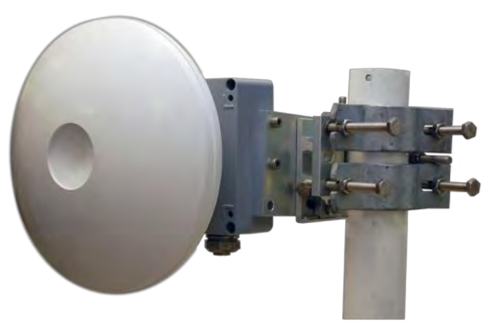
LIGHTPOINTE WHITE PAPER SERIES

# Millimeter-Wave (MMW) Radio Transmission: Atmospheric Propagation, Link Budget and System Availability



## Introduction

The millimeter wave spectrum at 30-300 GHz is of increasing interest to enterprise customers as well as service providers seeking an easy solution to establish a high capacity wireless network connection between remote locations. In particular, the wide bandwidth channels available at this frequency range are valuable in supporting applications including, but not limited to, high speed wireless data transmission between remote campus buildings, metropolitan area networks, and mobile wireless backhaul. As with any other RF/microwave radio system, planning for a millimeter wave system deployment must include accounting for the propagation characteristics of radio signals at this frequency range. When calculating the statistical system availability of a pt-t-pt radio it is therefore important to understand the underlying processes that impact radio signal propagation. Because a radio system has a specific fade margin based on design factors such a transmission power, antenna gain and receiver sensitivity to counterfeit radio signal propagation losses, one can calculate how well the radio link will perform under various climate and environmental conditions, and over specific distances. This white paper takes a closer look at signal attenuation mechanisms, explains how to calculate the radio link budget and discusses how these factors relate to the overall system availability figure.

## What attenuates a radio signal?

In the following we will first discuss the main propagation loss mechanisms that cause radio signal attenuation while propagating through the atmosphere.

### *Free Space Loss*

The Free Space Loss (FSL) is a frequency and distance dependent attenuation loss between two isotropic antennas. This generic loss factor is expressed in absolute numbers by the following equation:

$$LFSL = (4\pi R/\lambda)^2$$

where R is the distance between transmit and receive antennas; and $\lambda$ is the operating wavelength. After converting to units of frequency and putting in dB form, the equation becomes:

$$L_{FSL\ dB} = 92.4 + 20 \log f + 20 \log R \qquad \textbf{(Formula 1)}$$

where f is frequency in GHz; and R is the Line-of-Sight range between antennas in km.

Figure 1 shows the Free Space Loss for several different frequencies from 18 GHz to 100 GHz. This particular chart and several other figures in this white paper were taken from the a report commissioned by the FEDERAL COMMUNICATIONS COMMISSION, OFFICE OF ENGINEERING AND TECHNOLOGY as Bulletin Number 70 July, 1997 entitled "Millimeter Wave Propagation: Spectrum Management Implications"

Because the geometric signal loss increases with the square of the distance between the antennas, every octave change in range changes the differential attenuation by 6 dB. For example, when increasing the distance from a 2-kilometer to a 4-kilometer range, the increase in loss is 6 dB. Note that for very high frequencies even for short distances, the free space loss can be quite high. For millimeter wave radio systems operating at frequencies between 60…80 GHz and over distances from 500 to 5000 meters, the Free Space Losses are already between 130…145 dB. These high loss figures are one of the reasons why the millimeter wave spectrum is typically considered only for short distance communications links.

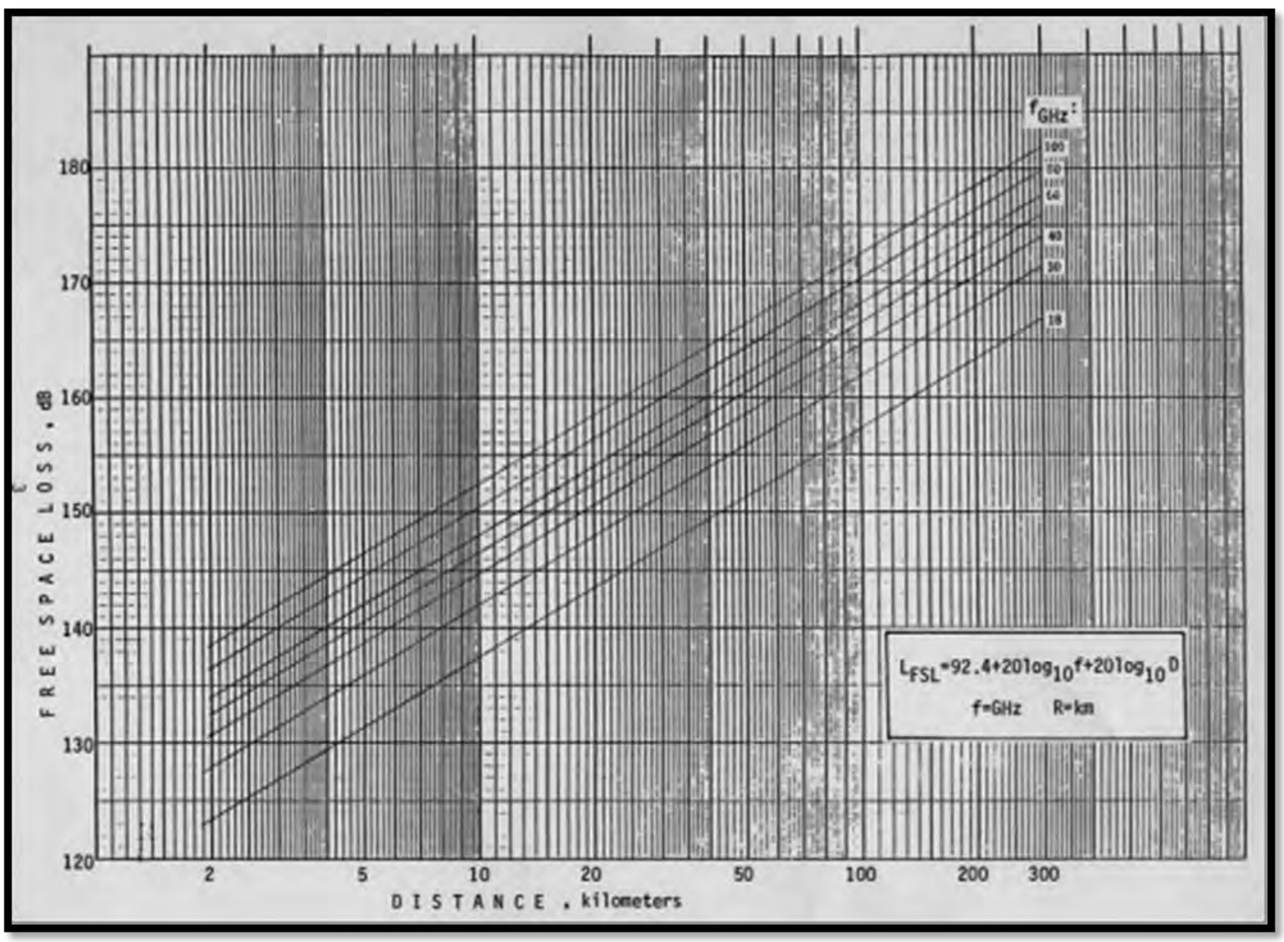



**Fig. 1:** Free Space Loss between Isotropic antennas (from FEDERAL COMMUNICATIONS COMMISSION, OFFICE OF ENGINEERING AND TECHNOLOGY, BULLETIN NUMBER 70 JULY, 1997)

## *Atmospheric Gaseous Losses*

In lower frequency microwave systems, and in particular at frequencies below 10 GHz, the transmission signal loss is primarily accounted for by Free Space Loss. However, in the millimeter wave range additional loss factors come into play, such as gaseous losses and losses due to rain.

Transmission losses occur when millimeter waves traveling through the atmosphere are absorbed by molecules of oxygen, water vapor and other gaseous atmospheric constituents. These losses are greater at certain frequencies, coinciding with the mechanical resonant frequencies of the gas molecules. Figure 2 gives qualitative data on gaseous losses. It shows several peaks that occur due to absorption of the radio signal by water vapor ($H_2O$) and oxygen ($O_2$). At these frequencies, absorption results in high attenuation of the radio signal and, therefore, short propagation distance. For millimeter wave propagation discussed in this paper, the 60 GHz $O_2$ absorption peak is of particular importance. Absorption at 60 GHz is around 15 dB/km[1]. 60 GHz radio frequencies are much more limited in distance when compared to frequencies operating in the 70/80 GHz bands, for example, where oxygen related absorption varies only between 0.4 dB/km and 0.7 dB/km. The spectral regions between the absorption peaks are called “atmospheric windows” because they are more transparent to radio signal propagation.

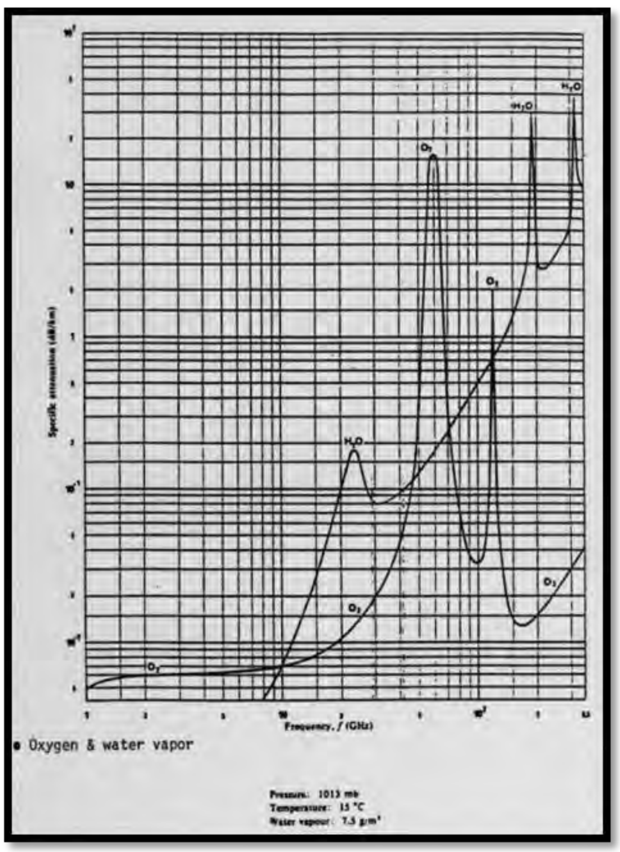
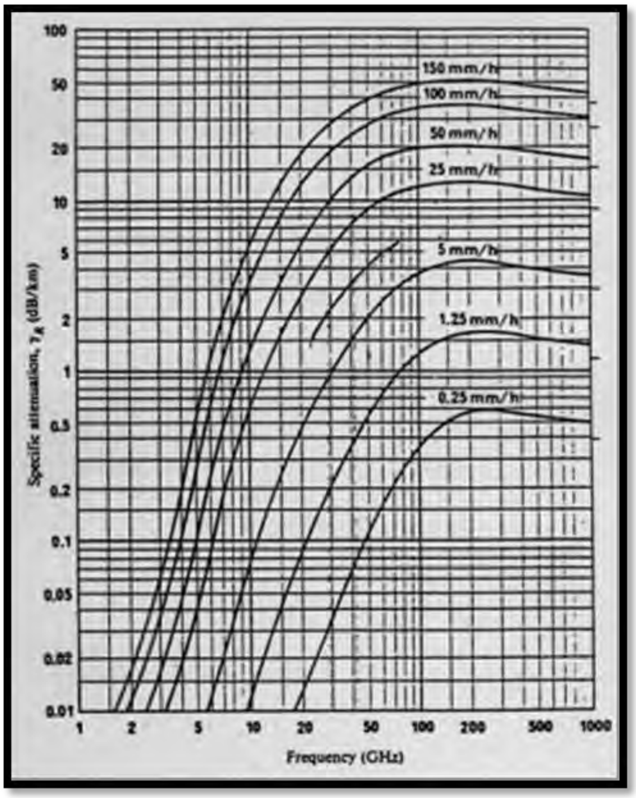



**Fig. 2:** Specific attenuation due to atmospheric gases (from FEDERAL COMMUNICATIONS COMMISSION, OFFICE OF ENGINEERING AND TECHNOLOGY, BULLETIN NUMBER 70 JULY, 1997)

[1] This is a value at sea level and attenuation at higher elevation is lower due to the lower oxygen content at higher altitudes. E.g. at 4 kilometer height and under dry humidity conditions the values can go down to 5 dB/km.

## *Rain Attenuation Losses*

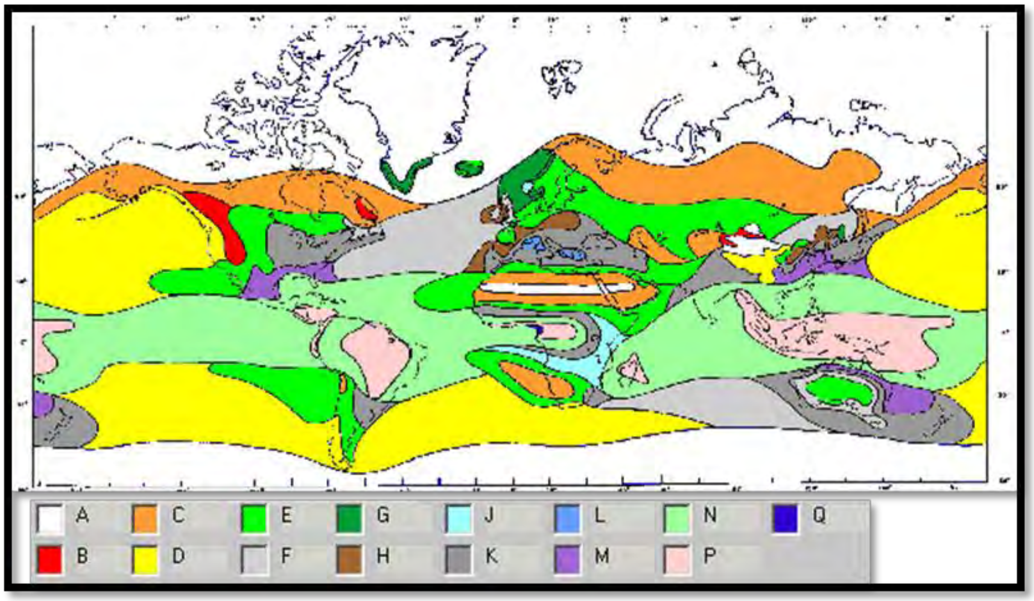



Millimeter wave propagation is also affected by rain. Raindrops are roughly the same size as the radio wavelengths and therefore cause scattering of the radio signal. Figure 3 shows the attenuation per kilometer as a function of rain rate or rain intensity. Rain attenuation increases with the rain rate and with the transmission frequency. At transmission frequencies below 5 GHz a radio signal typically does not experience high levels of attenuation even at very high rain rates. However, attenuation at higher millimeter wave frequency levels can be very high and can contribute significantly to signal fade.

**Fig. 3:** Specific attenuation due to rain as function of the transmission frequency (from FEDERAL COMMUNICATIONS COMMISSION, OFFICE OF ENGINEERING AND TECHNOLOGY, BULLETIN NUMBER 70 JULY, 1997)

Rain rates in all regions of the world have been measured for decades and are well documented. The International Telecommunications Union (ITU), an organization that produces global telecommunications standards, maintains a database of rain rates around the world that are measured with very high accuracy. These rain rate maps are generally referred to as ITU rain zone maps and the overall map divides the world into different rain zones according to the actual rain rates by using an alphabetical nomenclature. Regions having the lowest rain rates are classified as rain zone A; regions with the highest rain intensities are classified as rain zone Q. The ITU rain rate map and associated rain rate table showing the actual rain rates and durations of occurrence is shown in Figure 4. These rain rates ultimately determine the availability of a radio link in a specific rain region.

For example, using Figure 4, for an anticipated outage of a radio link for 0.01% of the year or an availability of 99.99%, the rain rate is about 42 mm/hour for the sub-region K. An increase in the rain factor reduces the communications signal availability. A measure of this availability and the corresponding communications outage is shown in the far left column of the rain rate table. For example, for an availability of 99.9%, the system outage is roughly 8 9? hours a year, but only about 1 hour in case of a 99.99% availability figure.




| Outage/Year | | Rain Climate Zone (rain rates in mm/hour) | | | | | | | | | | | | | | Availability |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | |
| | | A | B | C | D | E | F | G | H | J | K | L | M | N | P | |
| Percent | Time | | | | | | | | | | | | | | | |
| 0.0010 | (5 Min.) | 22.0 | 32.0 | 42.0 | 42.0 | 70.0 | 78.0 | 65.0 | 83.0 | 55.0 | 100.0 | 150.0 | 120.0 | 180.0 | 250.0 | 99.999% |
| 0.003 | (11 Min.) | 14.0 | 21.0 | 26.0 | 29.0 | 41.0 | 54.0 | 45.0 | 55.0 | 45.0 | 70.0 | 105.0 | 95.0 | 140.0 | 200.0 | |
| 0.01 | (1 Hrs.) | 8.0 | 12.0 | 15.0 | 19.0 | 22.0 | 28.0 | 30.0 | 32.0 | 35.0 | 42.0 | 60.0 | 63.0 | 95.0 | 145.0 | 99.990% |
| 0.03 | (1.8 Hrs.) | 5.0 | 6.0 | 9.0 | 13.0 | 12.0 | 15.0 | 20.0 | 18.0 | 28.0 | 23.0 | 33.0 | 40.0 | 65.0 | 105.0 | |
| 0.1000 | (9 Hrs.) | 2.0 | 3.0 | 5.0 | 8.0 | 6.0 | 8.0 | 12.0 | 10.0 | 20.0 | 12.0 | 15.0 | 22.0 | 35.0 | 65.0 | 99.900% |
| 0.3000 | (18 Hrs.) | 1.0 | 2.0 | 3.0 | 5.0 | 3.0 | 4.0 | 3.0 | 4.0 | 13.0 | 6.0 | 7.0 | 11.0 | 15.0 | 34.0 | |
| 1.0000 | (88 Hrs.) | - | 1.0 | - | 3.0 | 1.0 | 2.0 | - | - | - | 2.0 | - | 4.0 | 5.0 | 12.0 | 99.000% |

**Fig. 4:** ITU rain zone regions (top) and associated rain rates and durations (below)

## *Other Losses*

Free Space Loss, atmospheric gaseous losses, and rain losses are typically the main loss mechanisms contributing to the attenuation of a millimeter wave radio signal propagating through the atmosphere. However, and depending on the actual installation location, there are other factors such as signal path clearance, foliage losses, scattering and diffraction losses that can contribute to signal attenuation. But unlike the other physical, atmospheric and climate related signal attenuation mechanisms, these losses can largely be avoided by properly installing a millimeter radio system.

### *Summary of Loss Mechanisms*

The main loss mechanisms that contribute to the fading of a millimeter wave radio signal propagating through the atmosphere are:

1. Free Space Loss
2. Atmospheric Gaseous Losses
3. Rain Attenuation Losses

*Example:*

Transmission of a 70/80 GHz radio signal over 3 kilometers in rain zone K at 99.99% system availability:

| | |
|---|---|
| Free Space Loss | ~140 dB |
| Atmospheric Gaseous Losses | ~ 2 dB |
| Rain Attenuation Loss | ~ 50 dB |
| **Total losses** | **~192 dB** |

## How to calculate a radio link budget?

After discussing the atmospheric loss mechanisms that attenuate a radio signal, this paper now turns to calculating a radio link budget. To maintain the operation of a radio system over a given distance and in a specific geographic location, the radio's link budget must exceed all losses the radio signal is experiencing. In short:

*Total Radio Link Budget > Sum of all Losses*

From the high level perspective the calculation of the total link budget is very straight forward and it can be calculated by using the following simple formula:

$$B_{TLB\ dB} = T_{dB} + G_{Tx\ dB} + G_{Rx\ dB} - R_{dBm} \qquad \textbf{(Formula 2)}$$

where $T_{dB}$ is the transmission power at the antenna port; $G_{Tx\ dB}$ is the Gain of the transmission antenna; $G_{Rx\ dB}$ is the Gain of the receive antenna; and $R_{dBm}$ is the Receiver sensitivity @ the required bit-error rate (BER).

Although the formula is very simple in nature, there are a few particularities that have to be taken into consideration when calculating the total radio link budget:

- *$T_{dB}$ = Transmission power at the antenna port*

  The transmission power figure is sometimes presented differently. $T_{dB}$ can either be specific as the power transmitted by the actual power amplifier device, or by specifying it as the power transmitted at the antenna port. Since there are always internal signal losses between the actual transmitter device and the physical antenna port connection due to diplexer, filter, waveguide losses, etc., the actual transmission power at the antenna port is always less when compared to the power released by the power amplifier. For a typical MMW radio these losses can easily add up to 3…5 dB in total, and therefore they can't be neglected.

- *$G_{Tx\ dB}$, $G_{Rx\ dB}$ = Transmit and receive antenna gain*

  The gain of a MMW antenna can be calculated as a function of frequency and antenna size. As an example, a 2 foot parabolic antenna operating in the 80 GHz frequency range has a theoretical gain of 51 dBi. For field deployments, the use of the theoretical gain figure is questionable because for all practical purposes a "non perfect" antenna will have slight imperfections causing the gain to be lower. Causes include manufacturing tolerances, pointing inaccuracies, etc. Most MMW radios also operate in both the 70 GHz and the 80 GHz band. The gain of an antenna operating in the 70 GHz range is lower and, since both frequency bands are used at the same time, the lower gain number should be taken into account in the radio link budget calculation.

  In addition, the vast majority of MMW antennas are covered with a plastic radome to protect sensitive antenna sub-components from the environment (e.g. rain, snow, ice). The radome material itself causes an additional signal loss that can be relatively low (e.g. 0.5 dB), but it must still be taken into account.

  Due to the above, it is not reasonable to use a 51 dBi antenna gain for a MMW antenna operating in the 70/80 GHz frequency range. Within the radio link budget calculation an antenna gain figure of 43 dBi and 49 dBi for a one foot and 2 foot antenna, respectively is much more reasonable.

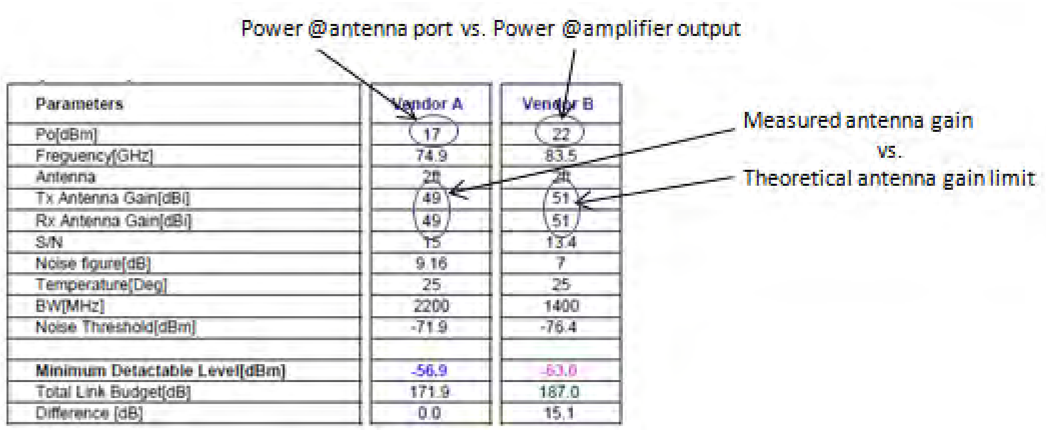
- $\mathbf{R}_{\mathbf{dBm}}$ = Receiver sensitivity

  The receiver sensitivity is probably one of the most discussed parameters within the link budget calculation. Within the simple link budget equation, $\mathbf{R}_{\mathbf{dBm}}$ is NOT to be confused with the receiver noise threshold figure that is sometimes used by radio vendors to specify the value of receiver sensitivity. However, considering the way in which Formula 2 (above) is written, $\mathbf{R}_{\mathbf{dBm}}$ is the minimum detectable receive power level at the stated transmission speed. In other words, the actual receiver sensitivity figure already accounts for the signal-to-noise (S/N) ratio, which is the signal level difference above the receiver threshold for the actual transmission signal to be detected. The S/N value depends on the actual modulation scheme used to transmit the signal. Because nearly all commercially available MMW systems use very simple and low order modulation schemes like ASK, QPSK or DQPSK the S/N figures do not vary as much when compared to higher order QAM modulations such as QAM64 or QAM128. While e.g. the S/N figure for a GbE modulated signal QPSK modulated signal is close to 13 dB, it is about 15 dB for ASK modulation. Actual values for receiver sensitivity therefore do not vary much.

To summarize, although the total radio link budget formula is very simple, one needs to understand how radio vendors use it to calculate the total link budget and, ultimately, the availability of a radio system in different climate (rain) zones.

## How to read and compare MMW vendor's link budget calculations

When comparing the total radio link budget of different MMW radios it is important to understand the underlying assumptions made by the radio vendor. While some radio vendor's budget models are more biased toward using theoretically calculated parameter values, other radio vendors prefer to use parameter values derived from field measurements. Both methods are valid but in nearly all cases the theoretical calculations will result in a higher radio link budget figure. An example is shown in Fig. 5, using parameters specified by different MMW vendors. The total link budget of the system from vendor B shows a 15.1 dB higher link budget when compared to a system offered by vendor A. Although this looks impressive at first glance, this paper will explain why there is such a difference in link budget performance.



| Parameters | Vendor A | Vendor B |
|---|---|---|
| Po[dBm] | 17 | 22 |
| Frequency[GHz] | 74.9 | 83.5 |
| Antenna | 2ft | 2ft |
| Tx Antenna Gain[dBi] | 49 | 51 |
| Rx Antenna Gain[dBi] | 49 | 51 |
| S/N | 15 | 13.4 |
| Noise figure[dB] | 9.16 | 7 |
| Temperature[Deg] | 25 | 25 |
| BW[MHz] | 2200 | 1400 |
| Noise Threshold[dBm] | -71.9 | -76.4 |
| | | |
| **Minimum Detactable Level[dBm]** | -56.9 | -63.0 |
| Total Link Budget[dB] | 171.9 | 187.0 |
| Difference [dB] | 0.0 | 15.1 |



**Fig. 5:** ITU rain zone regions (top) and associated rain rates and durations (below)

***Compare transmission power → Amplifier power out vs. power at antenna port***

Looking at the specific parameter values Fig. 5 shows that vendor B uses the 22 dB amplifier specification of the MMW component vendor as transmission power. This is a legitimate way to specify the transmission power but the actual budget model is based on the transmission power at the antenna port (not the amplifier output) and for all practical purposes additional diplexer, filter, and waveguide losses must be taken into consideration. Vendor A uses the same MMW amplifier with the 22 dBm power output but has taken 5 dB of losses into consideration to specify the power output at the antenna port.

**Result:** After taking the losses between amplifier and antenna port into consideration, the transmission power is basically identical. This is not surprising because both vendors use the same power amplifier.

***Compare antenna gain → Theoretical gain vs. field performance***

A further look at the antenna gain performance shows that vendor 2 uses the theoretical performance limit of a 2 foot MMW antenna operating at 83.5 GHz. There are no losses due to antenna imperfections, pointing losses, or radome coverings that have previously been taken into consideration. In addition the vendor's radio equipment works in parallel in the 70 GHz frequency range where the antenna gain will already be below the 51 dBi shown in the spec sheet. Vendor 1 shows a more realistic gain figure of 49 dBi, and is a more reasonable antenna gain figure for an antenna deployed in the field rather than in a laboratory environment.

**Result:** Both vendors use a 2 foot antenna with the same theoretical gain factor. Vendor A uses a more conservative gain figure to take "non-ideal" antenna performance and radome cover loss into account.

***Compare receiver sensitivity → Theory vs. field performance***

When specifying the receiver noise threshold, vendor B uses theoretical physical limits for the noise threshold as a baseline receiver sensitivity figure. This is a legitimate approach to start from, but it also starts from an extremely "optimistic" baseline assumption as it pertains to receiver noise threshold. The same is true for the stated S/N noise ratio requirement. Using theoretical values close to the physical limits automatically results in an outstanding figure for the minimum detectable signal power level $\mathbf{R}_{\mathbf{dBm}}$.

**Result:** Vendor A uses a slightly less effective modulation scheme that requires more channel bandwidth, but in addition vendor A uses a much more conservative approach when it comes to the actual receiver performance specifications (e.g. receiver noise figure) under non-ideal field conditions.

To summarize, it is important to ask a radio vendor specifics about the underlying link budget model that is used to calculate the total radio link budget. Some vendors are purely based on theoretically calculated performance parameters and using these theoretical values can easily lead to an overestimation of the actual system performance in the field, as presented in the next chapter of this white paper.

## MMW Radio Transmission Distance vs. Availability – A Reality Check

The previous chapter explained how to interpret different vendor claims on the radio link budget side. It should not come as a surprise that MMW radio vendors also claim very different distance vs. availability figures. Besides taking a very optimistic approach on the radio budget side, some distance claims are also underestimating the amount of attenuation a MMW radio signal is experiencing under adverse weather conditions.

There are some vendors selling MMW radios that claim relatively long distance ranges. One example is shown below in Fig. 6. Among others, this chart claims a 99.99% availability rating over a distance of 3.7 kilometers in ITU rain zone K, or 5.7 kilometers transmission distance in ITU rain zone E.

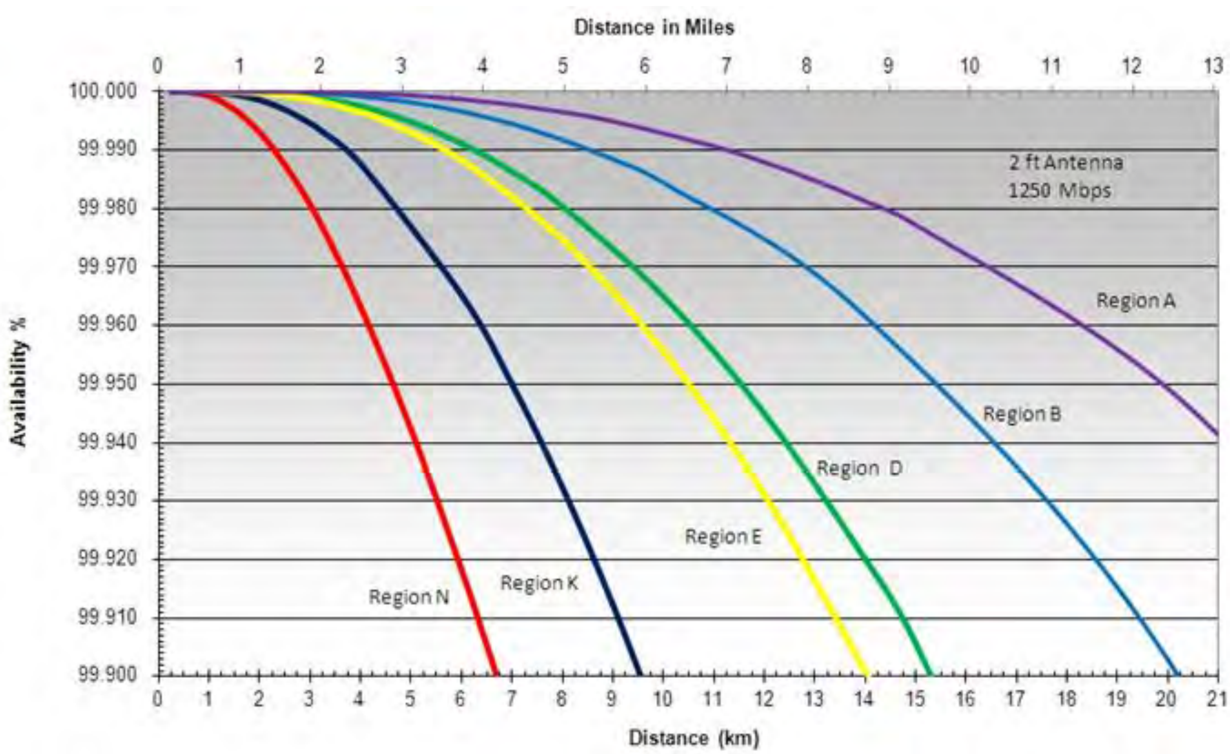



**Fig. 6:** MMW radio distance vs. availability chart as claimed by a MMW radio vendor.

According to the official ITU rain rate chart shown in Fig. 4, a radio system installed in rain zone K and/or E needs to overcome a rate rain of 42 mm/h and/or 22 mm/h, respectively, to maintain the availability figure of 99.99%. Below is a short summary of all major atmospheric losses a radio signal is experiencing while propagating over distances of 3.7 km and 5.7 km in rain zone K and E, respectively:

*Rain zone K*

| | |
|---|---|
| Free Space Loss (see Fig. 1) | ~142 dB |
| Atmospheric Gaseous Losses (see Fig. 2 → 3.7 km *0.7 dB/km) | ~ 3 dB |
| Rain Attenuation Loss (Fig. 3 → 3.7km * 16.5 dB/km) | ~ 61 dB |
| **Total losses** | **~204 dB** |

*Rain zone E*

| | |
|---|---|
| Free Space Loss (see Fig. 1) | ~146 dB |
| Atmospheric Gaseous Losses (see Fig. 2 → 5.7 km *0.7 dB/km) | ~ 4 dB |
| Rain Attenuation Loss (Fig. 3 → 5.7km * 10.5 dB/km) | ~ 60 dB |
| **Total losses** | **~210 dB** |

The simple atmospheric loss analysis shows that a radio link needs a link budget of 204 dB in rain zone K and 210 dB in rain zone E to maintain the claimed 99.99% availability figure over distances of 3.7 km and 5.7 km, respectively, as shown in Fig. 6. Even a radio link based on the maximum theoretical link budget of 187 dB (see Fig. 5) is not able to maintain operation at these atmospheric attenuation levels.

## Summary

Millimeter wave radio signals experience a fair amount of attenuation when propagating through the atmosphere. Major attenuation factors are free space loss, rain loss, and, in the case of 60 GHz, transmission losses due to oxygen absorption. To maintain operation under specific climate conditions and over a specified distance, the radio link budget must exceed all transmission losses.

Radio vendor's link budget calculations are not all the same and some vendors use more optimistic theoretical performance parameters to characterize the performance of the radio link. It is important that the user understands the underlying assumptions to be able to objectively compare the radio performance claims.

Because there are not many semiconductor vendors that provide MMW components suitable for operation in the 60/70/80 GHz frequency ranges, and virtually all MMW radio manufacturers use high power transmission amplifiers and receiving devices from the same semiconductor vendor, there aren't really a lot of performance differences when it come to specifications of internal radio components.

However, at first glance, the distance performance and system availability claims of various MMW radio vendors seem to vary a lot. The example presented in this white paper shows that some availability numbers for MMW radios operating over longer distances seem to be largely overstated and in violation of physical laws.

One of the reasons why these long distances are considered to be achievable could be related to the assumption that heavier rain is concentrated within a “smaller rain cell” that does not extend along the complete transmission path. Only by making such an assumption one can reduce the impact of rain attenuation over the total length of the transmission path. However, even under such an assumption, these long distance claims are difficult to maintain because it would require the rain attenuation to be present over only half of the distance and the other half operating with no rain attenuation at all. Such a scenario is very difficult to imagine in reality.

To summarize, the user of MMW radio systems need to be very careful when it comes to long transmission distance claims because of the underlying link budget model assumptions. “Real world” distance performance of MMW radios is similar when the same assumptions are used to compare equipment performance.

## About LightPointe

LightPointe was founded in 1998 and has become a global market leader for high capacity wireless outdoor bridges with over 6000 systems deployed in over 60 countries worldwide and in vertical markets such as Health Care, Education, Military & Government networks, large and small campus enterprise networks, Wire line and Wireless Service Provider networks. Over the last 10 years the company has established a unique diversified product portfolio based on high capacity Free Space Optics (FSO) and Millimeter Wave (MMW) technology. With more than 10 patents granted in the FSO, RF/MMW and in the hybrid bridging solution space LightPointe has established a strong IP and patent portfolio position manifesting the company’s technology leadership position.

LightPointe has a long list of global customers including but not limited to Wal-Mart, DHL, Sturm Foods, Siemens, Sprint, AOL, FedEx, BMW, Lockheed Martin, Dain Rauscher, Barclays, Nokia, Deutsche Bank, IBM, Corning, Cisco, Huawei just to mentioned a few. For more information please visit the LightPointe website at www.lightpointe.com