Understanding Millimeter Wave Wireless Communication

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INTRODUCTION

With end users ranging from corporate data centers to teenagers with iPhones demanding higher bandwidth, the demand for newer technologies to deliver this bandwidth is higher than ever before. A plethora of technologies exist for the delivery of bandwidth, with fiber optic cable considered to be the ultimate bandwidth delivery medium. However, the fiber optics are not unmatched by any means, especially when all economic factors are considered.

Millimeter wave wireless technology presents the potential to offer bandwidth delivery comparable to that of fiber optics, but without the financial and logistic challenges of deploying fiber. This white paper is intended to provide an overview of this new technology, its opportunities as well as its limitations.

THE TECHNOLOGY OVERVIEW

Millimeter wave generally corresponds to the radio spectrum between 30 GHz to 300 GHz, with wavelength between one and ten millimeters. However, in the context of wireless communication, the term generally corresponds to a few bands of spectrum near 38, 60 and 94 GHz, and more recently to a band between 70 GHz and 90 GHz (also referred to as E-Band), that have been allocated for the purpose of wireless communication in the public domain.

The History

Though relatively new in the world of wireless communication, the history of millimeter wave technology goes back to the 1890's when J.C. Bose was experimenting with millimeter wave signals at just about the time when his contemporaries like Marconi were inventing radio communications. Following Bose's research, millimeter wave technology remained within the confines of university and government laboratories for almost half a century. The technology started so see its early applications in Radio Astronomy in the 1960's, followed by applications in the military in the 70's. In the 80's, the development of millimeter-wave integrated circuits created opportunities for mass manufacturing of millimeter wave products for commercial applications.

In the 1990's, the advent of automotive collision avoidance radar at 77 GHz marked the first consumer-oriented use of millimeter wave frequencies above 40 GHz. In 1995, the FCC (US Federal Communications Commission) opened the spectrum between 59 and 64 GHz for unlicensed wireless communication, resulting in the development of a plethora of broadband communication and radar equipment for commercial application. In 2003, the FCC authorized the use of 71-76 GHz and 81-86 GHz for licensed point-to-point communication, creating a fertile ground for new of industries developing products and services in this band.

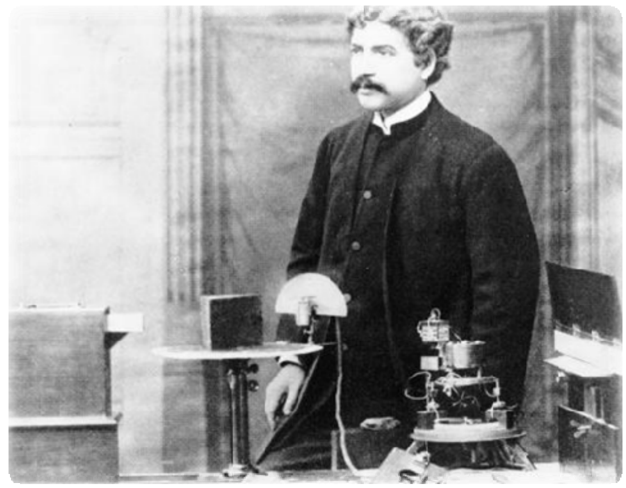

Figure 1: J.C. Bose Demonstrating Millimeter Wave in 1897

The Band and the Bandwidth

In the US, four bands in the upper millimeter wave region have been opened for commercial applications. Of the four bands, the 59-64 GHz band (commonly referred to as V-band or the 60GHz band) is governed by FCC Part 15 for unlicensed operations. The regulations of FCC Part 15 and the significant absorption of the 60 GHz band by atmospheric oxygen makes this band better suited for very short range point-to-point and point-to-multipoint applications. The 92-95 GHz band (commonly referred to as W-band or the 94 GHz band) is also governed by the FCC Part 15 regulations for unlicensed operation, though for indoor applications only. The 94 GHz band may also be used for licensed outdoor applications for point-to-point wireless communication per FCC Part 101 regulations. However the band is less spectrally efficient than the other three bands due to an excluded band at 94-94.1 GHz.

This leaves 71-76 GHz and 81-86GHz (commonly referred to as E-band or the 70GHz and 80GHz bands, respectively), whose use in the US is governed by FCC Part 101 for licensed operation, as the most ideally suited millimeter wave band for point-to-point wireless communication applications. With the 5 GHz of spectrum available in each of these two bands, the total spectral bandwidth available exceeds that of all allocated bands in the microwave spectrum. Through the remainder of this paper, we confine our discussion to these two bands.

The 5 GHz of spectrum available in each sub-band of the E-band spectrum can be used as a single, contiguous transmission channel (which means no channelization is required), thereby allowing the most efficient use of the entire band. Even with simple modulation techniques such as OOK (On-Off-Keying) or BPSK (Binary Phase Shift Keying), throughput of 1to3 Gbps is achieved today in each sub-band of the spectrum, more that what can be achieved with more sophisticated, higher order modulation schemes in other bands of licensed spectrum. Migrating to such modulation techniques at E-band, even higher throughputs can be achieved. It is only a matter of sufficient market demand before such higher throughput millimeter wave links become a commercial reality.

Propagation Characteristics

Radio signals of all types, as they propagate through the atmosphere, are reduced in intensity by constituents of the atmosphere. This attenuating effect, usually in the form of absorption or scattering of the radio signals, dictates how much of the transmitted signal actually makes it to a cooperative receiver and how much of it gets lost in the atmosphere. The atmospheric loss is generally defined in terms of decibels (dB) loss per kilometer of propagation. Since the fraction of the signal lost is a strong function of the distance traveled, the reader should note that the actual signal loss experienced by a specific millimeter wave link due to atmospheric effects depends directly on the length of the link.

The propagation characteristics of millimeter waves through the atmosphere depend primarily on atmospheric oxygen, humidity, fog and rain. The signal loss due to atmospheric oxygen, although a source of significant limitation in the 60 GHz band, is almost negligible – less than 0.2dB per km in the 70 and 80 GHz bands. The effect of water vapor, which varies depending on absolute humidity, is limited to between zero and about 50% loss per km (3dB/km) at very high humidity and temperature. The additional loss of signal as it propagates through fog or cloud is similar to the loss due to humidity, now depending on the quantity and size of liquid water droplets in the air. Though 50% loss of signal due to these atmospheric effects may seem significant, they are almost insignificant compared to losses due to rain, and are only important for long distance deployments (more than 5 km)

Table 1: Signal Loss through Atmosphere

Effect	Comments	Signal Loss (dB/km)
Oxygen	Sea Level	0.22
Humidity	100% at 30°C	1.8
Heavy Fog	10°C, 1 gm/m^3 (50m visibility)	3.2
Cloud Burst	25 mm/hr rain	10.7

Of all atmospheric conditions, rain causes the most significant loss of 70 GHz and 80 GHz signal strength, as is the case with microwave signals as well. The amount of signal loss due to rain depends on the rate of rainfall, often measured in terms of millimeters per hour. Table 1 provides a summary of various rain rates and the corresponding amount of attenuation of millimeter wave signals per kilometer of propagation. The reader should note that 10 dB of loss over 1 km of propagation also means 20 dB of loss over 2 km of propagation

Table 2: Signal Loss Due to Rain

Description	Rain Rate	Signal Loss (dB) per km
Light Rain	1 mm/hour	0.9
Moderate Rain	4 mm/hour	2.6
Heavy Rain	25mm/hour	10.7
Intense Rain	50 mm/hour	18.4

From Table 2, one may come to the conclusion that, because of severe attenuation due to rain, millimeter wave wireless links are not reliable for deployments likely to experience rain. However, such conclusions are not well founded. Millimeter wave links can indeed perform flawlessly year after year without disruption, even in the presence of occasional downpours in excess of 100 mm/hour. The actual performance of a millimeter wave link depends on several factors, in particular the distance between radio nodes and the link margin of the radios, and sometimes includes additional factors such as diversity of redundant paths.

PERFORMANCE RELIABILITY

The performance reliability of a communication system is often benchmarked in terms of percent (%) availability of the system or the service it offers. The percentage availability signifies the average percentage of the time the system is expected to operate to its specification, i.e., to be "available."

As stated before, there are other factors that dictate the performance of a millimeter wave link. An intense rain event may cause significant attenuation of millimeter wave signals, but it may not cause an outage of a millimeter wave data link if the link has sufficient margin. Whether or not a link has sufficient margin to overcome an outage due to intense rain depends on the technical specification of the product (for instance transmit power, receive sensitivity, and beam divergence) as well as the distance of the communication link.

The availability of a link also depends on the probability of occurrence of sufficiently heavy rain to cause an outage. For example, in the southwestern US where the probability of rainfall rates exceeding 100 mm per hour is virtually zero, the availability of a 2 km link may be 99.999%. However, the availability of the same 2 km link may be less than 99.9% in the southeastern US where rain rates exceeding 100 mm per hour are more common. Therefore, the percentage availability of a millimeter wave link is inherently tied to the rainfall characteristics of the location where the link is deployed, as well as its path length.

The characteristics of rainfall throughout the world have been well studied by various organizations. Based on such studies, the ITU (International Telecommunication Union) has developed a model for computing the probability of rain rates at various geographical locations. The model has become a well accepted standard for estimating the performance of microwave systems and can also be used to estimate a millimeter wave link's performance in any part of the world.

Table 3 provides a comparative list of the expected performance of a commercially available millimeter wave product in a few large metropolitan areas around the world based on the ITU model. The second column ("Link Range") lists the maximum range of the link that can achieve 99.999% availability. The third column ("Availability") lists the availability of a link that is 2 km long.

Table 3: Performance of a Typical System

Location	Link Range (km, at 99.999% Availability)	Availability (of a 2 km link)
Los Angeles	1.75	99.998%
New York	1.25	99.991%
London	1.65	99.998%
Milan	1.35	99.994%
Sydney	1.2	99.99%
Riyadh	2.85	>99.999%

FREQUENCY LICENSING

The coordination and licensing of radio frequency use in various sovereign regions of the world is administered by their corresponding authorities. In some parts of the word, the E-band millimeter wave spectrum has not been opened for public use while in other parts of the world where it has been opened, the details of the licensing scheme are still being worked out. However, in the United States and the European Union, these millimeter wave bands have been released to the public with well-defined regulations for their use.

In the United States, the FCC opened the 70GHz and 80GHz bands for licensed operation in 2003. The licensing scheme is based on a two-tier approach. At first, a non-exclusive nationwide license is acquired from the FCC for operation of equipment using millimeter wave bands. The FCC license is by itself not a permission to deploy millimeter wave links with impunity, but rather is a prerequisite for the second step. As the second step, a "license" to deploy is obtained by registering individual point-to-point links through an independent link registration system (LRS) developed and maintained by an FCC-appointed database manager. The cost of a nationwide FCC license and the registration of each link is of the order of a few hundred dollars.

The registration process verifies that the link being registered will not interfere with previously registered links. This process ensures that the interference protection priority is based on the date of registration, with all prior licensees entitled to interference protection from all subsequent deployments. The exclusive right to use the spectrum is granted on a per link basis, rather than a nationwide or even regional basis.

The European Union has also opened the band for licensed operation, following a coordination similar to that of the FCC, but with some minor differences. In particular, EU has stipulated channelization of the spectrum, with each channel covering 250 MHz, but allowing for combining of channels contiguously, without guard bands, as needed for any specific bandwidth requirement.

Other parts of the world have also started to open the E-band spectrum. Countries like Mexico and Australia have already taken major steps to open the spectrum for licensed operation, while similar efforts have recently commenced in countries like Ireland and Saudi Arabia. It appears to be only a matter of time before the spectrum is opened in these places and eventually across most of the world.

KEY BENEFITS

Unmatched Bandwidth with Scalable Capacity

One of the key advantages of millimeter wave communication technology is the large amount of spectral bandwidth available. The bandwidth available in the 70 GHz and 80 GHz bands, a total of 10 GHz, is more than the sum total of all other licensed spectrum available for wireless communication. With such wide bandwidth available, millimeter wave wireless links can achieve capacities as high as 10 Gbps full duplex, which is unlikely to be matched by any lower frequency RF wireless technologies.

The availability of this extraordinary amount of bandwidth also enables the capability to scale the capacity of millimeter wave wireless links as demanded by market needs. Typical millimeter wave products commonly available today operate with spectral efficiency close 0.5 bits/Hz. However, as the demand arises for higher capacity links, millimeter wave technology will be able to meet the higher demand by using more efficient modulation schemes.

Narrow Beam with Highly Scalable Deployments

Unlike microwave links, which cast very wide footprints reducing the achievable amount of reuse of the same spectrum within a specific geographical area, millimeter wave links cast very narrow beams, as illustrated in Figure 2. The narrow beams of millimeter wave links allow for deployment of multiple independent links in close proximity. For example, using an equivalent antenna, the beamwidth of a 70 GHz link is four times as narrow as that of an 18 GHz link, allowing as much as 16 times the density of E-band millimeter wave links in a given area.

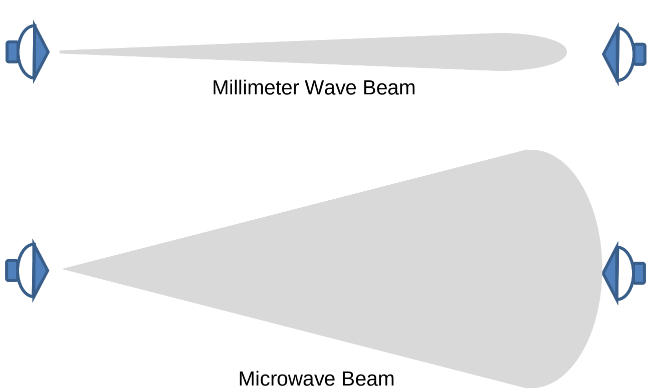

Figure 2: Millimeter wave Links Have Narrow Beams

A key benefit of the highly narrow beam millimeter wave links is the scalability of their deployments. For, example, millimeter wave is well suited for network topologies such as point-to-point mesh, a dense hub-and-spoke or even a ring. Other wireless technologies often reach their scalability limit due to cross interference before the full potential of such network topologies can be realized.

Licensed Spectrum with Low Cost Licensing

Without the protection of licensed use of a spectrum, a viable business case cannot be made for wireless services, whether LAN extension services or cellular backhaul services. One of the key benefits of the 70 and 80 GHz bands is that they are licensed, giving both the users and the service providers a peace of mind. However, unlike the microwave bands, in which licensing costs require significant investment, the cost of licensing E-band links is exceptionally low, less than $500 per link for 10 years of interference protected use.

The traditional form of spectrum licensing has been a challenge for those who own licenses as well as for those who do not. For the owner of a license, it often represents a significant upfront investment combined with, in certain cases, legal obligations to make some specific use of the spectrum. For those who do not own this license, it represents a barrier to competitive entry into this particular market. The licensing scheme of the E-band millimeter wave band has the significant benefit of eliminating both of these challenges.

Mature Technology with Multi-vendor Solutions

Though its application in communication is fairly new, millimeter wave technology has a strong history and technological evolution behind it. Like microwaves, millimeter wave characteristics have been well understood for many decades. Properties of millimeter wave propagation, either through the atmosphere or through material objects, have been well researched and documented. Weather phenomena that affect millimeter wave propagation, such as rain rates, have also been well characterized and understood regionally throughout the world. With many decades of military and government-funded research behind it, millimeter wave technology has reached a level of maturity comparable to older forms of radio technologies.

With the maturity of the technology and the potential business opportunity in millimeter wave communications, multiple vendors have entered the market offering millimeter wave wireless solutions. This has resulted in not only competitive pricing of the products but in differentiated features targeted for specific applications and markets. This competitive landscape has given the adopters of millimeter wireless technology not only a wider set of products to choose from, but also peace of mind knowing that they are not gambling with a niche technology with an uncertain future being monopolized by a small number of players.

APPLICATIONS

Metro Network Services

With the economy becoming more information dependent, the bandwidth needs of corporations, large and small, continue to grow apparently without bound. However, a large majority of corporate buildings are still being served only by archaic copper wires barely able to deliver a few megabits per second of bandwidth.

What is even more astounding is that while 90% of commercial buildings are "out of the loop," literally the fiber-loop of the metro rings, a large majority of these buildings are within a mile or two of a high bandwidth metro ring. What has been missing is the practical ability to extend the metro network services from an existing metro ring to the commercial buildings not touched by the ring. Millimeter wave technology creates an opportunity to fill these gaps in a cost effective manner. As illustrated in Figure 3, a single millimeter wave link can be used to connect a commercial building with a metro ring. With the bandwidth of the millimeter wave link being comparable to that of the metro core itself, this single wireless link would be sufficient to serve a large-occupancy building with high bandwidth demands.

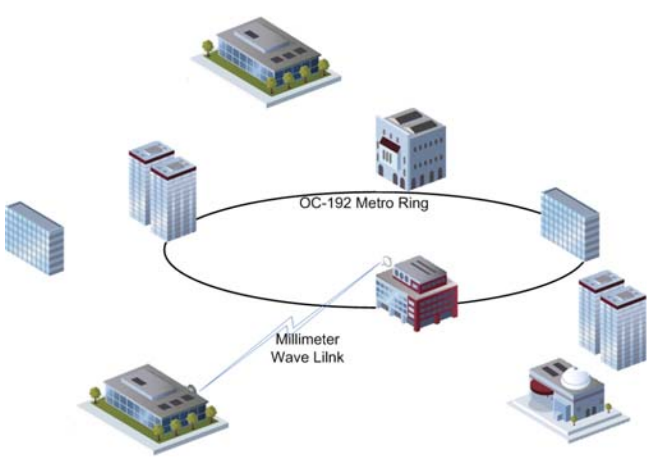

Figure 3: Extending the Metro Network

Cellular/WiMAX Backhaul

With the use of mobile handheld devices growing and newer bandwidth-intensive applications emerging, the need to deliver higher bandwidth to mobile users will continue to rise. As newer technologies such as WiMAX and new spectrum such as 700 MHz are used to serve these needs at the access point, the need for a technology to transport the bandwidth from the point of access to the core of the network will rise swiftly. To this day, most of those needs have been met by slower capacity channels such as T1/E1 leased lines. However, these solutions will not be able to meet the needs of the next generation of mobile networks in a practical manner.

Millimeter wave based technologies are well positioned to serve the needs of these applications well into the foreseeable future. Solutions based on lower frequency microwave wireless systems may perhaps be able to meet the short term bandwidth demand of the next generation of wireless networks. However, when the cost of such solutions and the cost of spectrum licenses are factored in, millimeter wave solutions begin to appear more attractive. When the ability to scale the bandwidth and deployment density is considered, millimeter wave solutions become much more appealing. Compared to the cost of laying fiber to a cell tower, the only other scalable solution, the millimeter wave solution becomes an obvious choice.

Cellular Distributed Antenna Systems (DAS)

In cellular networks, it is often necessary or more efficient to enhance network coverage by distributing a network of remote antennas instead of providing coverage by way of centrally located antennas. Such distributed antenna systems (DAS) are basically extensions of the antenna of base stations. DAS are often used to provide cellular coverage in spots that are shadowed by large structures, such as buildings, from base station antennas. DAS may also be used to provide coverage in areas where it is not efficient to install a base station.

For example, as illustrated in Figure 4, an area behind a large commercial building may be covered better by installing a remote antenna behind the building and transmitting the radio signal back to the nearest base station. In another scenario, for a corporate building with a large subscriber base, it may be desirable to distribute antennas throughout the building and transport the signal to the base station over several wireless paths.

The industry standards covering DAS technology for cellular systems require digitizing the antenna signal before transmitting it to a remote antenna. With this digitization generating as much as 3 Gbps of digital data throughput, technology capable of transporting the signal to remote antenna is very limited. While it is often the case that fiber optic cables are used to transport DAS signals, millimeter wave is an ideal technology, if not the only technology, when DAS signals need to be transported wirelessly.

Failure Recovery and Redundancy

For applications requiring high end-to-end bandwidth, broadband connectivity by means of fiber optic cables is often the technology of choice when access to fiber optic cables is readily available. However, cases abound where fiber connections have been broken by accident, for instance during trenching operations, often bringing down mission critical networks for a substantial period of time. Therefore, it is highly desirable to design such mission critical networks with redundancies that minimize probability of such failures.

A millimeter wave wireless link is very well suited to provide such redundancy. As an example, a data center connected to a network service provider's point-of-presence (PoP) by means of a fiber optic network may also be connected to the PoP by means of a high capacity millimeter wave wireless link. In the event that a failure is detected in the fiber optic network, the data traffic could be routed through the millimeter wave link without impacting the availability or performance of the network.

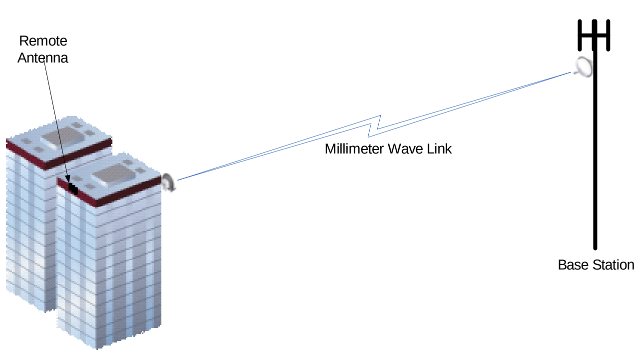

Figure 4: Millimeter Wave Wireless for Distributed Antenna Systems

Enterprise and Campus Networks

The needs of enterprises to extend LANs from one building to a neighboring building are often so compelling that users in such applications have been the earliest adopter of point-to-point wireless technologies. As organizations expand their facilities by growing into neighboring buildings, the cost of leasing interconnecting communication services becomes significant, eventually persuading them to look for alternate solutions.

Whether for an organization that is growing its facility or a large organization with a need to connect existing facilities by means of broadband networks, millimeter wave links are highly suitable as both a long term and short term solution. With the ability to set up wireless links in a matter of hours, as compared to the weeks it may take leased service to be turned on, millimeter wave wireless can be a compelling short term solution. With long term interference protection and sufficient bandwidth to provide for increasing demand, it also is a very compelling long term solution. It is often the case that an organization deploying millimeter wave links can quickly recoup the cost of such equipment from the savings realized by not leasing broadband services.

REFERENCES AND FURTHER INFORMATION

[1] To find our more information about Loea's millimeter wave product, visit: http://www.loeacom.com

[2] For more information on the history of millimeter wave, visit: http://www.tuc.nrao.edu/~demerson/bose/bose.html

[3] More information on ITU model can be found in ITU document "Recommendation ITU-R P.837-5"

[4] For more FCC information on millimeter wave, visit: http://wireless.fcc.gov/services/index.htm?job=service_home&id=millimeter_wave

[5] More information on standardization of millimeter wave in Europe can be found in ETSI document "ETSI TS 102 524" obtained from http://www.etsi.org

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