infrastructure was the only economical way to connect LANs. However, the early growth of the Internet-related applications resulted in numerous wireless broadband infrastructures whose main focus was the provision of efficient transport capacity at acceptable costs to the last-mile. One of these infrastructures is the Wireless Local Loop (WLL), which utilizes wireless technologies to replace the traditional copper local loop. These technologies include Fixed Wireless Broadband (FWB), and more precisely, *Local Multipoint Distribution Services* (LMDS) and *Multichannel Multipoint Distribution Services* (MMDS).

Indeed, the FCC has defined 15 frequency bands at frequencies of 2 to 40 GHz for use in commercial fixed wireless service. The LMDS and MMDS technologies are of the most interest to the WLL in this range[13]. The development of LMDS and MMDS is critical for the evolution of the WLL because these technologies are capable of providing video, telephony and data at data rates in the Mbps range and at relatively low cost in comparison with cable alternatives. Even though LMDS and MMDS may vary from one manufacturer to another as far as capabilities and features are concerned, they do share a number of common architectural features. The core components are a base–station transceiver, a customer premise transceiver and a network interface unit (NIU) or card, analyzed further in this chapter.

To provide a standardized approach to WLL in combination with the growing interest in LMDS, the IEEE 802 committee set up the 802.16 working group in 1999 to develop broadband wireless standards. As a result, IEEE 802.16 standardized the air interface and related functions associated with WLL and provided a communications path between the subscriber site and the core network, as shown in Figure 9. The IEEE802.16 applies to systems operating in the 2 to 66 GHz range and its specification enables the

[13] William Stallings, Wireless Communications and Networks, p. 357, Prentice Hall, Inc., 2002.

transport of voice, video and data. Its purpose is to "*enable rapid worldwide development of innovative, cost effective and interoperable multivendor broadband wireless access products*".

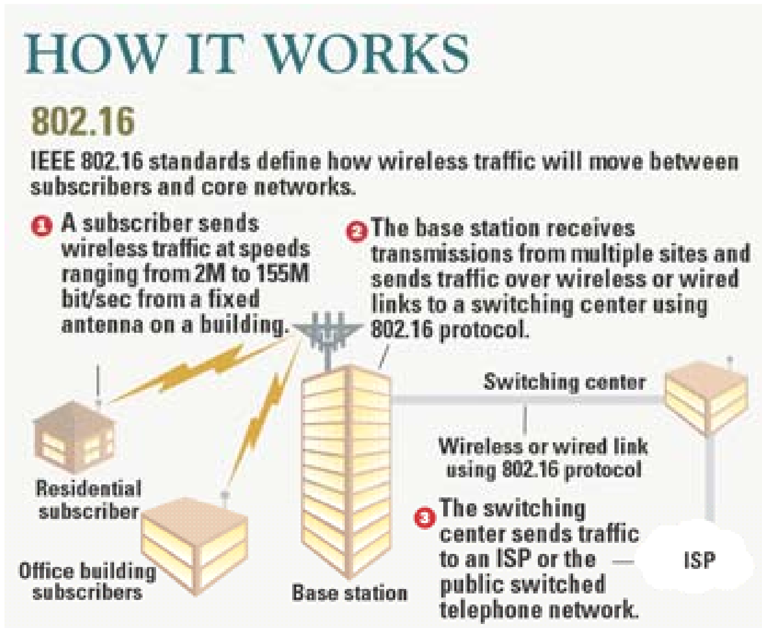

Figure 9. IEEE802.16-How It Works. [From: IEEE 802.16 for Broadband Wireless, William Stallings, [http://www.nwfusion.com/news/tech/2001/0903tech.html#img], February 2004]

In essence, the protocol standardizes both MMDS and LMDS. The physical layer specifies the frequency band, the modulation scheme, error-correction techniques and data rates as well as synchronization between transmitter and receiver to be thoroughly described in the LMDS analysis.

B. LOCAL MULTIPOINT DISTRIBUTION SERVICES

1. Definition-History

LMDS is currently a promising emerging technology in Broadband Fixed Wireless (FBW) communications operating in the 25 GHz and higher spectrum. In fact, it is a broadband wireless point-to-multipoint communications system that provides reliable digital two-way voice, data and Internet services[14]. It utilizes microwave radio as the fundamental transport medium, and a cellular-like network, which provides fixed services as well as allows multiple users to access the same radio spectrum. The cellular structure, high data rates and flexibility make LMDS ideal for multimedia and interactive services.

The term "*Local*" indicates the signal's range limit. Indeed, the propagation characteristics of signals in such a frequency range limit the potential coverage area of a single cell site, and thus limits the range of LMDS transmitters to 5 miles[15]. This is a result, first, of the need for a line-of-sight (LOS) path between the transmitter and receiver in order to receive sufficient signal strength for reliable services. Second, sufficient link margin is necessary in order to overcome the amount of rain attenuation that may be experienced at the link. As analyzed in Chapter V, rainfall severely attenuates radio signals at 28 GHz .

The term "*Multipoint*" indicates a broadcast signal from the subscribers. Indeed, the signals are transmitted in a Point-to-Multipoint method for the downlink and a Point-to-Point method for the uplink as shown in Figure 10. By being able to provide the service not only to one customer in a sector, but to multiple customers, LMDS is capable of having multiple customers per geographic area, which reduces both the cost of acquisition for any customer and the operating costs.

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[14] John R. Vacca, Wireless Broadband Networks Handbook 3G, LMDS &Wireless Internet, McGraw-Hill, p. 227, 2001.

[15] Local Multipoint Distribution System, The International Engineering Consortium [http://www.iec.org/online/tutorials/lmds/comment.html], January 2004.

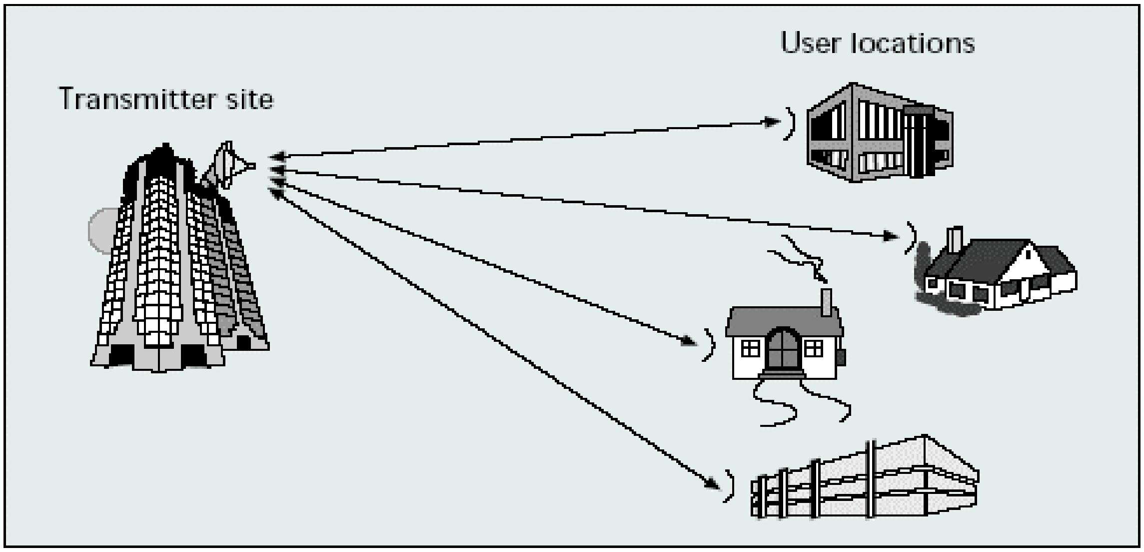

Figure 10. Point-to-Point Uplink and Point-to-Multipoint Downlink. [From: LMDS Systems and Heir Application, Agne Nordbotten, IEEE Communications Magazine]

The term "*Distribution*" defines the wide range of data that can be transmitted. Indeed, the signals may consist of simultaneous Internet, voice, data as well as video traffic. Finally, the term "*Services*" implies the subscriber nature of the relationship between the customer and the operator. Taking into consideration that all services must satisfy the bandwidth requirement that the transport layer can support, some of the services that LMDS can offer include the following[16]:

- Internet Connectivity
- Web Services
- Voice over IP
- Voice Telephony
- Long-Distance and International Telephony
- Frame Relay
- LAN/WAN
- Video Conferencing
- Digital Circuits T1/E1 Replacement

16 Clint Smith, LMDS, McGraw-Hill, pp. 15-16, 2000.

In 1997, the FCC released the service and competitive bidding rules for the LMDS spectrum: 27.5-to-28.35 GHz, 29.1-to-29.25 GHz and 31.0-to-31.30 GHz bands. This 1.3 GHz frequency spectrum was the largest spectrum ever allocated. On February 18, 1998, the FCC commenced the auction for the above frequency spectrum. After five weeks and 128 rounds of bidding, on March 25, the auctions raised almost $578 million for the U.S. Treasury. A total of 986 licenses were assigned to 104 companies within each of the geographic Basic Trading Areas (BTA)[17]. Since the FCC generally wanted to promote competition in the telecommunications industry, it should be noted that cable companies and the Incumbent Local Exchange Carriers (ILECS) were prohibited for three years from obtaining LMDS licenses in their regions. As shown in Figure 11, the total 1.3 GHz spectrum was split into 2 blocks. A license from each block was awarded for each BTA:

- Block A, 1150MHz wide
- Block B, 150MHz wide

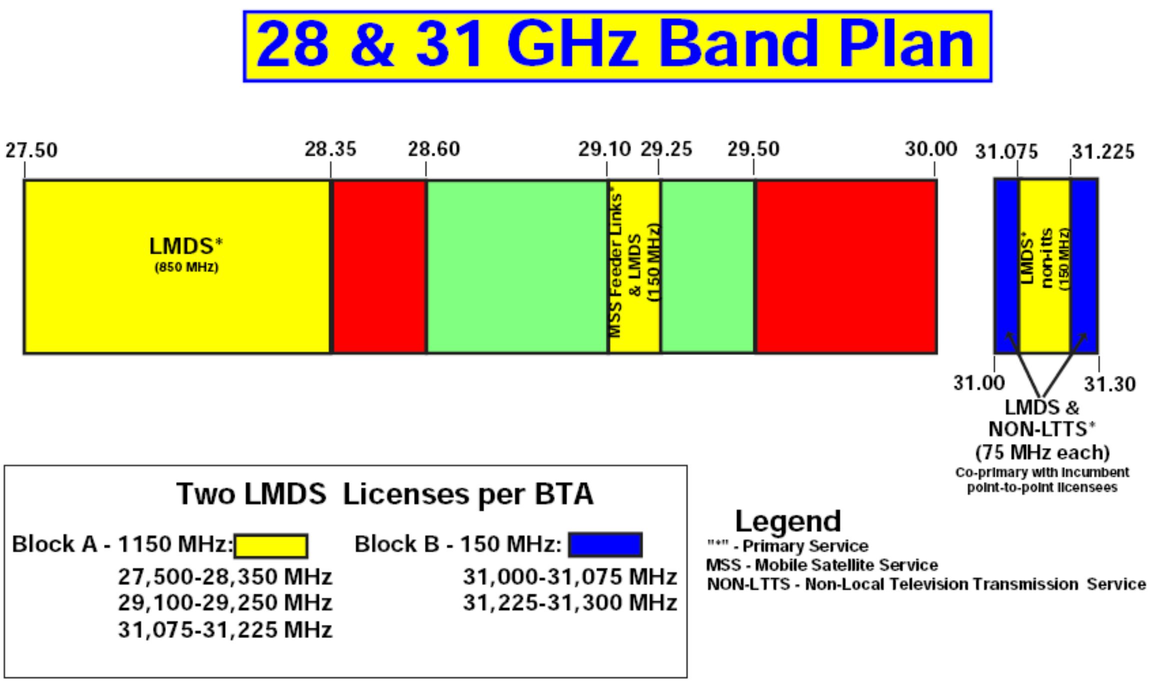

Figure 11. LMDS Band Allocation. [From: Federal Communication Commission, [http://nwest.nist.gov/article_network.pdf], January 2004]

17 John R. Vacca, Wireless Broadband Networks Handbook 3G, LMDS &Wireless Internet, McGraw-Hill, pp. 256-258, 2001.

As shown in Figure 12, 850 MHz of the spectrum between 27.5 and 28.35 GHZ are available for LMDS services. Another 150 MHz is available between 29.1 and 29.5 GHz and finally an additional 300 MHz of spectrum is available between 31 and 31.3 GHz. Approximately 150 MHz of the spectrum is assigned for upstream communications and the rest of the spectrum is assigned for downstream communications. Thus, it becomes clear that the LMDS band has a large available bandwidth and that it is able to use it in order to provide high-capacity point-to-point and point-to-multipoint fixed wireless connections.

2. Network Architecture

An LMDS system has many similar fundamental blocks with many wireless systems and its basic purpose is to provide the last-mile of access through the use of radio. After all, LMDS utilizes a radio frequency spectrum as the transport mechanism in such a way that it transports the maximum amount of information with a constant bandwidth. Its greatest advantage is that the end-user is stationary and not mobile. Therefore, many complications, such as fading, analyzed in Chapter V, have a lot less impact compared to other wireless systems. A normal LMDS setup has a central facility with a fiber-linked PSTN and Internet connections. The network architecture consists of primarily four parts[18]:

- The ***network operations center*** (NOC), which contains the network management system equipment that manages large regions of the customer network.
- The ***fiber-based infrastructure***, which consists of the central office (CO) equipment, interconnections with the PSTN, optical carrier links and IP and ATM switching systems.
- The ***base station*****,** usually located on a tower, where the conversion from fiber infrastructure to wireless infrastructure and vice versa occurs.
- The ***customer premises equipment*** (CPE), where the microwaves are reconverted back into a digital bitstream.

In order to understand the above better, assume that some type of information needs to be transported from the base station to the CPE. The base receives a digital

18 Local Multipoint Distribution System, The International Engineering Consortium [http://www.iec.org/online/tutorials/lmds/comment.html], January 2004.

bitstream and then converts the digital bitstream into microwaves that are transmitted to the antenna on the CPE. The microwaves are then reconverted into a digital bitstream with the use of a NIU and delivered to the end-user[19]. The process is reversed in the case of upstream traffic. In other words, the base station now receives a microwave signal. It converts it into a digital bitstream and routes it to the wider network where the data is delivered to its final destination.

The base station includes the network interface for fiber termination, modulation and demodulation functions as well as microwave transmission and reception equipment. The most important parts are the *base station transceiver* and the *digital controller* shown in Figure 12. Since most cell sites are divided into four 90-degree sectors, a separate transceiver is used each individual sector. The digital controller itself is interconnected to the network via fiber or radio.I Its purpose is to manage the cell site.

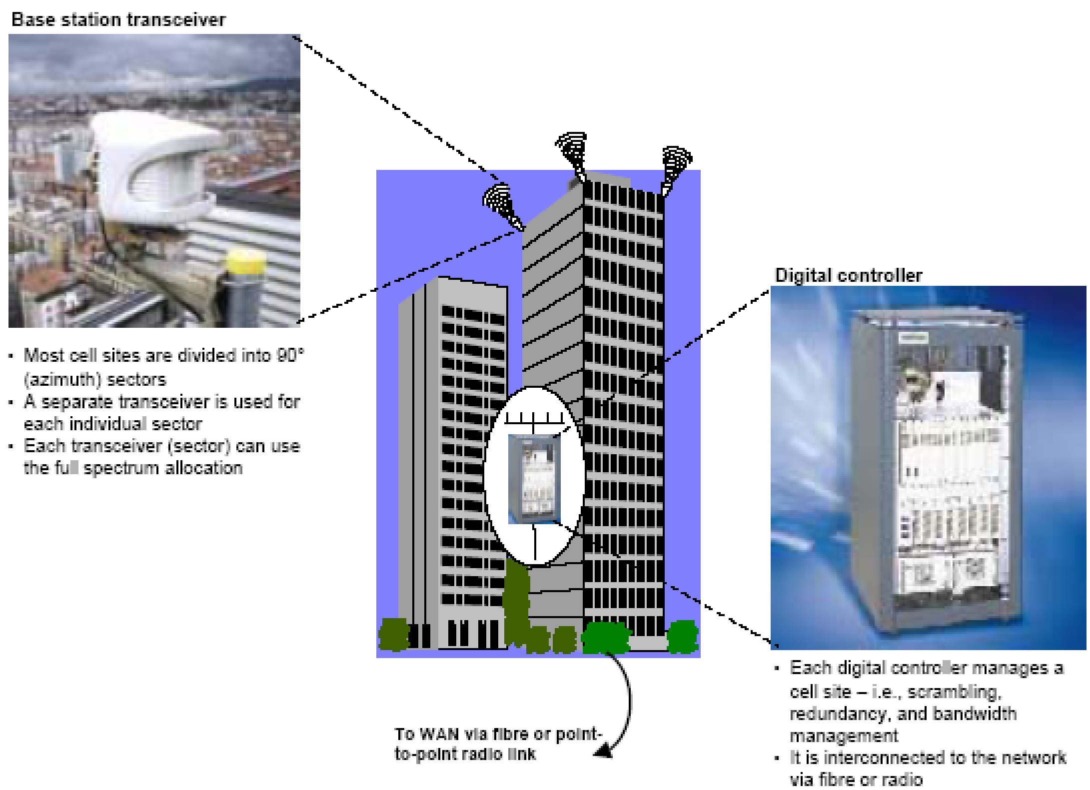

Figure 12. Base Station Equipment. [From: Broadband Access Platforms, Stagg Newman]

19 MMDS/LMDS Multipoint Distribution Services, [http://www.mobilecomms-technology.com/projects/mmds/], February 2004.

All CPE configurations include indoor digital (located within a building) and outdoor microwave (mounted on the outside of a consumer's home or business) equipment which provide modulation, demodulation, control and functionality. Nevertheless, they vary widely from vendor to vendor and they depend on the location and the desired modulation scheme. The location is extremely important because it could be a large enterprise where the microwave equipment is shared among many users and even optical carriers would be used, but on the other hand, it could also be a residence where a 10BaseT would be sufficient. Obviously, different CPE locations require different equipment configurations and different price points[20].The modulation scheme is based on customer requirements and will be analyzed further. Figure 13 provides a closer look of the CPE. The antenna is relatively small, and in contrast with the base station, only one antenna is needed per premise. The NIU is responsible for converting the microwaves into digital bitstreams, and in the case of multiple customers within the same CPE multiple, NIUs are required.

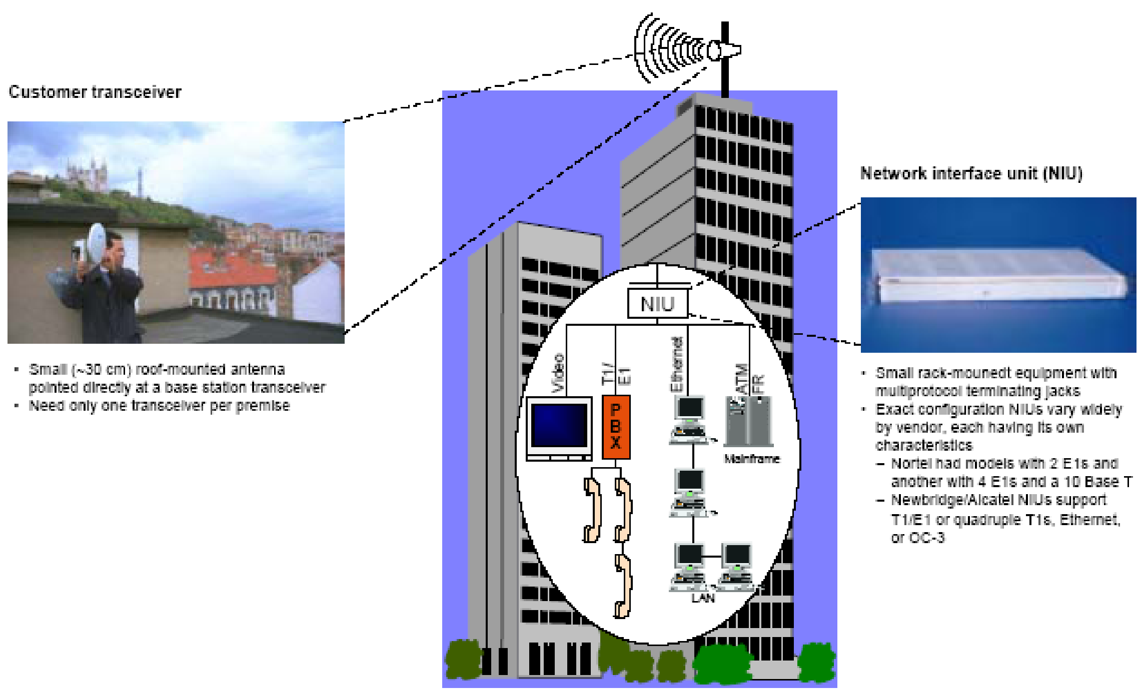

Figure 13. Customer Premises Equipment. [From: Broadband Access Platforms, Stagg Newman]

[20] Local Multipoint Distribution System, The International Engineering Consortium [http://www.iec.org/online/tutorials/lmds/comment.html], January 2004.

The most common architectural options are ***co-sited base station*** and ***analog fiber*** architecture[21]. Co-sited base station is the most common type. It includes indoor digital equipment, which is connected to the network infrastructure and outdoor microwave equipment, which is mounted on the rooftop. The outdoor equipment in this case is based at the same location with the indoor equipment. This kind of architecture uses multiple sector microwave systems in which the antennas provide service over a 90-, 45-, 30-, 22.5- or 15-degree beamwidth. In that way, the coverage area around the cell site is divided into 4, 8, 12, 16, or 24 sectors accordingly. Figure 14 shows the co-sited base station architecture, where it is clear that the base stations are housed in the same location with the base station digital elements.

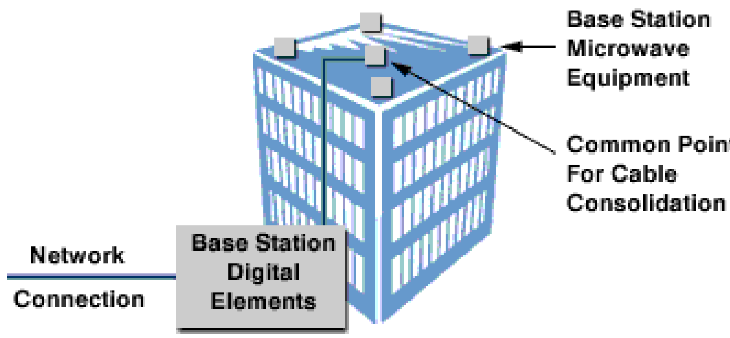

Figure 14. Co-Sited Base Station. [From: Local Multipoint Distribution System, The International Engineering Consortium [http://www.iec.org/online/tutorials/lmds/comment.html], January 2004

An alternative architectural option is the analog fiber architecture. It similarly includes indoor and outdoor equipment. However, in this case, the outdoor equipment can also be in a location other than that of the indoor equipment. This is shown in Figure 15, where the base station indoor unit can be connected to multiple remote microwave transmission and reception systems. The key element is the analog fiber interconnection between the indoor and outdoor units. The advantages of this approach are the increased sharing of digital resources and the reduced servicing costs. Nevertheless, the lack of analog fiber resources greatly limits the applicability of that type of architecture and thus, this approach is early in the design process for most vendors[22].

21 Ibid.

22 Ibid.

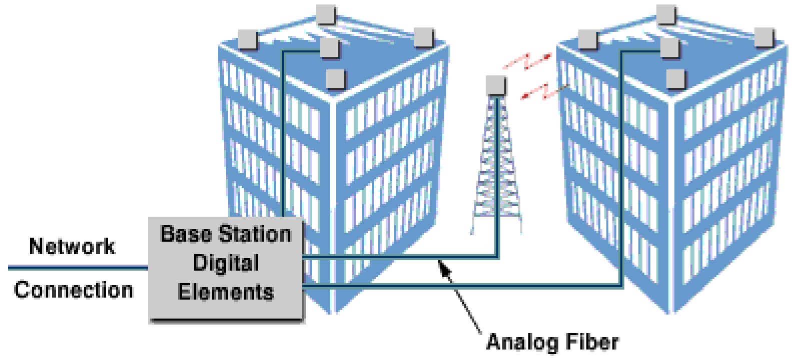

Figure 15. Analog Fiber Architecture. [From: Local Multipoint Distribution System, The International Engineering Consortium [http://www.iec.org/online/tutorials/lmds/comment.html], January 2004

3. Antenna Performance Criteria

The antenna system is the most critical part of any wireless communications system because it is the interface between the radio system and the external environment. It is an RF component capable of transmitting and receiving signals. Even though the same antenna can serve as a transmitting or receiving device, it is customary to consider the operation of an antenna either in the transmitting or receiving mode only. A transmitting antenna sends a signal through free space and the receiving antenna picks it up and thus maintains a communication link. As far as FBW is concerned, antennas are used by the base station and host terminal. Even though the host terminal station only has one antenna, the base station can have either one or multiple antennas.

Many types of antennas are available whose goal is to increase the radiation in a desired direction depending on the specific requirements of each application. The choice of the antenna directly affects the performance of the base station, host terminal and the overall network. Although the *gain* of the antenna is the driving factor in determining the right antenna, the performance of an antenna is by no means restricted to gain. Many parameters that provide information on the antenna's characteristics are additionally used to evaluate antennas. These parameters that define the performance of an antenna are referred to as *Figure of Merit* (FOM)[23]. Some of the most significant FOM are discussed in the following list:

[23] Clint Smith, LMDS, McGraw-Hill, pp. 79-87, 2000.

- ***Power Radiation Pattern:*** This provides information on how the antenna directs the energy it radiates. That is, "*it is the plot of the variation of power density in the far-field region with angular positions"*[24]. The antenna pattern chosen needs to match the coverage requirements for the base station. For example, if the desire is to utilize an antenna for a 45 degrees sector of a cell site, choosing an antenna pattern which covers 90 degrees in azimuth would not be the proper choice. For an ideal isotropic antenna, the radiation pattern is a sphere. However, for all others, the shape depends on the directivity. There are two primary classifications of antennas: *omni* and *directional*. The omni antennas are used in order to obtain a 360-degree radiation pattern, while the directional are used when a more refined pattern is desired. FBW systems use highly directional antennas. Figure 16 shows the pattern of a generally directional antenna.

- ***Directivity:*** This is defined as the ratio of radiation intensity in a given direction to that of the radiation intensity averaged over all the other directions. Directivity refers to the ability of the antenna to focus energy in a specific direction when transmitting or accordingly, to receive energy from a specific direction when receiving.

- ***Main-Side-Reverse Lobes:*** The main lobe reflects the directivity of the antenna and is the radiation lobe containing the direction of maximum radiated power. The side lobes are radiation lobes in any direction other than the main lobe. They serve no useful purpose. Instead, they create interference and the goal of the antenna designer is to minimize them. A special type of side lobe is the reverse or back lobe, which is also a source of interference. It plays an important role in the measurement of the *front-to-back ratio*, which is a measure of the antenna's ability to consecrate its radiation in the desired direction. Figure 16 shows the above lobes for a directional antenna.

[24] Oliver C. Ibe, Fixed Broadband Wireless Access Networks and Services, John Wiley & Sons, Inc., p. 32, 2002.

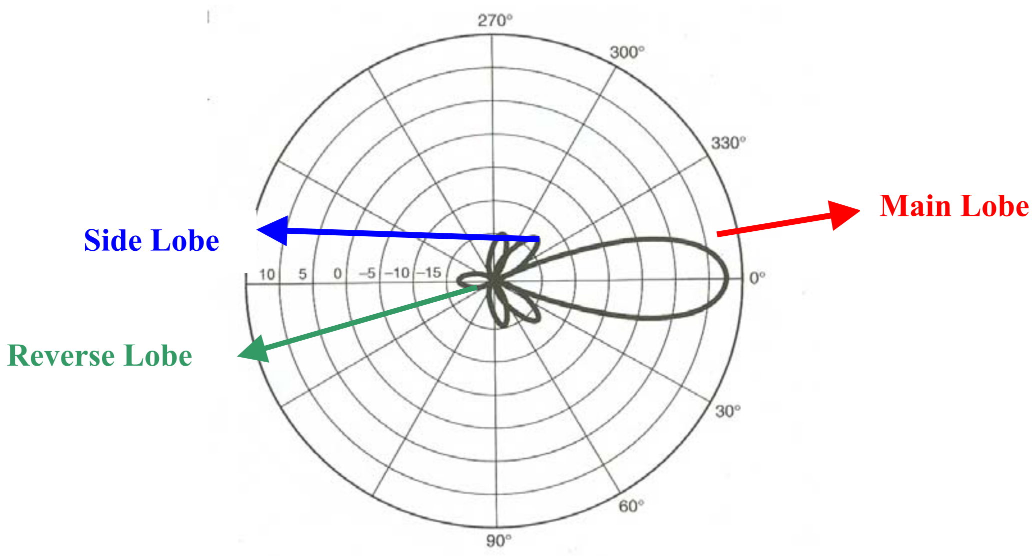

Figure 16. Graphical Representation of a Directional Antenna. [After: LMDS, Clint Smith]

Equation Chapter 3 Section 3 ?

- **Power Gain:** This is a FOM of extreme importance. It is "the ratio of the power density of the antenna to that of an isotropic radiator radiating the same total power as the antenna"[25]. It is described by Equation 3.1 as follows:

$$G = n\,D \qquad (3.1)$$

where G = the gain expressed in dBi (the isotropic radiator is used as a reference)

n = the efficiency of the antenna (unitless)

D = the directivity of the antenna expressed in dBi

For the ideal antenna without loss, the efficiency equals to 1 and thus the gain equals the directivity of the antenna.

- ***Polarization:*** The antenna's polarization is defined by the orientation of the electric field. In *horizontal* polarization, the electric field lies in the horizontal direction relative to the propagation's direction. While on the other hand, in *vertical* polarization, it lies in the vertical direction. Cellular systems utilize vertical polarization while LMDS utilize both polarizations. Each type has advantages and disadvantages. For example, and as far as FBW is concerned, horizontal polarization introduces less losses when the antennas are located near dense forests or among buildings. Nevertheless, it encounters more interference in urban areas

[25] Ibid., p. 33.

where there are many TV and FM radio stations because most VHF and UHF broadcasts use horizontal polarization. Furthermore, vertical polarization is less affected by aircraft flying over the direct path. However, small changes in the location of the antenna significantly affect the received signal strength.

- ***Bandwidth:*** This defines the operating range of the frequencies for the antenna. In fact, it is the range of frequencies where the power gain is at least half of the maximum value. It needs to be selected very carefully not only by taking into consideration the current requirements, but additionally, any future possible configurations.
- ***Power Dissipation:*** This is defined as the maximum power that the antenna is able to accept at its input terminals. This becomes important if someone realizes that there is a need for handling such a power without the possibility of damaging the antenna.
- ***Construction-Cost:*** Since the LMDS antennas are mounted externally on a rooftop, they are affected by a broad range of weather conditions. The types of metal, the dimensions and the mounting requirements (whether the elements are bolted or soldered together), in accordance with the external environment in which the antenna is located, is a very significant FOM. A good illustration of this is the case of areas near the sea, where there must be protection from the presence of salt water. This is more important for FBW because the antennas are in fixed locations. In addition, the cost will always play an important role in the final choice. Most likely, a designer will choose the antenna that meets the given requirements at the lowest cost and not the antenna that performs best regardless of cost.

Thus, it is clear that the challenge lies in designing an antenna that not only performs well electrically and with the desired gain and directivity, but also in producing it economically, is unobtrusive and able to survive a wide range of environmental extremes. More specifically, the LMDS antennas, since they are microwave antennas operating in the 28-to-31 GHz range, have dimensions that are smaller, usually on the order of centimeters and millimeters. As a result, it becomes obvious that such antennas require more precision in design than other antennas. Furthermore, as analyzed in the beginning of the chapter, LMDS has a point-to point uplink and a point-to-multipoint downlink. As a result, the antennas need not only have high gain but also very narrow beams. The beam aperture depends on the manufacture. However it is generally limited to 5 degrees. Moreover, the antennas are directional antennas in order to focus the energy in a particular direction. Many directional antennas are used at the base station, and each provides coverage for each sector of the base station.

The most important LMDS antennas are parabolic antennas because these antennas are high-gain antennas used in point-to-point systems. The principle of the parabolic antenna is shown in Figure 17. It is essentially a metal dish that is illuminated by a source located at its focal point[26]. The source, which is located at the focal point, generates a spherical waveform that is directed toward the dish. The dish itself converts this spherical wavefront into a parallel-plane wavefront as the figure shows. The final reflect waves are parallel to one another, forming a highly directional wave, resulting from microwaves behaving as light waves in the sense that they can be focused, and travel parallel in straight lines.

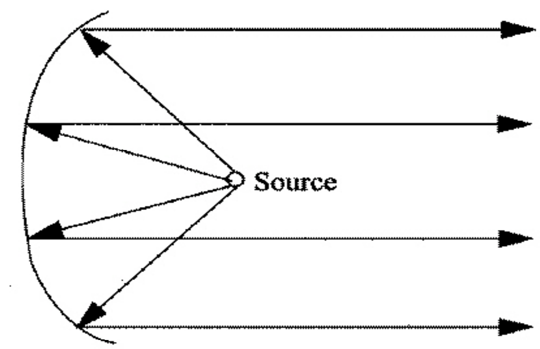

Figure 17. Principal of Parabolic Antenna. [From: Fixed Broadband Wireless Access Networks and Services, Oliver C. Ibe]

4. Access Options-Modulation

The difference between the upstream and downstream direction is due to the asymmetric nature of Internet traffic. For any wireless broadband connection from the CPE to the base station, also referred to as the upstream direction, there are three primary access technologies: Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA) and Code Division Multiple Access (CDMA).

TDMA divides the radio spectrum into time slots and only one user is allowed in each slot to either transmit or receive. Thus, the carrier frequency is shared with several users and each user occupies a cyclically repeating time slot. On the other hand, FDMA assigns individual channels to individual users, and therefore, each user is allocated a

[26] Ibid., p. 42.

unique frequency channel. Finally, in CDMA, many users are able to share the same frequency and may transmit simultaneously. However, since most current operators use TDMA and FDMA, it is not further analyzed. The choice between FDMA and TDMA is based on customer requirements and system design.

Indeed, FDMA may use the channel more efficiently (100%) than TDMA (88%), but it allocates either a constant, or a slowly varying over time bandwidth. The link is always on regardless of whether the user sends data or not. If a channel is not in use, then it remains idle, unable to be used by other users, and it becomes a wasted resource[27]. Consequently, when the customer has heavy upstream traffic and a constant bandwidth is required, FDMA fits well and would be the proper choice. However, if there is heavy upstream traffic, TDMA would make more sense because it allows for a bursty response and does not require slots unless it is necessary. In fact, it allocates bandwidth in such a way that it successfully responds to data bursts from the customer site. From the above, it is clear that it is extremely important to correctly estimate the peak and average expected traffic data rate. If the resulting burstiness is smooth enough, FDMA can better handle the upstream traffic. On the other hand, if burstiness persists within the traffic stream, then TDMA is a better choice[28].

As far as the connection from the base station to the CPE, also referred to as downstream direction, most companies initially supplied synchronous Time Division Multiplexing (TDM). TDM is a type of multiplexing where two or more channels of information are transmitted over the same link by allocating a different time slot for the transmission of each channel. Simply stated, the channels take turns in using the link. TDM becomes quite inefficient when traffic is intermittent because the time slot is still allocated even when the channel has no data to transmit. Regardless, *Orthogonal Frequency Division Multiplexing* (OFDM) has begun to be used today. It is utilized in many applications. It has many advantages and will be thoroughly analyzed in Chapter IV. Figure 18 illustrates a scheme in which multiple customer sites share the downstream connection using OFDM, whileFDMA is used for the upstream connection.

[27] Theodore S. Rappaport, Wireless Communications Principles and Practices, Second Edition, p. 449, Prentice Hall, Inc., 2002.

[28] Local Multipoint Distribution System, The International Engineering Consortium [http://www.iec.org/online/tutorials/lmds/comment.html], January 2004.

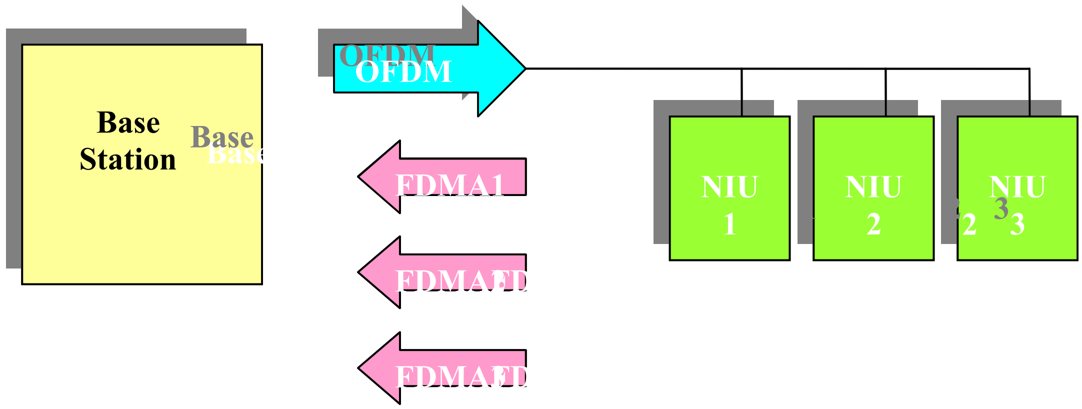

Figure 18. OFDM Downstream and FDMA Upstream. [After: Local Multipoint Distribution System, The International Engineering Consortium [http://www.iec.org/online/tutorials/lmds/comment.html, January 2004]

Finally, generally there are several domains in which multiplexing can be accomplished including phase, time and frequency. LMDS modulation methods are separated into phase shift keying (PSK) and amplitude modulation (AM). The modulation schemes are specifically mentioned in IEEE802.16, shown in Chapter IV, and they do directly affect the achieved data rate and the coverage area. The highest data rates are achieved using a combination of AM and PSK defined as *Quadrature Amplitude Modulation* (QAM), which is also thoroughly analyzed in Chapter IV. Currently, TDMA is not able to include the highest QAM schemes, and as a result, has a lower bandwidth spectral efficiency than FDMA.

5. Cell Sites Design

The type as well as the size of the cell site plays a significant role not only in the performance of the network but also in recurring costs. For example, the smaller the cell cites, the lower the lease and maintenance costs, but on the other hand, the higher the number of sites that are required to cover a specific geographic area. The attributes that require attention when designing the cell sites of an LMDS network are the following[29]:

- ***Link Budget:*** It is an estimation of the maximum distance that a user can be located from an access point while being able to achieve acceptable service reliability. It determines the range and deployment pattern used by taking into consideration not only physical but also marketing issues. To illustrate, if marketing determines that a link availability of 99.99% is needed, then designing the network for 99.9% even though it would reduce the cost, it might not satisfy the requirements, while designing the network for 99.999% makes little sense. It accounts for all system losses and gains through various types of equipment, such as an antenna's gain, fade margin and cable and connector losses, and determines not only the radius of the site but also the distance between the cells for best coverage.
- ***Cell Size Selection and Number of Cells:*** The cell size depends on the link budget because it is related to the desired link availability as mentioned previously. Regardless, the type and size of the antennas additionally affect the cell size. The size itself in combination with the type of the coverage area (urban or low density) determines the number of cells that are needed in a sector.
- ***Subscriber Penetration - Quality of Service:*** Subscriber penetration is the number of subscribers (percentage) whom have sufficient signal level to achieve excellent quality of service. The quality of service can be affected by many factors such as LOS obstruction and cell overlap.
- ***Cell Overlap:*** Since LMDS require LOS, sufficient cell overlap must be present (15% is normal) in order to increase redundancy (analyzed in Chapter VI), resolve the variability in building heights and ensure that LOS can be achieved in all buildings in the coverage area. Thus, the target area is covered efficiently and the maximum sales potential can be recognized. However, a larger cell overlap would create significant problems and negatively affect the quality of service.
- ***Capital Cost per Cell:*** It estimates the network capital requirements by taking into consideration the link budget, the number of sectors, the number of cells in each sector, the size of the cells and the capital cost of each cell.
- The mainly different types of cell sites that can generally exist in a network depend on the coverage and capacity requirements and are described below[30]. First, there is the ***2-Sector*** type, which uses one or two 90-degree sectors for immediate operation with the other sectors

[29] John R. Vacca, Wireless Broadband Networks Handbook 3G, LMDS &Wireless Internet, McGraw-Hill, p. 253, 2001.

[30] Clint Smith, LMDS, McGraw-Hill, Inc., p. 159, 2000.

temporarily not operational. The non-operational sectors remain non-operational as long as the cell site satisfies the coverage requirements and can become operational if needed. Furthermore, the ***4-Sector*** type uses four 90-degree sectors, the ***6-Sector*** type six 60-degree sectors, the ***8-Sector*** type eight 45-degree sectors and finally, the ***12-Sector*** uses twelve 30-degree sectors as shown in Figure 19. Regardless of the sector type, using frequency reuse, the available spectrum can be used more efficiently as analyzed in Chapter VI.

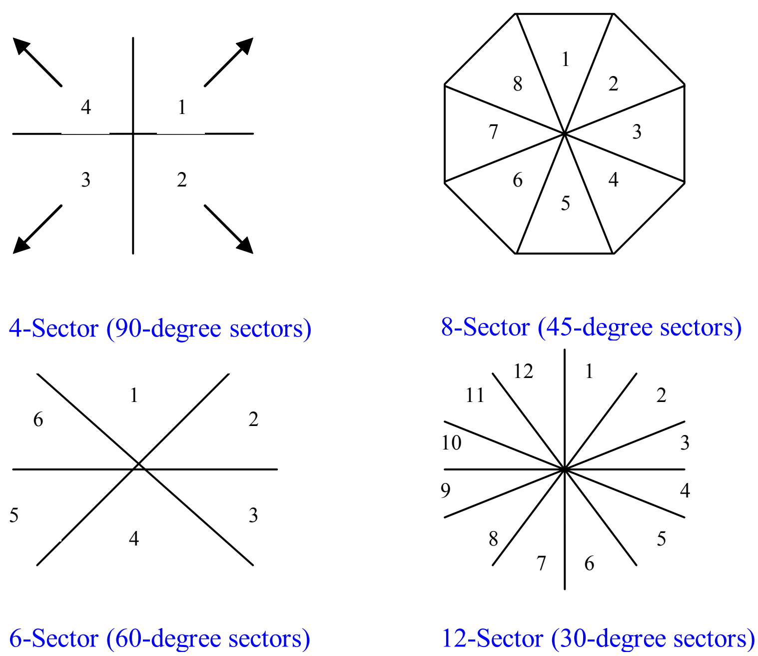

Figure 19. Different Types of Cell Sites. [After: LMDS, Clint Smith]

The increase in sectors enables a higher density of $Mbps/Km^2$ to occur. Indeed, the more sectors, the higher the achieved density out of an LMDS system, which means that the 12-sector has the highest density of Mbps. The 4-sector is the predominant type of LMDS site deployed[31]. However, when capacity is needed for a specific area, a higher-sector type can be used. Thus, it is clear that the combination of capacity and coverage requirements is the determining factor in deciding which cell type to use in an LMDS configuration. Even though mixing different site configurations is possible, there are design implications associated with frequency reuse and should be avoided.

31 Ibid., p. 160.

6. Services-Platforms

FBW, like other last-mile solutions, has as primary goal of providing access to the Internet. However, the telecommunications industry is moving towards the convergence of the various service protocols, which makes the goal of FBW to provide access to the converged network not only for data but also for voice and video applications possible.

The FBW networks, depending on the services offered, mentioned in the Definition section in the beginning of the chapter, must deal with multiple protocols. The convergence mentioned above has either an Internet Protocol (IP) or Asynchronous Transfer Mode (ATM) as the leading platforms. As a result, there are two ways to deploy LMDS: the IP-based development and the ATM-based development. Each platform has its advantages and is used for different applications. However,; they both are flexible enough to account for the future changes in the services to be offered.

Simply, stated, IP is a protocol that allows information to be transported. It is a connectionless service in that a source never really knows which packets arrive at the destination. This happens because there is no *"handshaking"* prior to the transmission of the packets. Handshaking means that the server and the client send control packets to each other before sending packets with real data[32]. Nevertheless, the data can be delivered faster. As a result, IP is best for data and but not so for voice and video since it cannot guarantee that all messages are delivered and in the right order. However, with the advent of VoIP, IP has been adapted to handle voice and video applications as well.

Depending on the requirements, LMDS are able to provide different levels of QoS for IP traffic. Figure 20 shows how LMDS can be used to offer service to either a small business or a residential end-user that wants web access. Additionally, LMDS have the ability to provide connectivity between LANs and WANs.

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[32] Kurose and Keith W. Ross, Computer Networking, A Top-Down Approach Featuring the Internet, pp. 11-13, Addison Wesley Longman, Inc., 2001.

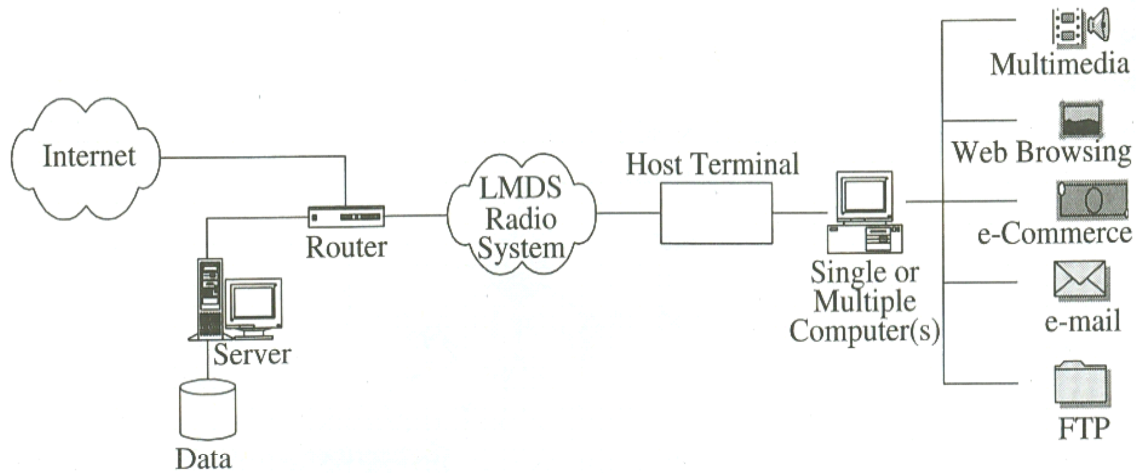

Figure 20. IP Platform. [From: LMDS, Clint Smith]

On the other hand, ATM is a connection-oriented service and has provisions for flow and congestion control. Therefore, it excellently supports data as well as voice and video applications. An ATM network can consist of either single or multiple ATM switches. At the end of the ATM network, there is an *edge* switch which converts to the appropriate protocol. Figure 21 shows how an ATM edge switch is located between an LMDS central office and a base station. The ATM switches are able to handle many types of traffic with different QoS associated with each other.

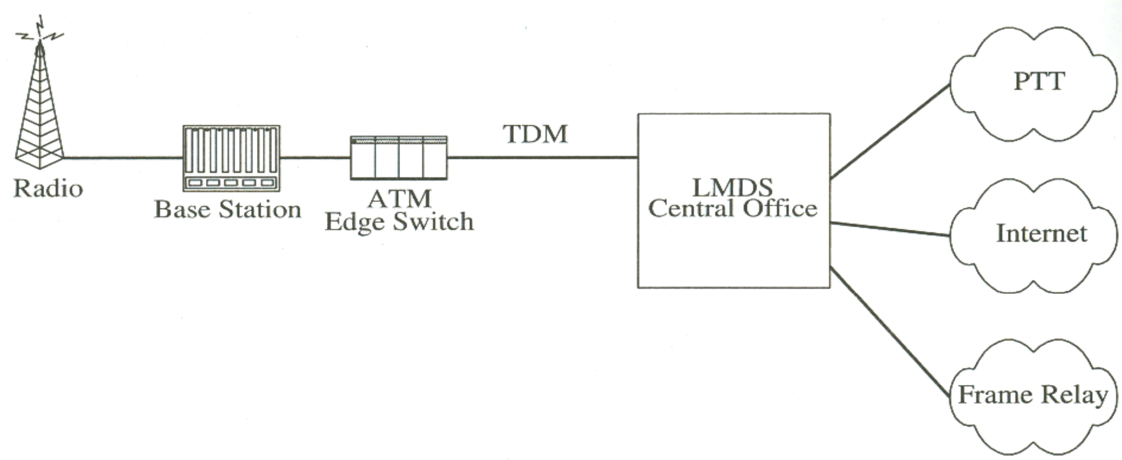

Figure 21. ATM Platform. [From: LMDS, Clint Smith]

To summarize, the choice of the transport platform is quite significant since it determines not only the types of services offered to the end-user, but also the operational characteristics of the system. So how should a designer decide which platform to utilize?

From the aforementioned analysis, it is clear that no one platform is a solution for all requirements. The designer needs to take into consideration not only the services that need to be supported, but also other factors such as the protocols with which the host terminal and the base station will interface. A good rule of thumb is to utilize ATM for the core of the network and IP for the edge of the network[33].

C. MULTICHANNEL MULTIPOINT DISTRIBUTION SERVICES

1. Introduction

Multichannel Multipoint Distribution Services (MMDS) are the oldest of all FBW access services and have their historical roots in television. They were the first microwave distribution systems implemented in the United States and have been around for more than 20 years. Indeed, Multipoint Distribution Services (MDS), MMDS's precursor, were established by the FCC in 1972 and became popular for transmitting entertainment programming in a subscriber-based audience. MMDS originally operated around 2.5 GHz and were entirely broadcast systems, providing analog TV with no capability for a return path. MMDS is widely known as the "wireless" cable industry.

However, wireless cable found strong competition from satellite-based providers, and in 1998, the FCC allocated its 200 MHz of frequency spectrum for digital transmission and thus permitted the MMDS to be used for bidirectional services. More precisely, on September 25, 1998, the FCC released a Report and Order (Docket 97-217), which allowed MMDS operators to *"transform their services from one-way analog TV broadcast into two-way digital data services"*[34]. Therefore, that spectrum became another option to deliver broadband wireless services and could now be used as a transport mechanism for high-speed Internet access. As a result, from the beginning of 1999, long distance carriers began purchasing MMDS operators in order to bypass the local loop operators and gain direct access to homes and businesses.

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[33] Clint Smith, LMDS, p. 208, McGraw-Hill, Inc., 2000.

[34] William Webb, Introduction to Wireless Local Loop, Broadband and Narrowband Systems, pp. 220-221, Artech House Publishers, 2000.

Consequently, today MMDS is a FBW technology that allows two-way voice, data and video streaming operating at a lower frequency than LMDS, typically in the 2-3 GHz range. It has the ability to deliver *multichannel* Internet access data transfer service, television programming and other interactive services. The term Multichannel refers to the multiple streams of data within a MMDS signal. The frequency designation is shown in Figure 22 and it is 2.15 to 2.162 GHz and 2.5 to 2.69 GHz. There are a total of 33 channels, each 6 MHz wide which compose the MMDS band. The evolution from analog to digital enabled Sprint to convert 33 analog channels into 99 digital data streams each transmitting at 10 Mbps. Therefore, Sprint is able to deliver up to 1 Gbps of capacity from a single transmitter[35]! To put that speed into perspective, "*a 10-Mbps wireless modem could download the 3¼-hour movie Titanic in 7 minutes and 23 seconds while a 56K modem on the other hand would need almost 22 hours*". The MMDS band refers to the spectrum assigned not only to the MMDS but also to the MDS and Instructional Television Fixed Services (ITFS), which are all sister bands to LMDS. ITFS operators are different in a sense that they usually use the spectrum for operating a remote learning center of educational institutions.

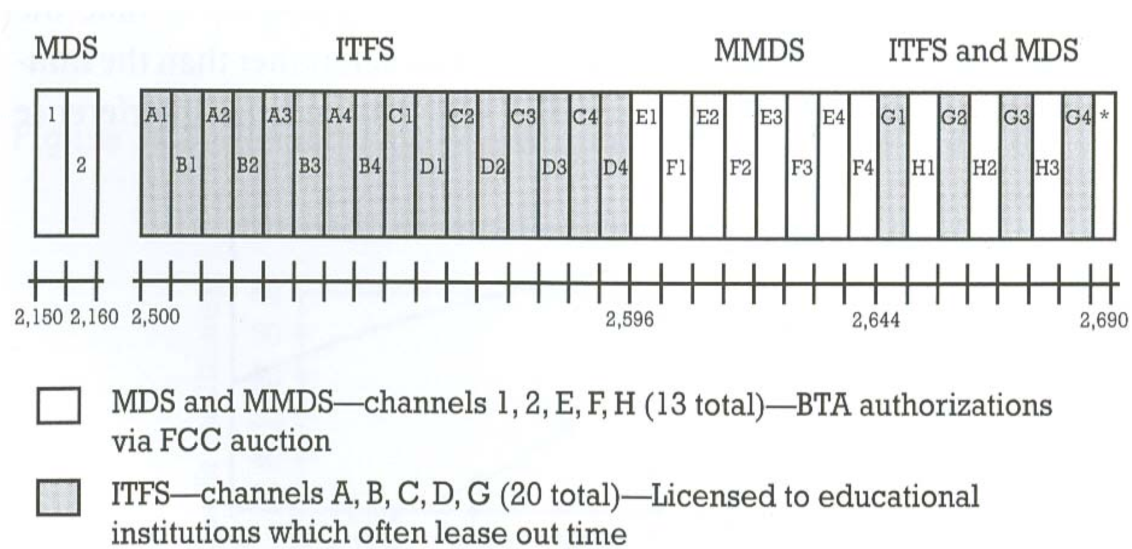

Figure 22. MMDS Spectrum Assignment. [From: Introduction to Wireless Local Loop, Broadband and Narrowband Systems, William Webb]

[35] John R. Vacca, Wireless Broadband Networks Handbook 3G, LMDS &Wireless Internet, McGraw-Hill, 2001.

2. Technology Issues

As mentioned previously, LMDS and MMDS share many common architectural features and the core components are the same and were introduced in the LMDS section. Thus,as in the case of LMDS, the base station and the CPE are the main components of MMDS and their main purpose is the conversion from fiber infrastructure to wireless infrastructure and the reconvention of the microwaves back into a digital bitstream accordingly. Figure 23 shows the actual antennas and modems and their sizes are relatively small.

RF Base Station – Integrated RF and Digital Modem

CPE Antenna and Modem

Figure 23. MMDS Base Station and CPE. [From: [www.espteam@xilinx.com], October 2003]

System operators that wish to use MMDS for two-way communications can either use MMDS for downstream and another technology for upstream, or use MMDS for both directions[36]. The first approach has the advantage of maximum downstream data capacity since the entire spectrum is used for the transmissions from the base station to the CPE. However, this approach is dependent on the technology available at the given location. This reduces the market potential for the specific area since many rural or suburban end-users might not have access to the appropriate wired infrastructure.

The second approach uses a portion of the spectrum for the transmission from the CPE to the base station. It has a less downstream capacity but is independent of the wired

36 James Schellenberg, Designing the Digital MMDS Network for Maximum Benefit: Technological Considerations in Service, Coverage and Subscriber Issues, 1997.

infrastructure in the area. Regardless, both approaches are very favored, especially in areas that lack high capacity wired infrastructure, due to the relatively inexpensive prices of the transceiver equipment at 2.5 GHz.

Even though both LMDS and MMDS involve a sectorised cell site that has multiple subscribers associated with each channel in every sector, their coverage is quite different. Indeed, the LMDS cells covers areas with only a 5-mile radius while a single MMDS cell is capable of serving a 35-mile radius coverage area. To illustrate this, it would take over 136 LMDS cells to cover the same area that one MMDS cell covers! This is a result of the lower frequencies used in the MMDS. First, at lower frequencies, there are less gaps and distortion, which allows further transmission distances. Second, as thoroughly described in Chapter V, there is significantly less impact of rain attenuation at 2.5 GHz than at 28 GHz.

MMDS networks can be displayed using a few large cells (>20-mile radius), many small cells (<5-mile radius) or a combination of both. The trade-off here is between capacity and cost. For example, the use of many small cell sites has higher capacity and better coverage than the large cell sites approach. However, it has higher initial deployment costs. For this reason, in order to choose which approach to use, the characteristics of the area that will be covered should be considered. For example, a large sell site approach is the right choice for rural areas with low population density. Regardless, only when the number of potential subscribers in a given area justifies the high cost of adding another base station should a designer consider installing a new cell site.

3. Comparison with LMDS

Some of the most important differences between MMDS and LMDS are shown in Table 8. The main advantages of MMDS vs. LMDS are the following:

- It can support greater distances
- Rain attenuation affects it negligibly
- CPE costs are significantly lower
- It has already proven its viability in currently operating networks

The main disadvantage of MMDS compared to LMDS results from the enormous difference in the available bandwidth. The 200 MHz bandwidth of MMDS, with the use of almost the same modulation schemes, cannot compete with the greater bandwidth of LMDS, and as a result, provide lower data rates. The actual data rates depend on the distance from the base station and the number of simultaneous users. However, typical rates for downstream are 1-3 Mbps for MMDS compared with the 45Mbps of LMDS. Moreover, LMDS use highly directional antennas and thus allow sectorization at base stations, and therefore, have greater capacity.

Feature	LMDS	MMDS
Frequency Range	28-31GHz	2.5-2.7 GHz
Typical Data Rate	45Mbps	1-3Mbps
Distance	Up to 5 miles	Up to 35 miles
CPE Cost	High	Low
Target Markets	Medium and Large Enterprises	Residential and Small Enterprises
Propagation[37]	LOS with high rain attenuation	LOS with high impact from vegetation and multipath fading

Table 7. LMDS and MMDS Comparison.

To summarize, the decision to implement LMDS or MMDS is based on both technological and business considerations. Since MMDS are able to cover large areas, they become a good solution for rural or suburban areas that are not able to receive service through wireline connections. Furthermore, the intermediate data rates and the cheap CPEs effectively meet the needs of residential end-users as described in Chapter II. On the other hand, LMDS, due to their short coverage, target areas with high population density. Their high capacity and data rates make them attractive for large enterprises

37 Propagation issues are analytically shown in Chapter V.

outside the reach of fiber networks. It is very unlikely for LMDS to attract residential end-users for the time being because of the extremely high cost of the CPE. CPE costs $5,000 in the range of 26 GHz[38].

38 [http://www.mobilecomms-technology.com/projects/mmds/], February 2004.

IV. NOISE EFFECTS IN FIXED BROADBAND WIRELESS

A. NOISE CATEGORIES

Noise is defined as any undesirable electrical energy that falls within the passband of the signal[39]. It is a major limiting factor in communications systems. In every data transmission even the received signal consists of the transmitted signal modified by that additional electrical energy, which is inserted somewhere between transmission and reception. Depending on whether the noise exists, regardless if a signal is present or not, noise is categorized as *correlated* and *uncorrelated*.

1. Correlated Noise

It exists only when a signal is present. It is a form of internal noise and its categories are:

- *Intermodulation Noise:* Occurs when signals at different frequencies share the same transition medium because unwanted sum and difference frequencies are generated.
- *Harmonic Distortion:* Occurs when unwanted harmonics of a signal are produced.
- *Impulse Noise:* It is generated from external electromagnetic disturbances, such as lighting, and consists of irregular high-amplitude peaks of short duration.

From the categories mentioned above, Intermodulation Noise and Harmonic Distortion are reasonably predictable with relative constant magnitudes, and therefore, it is possible to design systems that deal with them. For this reason, their analysis is not within the scope of this thesis. Impulse Noise on the other hand, although it is totally unpredictable and its effects can be devastating, it is non-continuous and will also not be further analyzed in this thesis.

[39] Wayne Tomasi, Electronic Communications Systems, Fundamentals through Advanced, Fourth edition, Prentice-Hall, Inc., pp. 34-35, 2001.

2. Uncorrelated Noise

This noise exists all the time regardless if a signal is present or not and is generated either within or outside the device or circuit. The most important categories are the following:

- *Extraterrestrial Noise:* It consists of electrical signals that originate from outside Earth's atmosphere. It can be subdivided into *Cosmic Noise,* which is generated directly from the sun's heat and into *Solar Noise*, which is noise that is continuously distributed throughout the galaxy.
- *Man-Made Noise:* it is produced by mankind and it is most intense in the more densely populated areas.
- *Atmospheric Noise:* Occurs when electrical disturbances originate within the earth's atmosphere and its magnitude is inversely proportional to its frequency.
- *Transit-Time Noise:* Occurs when the carriers pass from the input to the output of a device. It is important if the time it takes for a carrier to propagate through a device is an appreciable part of the tine of one cycle of the signal.
- *Additive White Gaussian Noise (AWGN):* It is due to thermal agitation of electrons and was first recognized in 1927 by J. B. Johnson of Bell Telephone Laboratories. Thermal agitation is random and most importantly, it occurs in all frequencies, is continuous and is present in all electronic devices and transmission media. As a result, AWGN is predictable, additive and present in all devices, and for this reason, it is the most important type of noise in all communications.

As far as the Extraterrestrial Noise is concerned, since the source of the noise is very far away, its intensity is relatively small. Furthermore, at frequencies above 30MHz Atmospheric Noise is considered insignificant[40] and Man-Made Noise is very rare. From the above analysis, it is clear that AWGN cannot be eliminated, it is the most significant of all noise sources and it does place an upper bound on the performance of communications systems. For this reason, the purpose of this chapter is to demonstrate the effects of AWGN in FWB. More precisely, using specific modulation schemes defined by IEEE 802.16, this chapter shows the relationship between the data rate achieved and the level of influence due to AWGN.

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40 Ibid.

B. AWGN NOISE EFFECTS

In order to observe the effects of AWGN in Fixed Broadband Wireless, the SystemView simulation package by Elanix[41] is used. More precisely, a modification, in order to satisfy IEEE 802.16 requirements, of a model created for IEEE 802.11a system simulation[42] is utilized. The overall block diagram used for the 802.11a case is shown in Figure 24.

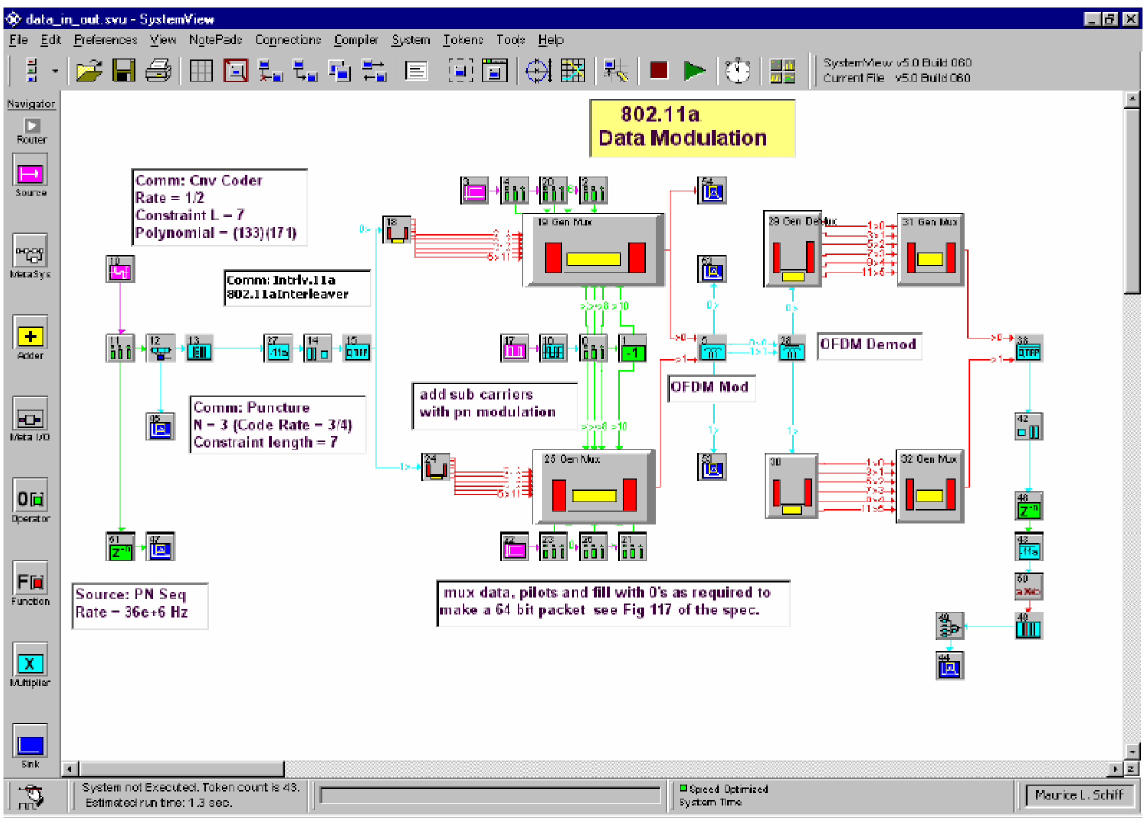

Figure 24. 802.11a Data Simulation. [From: 802.11a System Simulation Using System View by Elanix, Maurice L. Schiff, Ph.D.]

The suite of modulation as well as code rate parameters valid for IEEE 802.16 system is given in Table 9.

41 [http://www.elanix.com/], February 2004.

42 Maurice L. Schiff, Ph.D., 802.11a System Simulation Using System View by Elanix.

Modulation	Coding rate
QPSK	1/2
QPSK	3/4
16QAM	1/2
16QAM	3/4
64QAM	2/3
64QAM	3/4

Table 8. IEEE802.16 Modulation and Coding Rate. [From: Simulation Results for FEC in 802.16 OFDM System, IEEE802.16 Broadband Wireless Access Working Group]

IEEE 802.16 has adopted *Orthogonal Frequency Division Multiplexing* (OFDM) as its media access method because of its suitability for high data rate services. This method applies to connections from the base station to the *Customer Premises Equipment* (CPE), referred to also as downstream direction. The basic OFDM system is shown in Figure 25.

Both the carrier and the data signal are simultaneously generated in the transmitter and the high-speed serial data stream is divided into N low-speed subcarriers that the system transmits simultaneously at different frequencies. More precisely, with the use of *Serial-to-Parallel Converters* (S/P and P/S) and of a series of mathematical computations known as *Inverse Fast Fourier Transform* (IFFT), the bits are split and a complex modulated waveform is formatted at the output of the transmitter. On the receiver end, the message is reconstructed using *Fast Fourier Transform* (FFT).

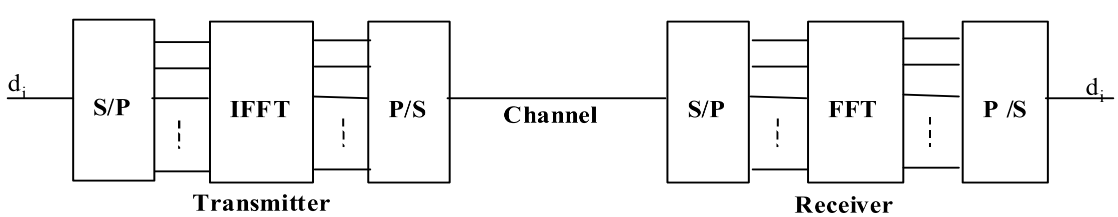

Figure 25. OFDM Diagram. [From: OFDM for Wireless Networks, Anibal Luis Intini]

OFDM is similar to FDM in the sense that the available bandwidth is divided into multiple channels that are allocated to multiple users. Nevertheless, it is composed of many narrowband carriers and allows channels to overlap, as shown in Figure 26. The channels are, therefore, spaced much closer together. In doing so, it uses the spectrum more efficiently than FDM.

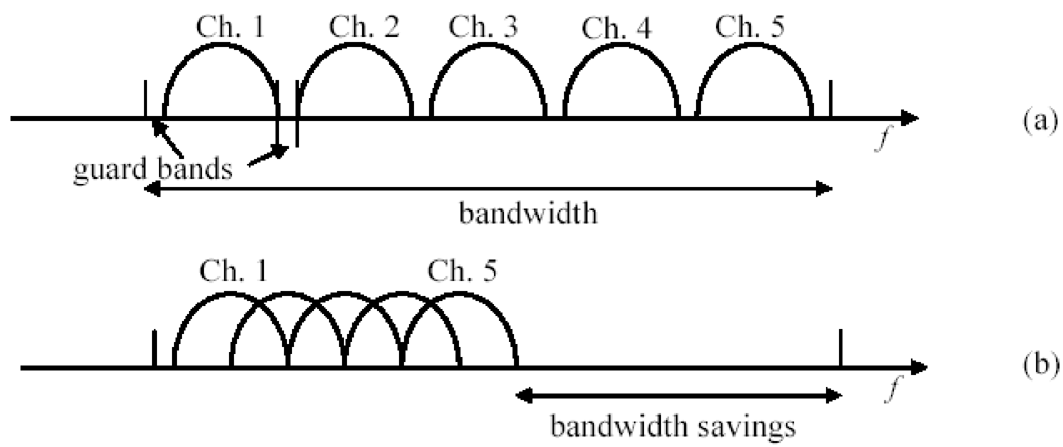

Figure 26. OFDM (b) vs. FDM (a). [From: Performance Analysis of OFDM in Frequency-Selective, Slowly Fading Nakagami Channels, Patrick A. Count]

The parallel transmission over multiple channels enables OFDM to achieve high data rates with remarkable resistance to multipath distortion and to narrowband interference[43]. It is extremely flexible in the choice of data rates in the individual channels, with the proper use of various modulation schemes, because it allows each channel to use the modulation scheme that optimizes the performance. Modulation schemes include, as mentioned in Table 9, QPSK, 16-QAM and 64-QAM. Thus, in order to achieve a specific data rate, designers are able to choose the appropriate modulation scheme as well as the code rate.

As a result and by taking into consideration Table 9, IEEE 802.16 specifies the following data rates (Table 10) in Mbps for different guard intervals assuming that all sub channels use the same modulation and coding rate.

[43] Oliver C. Ibe, Fixed Broadband Wireless Access Networks and Services, John Wiley & Sons, Inc., p. 60, 2002.

Net Bit Rate (Mbps) for different guard intervals

Modulation	Bit per Sub-Carrier	Code Rate	1/4	1/8	1/16	1/32
BPSK	1	1/2	6	6.67	7.06	7.27
BPSK	1	2/3	8	8.89	9.41	9.7
BPSK	1	3/4	9	10	10.59	10.9
QPSK	2	1/2	12	13.34	14.12	14.54
QPSK	2	2/3	16	17.78	18.82	19.4
QPSK	2	3/4	18	20	21.18	21.8
16-QAM	4	1/2	24	26.68	28.24	29.08
16-QAM	4	2/3	32	35.56	37.64	38.8
16-QAM	4	3/4	36	40	42.36	43.6
64-QAM	6	1/2	36	40.02	42.36	43.62
64-QAM	6	2/3	48	53.34	56.46	58.2
64-QAM	6	3/4	54	60	63.54	65.4

Table 9. Data Rates and Modulation Schemes for IEEE 802.16 [After: Initial OFDMA Proposal for the 802.16.4 PHY Layer, [http://www.ieee802.org/16/tg4/contrib/802164p-01_01.pdf], January 2004]

For the purpose of this thesis and as is highlighted in Table 10, a model with ¼ guard interval is simulated. The cases considered are shown below:

- 64-QAM, ¾ code rate, 54Mbps (Highest data rate)
- 64-QAM 2/3 code rate, 48Mbps
- 16-QAM 3/4 code rate, 36Mbps

The purpose of the simulation is to demonstrate the effects of AWGN in Fixed Broadband Wireless Networks and to extract the probability of Bit Error Rate (BER). Furthermore, the analysis will show the relationship between the data rate and the BER examining each modulation scheme separately. Figure 27 shows the simulation block diagram.

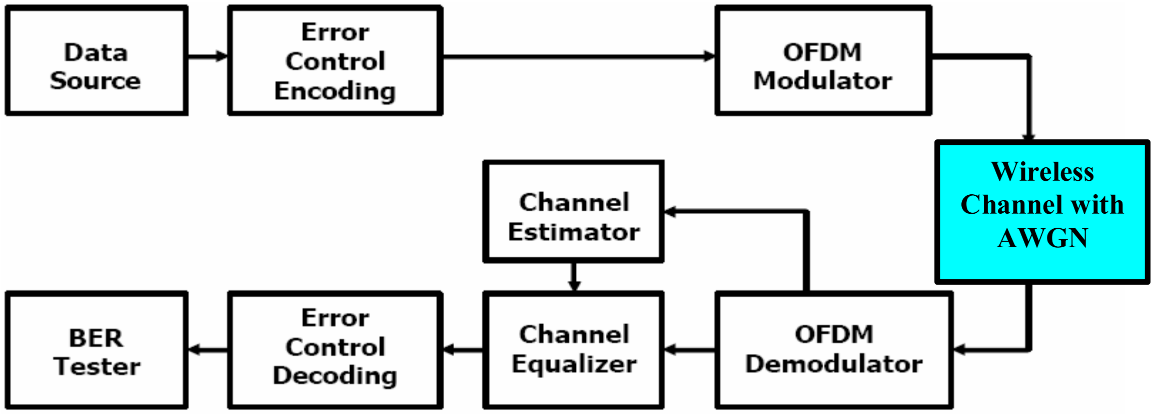

Figure 27. Simulation Block Diagram. [After: Performance Evaluation of the IEEE 802.16a Physical Layer Using Simulation, Alden J. Doyle, and Others]

Before proceeding to the development of the model with SystemView, it is necessary to consider the following:

- OFDM Modulator and Demodulator: the design of the OFDM transmitter and receiver is not part of the IEEE 802.16 and it is left to manufacturers to develop robust and cost effective implementations. For the purpose of this thesis, the scheme used for the IEEE 802.11a simulation is used.
- Error Correction Coding: it is essential for OFDM systems since it compensates for the bit errors that are inevitable in times of deep fade in the channel[44]. Standard specifications of 802.16 specify the use of the convolutional code.
- Perfect Synchronization: it is assumed that the transmitter and receiver are perfectly synchronized.

The final simulation model is shown in Figure 28 with this in mind. The numbers mentioned below correspond to the *tokens*, which are the building blocks of a SystemView simulation. The periodic source (token 10) generates cyclic data at a desired data rate. The data source is initially sampled at once per bit (token 11). Token 12 is the convolutional encoder. Token 55 performs the puncturing operation in order to achieve the ¾ code rate. In this case, for every 3 bits into the convolutional encoder, there are 4 bits out of the puncture token. The bit-to-symbol token 14 and the QMAP token 15 produce the baseband I and Q signals. The OFDM modulator requires a total of 64 carriers. The General DeMux Token 18 split the data symbols into the appropriate

[44] Alden J. Doyle, and Others, Performance Evaluation of the IEEE 802.16a Physical Layer Using Simulation.

segments for use by the GenMux 19 which reassembles the packets accordingly[45] for the I signal in order to achieve the 64 carriers. Similarly, token 24 and 25 apply for the Q signal. The steps just described for the modulation process in the transmitter are applied in reverse order in the receiver to recover the original data. The analysis tokens (57, 58, and 59) collect data for future analysis.

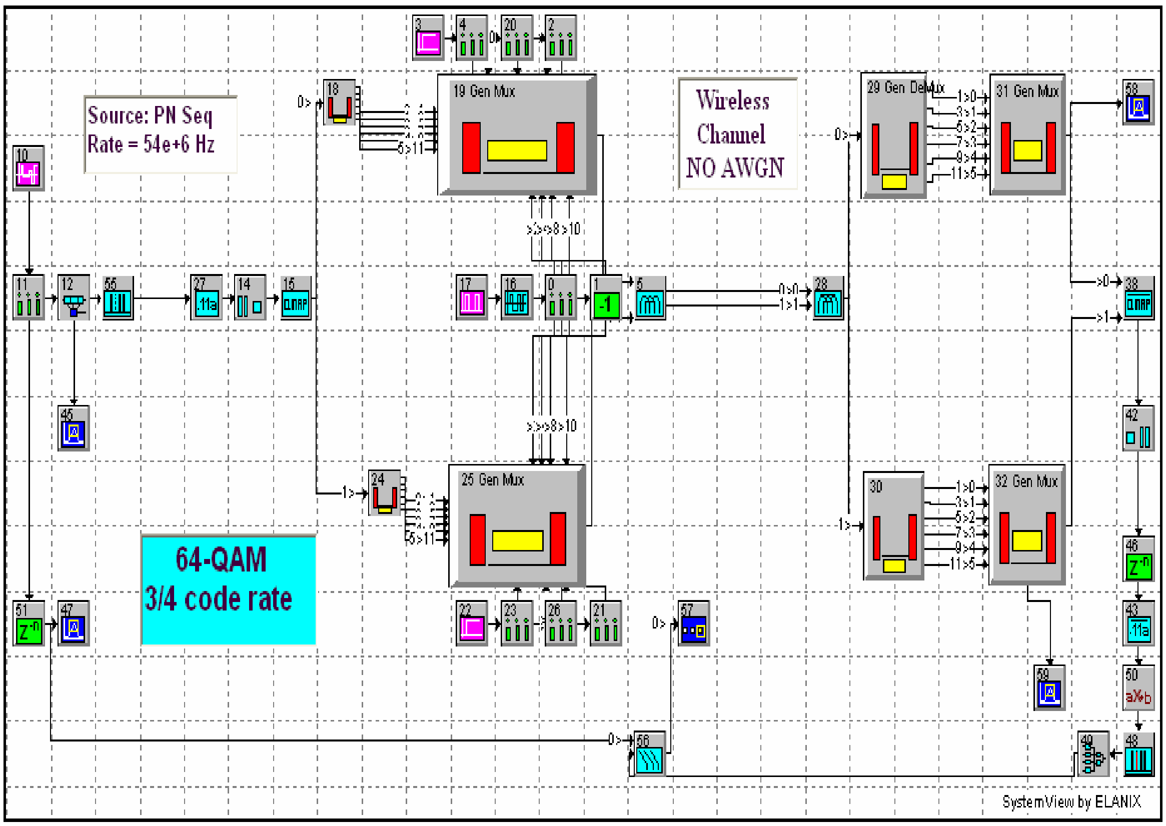

Figure 28. 64QAM-3/4 Code Rate without Noise.

1. 64QAM

a. 3/4 Code Rate-54Mbps

Quadrature Amplitude Modulation (QAM) is a combination of phase and amplitude modulation. QAM generally divides a digital data stream into two streams, which then amplitude modulate two carriers with the same frequency, but with a phase difference of 90^o. By doing so, the same physical channel is used to transmit two signals

45 Maurice L. Schiff, Ph.D., 802.11a System Simulation using System View by Elanix.

at the same time. The use of a combination of amplitude levels and number of phases can be used to achieve higher data rates. 64-QAM uses 6 bits per symbol and can be generated by a combination of 4 amplitude levels and 16 different phases as shown in the constellation diagram in Figure 29. The *Constellation Diagram* is the diagram that represents these various amplitude and phase combinations in a QAM. In our case, it shows that with 6 bits per symbol, a total of 2^6 possible combinations of 1s and 0s can be obtained.

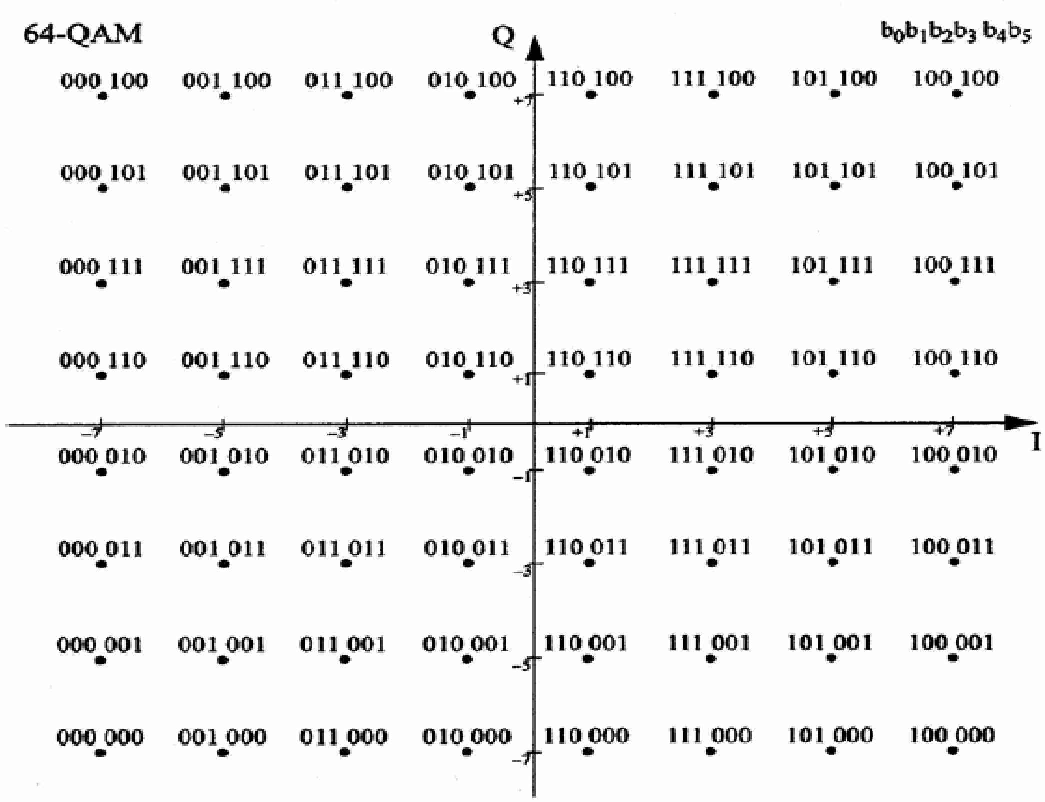

Figure 29. 64-QAM Constellation Diagram. [From: Institute of Electrical and Electronics Engineers, 802.11a, Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: High Speed Physical Layer Extension in the 5 GHz Band, 1999]

The coordinates of each symbol are entered in the QMAP (token 15) and each symbol has 6 bits. The data source is adjusted to a data rate of 54Mbps (token 10). The simulation model is run for 10 loops or 10 different values of Signal-to-Noise Ratio (SNR). For each loop, 2^{31} bits of information are sent which is the maximum number the system can handle. Having a large sample provides the analysis with more reliable results. Moreover, the fact that 2^{31} bits are used indicates that the model calculates a BER in the range as low as 10^{-9}. Figure 30 shows the resulting constellation diagram, where it is obvious that without the presence of noise, a perfect mapping of the symbols occurs which corresponds to a BER of zero (BER=0).

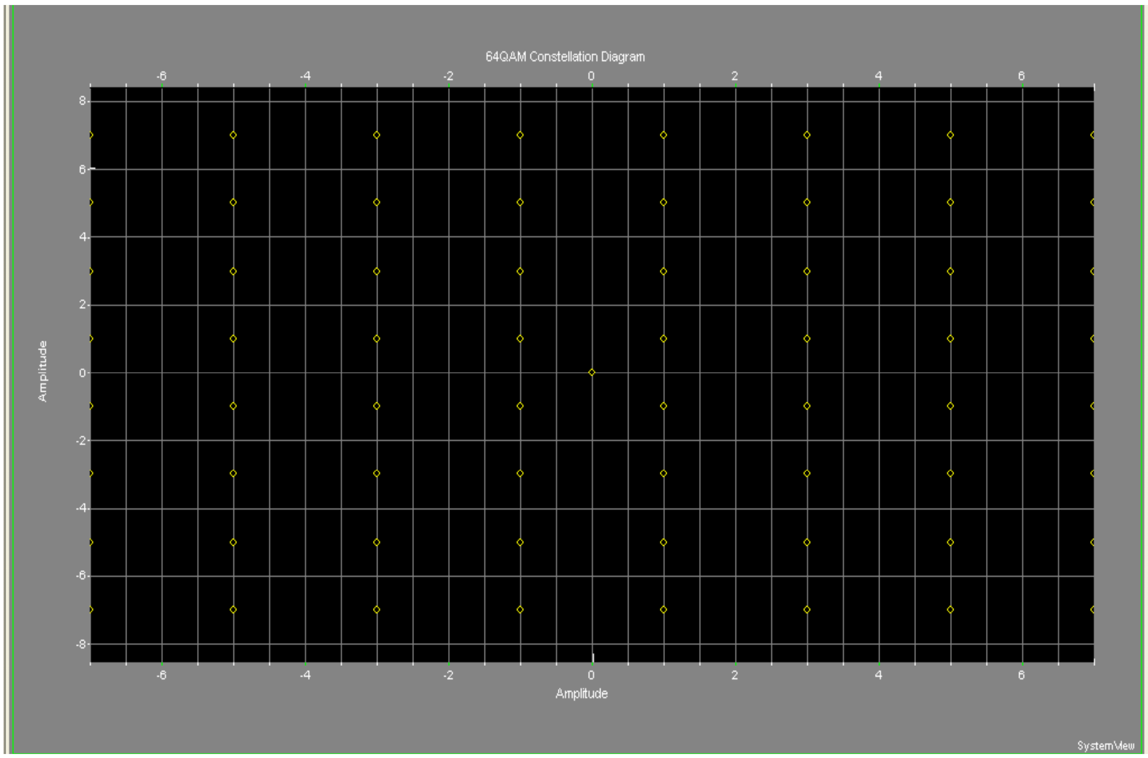

Figure 30. 64QAM Constellation Diagram without AWGN.

The Noise source (token 42) utilizes a random number generator to provide samples to support statistical analysis of the system. Thus, in the next step, AWGN interference is added in the channel with variable noise density (N) in order to show the BER results in a SNR range of 0-16 db. Figure 31 shows the resulting diagram.

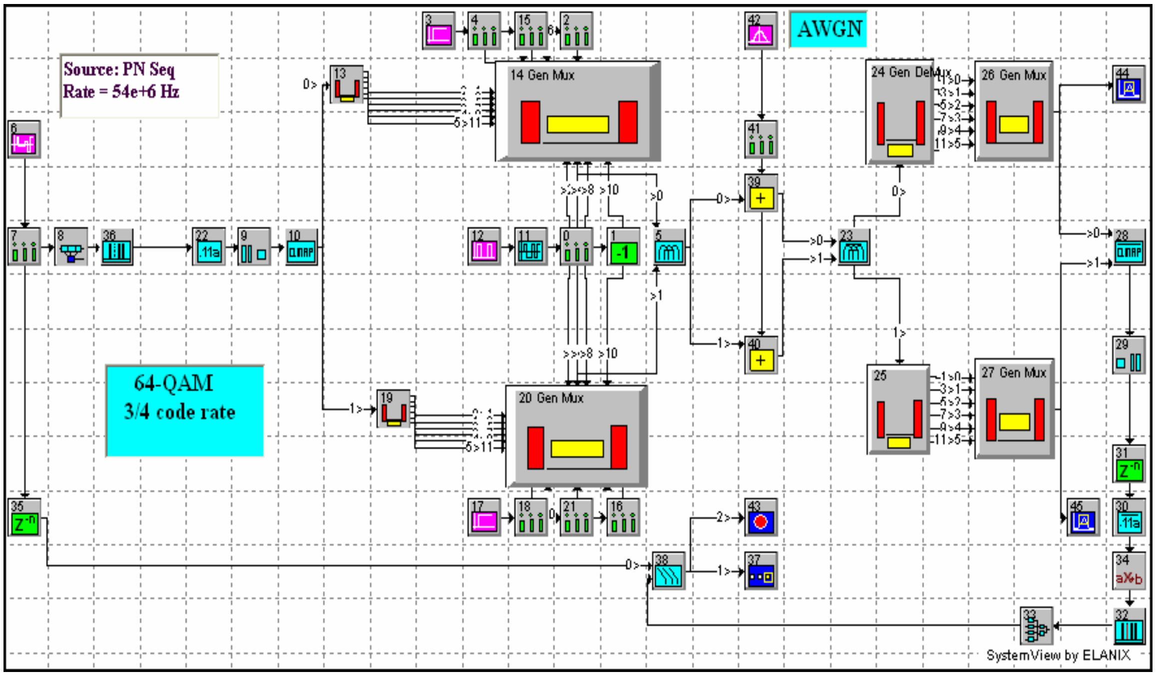

Figure 31. 64QAM-3/4 Code Rate with Additive White Gaussian Noise (AWGN).

The interference due to the presence of AWGN is obvious as it is observed in both the constellation diagram (Figure 32) and the BER diagram (Figure 33).

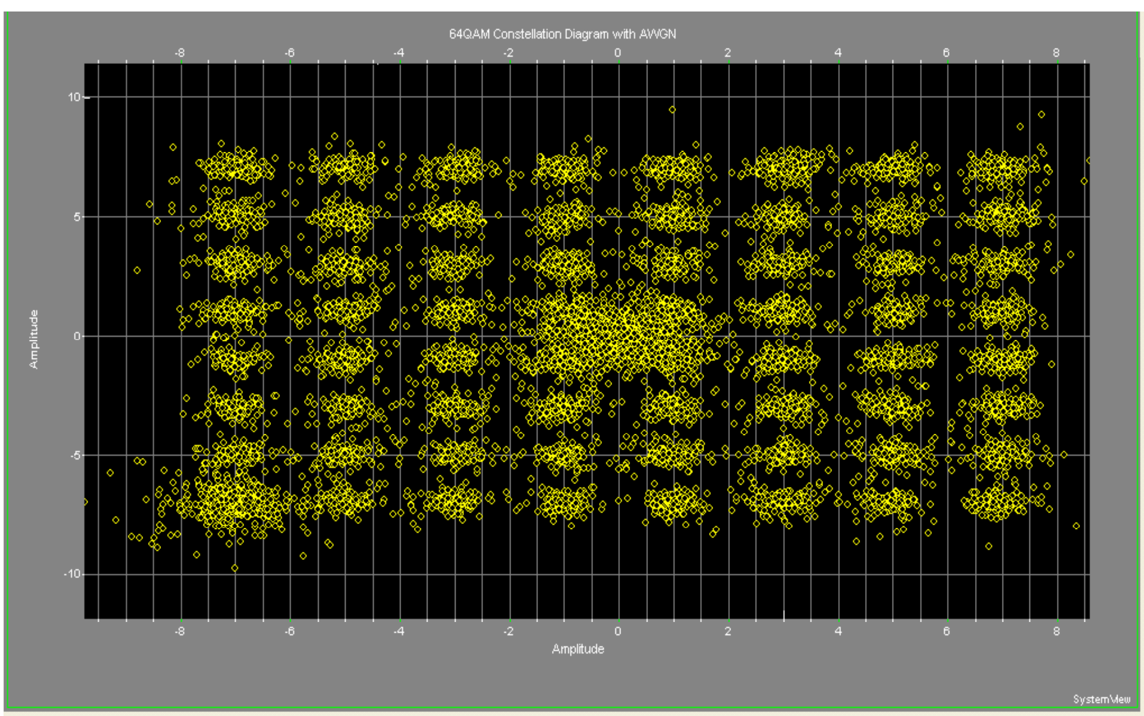

Figure 32. 64QAM Constellation Diagram with AWGN.

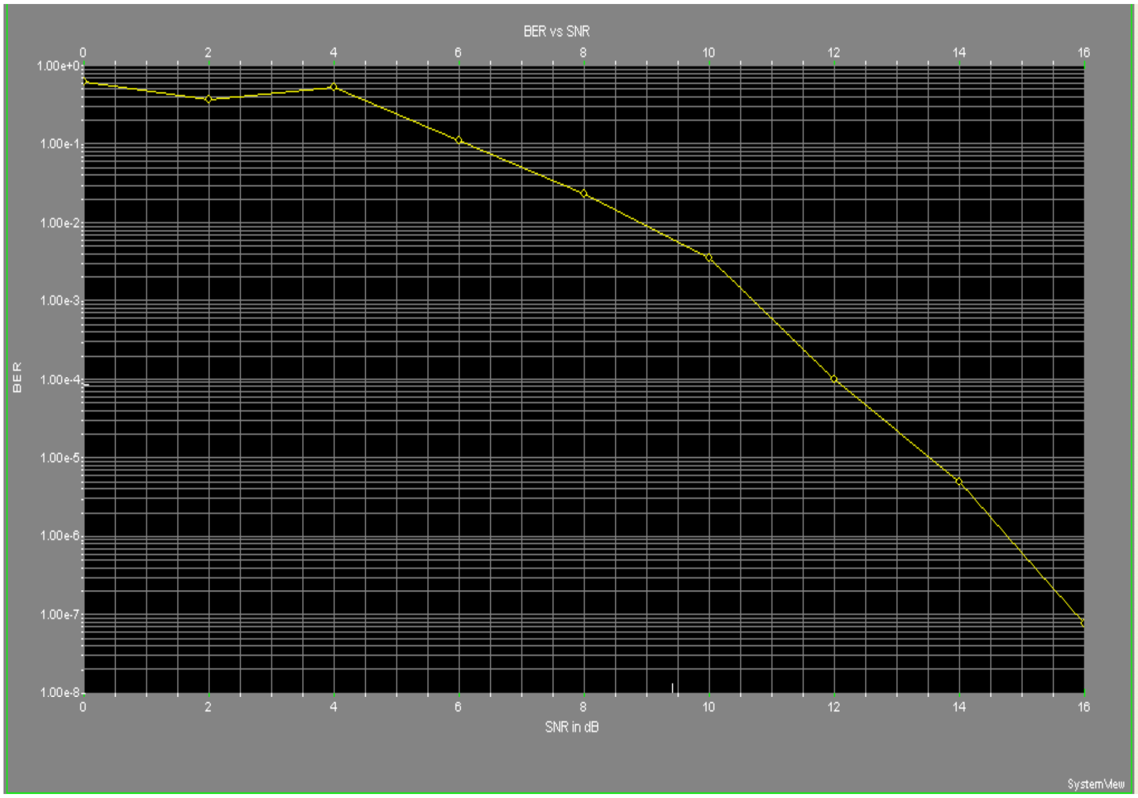

Figure 33. BER vs. SNR Diagram of 64QAM-3/4 Code Rate.

b. 2/3 Code Rate-48Mbps

In the next phase of the simulation analysis, the tokens performing the puncturing operation are adjusted in such a way that the 2/3 code rate is achieved. Thus, for every 2 bits into the convolution encoder, there are 3 bits out of the puncture token. Furthermore, the data source is adjusted, according to Table 10, to 48 Mbps. Similarly, with the previous case, the simulation parameters remain the same and AWGN interference is added to the channel with variable SNR. Figure 34 shows the corresponding simulation.

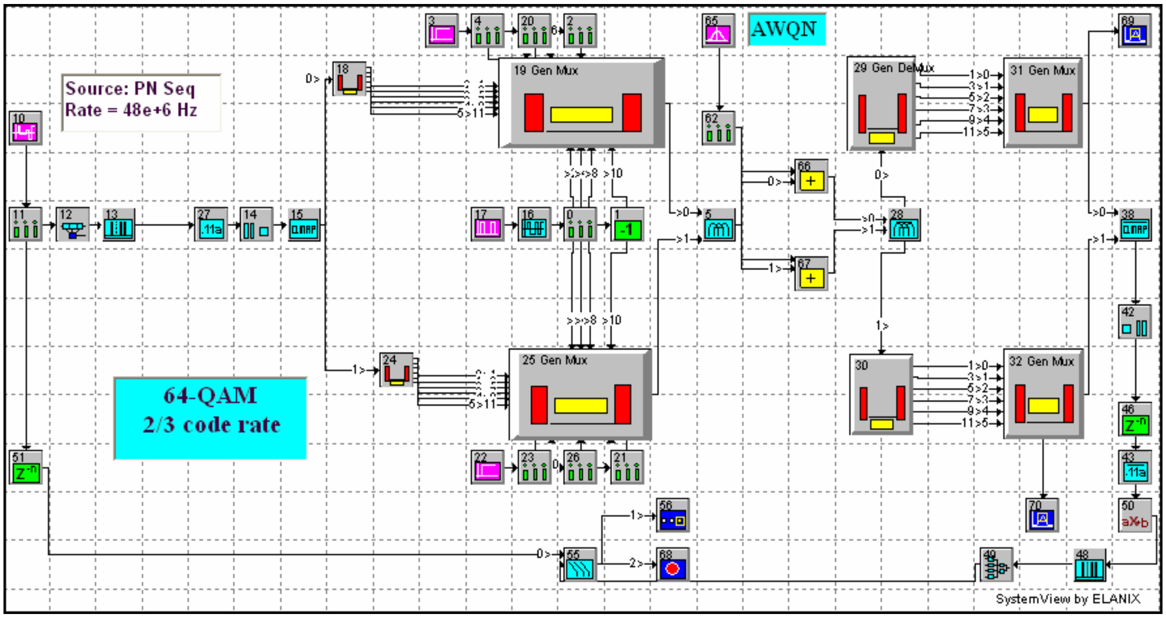

Figure 34. 64QAM-2/3 Code Rate with Additive White Gaussian Noise (AWGN).

The corresponding BER diagram shown in Figure 35 demonstrates that the BER is better than in the previous case. When the case of 16 QAM is also simulated, a comparison of the diagrams will show the relationship between the desired data rates and the resulting BER.

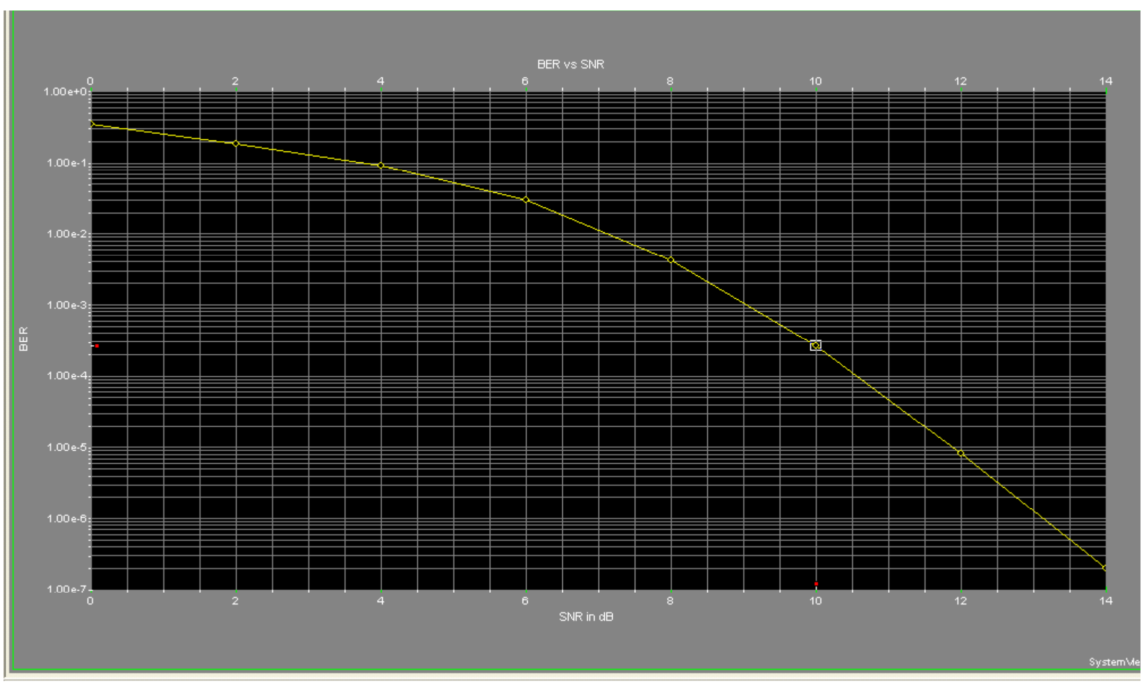

Figure 35. 64QAM-2/3 Code Rate BER vs. SNR Diagram.

2. 16QAM

a. 3/4 Code Rate-36Mbps

16QAM uses 4 bits per symbol and can be realized using two different amplitude levels and eight different phases. Using the model shown in Figure 36, the corresponding coordinates of each symbol are entered in the QMAP (token 15) in the same way as the 64QAM case. T difference is that each symbol now has 4 bits. In addition, the data source is adjusted to a data rate of 36 Mbps. Finally, the tokens performing the puncturing operation are adjusted in such a way that the 3/4 code rate is achieved.

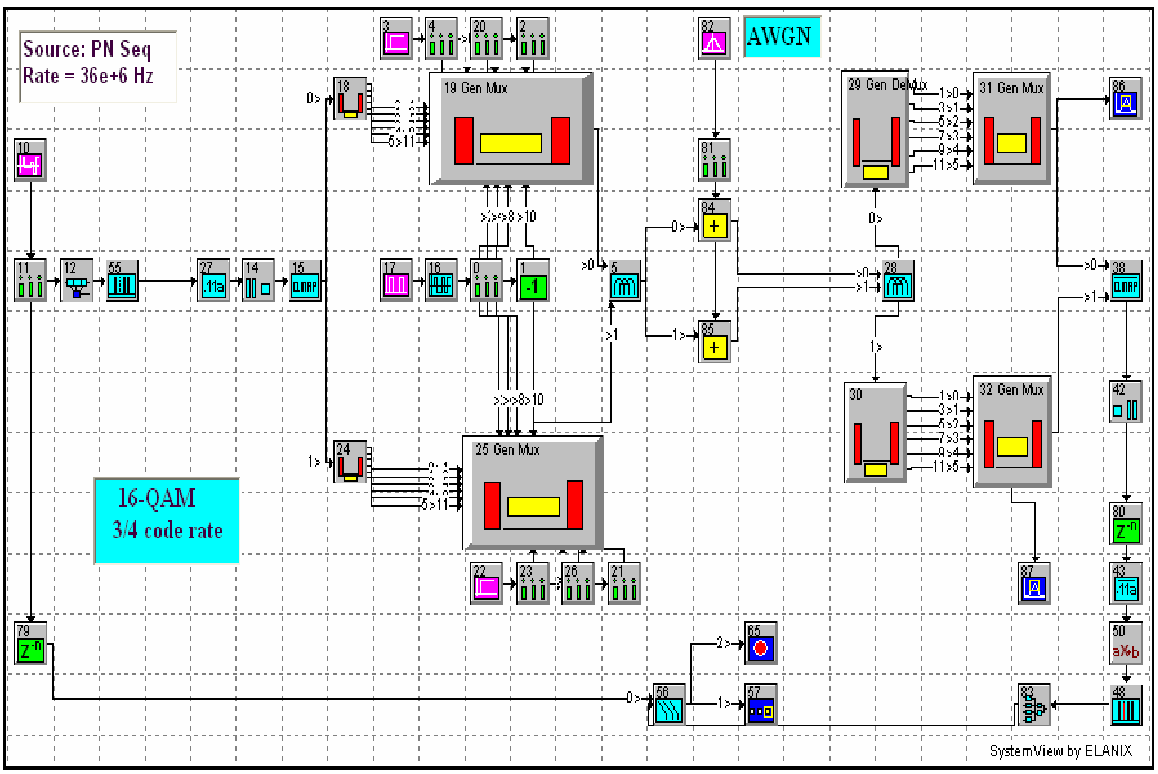

Figure 36. 16QAM-3/4 Code Rate with Additive White Gaussian Noise (AWGN).

Once more, when the wireless channel is free of AWGN, the constellation diagram shows that there is a perfect mapping of the symbols as illustrated in Figure 37.

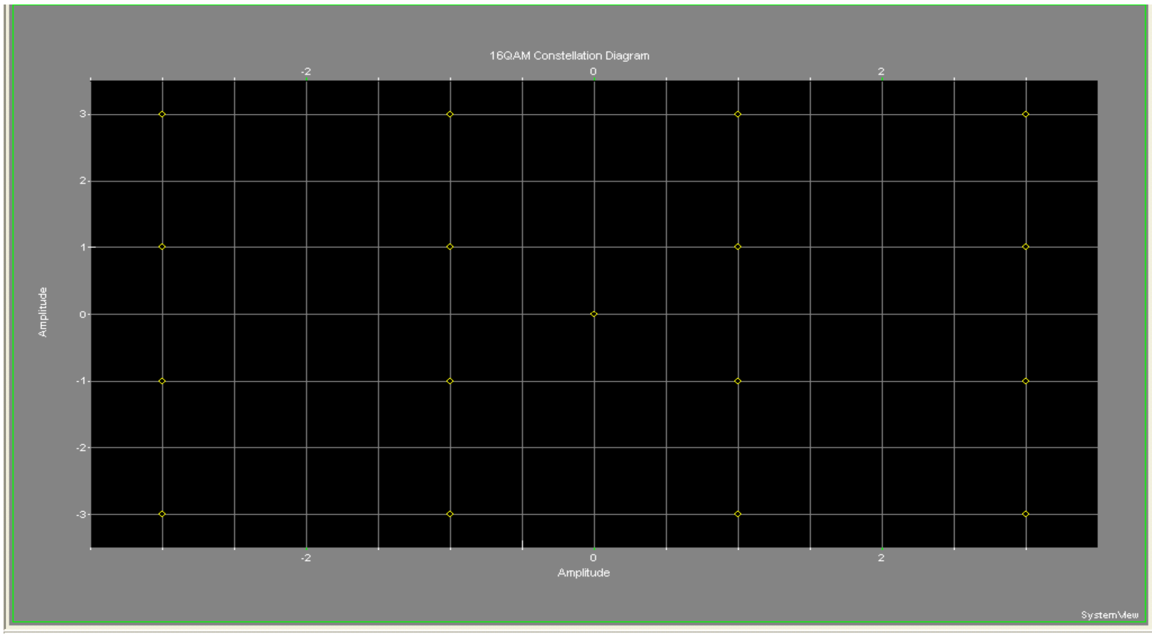

Figure 37. 16QAM Constellation Diagram without AWGN.

Next, as in the 64QAM case, AWGN is added. Similarly, there is again significant interference due to the presence of AWGN as shown in both the constellation diagram (Figure 38) and the BER diagram (Figure 39).

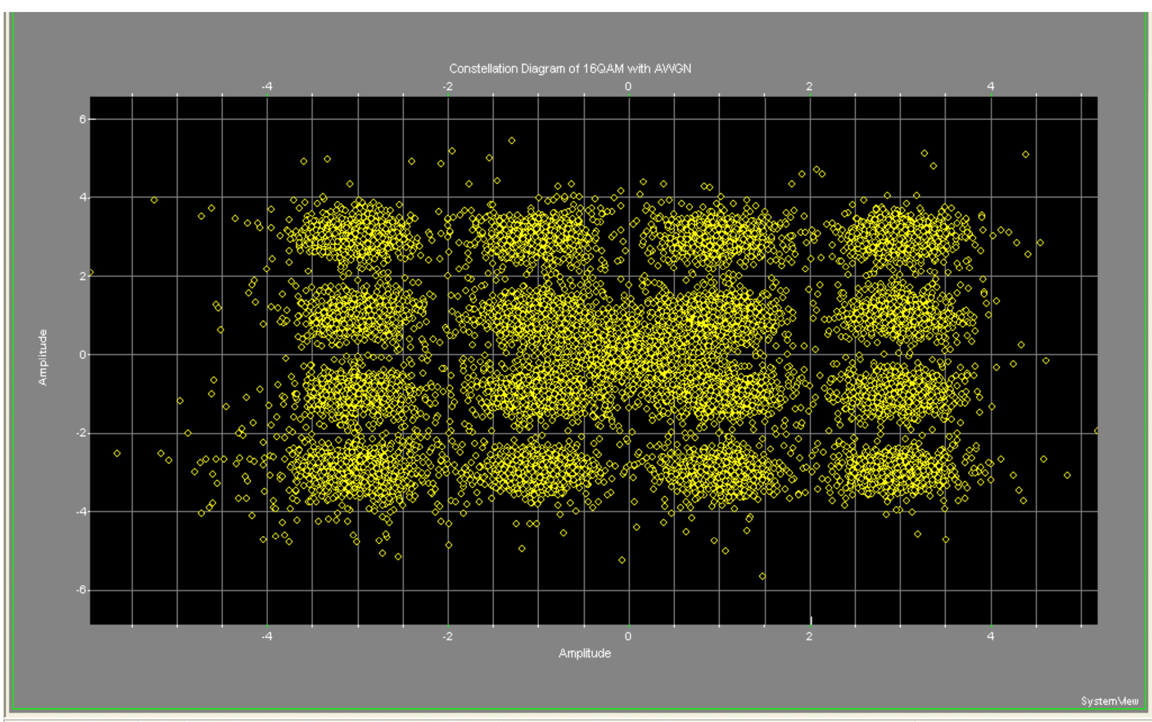

Figure 38. 64QAM Constellation Diagram with AWGN.

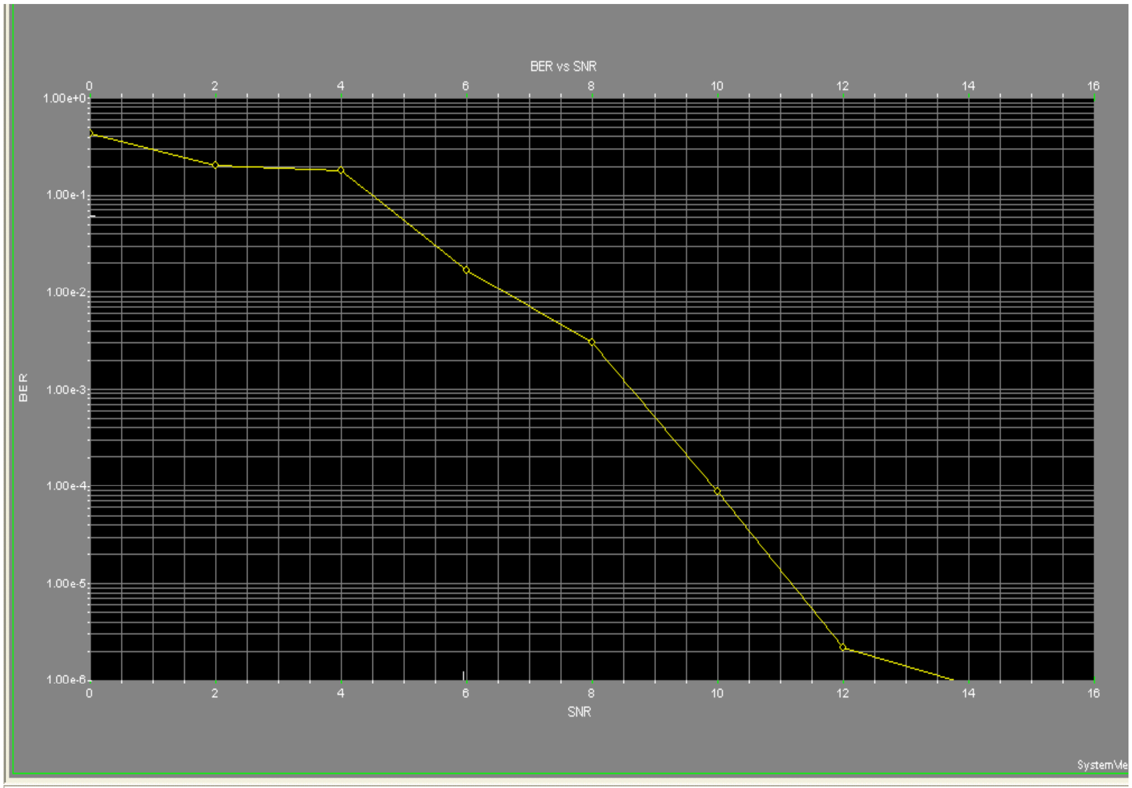

Figure 39. 16QAM-3/4 Code Rate BER vs. SNR Diagram.

The probabilistic comparison of the output BER curves from all modulation schemes that were used in the simulation analysis, (Figure 40) strongly indicates that there is a trade off between data rate and BER. The results show a direct relationship of BER with the data rate. For example, despite the higher data rate achieved in the case of the 64QAM with ¾ code rate, the BER observed is significantly worse than the other cases. Indeed, for a SNR of 13.5 dB, the simulation resulted in a BER of $2.8*10^{-8}$ for the 16QAM-¾ case, which has the lower data rate (36 Mbps), in contrast with the $5*10^{-7}$ in the case of the 64QAM- 2/3 code rate (48 Mbps) and with the 10^{-5} in the case of the 64QAM- ¾ code rate (54 Mbps).

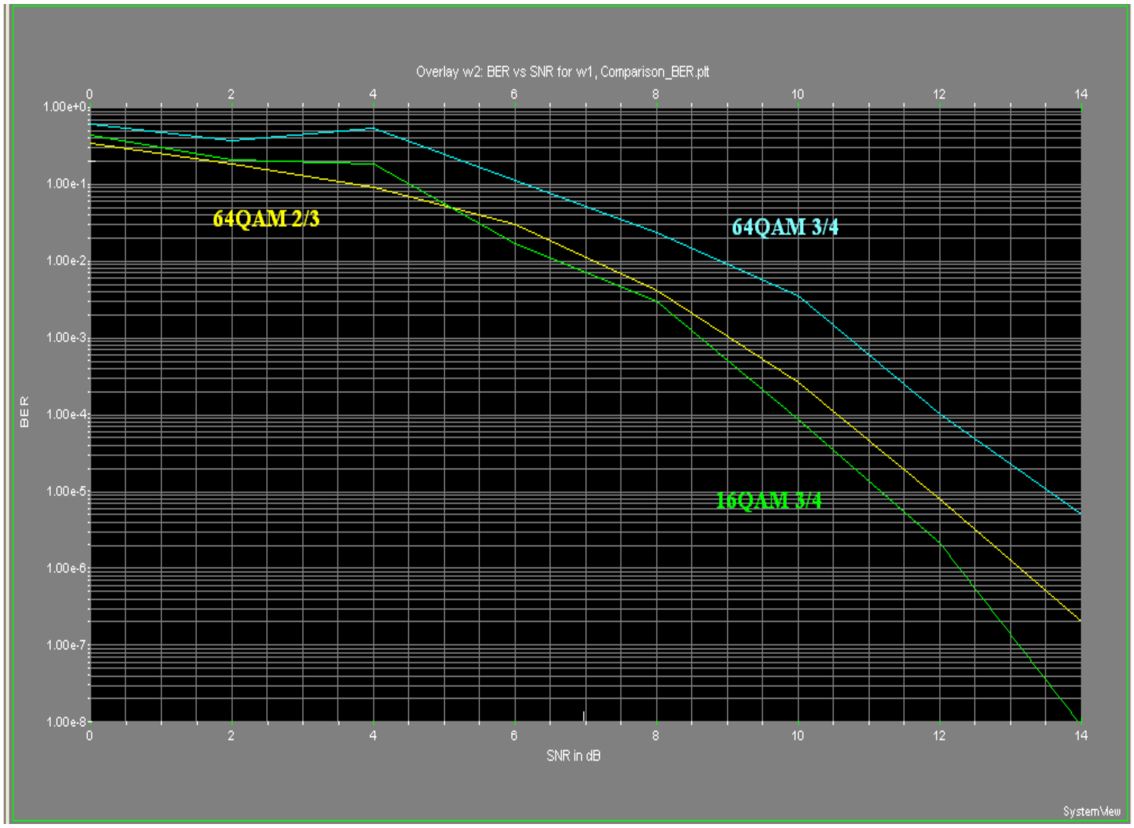

Figure 40. BER Comparison of 64QAM-3/4, 64QAM-2/3 and 16QAM-3/4.

In conclusion, the probability of BER depends on the modulation scheme used. More precisely, the modulation scheme that achieves the highest data rate has the worst BER, while, on the other hand, the lower the data rate, the better the BER observed. Thus, customer requirements should determine the choice of the modulation scheme used. If the customer chooses a low data rate scheme then the reliability of the system will be higher. Regardless, the customer should first define the tolerable acceptable level of risk.

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V. LINE-OF-SIGHT IMPAIRMENTS

In all communications systems, the signal received differs from the signal transmitted due to various transmission impairments. As described in Chapter III, MMDS and LMDS use very high frequencies, in the range of 2 GHz to 31 GHz. As such, their transmission characteristics are described by *microwave radio communication*. Microwaves are electromagnetic waves and, like light, propagate through free space in a straight line with a velocity of $3*10^8$ m/sec with frequencies that approximately range from 500 MHz to 300 GHz. As a result, microwaves have relatively short wavelengths in the range of 60 cm to 1 mm. Hence, the name “micro” waves. Microwave wavelengths are highly affected and may be completely blocked by obstructions. They require Line-of-Sight (LOS), literally meaning that the transmitter (receiver) can be seen by someone at the receiver (transmitter), since the waves travel only in a straight line. In addition, the wavelengths are small enough to become affected by water vapor and rain.

The purpose of this chapter is to first identify and analyze the various impairments, except for noise, which was analyzed in the previous chapter and to second, comment on their specific effects on the performance and reliability of communications links using both MMDS and LMDS. The most significant impairments are shown below:

- Free Space Loss
- Fresnel Zones-Vegetation
- Multipath Fading
- Atmospheric Absorption

A. FREE SPACE LOSS

Free-space loss is primarily caused by beam divergence which is the spreading of the signal over larger areas at increased distances from the source. As a result, the power density is less at any given point a fixed distance from the source. Indeed, an antenna with a fixed area receives less signal power the farther it is from the transmitting antenna[46]. Even if no absorption or reflection of energy from nearby objects and no other sources of attenuation are assumed, a transmitted signal still attenuates over distance because the signal is being spread over a larger area (Figure 41).

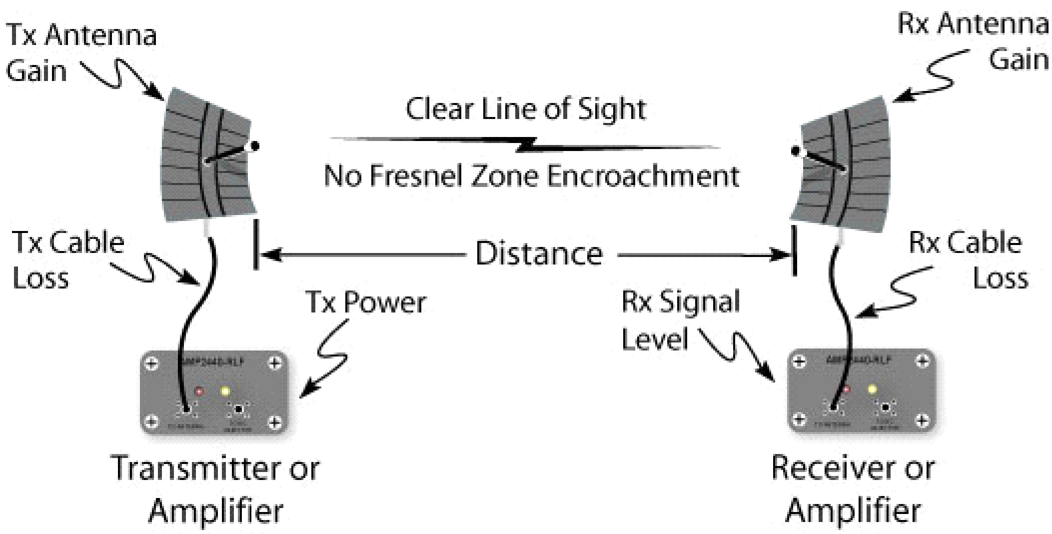

Figure 41. Free Space Loss. [From: [http://www.zeuswireless.com/support/free-space-loss.php,] January 2004]

The equation for free space loss[47] for a terrestrial microwave is given as:

Equation Chapter 5 Section 5 what is this?

$$L_p = (4\pi D/\lambda)^2 = (4\pi f D/c)^2 \quad (5.1)$$

where L_p = free space loss (unitless)

f = frequency in hertz

D = distance in kilometers

λ = wavelength in meters

c = $3*10^8$ m/sec (velocity of light in free space)

46 William Stallings, Wireless Communications and Networks, Prentice Hall, Inc., p. 111, 2002.

47 Wayne Tomasi, Electronic Communications Systems, Fundamentals through Advanced, Fourth edition, Prentice-Hall, Inc., p. 367, 2001.

Converting to dB yields:

$$\begin{aligned} L_{p(dB)} &= 20\log\left(4\pi f_{(Hz)} D_{(Km)} / c\right) = 20\log\left(4\pi f_{(Hz)} D_{(Km)}\right) - 20\log(c) \\ &= 20\log\left(f_{(Hz)}\right) + 20\log\left(D_{(Km)}\right) + 20\log(4\pi) - 20\log(c) \\ &= 20\log\left(f_{Hz}\right) + 20\log\left(D_{(Km)}\right) + 21.98 - 169.54 \end{aligned}$$

The final equation of free space loss in dB is

$$L_{p(dB)} = 20\log\left(f_{(Hz)}\right) + 20\log\left(D_{(Km)}\right) - 147.56 \tag{5.2}$$

When the frequency is given in MHz or GHz, Equation 5.1 is converted accordingly to the following equations:

$$L_{p(dB)} = 20\log\left(f_{MHz}\right) + 20\log\left(D_{(Km)}\right) + 32.4 \tag{5.3}$$

$$L_{p(dB)} = 20\log\left(f_{(GHz)}\right) + 20\log\left(D_{(Km)}\right) + 92.4 \tag{5.4}$$

For example, for a given frequency of 31 GHz and a distance between transmitter and receiver of 1 Km, Equation 5.4 yields a loss of 122.2 dB.

From Equation 5.1, it is obvious that free space loss depends on the square of the frequency used as well as the distance between the transmitter and receiver. Keeping this in mind and by taking into consideration the range of frequencies used in Fixed Wireless Broadband (FBW), it very clearly demonstrates that it greatly affects the communication link. Using Equation 5.4 for frequencies used in MMDS and LMDS, Figure 42 demonstrates the free space loss in dB as the distance between the transmitter and receiver increases.

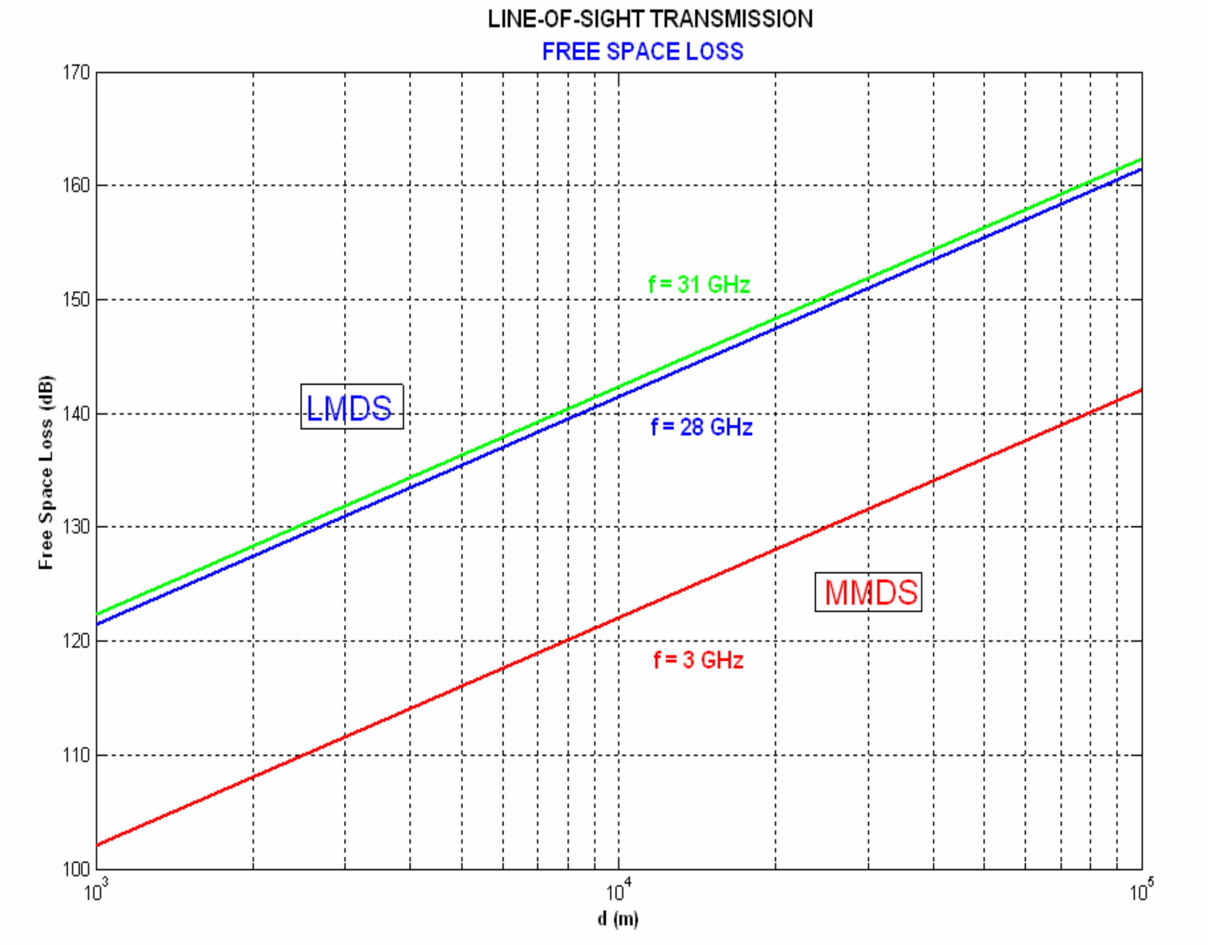

Figure 42. Free Space Loss.

Indeed, free space loss significantly increases as the distance increases. Amazingly enough, the diagram shows that regardless of the frequency used, the loss at 10 Km is 20 dB more than the loss at 1 Km. Thus, *the loss is in the first case is 100 times the loss in the second case*! Furthermore, the diagram shows the tremendous difference in the loss between MMDS and LMDS. Indeed, for all the range of distance, and due to the higher frequency used, the LMDS continuously shows a 20 dB difference with the MMDS, which again means that the loss in LMDS is amazingly 100 times larger than MMDS. Regardless, MMDS still demonstrates a large loss, and for distances of more than 10 Km, it becomes equivalent to the loss that LMDS has at smaller distances, of say, less than 1 Km.

B. FRESNEL ZONES - VEGETATION

It has already been mentioned that there must be an unobstructed line of sight between the transmitter and the receiver in order to achieve effective communications at millimeter wavelengths. However, LOS does not only refer to the exact visual LOS that waves spread out into after they leave the antenna, but it also refers to a certain amount of the area around that visual line-of-sight. In fact, a specific area around the direct path between transmitter and receiver that needs to be clear of obstacles exists.

Using a mobile propagation measurement laboratory, Bellcore investigated the performance of LMDS in Brighton Beach, Brooklyn, NY[48]. More precisely, the measurement van was on Emmons Avenue between 26th Street and 27th Street. The antenna was rotated 360 degrees in azimuth for each of the three heights, 4.0, 7.3 and 11.3 meters above ground. Figure 43 shows the measured signal strength where the arrow indicates the direction of the hub from the transmitter.

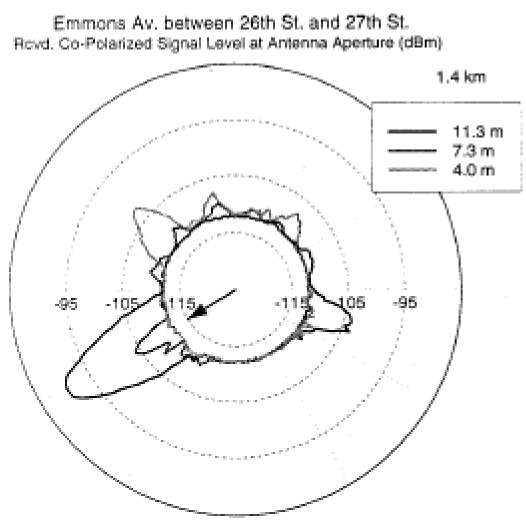

Figure 43. Measured Signal Strength for Three Different Antenna Heights. [From: Propagation Measurements at 28 GHz to Investigate the Performance of LMDS, Scott Y. Seidel and Hamilton W. Arnold]

Figure 43 shows that the signal level depends on the receiver antenna height. In fact, the signal level in the direction of the transmitter decreases rapidly as the antenna is

48 Scott Y. Seidel and Hamilton W. Arnold, Propagation Measurements at 28 GHz to Investigate the Performance of LMDS, 1995.

lowered. Furthermore, the signal level received via reflection is greater at the lower antenna heights. The above measurements shows that building blockage and vegetation is a major limitation in the ability to cover a particular location using LMDS and that, strong signals are only received at locations where a specific area, which is clear of obstacles around the direct path, is available. Using *Fresnel zones* defines this specific area.

The Fresnel zones were first proposed by Fresnel in 1818 in an attempt to explain diffraction phenomena. Today, Fresnel zones do explain the concept of diffraction loss as a function of the path difference around an obstruction. Fresnel zones theory is based on the fact that any small element of space in the path of an electromagnetic wave can be considered the source of a secondary wavelet. Fresnel zones, in fact, represent the successive region where these secondary wavelets have a path length from the transmitter to receiver. The cross section of the first Fresnel zone is circular as shown in Figure 44. Subsequent Fresnel zones are annular in cross section and concentric with the first. Obstacles lying within a series of concentric circles around the direct path have constructive or destructive effects on the communication link.

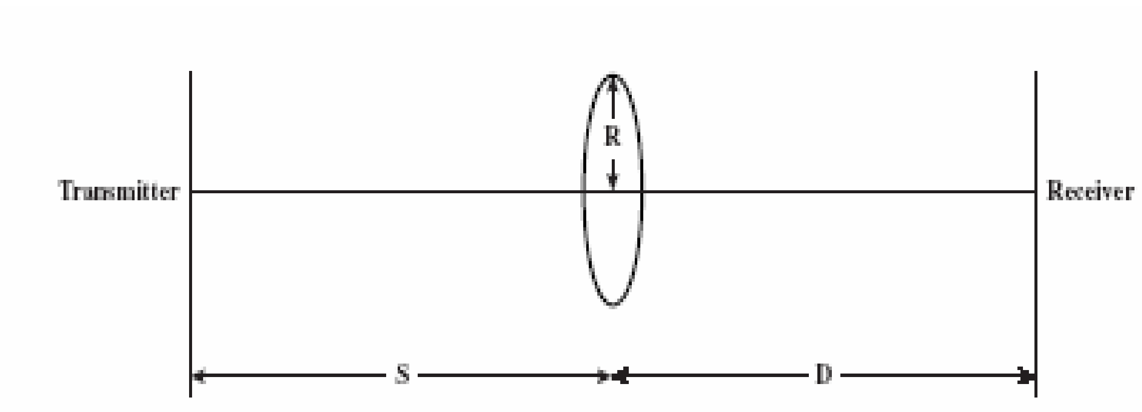

Figure 44. The First Fresnel Zone. [From: Wireless Communications and Networks, William Stallings]

The obstacles that fall within the first Fresnel zone have the most serious attenuation effects. Consider a point along the direct path between a transmitter and receiver. The radius of the n_{th} Fresnel zone is given by the following equation[49] where R_n, S and D are in the same units:

$$R_n = \sqrt{\{n\lambda SD/(S+D)\}} \quad (5.5)$$

where: R_n = radius of the n_{th} Fresnel zone

λ = wavelength of signal

S = distance of the point from the transmitter

D = distance of the point from the receiver

n = number of Fresnel zone

For the first Fresnel zone (n=1), which plays the most important role, Equation (5.5) becomes:

$$R_1 = \sqrt{\{\lambda SD/(S+D)\}} \quad (5.6)$$

For convenience, for the specific case of microwave propagation where frequencies are in the GHz range, Equation (5.6) can be restated as:

$$R_{1(m)} = 17.3\sqrt{\{(1/f_{(GHz)})(S_{(km)}D_{(km)}/(S+D))\}} \quad (5.7)$$

where frequency is expressed in GHz, distances in Km and R in meters. For example, for a given frequency of 3 GHz and a distance of 0.5 Km, the radius of the first Fresnel zone in the middle of the distance (S = D = 0.25 Km) is 3.53m.

Fresnel zones are an important area of concern for FBW systems because signals in the GHz range have a difficult time passing through trees and vegetation. This is a result of their water content. Indeed, trees contain high levels of moisture and microwaves absorb into water quite well.

49 Theodore S. Rappaport ,Wireless Communications Principles and Practices, Second Edition, Prentice Hall , Inc., p. 127, 2002.

Assuming a distance of 0.5 Km between a transmitter and receiver, a calculation of the various radiuses of Fresnel zones is demonstrated in Figure 45. More precisely, the figure shows 60% of the radii, because in the design of LOS microwave links, if no obstruction exists within approximately 0.6 of the radius of the first Fresnel zone at any point between the transmitter and receiver, then the attenuation due to obstruction is negligible[50]. The radii are calculated every 10m for the entire distance of 0.5 Km.

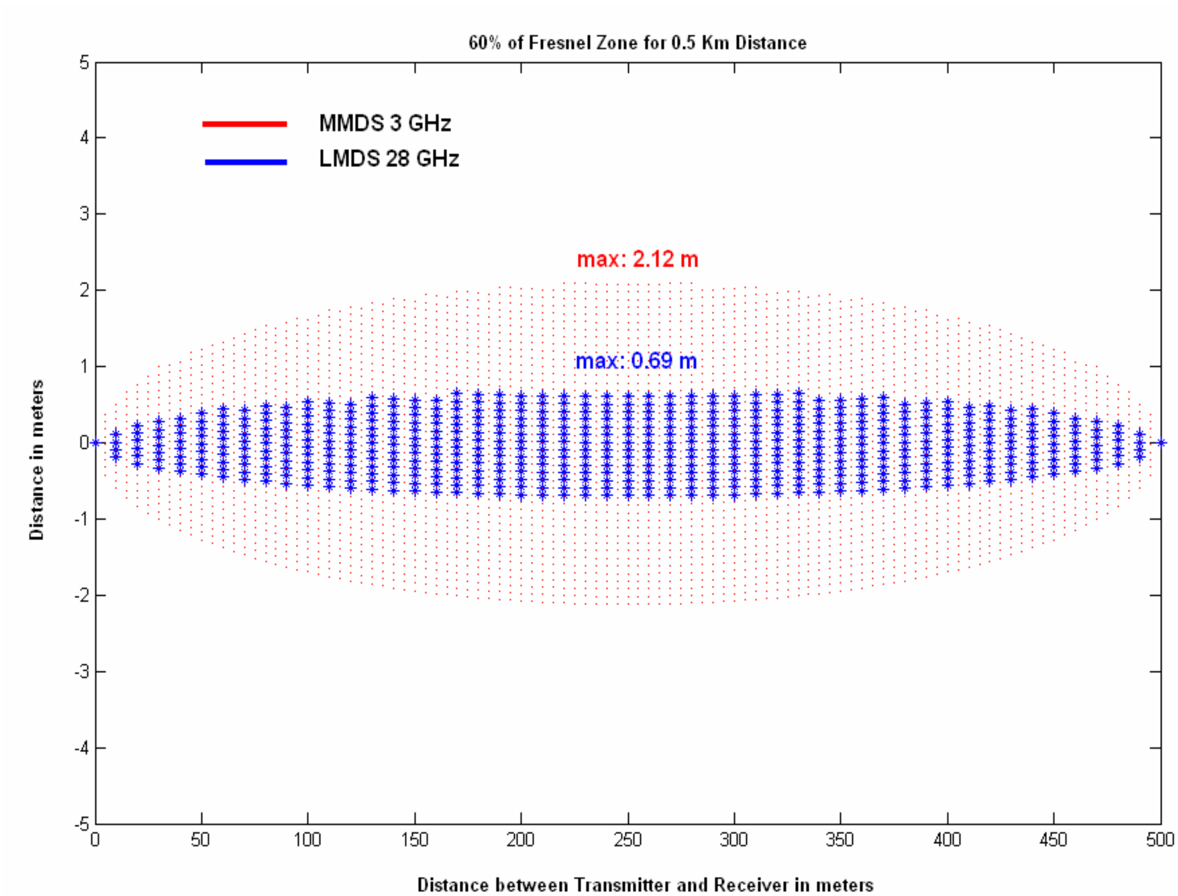

Figure 45. 60% of the Radius of First Fresnel Zone for a Distance of 0.5 Km for MMDS and LMDS Frequencies.

Figure 45 clearly shows that both systems require wide radii along the direct path. Nevertheless, the higher frequency of the LMDS requires a much smaller radius. Indeed, in the middle of the direct path, the 60% of the first Fresnel zone is 2.12m for the case of MMDS in comparison with 0.69m in the case of LMDS.

50 William Stallings, Wireless Communications and Networks, Prentice Hall, Inc., p. 359, 2002.

In order to demonstrate the relationship between the radius of the first Fresnel zone and the distance between the transmitter and receiver, a calculation of the various radii is shown in Figure 46 for a distance this time of 2.5 Km. In this case, the radii of the first Fresnel zone is calculated every 20m for the entire distance of 2.5 Km.

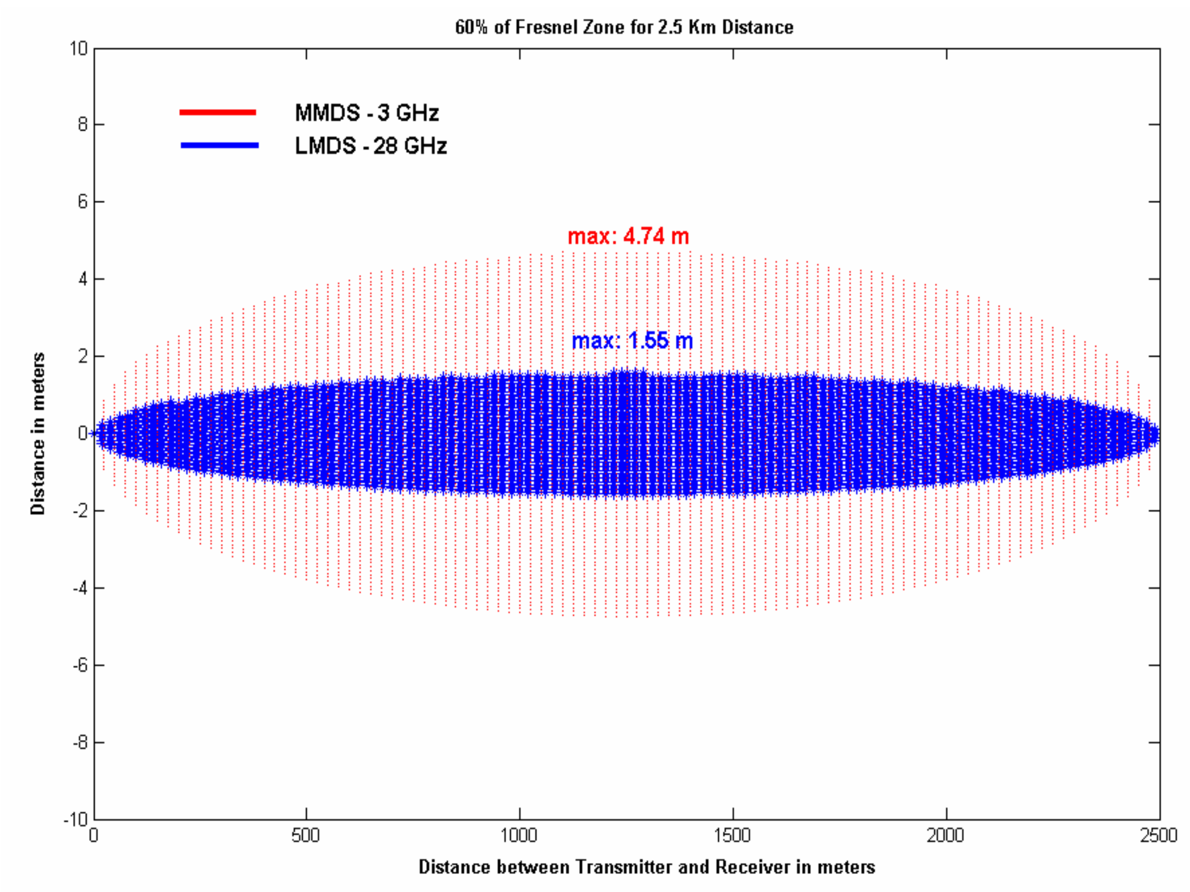

Figure 46. 60% of the Radius of First Fresnel Zone for a Distance of 2.5 Km for LMDS and MMDS Frequencies.

As in the previous case, a wider area needs to be clear from obstacles in the MMDS frequencies. In addition, the radii in both MMDS and LMDS systems are significantly larger, which demonstrates that the larger the distances between the two transceivers, the wider the area that needs to be free from obstacles. The above do not include only vegetation and obstacles, but also refer to the ground. For example, for the case of the MMDS and for the case of a distance of 2.5 Km shown in Figure 46, in order to avoid reflection from the ground, the antennas need to be placed at a height of at least 4.74m even if there are no obstacles at all. In fact, for this reason, it is necessary to place the antennas on high buildings when the distances become larger and larger.

The above analysis first shows that both the frequency used as well as the distance between the two transceivers play a significant role in effective communications using FBW. Second, due to their lower frequencies, the MMDS are more affected by vegetation and obstacles than LMDS, which makes LMDS particularly suited to densely populated urban areas. Finally, it shows that the antennas used need to be placed at significantly high positions from the ground. Indeed, considering the aforementioned examined cases, the height of the antennas needs to be such that there is no point along the direct path at which the ground is within the 60% of the radii of the first Fresnel zone.

C. MULTIPATH FADING

A wireless channel is characterized by multipath fading which is defined as the time invariant of received signal power caused by changes in the transmission medium or paths. It is caused by the interference among the time delayed replicas of the transmitted signal arriving at the receiver at any time and it is the primary propagation issue in lower-frequency bands like HF (3 to 30 MHz). This interference arises from the following phenomena, shown in Figure 47, that affect the transmitted signal:

- *Reflection*: Occurs when an electromagnetic signal encounters a surface of an obstacle that is large relative to the wavelength of the signal. A good illustration of this is the reflected light on the surface of a mirror.
- *Diffraction*: Occurs at the edge of an obstacle that is large compared to the wavelength of the signal. Thus, the LOS is obstructed and the electromagnetic wave is bent around the obstacle, as the light of the car bends around the edge of the wall in Figure 47.
- *Scattering*: Occurs if the size of the obstacle is on the order of the wavelength. Thus, the electromagnetic wave illuminates the object, which in a way, reradiates the signal most generally in any direction.

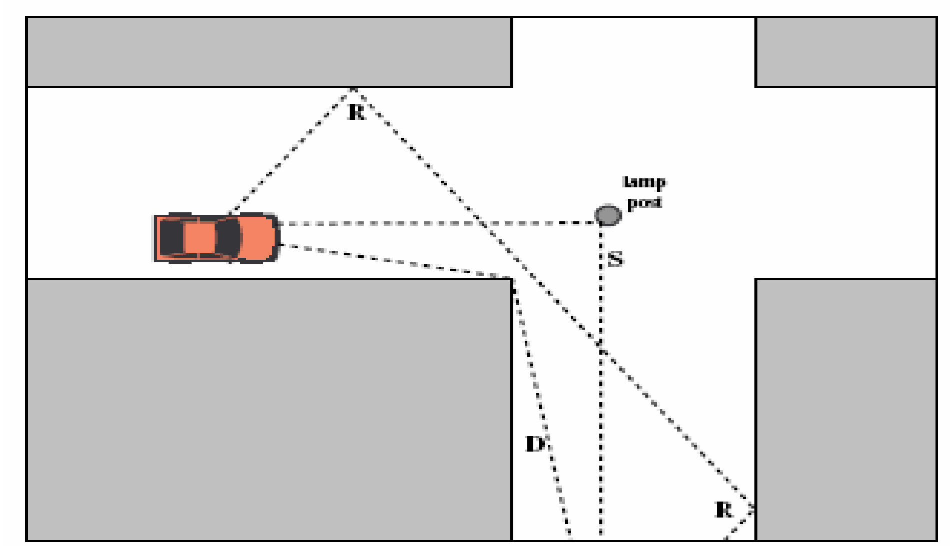

Figure 47. Reflection (R), Detraction (D) and Scattering(S). [From: Wireless Communications and Networks, William Stallings]

Therefore, multipath fading is a loss additional to free space loss and is attributed to the aforementioned described phenomena. From the description of these phenomena, it is clear that multipath fading depends on less predictable characteristics of microwave propagation such as terrain sensitivity, which manage to alter the LOS and reduce overall system performance. In order to account for such characteristics and observe the effects of fading not only as a function of frequency, *fade margin* is introduced. Fade margin accommodates fading as an additional loss considering these non-ideal and less predictable characteristics. Equation 5.8 describes the fade margin depending not only on frequency, but also on the desired availability, terrain sensitivity and the distance of the transceivers[51].

$$F_{m(dB)} = 30\log\left(D_{(Km)}\right) + 10\log\left(6\,A\,B\,f_{(GHz)}\right) - 10\log\left(1-R\right) - 70 \qquad (5.8)$$

where $F_{m(dB)}$ = fade margin in dB

$D_{(Km)}$ = distance in Km

$f_{(GHz)}$ = frequency in GHz

R = reliability expressed in as a decimal

51 Wayne Tomasi, Electronic Communications Systems, Fundamentals through Advanced, Fourth Edition, Prentice-Hall, Inc., p. 368, 2001.

A = roughness factor (clear number)

= 0.25 over mountainous or very rough terrain

= 1 over average terrain

= 4 over water or very smooth terrain

B = factor of convert a worst-month probability to an annual probability

= 0.125 over very dry or mountainous areas

= 0.25 over average inland areas

= 0.5 over hot humid areas

= 1 to convert an annual availability to a worst-month basis

Using the above equation for the case of MMDS, at 3 GHz, with an availability of 99.99 %, Figure 48 shows the fade margin as a function of distance and terrain roughness.

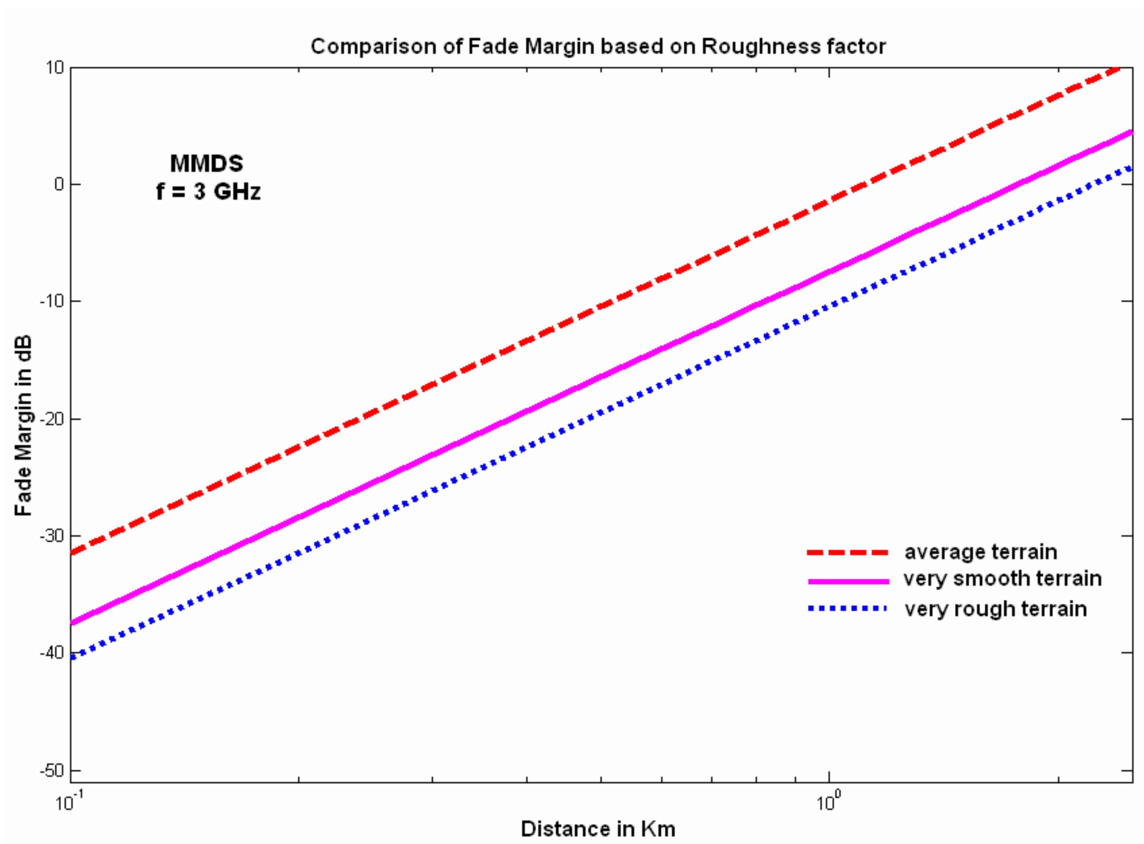

Figure 48. Fade Margin Based on Terrain Roughness.

As the distance increases, the effects of fading are more significant. Regardless, the terrain does play an important role and should be considered in the design of a FBW system.

Furthermore, from Equation 5.8 it is obvious that the desired availability is very significant in the determination of the fade margin. To illustrate this, LMDS and MMDS are compared using both 99.9% and 99.999% availabilities, assuming average terrain, as shown in Figure 49.

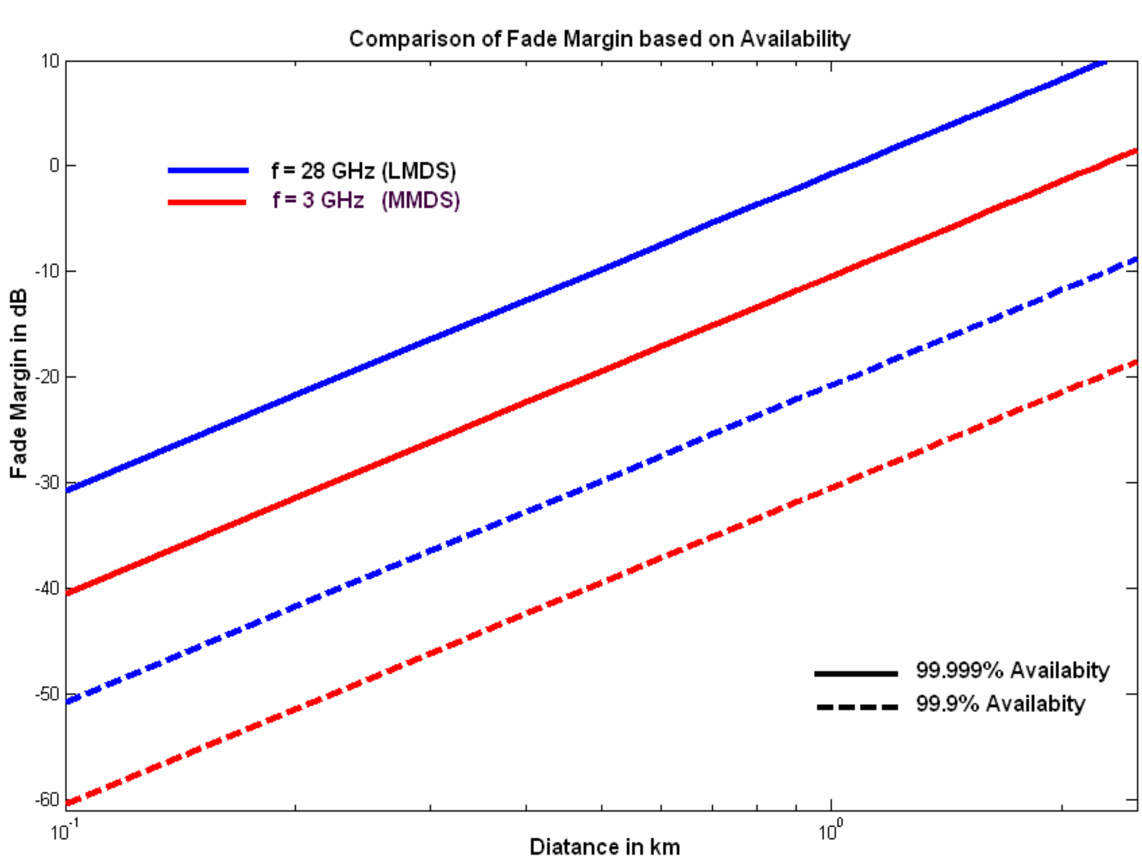

Figure 49. Fade Margin Based on Availability.

Indeed, the diagram clearly shows the difference in the fade margin depending on the availability in both cases. A difference of -20 dB exists between the two availability options, which even if it is small, it may need to be considered depending on the specific requirements.

Finally, assuming availability 99.999% and average terrain in average inland areas, Figure 50 compares the fade margin of LMDS and MMDS vs. distance. A difference of -10 dB exists in all range of distance. The difference is small and the figure shows that fading becomes more significant for distances of more than 1 Km for both cases, while for smaller distances, it is less significant.

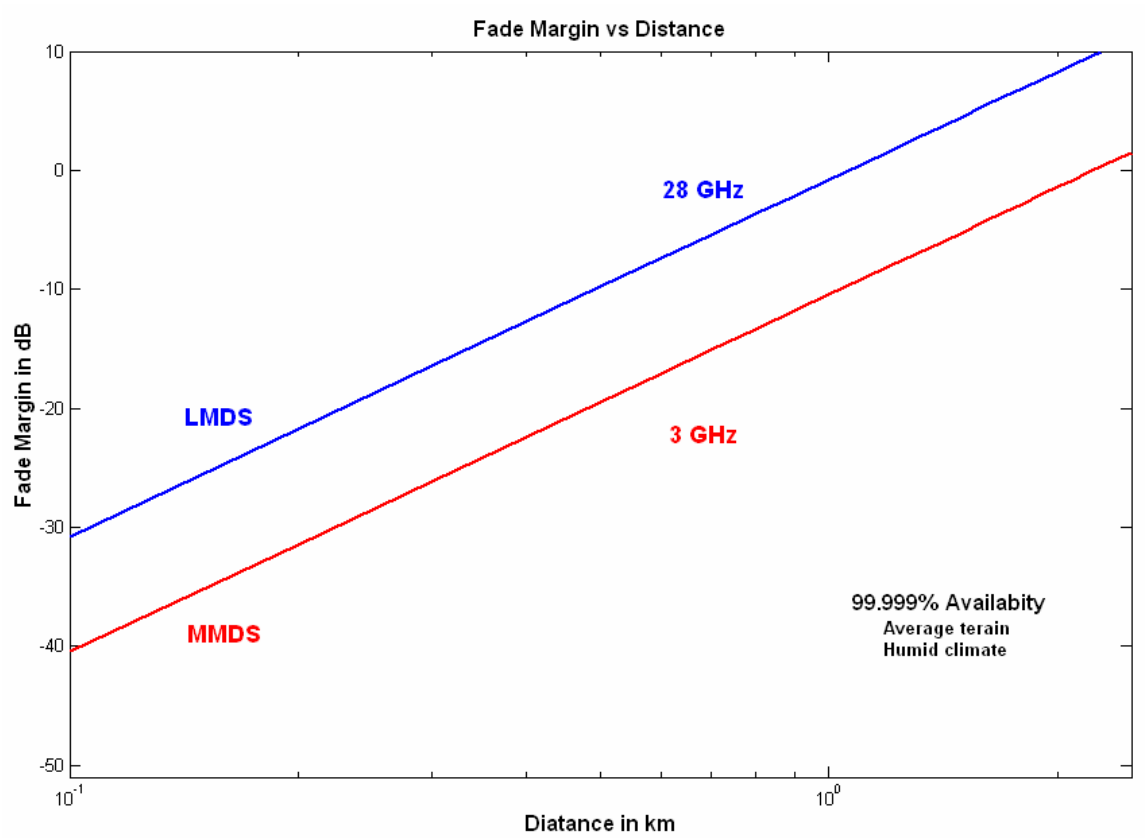

Figure 50. Fade Margin Based vs. Distance for LMDS and MMDS.

From the above analysis, it becomes clear that fading depends not only on the frequency used and the distance between the transceivers, but also on unpredictable characteristics such as terrain roughness and the desired availability. The fade margin observed is much less significant for distances less than 1 Km than for the free space loss previously discussed in this chapter. However, it becomes more important as the distance increases.

Indeed, while fading is the primary propagation issue in lower-frequency bands, at the specific FBW frequencies, multipath fading is an important but less critical factor compared with free space loss and atmospheric attenuation. This happens because first, in such frequencies, reflection and diffraction do not occur as often as at lower frequencies. Second, *cellular and personal communications service* (PCS) systems typically have customer-premises locations within six feet of the ground, whereas FBW systems have customer antennas located high on rooftops, which plays a major role in reducing multipath effects. Third, the antennas are highly directional (pointing to a single cell site), which also reduces multipath effects. Finally, in cellular and PCS systems the customer antenna may be moving, whereas FBW antennas are fixed on a rooftop. Thus, installers can choose better case locations on the rooftop, leading to improved performance. Regardless, and especially for the case of MMDS where larger distances can be achieved, fading needs to be taken into consideration when designing a system and choosing the locations of the antennas.

D. ATMOSPHERIC ABSORPTION

1 Atmospheric Gases and Weather Conditions

The propagation of electromagnetic waves through the atmosphere is strongly influenced by the particular conditions of the atmosphere. Losses occur in the earth's atmosphere due either to energy absorption by the atmospheric gases or adverse weather conditions.

Indeed, fog, rain and snow do affect communications. However, each one severely affects a specific type of communications and the others less. This originates from the difference in the size of raindrops, snowflakes and water droplets in fog, in combination with the specific range of frequencies, and thus, wavelengths used in each type of communications. This is illustrated in the case of Free Space Optics (FSO) in which fog is a major impairment because the sizes of the water droplets in fog are similar to the extremely low wavelengths that are used. As far as the FBW systems are concerned, and because of the specific wavelength range (millimeter), rain severely affects microwave communications because the size of the raindrops, from about 0.5 mm to 3 mm, is in the order of the microwave's signal wavelength.

Furthermore, water vapor and oxygen are the most important gases. The absorption as a function of frequency is very uneven as shown in Figure 51. The diagram shows the atmospheric absorption at a particular temperature (15°C), atmospheric pressure (1013 mb) and water vapor (7.5 g/m^3). Although the actual values vary depending on the above parameters, the actual shape of both curves remains the same.

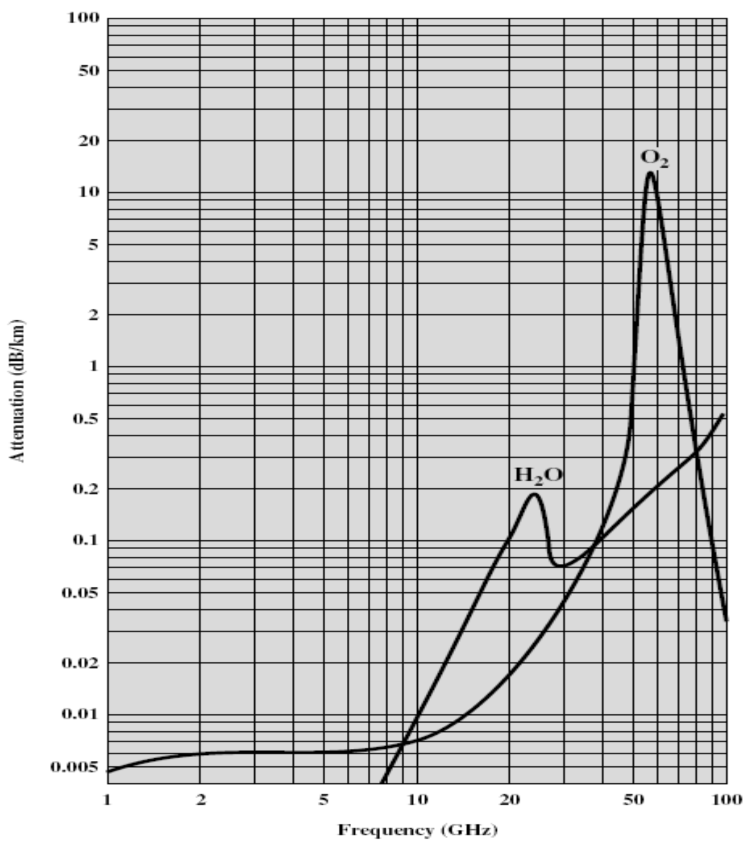

Figure 51. Absorption Due to Atmospheric Gas. [From: Wireless Communications and Networks, William Stallings]

A peak of oxygen absorption between 50 and 60 GHz is clearly demonstrated as is a peak for water absorption between 22 and 24 GHz. This observation becomes quite significant for the FWB systems and especially for the case of LMDS, which operate at the 28 to 31 GHz. Even though this range is not in the peak of water absorption, it is very close to it and it shows that the effects of rain to the performance are crucial. The purpose of this analysis is to demonstrate these exact effects and to identify the parameters that most influence the level of attenuation observed.

2. Rain Attenuation

Indeed, rain attenuation is a major impairment in microwave propagation. It depends on rain intensity, drop size and shape, polarization and frequency. In order to calculate rain attenuation in dB per kilometer, Equation 5.9 is used where *a* and *b* are parameters depending on frequency and polarization[52]. Polarization was introduced in Chapter III.

$$A_{(dB/Km)} = a\,R^{b} \tag{5.9}$$

where A = rain attenuation in dB/Km

R = rain intensity in mm/hr

The *International Telecommunications Union* (ITU) divides the earth into 15 climate zones, referenced from 1 to 15 below, with 1 being the driest and 15 being the one with the greatest precipitation, based on precipitation patterns. Table 11 shows the value of the rain intensity in mm/hr that is exceeded for various percentages of time over the course of a year[53]. For example, a rain rate of 0.1 percent means that the rain rate would be exceeded for 0.1 percent of the year, which is approximately 8.8 hours, during any one year. For the purpose of this analysis, a percentage of 0.1 is assumed.

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[52] Denis Roddy, Satellite Communications, Third Edition, McGraw-Hill, p. 95, 2001.

[53] William Stallings, Wireless Communications and Networks, Prentice Hall, Inc., p. 361, 2002.

Rain Intensity Exceeded for various Rain Zones (mm/hr)

Percentage	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.1	0.5	1	2.1	0.6	2	3	2	8	1.5	2	4	5	12	24
0.3	0.8	2	3	4.5	2.4	5	7	4	13	4.2	7	11	15	34	49
0.1	2	3	5	8	6	8	12	10	20	12	15	22	35	64	72
0.01	8	12	15	19	22	28	30	32	35	42	60	63	95	145	115

Table 10. Rain Intensity Exceeded for Various Rain Regions. [After: Wireless Communications and Networks, William Stallings]

From Equation 5.9, it is clear that rain intensity plays a major role in determining rain attenuation. The various rain zones determine the exact value of the rain intensity that should be used in the equation. Even though those 15 zones cover the entire world, this does not mean that small geographic areas, compared to the world, contain only a few of them. In fact, depending on the various climate conditions, many zones may exist within a range of a few kilometers. A good illustration is the state of California, where 9 out of the 15 zones exists, varying from zone 3 to zone 15, as shown in Figure 52.

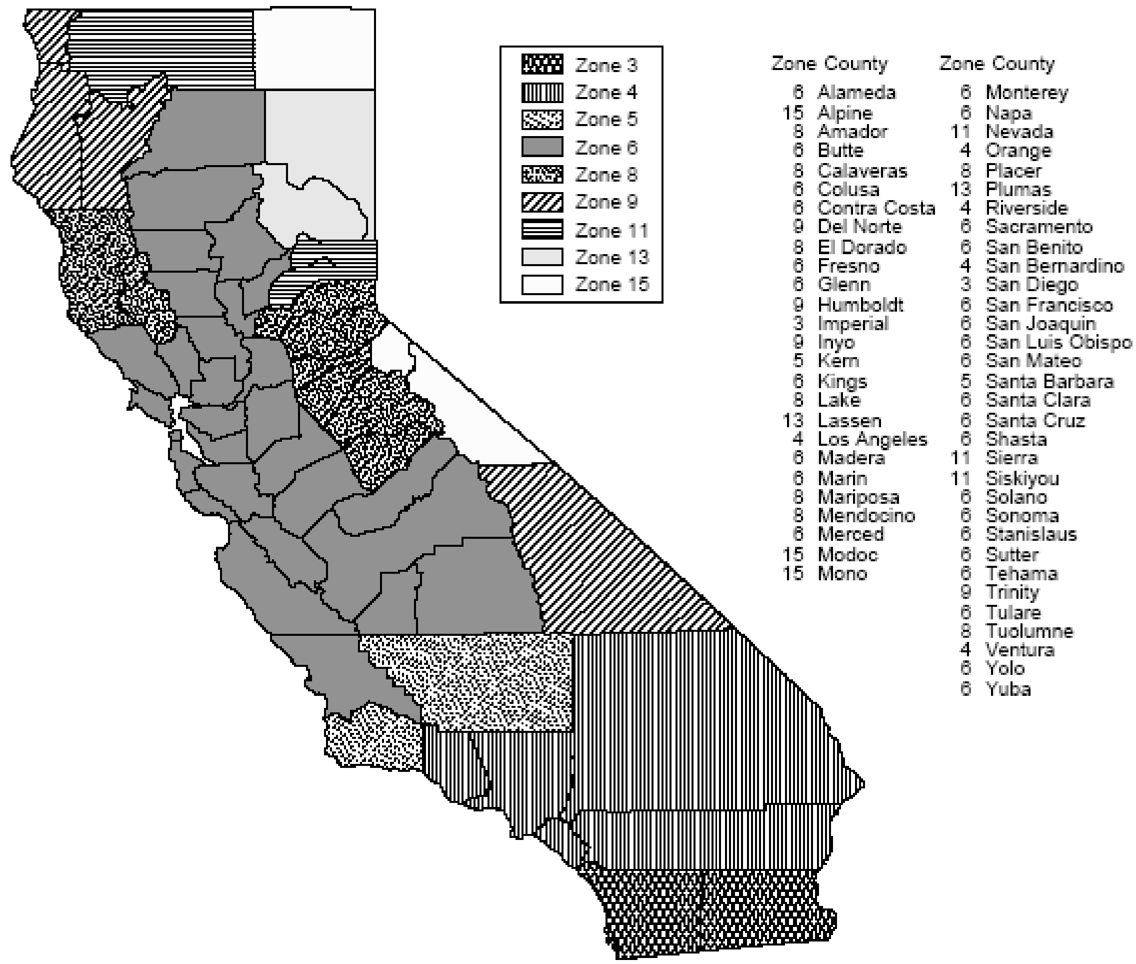

Figure 52. California Climate Zones [From: [http://www.energycodes.gov/rescheck/pdfs/allstates.pdf], February 2004]

Furthermore, assuming vertical polarization, Table 12 and Figure 53, based on the specific pair of parameters a_v and b_v for the various frequencies in the first column, and by using Equation 5.9, show the various rain attenuation values in dB/Km for a number of towns in California that belong to different rain zones. The ranges of MMDS and LMDS are highlighted accordingly in the table.

	Vertical	Polarization	Rain Attenuation in dB/Km				
Frequency in GHz	a_v	b_v	San Diego (Zone 3)	Monterey (Zone 6)	Sierra (Zone 11)	Plumas (Zone 13)	Alpine (Zone 15)
1	0.0000352	0.88	0.000	0.000	0.000	0.001	0.002
2	**0.000138**	**0.923**	**0.001**	**0.001**	**0.002**	**0.004**	**0.007**
4	**0.000591**	**1.075**	**0.003**	**0.006**	**0.011**	**0.027**	**0.059**
6	0.00155	1.265	0.012	0.022	0.048	0.139	0.347
7	0.00265	1.312	0.022	0.041	0.093	0.281	0.725
8	0.00395	1.31	0.033	0.060	0.137	0.416	1.071
10	0.00887	1.264	0.068	0.123	0.272	0.794	1.975
12	0.0168	1.2	0.116	0.204	0.433	1.197	2.845
15	0.0335	1.128	0.206	0.350	0.711	1.848	4.170
20	0.0691	1.065	0.384	0.633	1.236	3.047	6.570
25	**0.113**	**1.03**	**0.593**	**0.962**	**1.838**	**4.400**	**9.250**
30	**0.167**	**1**	**0.835**	**1.336**	**2.505**	**5.845**	**12.024**

Table 11. Rain Attenuation in dB/Km for Various Climate Zones.

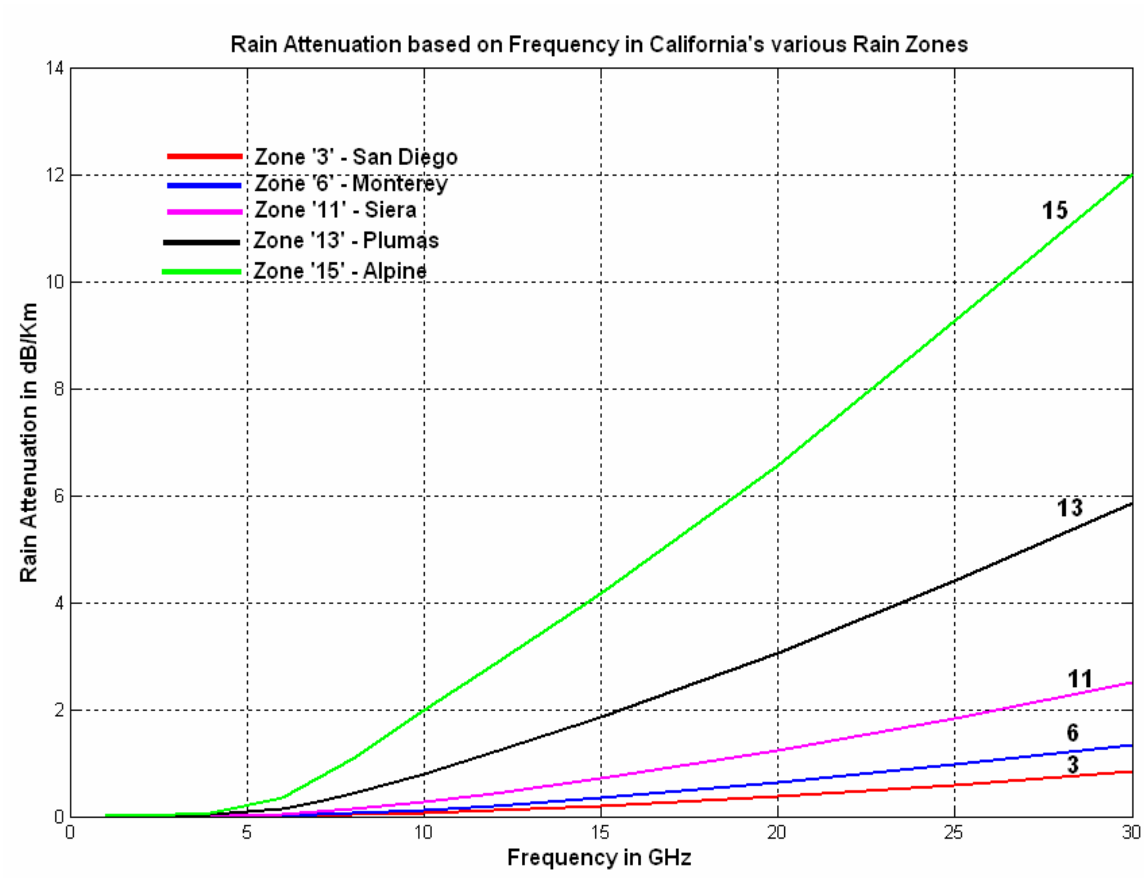

Figure 53. Rain Attenuation in dB/Km for Various Climate Zones in California.

Figure 53 clearly demonstrates the difference in the rain attenuation levels for all the range of frequencies shown in Table 12 for various climate zones in California. The difference in the attenuation is enormous and it is a reason for the water absorption peak at 22-24 GHz mentioned earlier in the analysis. In the MMDS case (2 to 4GHz), it is clear that the attenuation due to rain remains considerably low in all regions, while on the other hand, in the LMDS case (28 to 31GHz), the difference is very significant between the zones. More precisely, *the difference between zone 3 and zone 15 with a frequency of 30 GHz is more than 11 dB per Kilometer!*

The distribution of rain attenuation for all climate zones for the cases of MMDS and LMDS is shown in Figures 54 and 55 accordingly. The y-axis in Figure 54 is scaled by 10^{-3} in order to visualize the small attenuation values.

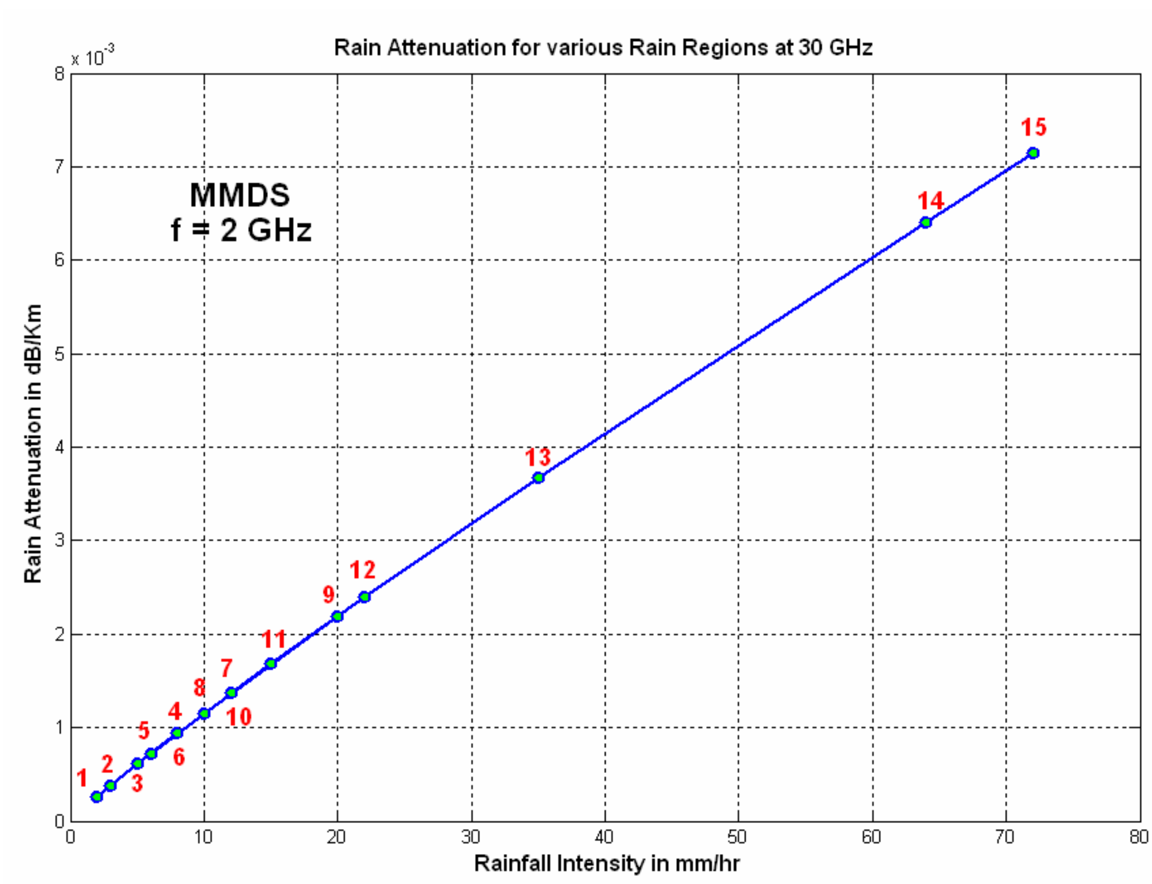

Figure 54. MMDS Rain Attenuation in dB/Km for all Climate Zones.

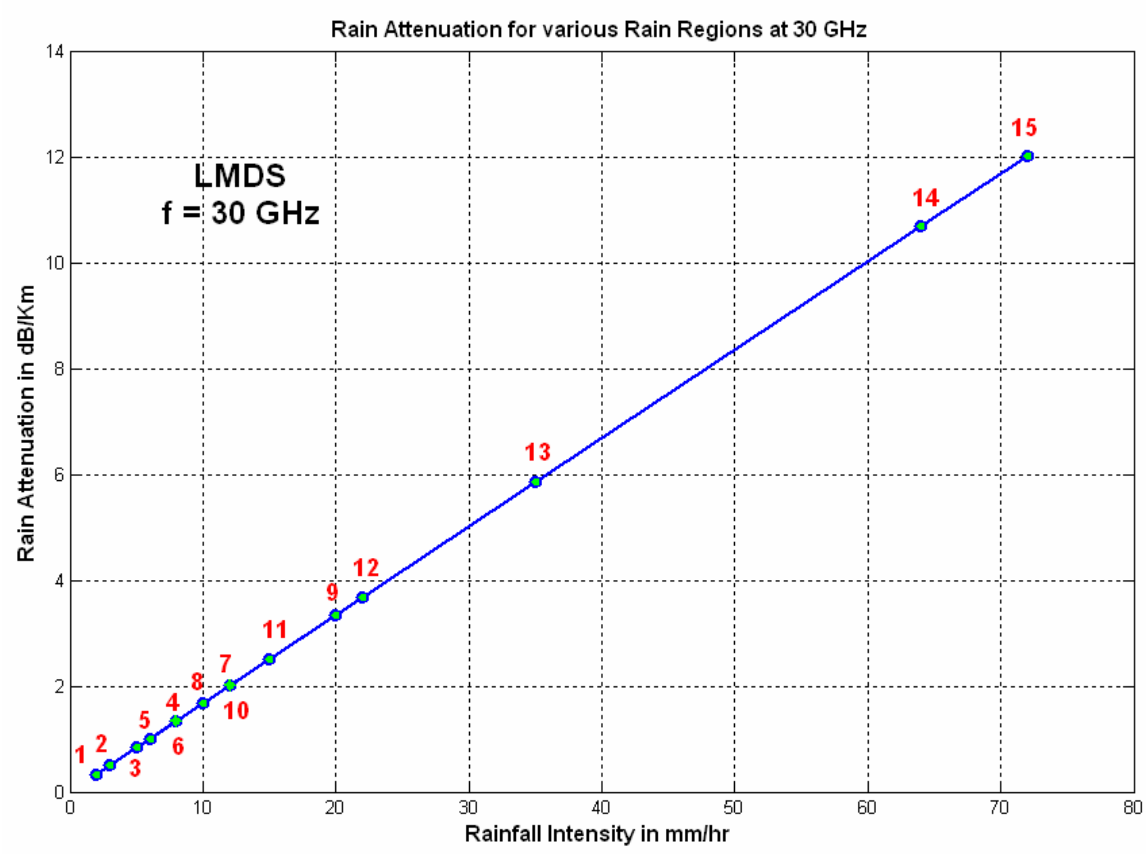

Figure 55. LMDS Rain Attenuation in dB/Km for all Climate Zones.

To summarize, from the above analysis it is clear that, depending on the rain zone, the effects of rain can be devastating for the case of LMDS. For example, areas that belong in the 15^{th} climate zone may observe attenuation of 12 dB per Kilometer. Especially for large distances, this value increases at such a level that makes rain attenuation comparable even to free space loss. On the other hand, the lower frequencies used in MMDS do not provoke high rain attenuation, while although it exists, it by no means is comparable to free space loss even for large distances.

VI. DESIGN PLANNING ISSUES

A. CHOOSING BETWEEN WIRELESS BROADBAND AND OTHER SOLUTIONS

Chapter II introduced, depending on the specific requirements of residential and enterprise end-users, a number of both wireline and wireless solutions other than Fixed Broadband Wireless (FBW). Despite the potential and advantages of these different technologies, significant problems can occur and it should carefully be considered whether each solution is proper for a given set of requirements. As a result of the problems involved with these approaches, FBW was proposed as a significant alternative to the last-mile challenge.

FBW not only are able to supply broadband services to both homes and business but they also successfully address the issues of the high costs to lay fiber, low capacity per user and low return channel capacity. Furthermore, MMDS with its high range limit (Table 8) addresses the coverage limitations of xDSL and 802.11. Moreover, the extreme data rates that LMDS are capable of providing can be compared only to Free Space Optics (FSO). Regardless, there are some important parameters that in a way “mandate” the use of wireless broadband solutions.

First of all, if no excellent wireline options are available, and therefore, there is no fiber network, FBW should be seriously considered. Moreover, if the potential service crosses different Local Exchange Carriers (LEC) areas, then the FBW connection is exceptionally cheaper than the wireline service[54]. In addition, the designer should consider FBW if there is a need to bridge LANs in two buildings in close proximity. Indeed, a licensed microwave connection could be cost effective compared to the cost of leasing a digital circuit line. Regardless, the designer needs to compare the offerings between the various technologies, and even if another option is chosen, temporary or back up connectivity using FBW should always be taken into consideration. Indeed, in

[54] John R. Vacca, Wireless Broadband Networks Handbook 3G, LMDS &Wireless Internet , McGraw-Hill, p. 413, 2001.

many cases where FSO or 802.11 is a valuable solution, FBW might be the best option for back up connectivity in order to increase the reliability and effectiveness of the network.

Overall, FBW not only provides a wireless alternative to fiber, satellite, xDSL or FSO, but also presents scalable architectures which have the unique advantage of "enabling expanded coverage and services in direct relation to the level of demand." This, in combination with the high total capacity, gives FBW a superior advantage. As seen in Chapter III, the smaller the cell, the higher the capacity per Km^2, ranging from 1500-150Mbps for a range of 2-20 Km^2 accordingly[55]. In order to increase the capacity and achieve high Mbps, FBW should maximize the utilization of the spectrum. This is done through proper frequency reuse and planning.

B. FREQUENCY PLANNING

The frequency spectrum is partitioned into frequency channels that can be assigned to users. Frequency reuse and planning deals with the allocation of these channels to groups of cells. Every cell is associated with the specific coverage area around its base station. In order for the radio receiver to reliably receive transmission from the various base stations, there should be a distribution of carrier frequencies across the area over many adjacent cells. In a perfect world, there would be no frequency reuse since there would be an infinite pool of channels upon which to draw. However, in reality, the designer comes across spectrum restrictions and different modulation formats that mandate proper frequency planning.

1. Frequency Planning in Mobile Wireless Networks

One of the most important considerations in mobile communications is the fact that the number of available frequency channels is limited. As a result, the channels that are assigned to the users over a specific service area may simultaneously be assigned to other users in other service areas. Clusters and cells are used for this reason.

[55] Agne Nordbotten, LMDS Systems and their Applications, IEEE Communications Magazine, 2000.

The cells within each service area are shaped like hexagons and are grouped together in clusters. The number of cells in a cluster is such that clusters fit together into a contiguous area as shown in Figure 56. All the available channels are assigned to the cells in every cluster. In order for the designer to be able to use the same frequencies in cells in different clusters without causing interference, the transceivers need to have low enough transmitting power so that the transmission range of the antennas can be shaped to fit a single cell[56]. If there are *N* channels and *m* cells available in a cluster, then each base station is allocated *N/m* channels. The number of cells in a cluster is defined as the *reuse factor*.

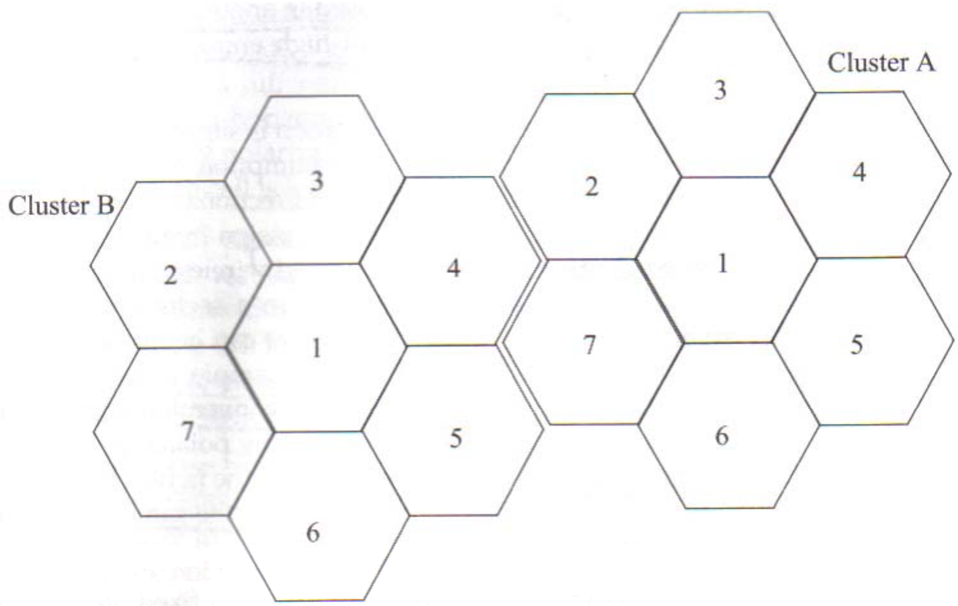

Figure 56. Mobile Channel Allocation in Seven-Cell Clusters. [From: Fixed Broadband Wireless Access Networks and Services, Oliver C. Ibe]

There are two clusters in Figure 56 and each one has 7 cells. The number within the cells indicates the specific radio channel that is allocated. The reuse factor in this case is seven, which means that each cell is allocated 1/7 of the total available radio channels. The figure clearly demonstrates that the radio channels are assigned in the cells in such a manner that it is not possible for the adjacent cells in each cluster to share the same channels. Otherwise, the system would suffer from *co-channel interference* since cells

56 Oliver C. Ibe, Fixed Broadband Wireless Access Networks and Services, John Wiley & Sons, Inc., pp. 224-228, 2002.

could experience interference from transmitters in surrounding cells that use the same frequency. As a rule of thumb, in a cluster with many cells, there is less chance of co-channel interference.

2. Frequency Planning in Fixed Broadband Wireless

The purpose of the previous section was to make it clear to the reader that the number of radio channels associated with a given frequency allocation is limited and that a poor choice of reuse factor may lead to co-channel interference. Although, in both cases, the goal is to allocate the spectrum efficiently and minimize co-channel interference and frequency reuse, and planning in FBW networks is different from that of mobile wireless networks.

As mentioned in Chapter III, the antennas used in FBW are highly directional in contrast with the omni directional antennas used in mobile networks. This creates a significant advantage for FBW, because it enables sectorization within each cell, allowing multiple sectors within the same cell to be assigned a different channel. Even better, in cases where the use of alternating polarization is possible, the number of channels available to the designer is practically doubled as shown in Figure 57.

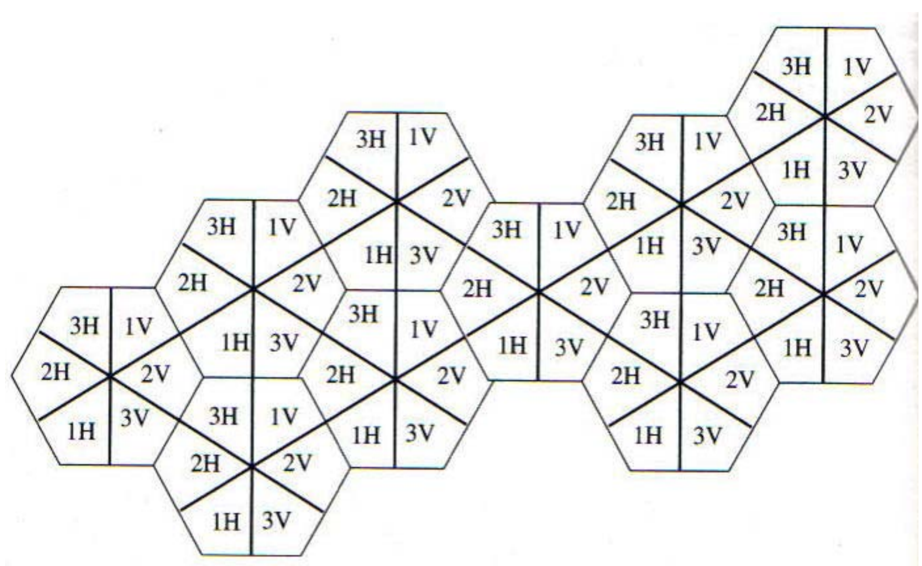

Figure 57. 3-Frequency Dual Polarization Reuse Plan. [From: LMDS, Clint Smith]

Figure 57 shows an example of frequency planning in a FBW network where the antennas of the base station have a 60º beamwidth. If the option of using alternating polarization was not feasible, the designer would have to use six different frequencies (6-frequency reuse plan) to cover the six sectors of each cell. However, in this case, the use of both polarizations creates a 3-frequency reuse plan. xV represents a vertical polarized channel, while xH stands for a horizontal one. Horizontal and vertical polarization is employed throughout the system in an alternate pattern between the sectors, and thus maximizing the isolation between the adjacent sectors[57]. Figure 57 clearly shows that within each cell, the same frequency is used twice with different antenna polarization. Furthermore, after careful study of the figure, first notice that the diametrically opposed sectors use the same frequency but with different antenna polarizations, e.g. 1H, 1V. Secondly, the designer does not use adjacent channels, but uses channels 1, 3, 5, in an attempt to minimize the adjacent channel interference.

For the specific case of the LMDS, the significant effects of rain attenuation shown in Chapter V limit the range of each cell, making frequency reuse and planning extremely important. As long as the transmitting power is not high enough to cause co-channel interference, then regardless of the short distance between the base station and the CPE, the frequencies used in one cell can still be safely used in other cells, and thus maximize the total capacity of the system.

The above example of a 3-frequency reuse plan is not the only one available. In fact, depending on the antennas beamwidth and assuming that alternating polarization is possible, there can be, for example, 2-frequency reuse plans (90º beamwidth) or 6-frequency plans (30º beamwidth). The latter is shown in Figure 58, and again, adjacent channels are not used and diametrically opposite sectors use the same frequency with different polarizations.

57 Local Multipoint Distribution System, The International Engineering Consortium [http://www.iec.org/online/tutorials/lmds/comment.html], January 2004.

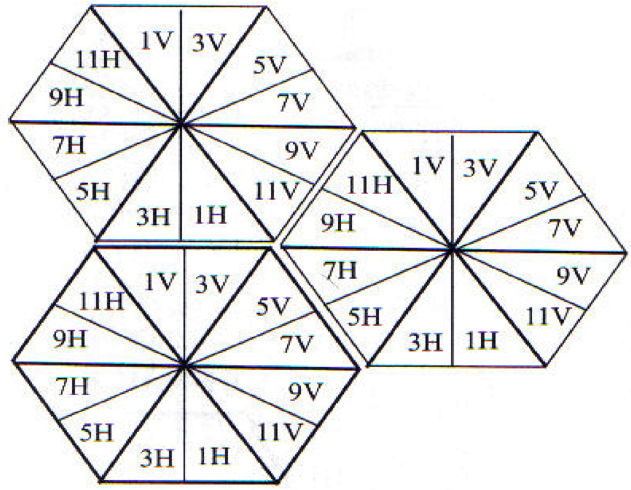

Figure 58. 6-Frequency Dual Polarization Reuse Plan in 30º Sectors. [From: Fixed Broadband Wireless Access Networks and Services, Oliver C. Ibe]

For all the above reuse plans, the objective is to maximize the utilization of the spectrum. In all cases, maximization is achieved because by reusing the spectrum, more Mbps, that is more capacity, can be carried for any geographic area. However, the choice of which plan to use is not only affected by the available spectrum and the modulation format. It is also affected by the channel plan. Indeed, for each frequency reuse plan, there must be a specific number of channels available. A good illustration of this is the case of the 6-frequency reuse plan of Figure 58. This plan uses six non-adjacent channels, and therefore, there must be 11 different channels available to the designer. In other words, if the total bandwidth allocated cannot be divided in 11 channels with sufficient bandwidth, then the specific reuse plan is not an option. Typical configurations for LMDS involve 4-sector cells using 90º beamwidth antennas[58]. If there is no alternating polarization that leads to a 4-frequency reuse plan using either vertical or horizontal polarization, it then leads to a 2-frequency reuse plan.

Finally, as is shown in Figure 59, in cases of optimum antenna design there is the option of using a 3 instead of a 6-frequency reuse plan while still using the 30º beamwidth antennas used in Figure 58.

58 Ibid.

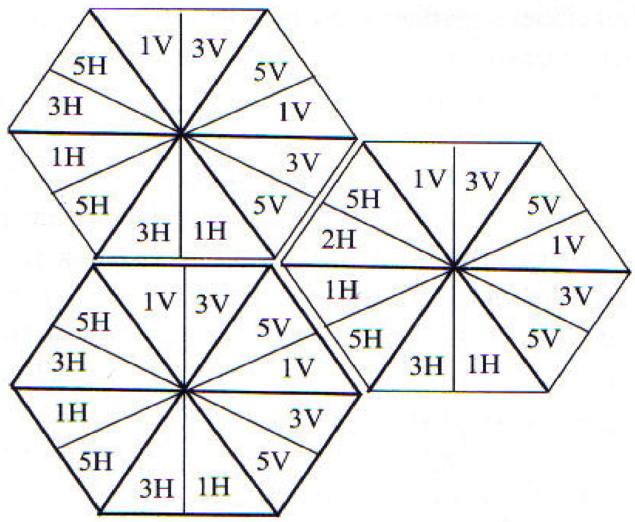

Figure 59. 3-Frequency Dual Polarization Reuse Plan in 30º Sectors. [From: Fixed Broadband Wireless Access Networks and Services, Oliver C. Ibe]

In this case, the difference is that the sectors with the same frequency but different antenna polarization are not diametrically opposite to each other, but instead, have a 90º difference. After this observation now notice that the channels used are 1, 3 and 5 (Figure 59), while in the previous case, they were 1, 3, 5, 7, 9 and 11 (Figure 58). Such a solution has the advantage of conserving bandwidth. However, in order for this to work efficiently, the antennas need to be extremely carefully designed to have minimum side lobes in the 90º angle in an attempt to reduce the co-channel interference.

C. REDUNDANCY PLANNING

Many times, especially in the case of enterprise end-users, the reliability of the network is a very important intangible factor. In such cases, more redundancy is needed and the ability of a given technology to easily provide it is critical. FBW may provide redundancy depending on the architecture of the vendor's network. When the components of the radio terminal, that is the radio, modem and antenna, are an integrated unit, redundancy can be implemented either by an *overlay method* or by using *two access points per sector*.

With the overlay method, the antennas at the base station are deployed in such way that one sector overlaps with the next sector, permitting each CPE to see at least two different base station antennas[59]. Thus, the CPE is able to be dynamically assigned to the sector with the strongest *Received Signal Strength Indicator* (RSSI). By monitoring signals from various access points within its covering area, the CPE can register with the access point with the strongest RSSI in case of connectivity loss. On the other hand, by using two access points per sector, one access point is always active and one is always on standby. Only in case of connectivity loss does the standby access point become active. It is a more expensive approach and additionally requires a lot of coordination in order to synchronize the states of the two access points.

When the components of the radio terminal are not integrated into one box, then unfortunately, there is no way to provide redundancy dynamically. The antenna and the radio are considered extremely reliable, making the modem the weakest link. In this case, assuming that N units are active, a N+1 redundancy in the modem is applied so that if any of the N modems should fail, it is replaced by the redundant modem.

D. SITE SELECTION

Chapter V recognized and evaluated many possible attenuation factors. Weather is not a significant factor for MMDS bands. However, for the case of LMDS, rain absorption becomes so critical that areas that belong to high rain intensity zones may suffer from extreme attenuation. Apart from that, the LOS restrictions are the ones that guide the selection of the base station sites.

These locations are very important because they directly affect the performance of the network. The locations of the CPEs depend on the current and future customers that subscribe to the service. Since neither the number nor the location of the future customers is predictable, the base stations need to be located in the most advantageous area. For this reason, the following factors should be seriously considered when selecting the locations of the base stations.

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[59] Oliver C. Ibe, Fixed Broadband Wireless Access Networks and Services, John Wiley & Sons, Inc., p. 231, 2002.

- If there are buildings in the area high enough to provide LOS coverage to the current as well as potential customers, then roof rights to install a base station should be obtained from the property owners. Otherwise, towers may need to be installed which would significantly increase installation costs.
- The height of the buildings in the surrounding area must be noted for two reasons as illustrated in Figure 60. First, both transceivers need to be within visual range of one another and secondly, the chance that potential customers will fall below the limited signal beam must be minimized.

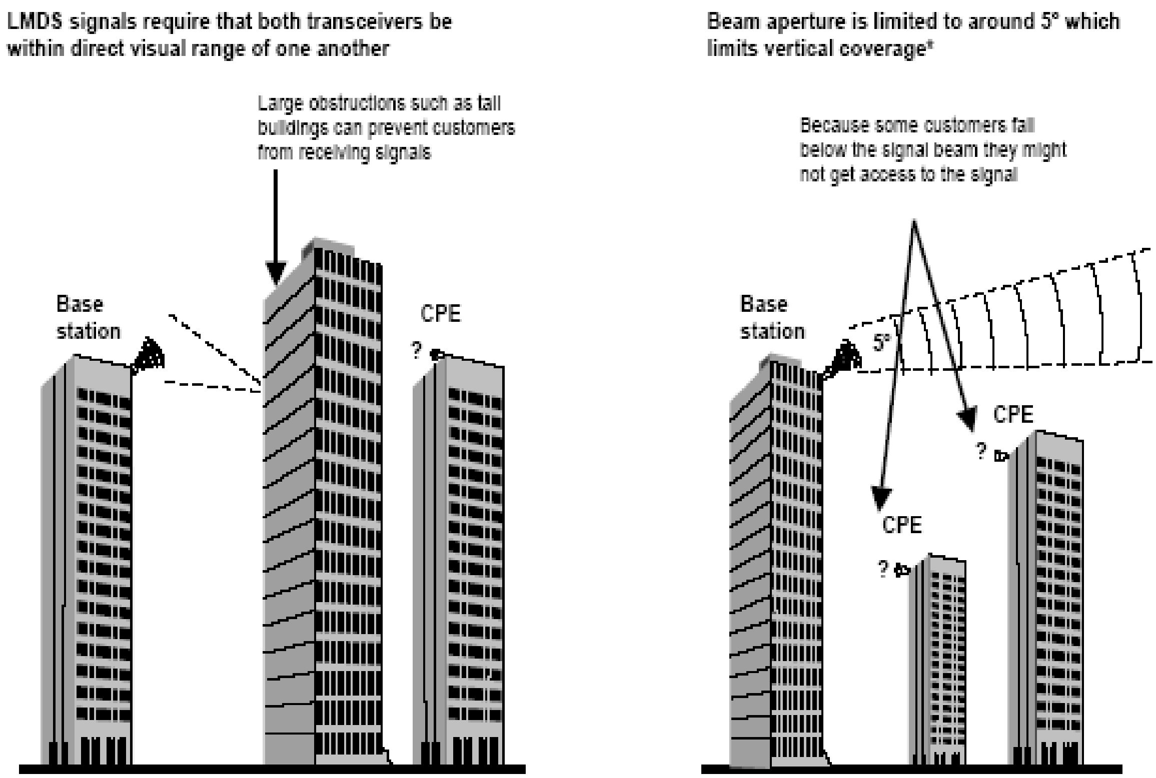

Figure 60. Line-of-Sight Challenges. [From: Broadband Access Platforms, Stagg Newman]

- There must be no obstructions in the form of either buildings or trees between the access point and the CPE antenna, not only in the direct path but also in the Fresnel zone around it.

Regardless of the chosen location, once the base station locations and the locations of the CPEs for each base station have been established, the designer should consider any possible interconnections as well as the connections to the service provider's IP network backbone.

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VII. CONCLUSIONS

A. SUMMARY

Before 1996, Internet access from the home was almost exclusively made with the use of dial-up modems over twisted copper pair. However, the rapid growth of the Internet caused a demand for high-bandwidth capacity at acceptable cost.

A recent report from the Federal Communications Commission (FCC)[60] shows a continuous increase in the demand for high speed Internet services, and especially for the subscribers of Fixed Broadband Wireless (FBW) high-speed lines, compared to the majority of the other technologies. In addition, the report shows an inverse association in areas with low population density and low median household income, which strongly indicates that the last-mile solutions currently available, are neither inexpensive enough to attract the majority of the population, nor are they available in low density populated areas. Therefore, it is clear that regardless of the numerous technology innovations that try to solve the problem, the dilemma of how to support high bandwidth requirements at affordable cost has not yet been resolved.

The problem of the last-mile is complicated because of the diversity of the market that includes individual end-users to large organizations, all of which have unique requirements. For example, large businesses have a tremendous need for moving reliable and securely high amounts of data downstream as well as upstream, while for most individual end-users, affordable access in the downstream direction is the most important criterion. For this reason and also in order to identify the solutions that satisfy the specific key requirements of every end-user, the market is segmented into residential and enterprise end-users.

FBW provides a wireless alternative to fiber, satellite, cable, xDSL, 802.11 and FSO, with Local Multipoint Distribution Services (LMDS) and Multichannel Multipoint Distribution Services (MMDS) being its most promising emerging technologies. They are point-to-multipoint line-of-sight (LOS) communications systems that provide reliable

[60] Federal Communications Commission, Federal Communications Commission Releases Data on High-Speed Services for Internet Access, June 10, 2003.

digital two-way voice, data and Internet services utilizing a microwave radio as their fundamental transport medium and allowing multiple users to access the same radio spectrum. Although they have the ability to move identical types of traffic within their service areas, share many common architectural features and have the same core components, each one targets different markets.

Indeed, MMDS operates in the 2-3 GHz range and is able to support up to 35 miles between cell sites, delivering downstream speeds in the neighborhood of 1-3 Mbps. Additionally, it is a cost-effective alternative because it requires a less complicated and less inexpensive Customer Premises Equipment (CPE). As a result, the intermediate data rates and the cheap CPEs effectively make MMDS a valuable solution for residential end-users. Furthermore, since it covers large areas, it also becomes a good solution for rural or suburban areas that are not able to receive service through high-speed wireline connections.

The other major FBW technology, LMDS, operates at a higher frequency than MMDS, typically in the 28-31 GHz range, and has a larger bandwidth. Although it covers much less distance than MMDS, up to 5 miles between cell sites, it does so with much faster downstream speed, typically 45 Mbps. Due to its shorter coverage, LMDS targets densely populated urban areas. High capacity and data rates make it an attractive solution for large enterprises that are outside the reach of fiber networks. For the time being and because of the extremely high cost of CPE, it is very unlikely that LMDS will attract residential end-users.

B. CONTRIBUTION OF THIS THESIS

The thesis reports a study of the characteristics of microwaves in the sprsific frequency range used by MMDS and LMDS communication systems. It shows that both technologies demonstrate large free space loss, with LMDS continuously showing a 20 dB difference (100 times larger) with MMDS for all ranges of distance. Regardless, even though MMDS demonstrates less loss for the same distance, for distances of more than 10 Km, it becomes equivalent to the loss that LMDS have at distances of less than 1 Km. Furthermore, vegetation and obstacles affect the lower frequency of MMDS more , making multipath fading a very important factor of interference that needs to be taken into consideration when designing a MMDS system. Even though multipath fading is a less critical factor for LMDS, in both cases, the Fresnel zones theory needs to be considered when choosing the locations of the antennas. In addition, due to the peak for water absorption between 22 and 24 GHz, depending on the rain zone, the effects of rain can be devastating for LMDS. For example, areas that belong in the zones with the heaviest rain intensity may observe an attenuation of 12 dB per Kilometer. Thus, for large distances, this value increases at such a level that makes rain attenuation comparable even to free space loss!

By using frequency planning and high-level modulation techniques, FBW can increase cell capacity and achieve higher data rates. However, the simulation analysis shows that there is a positive association between the data rate achieved and the level of influence due to Additive White Gaussian Noise (AWGN). In fact, the probability of Bit Error Rate (BER) depends on the modulation scheme used. More precisely, the modulation scheme that achieves the highest data rate has the worst BER, while on the other hand, the lower the data rate, the better the BER observed.

The thesis concludes that LMDS is a favorable solution for enterprise end-users for urban areas with high population density. On the other hand, MMDS better fits the requirements of residential end-users and are favorable for rural areas. As far as the weather and line-of-sight limitations are concerned, apart from free space loss, rain absorption is the most significant attenuation factor for the case of LMDS, while multipath fading and Fresnel zones need to be considered further when designing MMDS systems.

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LIST OF REFERENCES

Agne Nordbotten, LMDS Systems and their Applications, IEEE Communications Magazine, 2000.

Alden J. Doyle, and others, Performance Evaluation of the IEEE 802.16a Physical Layer Using Simulation.

Broadband Wireless Association, Overview of Point to Multipoint Fixed Wireless Broadband Wireless Access Solutions, [http://www.broadband-wireless.org/overview.html], February 2004.

Clint Smith, LMDS, McGraw-Hill, Inc., pp. 15-16, 79-87, 159, 208, 2000.

Denis Roddy, Satellite Communications, Third Edition, McGraw-Hill, p. 95, 2001.

Douglas E. Comer, Computer Networks and Internets, Third Edition, Prentice Hall, Inc., p. 189, 2001.

Federal Communications Commission, Federal Communications Commission Releases Data on High-Speed Services for Internet Access, June 10, 2003.

[http://www.elanix.com/], February 2004.

[http://www.mobilecomms-technology.com/projects/mmds/], February 2004.

James Schellenberg, Designing the Digital MMDS Network for Maximum Benefit: Technological Considerations in Service, Coverage and Subscriber Issues, 1997.

John R. Vacca, Wireless Broadband Networks Handbook 3G, LMDS &Wireless Internet, McGraw-Hill, pp. 227, 253, 256-258, 413, 2001.

Kurose and Keith W. Ross, Computer Networking, A Top-Down Approach Featuring the Internet, Addison Wesley Longman, Inc., pp. 11-13, 2001.

Local Multipoint Distribution System, The International Engineering Consortium [http://www.iec.org/online/tutorials/lmds/comment.html], January 2004.

Maurice L. Schiff, Ph.D., 802.11a System Simulation Using System View by Elanix.

MMDS/LMDS Multipoint Distribution Services, [http://www.mobilecomms-technology.com/projects/mmds/], February 2004.

Oliver C. Ibe, Fixed Broadband Wireless Access Networks and Services, John Wiley & Sons, Inc., pp. 1-2, 32, 60, 224-228, 231, 2002.

Scott Y. Seidel and Hamilton W. Arnold, Propagation Measurements at 28 GHz to Investigate the Performance of LMDS, 1995.

Stagg Newman, Broadband Access Platforms, pp. 3-5, 61-62, 89, 2002.

The Shpigler Group Strategy Management Consulting Services, Opportunities in Last-mile Wireless Access, 2002.

Theodore S. Rappaport ,Wireless Communications Principles and Practices, Second Edition, Prentice Hall , Inc., pp. 41, 127, 449, 2002.

Wayne Tomasi, Electronic Communications Systems, Fundamentals through Advanced, Fourth Edition, Prentice-Hall, Inc., pp. 34-35, 367, 368, 2001.

William Stallings, Wireless Communications and Networks, Prentice Hall, Inc., pp. 111, 357, 359, 361, 2002.

William Webb, Introduction to Wireless Local Loop, Broadband and Narrowband Systems, Artech House Publishers, pp. 220-221, 2000.

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