International Journal of Applied Engineering Research ISSN 0973-4562 Volume 12, Number 11 (2017) pp. 2635-2646

Broadband Access utilizing the Unlicensed Wireless 60 GHz Band and Free Space Optics

Osama W. Ata
Electrical Engineering Department,
Palestine Polytechnic University, P. O. Box 198, Hebron, Palestine.

ORCID: 0000-0002-8227-7278

Abstract

The exploration of wireless alternatives to Broadband access has continued to be very important to service providers. The Line-of-Sight (LOS) Free Space Laser (FSL) and 60-GHz radios are two promising wireless alternatives since they fall in the FCC license –free spectrum and thereby mitigate the tremendous expense of spectrum acquisition. However, the FSL solution is very limited as a carrier solution because of its very short (<300 m) range carrier when a 99.95% or higher link availability is required. The license-free 60 GHz radio can deliver similar links over a much longer distance than FSL solutions when a higher link availability of 99.999% is required. The 60-GHz OC-24 link can reach 460 to 870 meters over continental US, depending on the rain region and link availability percentage (4-nine to 5-nine). Furthermore, it is relatively more robust than an FSL link in dense fog, sheet rain or severe sand storm weather conditions.

Keywords: LOS; FSL; FCC; Broadband access; Link availability; Rain attenuation; 5G hybrid networks.

INTRODUCTION

FSL communication systems establish communication links between two laser transceivers by propagating optical signals through the atmosphere. FSL systems can deliver OC-3 (155.52 Mbps) or OC-12 (622.08 Mbps) capacity. Some OC-24 (1.244 Gbps) FSL products have also been introduced. The other significant benefit of an FSL communication system is its low throughput cost. By contrast to the license-free RF-based systems, FSL systems introduce little optical signal interference to each other because of the narrow beams they radiate. This makes them less susceptible to mutual interference than license-free RF-based systems. FSL requires neither radio-frequency (RF) allocation, nor governmental approval. All these are attractive for quick deployment. However, FSL systems are subject to some severe limitations. An unobstructed LOS has to be maintained between transmitting and receiving units all the time. The link range or quality is very sensitive to weather conditions like fog and sheet rain. High link availability can be guaranteed only over a short distance up to 300 meters at most locations. For 32 cities out of the 98 major North America cities, the FSL link distance could be extended to 500 meters when the link availability is reduced to 99.5%, equivalent to an annual outage time of 44 hours. The FSL systems have been primarily deployed as enterprise solutions over a distance of a couple of hundred meters to 2,000 meters, where a potentially high rate of link outage is considered acceptable.

On the other hand, the FCC has allocated a 7-GHz wide spectrum from 57 to 64 GHz for use by general unlicensed devices under Part 15 [1] of its rules. Such a wide spectrum allows low-cost and high-capacity links of up to 1 Gbps although the links are subject to some severe limitations; a clear LOS has to be maintained and the transmission range with 4-nine link availability is typically less than 1 km. The range is short because of the high atmospheric absorption and huge rain attenuation in presence of heavy or sheet rain. The high oxygen absorption and rain loss plus narrow antenna beamwidth, however, help minimize co-channel interference, which leaves the interference of less concern, compared to other unlicensed frequency bands. The license-free 60 GHz link systems are relatively newer than the FSL systems, in terms of historical development. However, the 60-GHz systems can offer a number of advantages over FSL systems and can be complementary to the latter, in deployment scenarios, if economic costs could be further mitigated.

RF LINK OUTAGE COMPUTATION

There are several propagation effects that must be considered in the design of line-of-sight microwave link system. Some of these may include attenuation due to atmospheric gases, multipath fading, rain precipitation and diffraction fading due to path obstruction, to name a few.

Notably, rain precipitation loss is the most predominant cause of path loss, particularly in heavy rain zones and as the frequency increases above 10 GHz. The oxygen absorption, particularly in the 60 GHz band is another major cause. The ITU specific attenuation model [2] for rain, used in prediction methods, relates the specific attenuation γ_R(dB/km) and the rain rate R(mm/hour) through the following power-law relationship:

$$\gamma_R = kR^{\alpha} \quad (1)$$

Where, k and α are frequency dependent coefficients, determined in the frequency range 1 – 1000 GHz. k can be either k_H or k_V and α can be either α_H or α_V , for horizontal and vertical polarization, respectively. Table 1 [2] shows the values of these constants in the 60 GHz range.

Table 1: Frequency-Dependent Coefficients for Estimating Specific Rain Attenuation

Frequency (GHz)	k_H	α_H	k_V	α_V
57	0.8032	0.7771	0.7931	0.7587
58	0.8226	0.7731	0.8129	0.7552
59	0.8418	0.7693	0.8324	0.7518
60	0.8606	0.7656	0.8515	0.7486
61	0.8791	0.7621	0.8704	0.7454
62	0.8974	0.7586	0.8889	0.7424
63	0.9153	0.7552	0.9071	0.7395
64	0.9328	0.752	0.925	0.7366

Rain rates on the other hand, are tabulated with reference to rain zones and percentage of time the rain rate is exceeded [3]. The US continent has 6 rain zones. These are rain zone B, D, E, K, M and N. Zones B, D, E include the Western region, Zone K includes the Central North and North East regions, Zones M, N include the Central South and the South East regions. Some US main cities that are represented by these rain zones are Las Vegas (Zone B), San Francisco and Seattle (Zone D), Denvor and Los Angeles (Zone E), Chicago, New York and Washington DC (Zone K), Atlanta and Dallas (Zone M), Houston and Miami (Zone N).

Table 2: Rainfall Intensity in Various Rainfall Zones for Various Link Availability %

Time % exceeded	LOS Link availability %	Zone B (mm/h)	Zone D (mm/h)	Zone E (mm/h)	Zone K (mm/h)	Zone M (mm/h)	Zone N (mm/h)
1	99	0.5	2.1	0.6	1.5	4	5
0.3	99.7	2	4.5	2.4	4.2	11	15
0.1	99.9	3	8	6	12	22	35
0.03	99.97	6	13	12	23	40	65
0.01	99.99	12	19	22	42	63	95
0.003	99.997	21	29	41	70	95	140
0.001	99.999	32	42	70	100	120	180

Table 2 [3] shows the rainfall intensity (mm/hour) for all six rain zones. Each zone shows the rainfall intensity exceeded time percentage from which the LOS link availability can be calculated, as a required link specification. The calculated link availability excludes availability of the link due to hardware system failure.

Hence the total path loss for an LOS RF link can be expressed as:

$$L_{total} = L_{FS} + \gamma_R d + \gamma_{ATM} d \quad (2)$$

where the free space path loss [4] is expressed as:

$$L_{FS} = 20log_{10}(d) + 20log_{10}(f) + 92.45 \quad (3)$$

and

d is distance in km

f is frequency in GHz

γ_R is the specific rainfall attenuation in dB/km as expressed in equation (1)

γ_{ATM} is the specific atmospheric attenuation due to gaseous absorption in dB/km

CHARACTERIZATION OF THE 60 GHZ BAND

The path length of a radio link at microwave frequencies has always posed a challenge for link system designers. While availability, equipment specifications, climate and terrain characteristics all impact the range; rain attenuation could be severe, particularly for frequencies above 10 GHz. Heavy rain absorbs and scatters the transmitted power and causes the signal to be severely faded. The fading is worse with horizontal polarization of the transmitted wave as compared to vertical polarization. Depending on the frequency, its electrical polarization tilt, rain rate and rain distribution, the attenuation at 60 GHz can be as much as 26 dB (99.99% availability) and 42 dB (99.999% availability) at 1 km distance from a vertically polarized transmitter, for heavy rain falling at 180 mm/hour; e.g. in Miami. Figure 1, 2 and 3 illustrate the rain attenuation versus range for rain zone D, e.g. San Francisco (rain intensity 42 mm/hour), rain zone K, e.g. Chicago (rain intensity 100 mm/hour) and rain zone N, e.g. Miami (rain intensity 180 mm/hour), considered at percentage time exceeding 0.001%, respectively. ITU-R models [2, 3] were utilized to calculate rain attenuation. The 60 GHz band lies within a narrow spectral window pertaining to a high atmospheric loss due to oxygen molecular absorption. The value peaks at around 60 GHz frequency, rated at 15.5 dB/km, at sea level. Unlike the IS RF link range, M and U-NII unlicensed bands below 10 GHz, the 60 GHz is not heavily utilized. The higher frequency, rain attenuation and atmospheric absorption at the 60 GHz band , compared to the licensed 28, 31 and 39 GHz bands, physically imposes a much shorter RF link range, for a given rain zone and link availability. This reduces interference level as usually experienced in the LMS bands; hence making the interference in the 60 GHz band, more manageable. Co-channel interference in all unlicensed bands is a major concern to carrier-class applications because there is no regulatory protection of the links from interference due to other users. The relative high path loss, high rain attenuation, which depends on frequency, distance, rain zone and required link availability, as well as, atmospheric absorption reduce the transmission range of both intended and interfering signals. This makes it likely for the 60 GHz link to be noise limited, instead of interference limited. In addition, 3-dB beamwidth of the antenna is typically in the 1-3 degree range. Such narrow beamwidth effectively mitigates possible sources of cochannel interference in the way of the RF link.

For an OC-24 link at 99.999% availability, maximum range can vary from 460 m to 740 m at 60 GHz and 500 m to 900 m at 64 GHz. With the same availability, but at OC-3 rates, the range increases to 580 m to 960 m at 60 GHz and 640 m to 1200 m at 64 GHz. By relaxing the availability requirements from 99.999% to 99.99%, a 20-31.5% increase in range can be expected for OC-3 and 17.5-26% for OC-24 at 60 GHz. At 64 GHz, the increase in range for OC-3 and OC-24 is 29-43% and 28-38.5%, respectively.

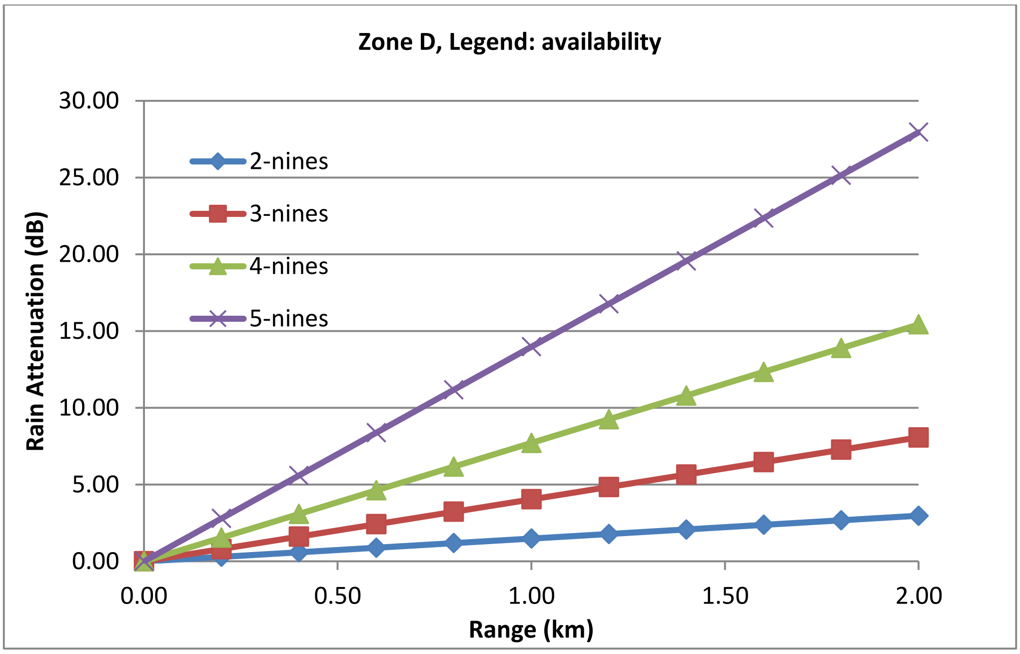

Figure 1: Rain Attenuation vs. Range (km) for Different Link Availability for Region D

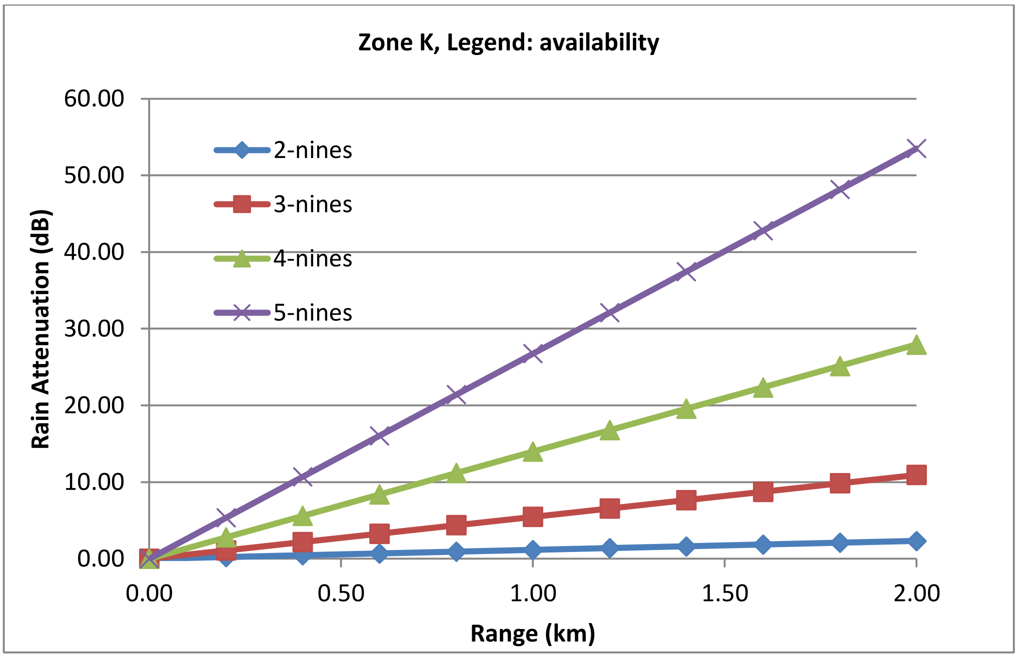

Figure 2: Rain Attenuation vs. Range (km) for Different Link Availability for Region K

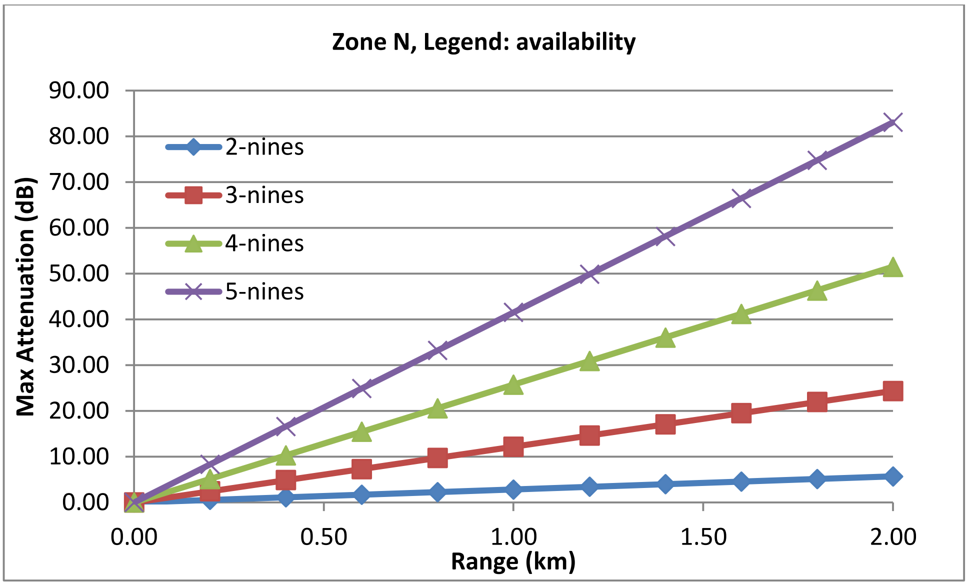

Figure 3: Rain Attenuation vs. Range (km) for Different Link Availability for Region N

Figure 4 demonstrates a comparative example of total path loss (Free space path loss + rain attenuation + atmospheric attenuation) versus range for rain zone (region) K, e.g. New York at link availability 99.99% and rain intensity 42 mm/hour. While the atmospheric loss at 60 GHz is 15.5 dB /km, at sea level, it is equal to 0.15 dB /km at 24 GHz and negligible at 10 GHz. Rain attenuation is dominant at 84 GHz, 64 GHz and 60 GHz. Atmospheric attenuation is particularly dominant at 60 GHz.

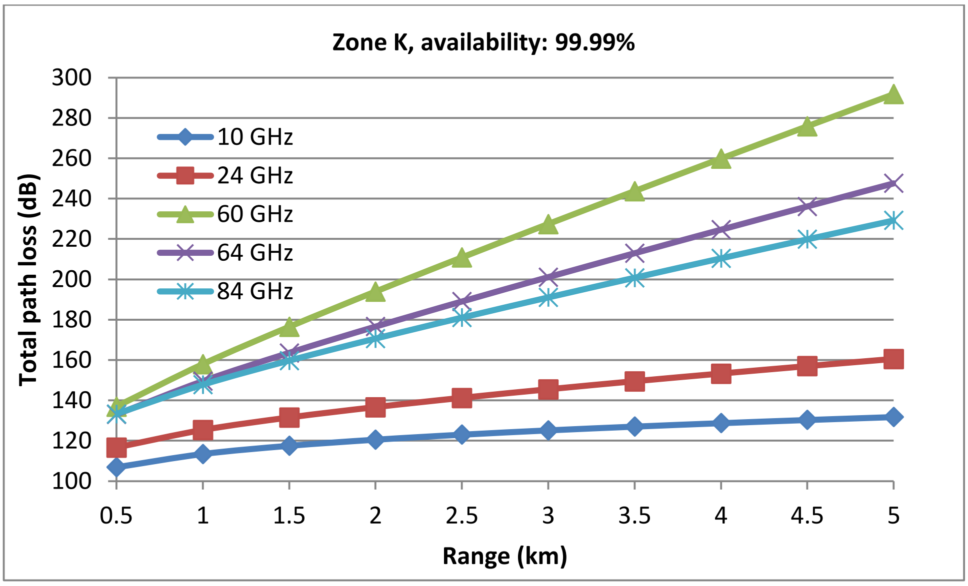

Figure 4: Total Path Loss (LOS) Comparison versus Range (km) at Various Frequencies for Rain Zone K (New York) at 4-nine Link Availability (vertical polarization)

LINK BUDGET RESULTS

Maximum range for various rain zones and various frequencies in the 57 – 64 GHz band was calculated for OC-3 and OC-24 data rates with 5-nine and 4-nine link availability for each data rate, using a standard link budget as shown in Table 3. While the recommendation spells out a maximum transmitter output of 10 dBm, a maximum EIRP of 55 dBm and a minimum antenna gain of 30 dB, the FCC recommendation spells out a maximum EIRP of 82 dBm with a maximum antenna gain of 51 dB [5]. Hence we suggested a transmitter power of 10 dBm and an antenna gain of 50 dB. Typical bandwidth and noise figure were considered 300 MHz and 11 dB, respectively [6].

Table 3: Link Budget

LINK BUDGET	**Value**	**Unit**
Frequency	60	GHz
Distance	0.74	km
Transmit Power	10	dBm
Antenna Gain (TX)	50	dBi
Antenna Gain (RX)	50	dBi
Free space attenuation	125.3476594	dB
Oxygen Attenuation / km	-16	dB/km
Oxygen Attenuation	-11.84	dB
Receiver Sensitivity	-78.2	dBm
S/N (min)	20.5	
Rain Attenuation / km	-13.97491165	dB/km
Rain Attenuation	-10.34143462	dB
Boltzmann's Constant	1.38× 10^-23	J/K
Bandwidth	300	MHz
Temperature	290	K
Thermal Noise	-89.20601661	dBm
Noise Figure	11	dB
Margin	0.170905973	dB

The relative reduction in maximum range for each zone (D, K and N), due to increase of data rate from OC-3 to OC-24 (8 folds), which affects, in turn, an increase in the SNR of the link budget, is shown in Figures 5-7. In addition, rain attenuation varies with frequency, distance, link availability and rain zone, as described in Figures 1-3. Standard link budgets can be developed with specific parameters to maximum allowed transmitted power, antenna gain, receiver sensitivity, signal to noise ratio, noise figure to mention a few. In the above example, S/N= 20.5 dB, which is based on 16-QAM modulation (E_b/N_0 = 14.5 dB at bit error probability of 10^{-6}). For 64-QAM modulation, S/N= 26.6 dB where (E_b/N_0 = 18.8 dB at bit error probability of 10^{-6}) [7-8].

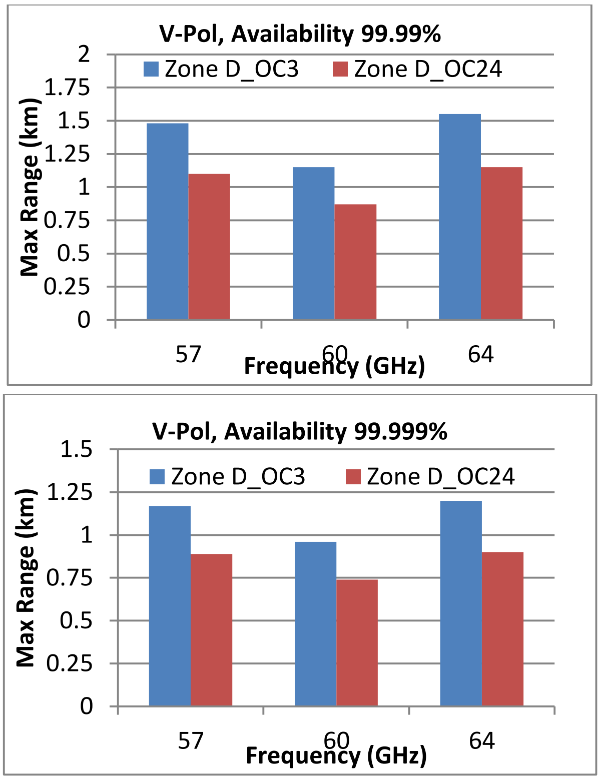

Figure 5: Maximum Range Performance versus frequency for rain zone D and data rates OC3 and OC24
(left) 4-nine availability, (right) 5-nine availability

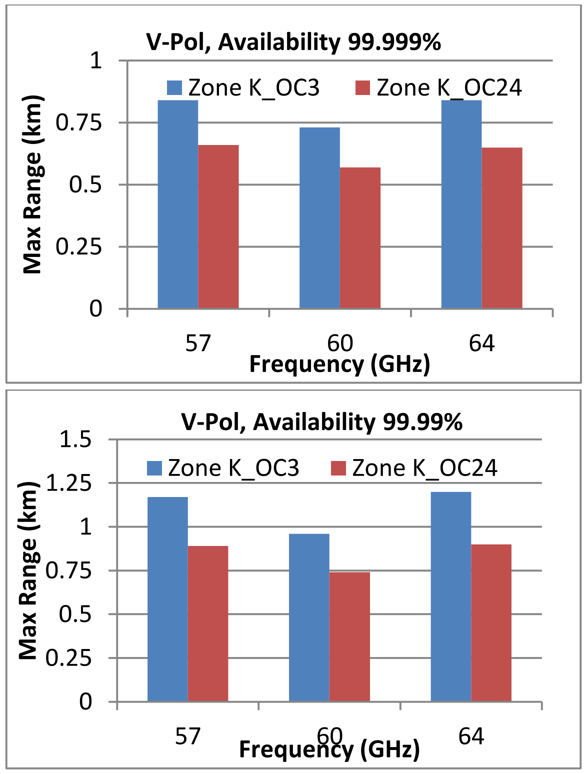

Figure 6: Maximum Range Performance versus frequency for rain zone K and data rates OC3 and OC24
(left) 4-nine availability, (right) 5-nine availability

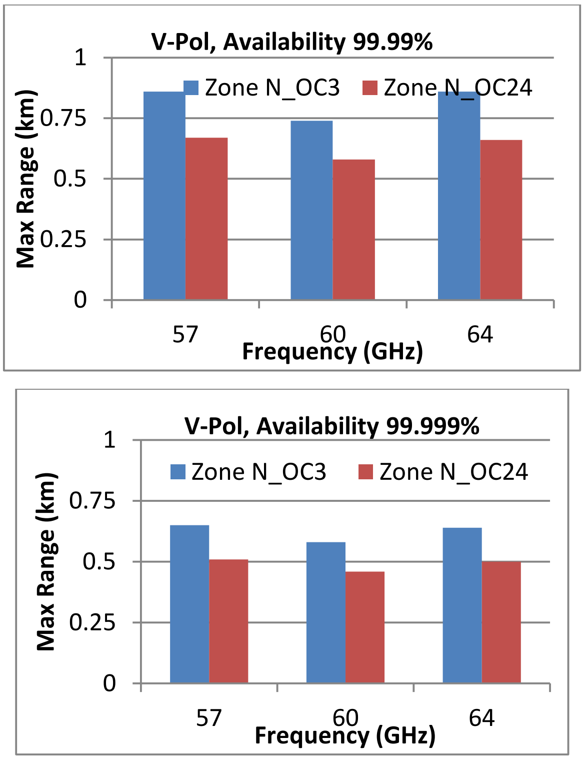

Figure 7: Maximum Range Performance versus frequency for rain zone N and data rates OC3 and OC24 (left) 4-nine availability, (right) 5-nine availability

The impact of availability, rain zone, frequency on the maximum range of the link is shown in Table 4. As the availability is reduced from 5-nines to 4-nines, the maximum range is increased by 20% for D zone, 31.5% for K zone and 28% for N zone at 60 GHz frequency. Hence the impact of availability on maximum range is not necessarily more effective with increased specific rainfall attenuation. On the other hand, because the atmospheric absorption is more pronounced at 60 GHz than the frequencies around it, the impact of availability reduction on maximum range is more effective as the frequency deviates to 61 GHz and 64 GHz and to a relatively less extent at 57 GHz. All in all, for the mentioned availability range, extreme zones between D and N (including the intermediate zone K) and within the 57-64 GHz microwave band, the expected maximum range is 1 - 1.5 km for D zone, 0.7 – 1.2 km for zone K and 0.6 – 0.9 km for zone N. Those figures were calculated for links transmitting at data speed of OC-3. A similar trend is expected but with modified maximum ranges with higher data speeds like OC-12 and OC-24.

Table 4: Availability, Rain Zone, Frequency, Maximum Link Range and % Range Increase

	Link Availability 99.999% (i.e. < 5.3 minutes Outage/year)			Link Availability 99.99% (i.e. < 53 minutes Outage/year)					
Frequency GHz	D zone km	K zone km	N zone km	D zone km	K zone km	N zone km	% range D zone	% range K zone	% range N zone
57	1.17	0.84	0.65	1.48	1.17	0.86	26.5	39.3	32.3
60	0.96	0.73	0.58	1.15	0.96	0.74	19.8	31.5	27.9
64	1.20	0.84	0.64	1.55	1.20	0.86	29.2	42.9	34.4

Link performance and availability can be portrayed in a slightly modified way. A maximum link range of 1.25 km, such as in New York City (K zone) for a link availability of 99.999% was reported [9]. When the availability was relaxed for an extended link range of fixed 2 km, that resulted in a new link availability of 99.991% and an increase in range by 60%.

CHARACTERIZATION OF THE FSL WIRELESS LINK

In an FSL communications system, the link distance is independent of the laser beam pointing loss and the optical losses of transmitting and receiving units. On the other hand, the geometrical spreading loss (dB) is proportional to the link distance as the laser beam diverges over distance [10]. The other main link-distance dependent losses are atmospheric attenuation (flat fading) and scintillation (signal rapid fluctuation). Severe scintillation is likely to occur on a hot sunny day while severe atmospheric attenuation is always associated with diverse weather conditions, like fog and heavy rain.

To close a communication link, an FSL system must have a positive link margin to overcome the atmospheric attenuation impairment, including atmospheric attenuation scintillation.

As opposed to the deterministic fibre attenuation, the atmospheric impairments that FSL communication links are subject to, are stochastic and highly depend on the local weather conditions. The random media of atmosphere impairs the FSL links in three fashions. The first and primary impairment is the variable atmospheric attenuation between the transmitting and receiving unit. The atmospheric attenuation is low when the weather is clear. But this attenuation could become very high during heavy rain days and even higher during foggy days. For instance, sheet rain of 100 mm/hour could introduce an attenuation of 18.3 dB /km, according to a theoretical model [11]. The attenuation due to fog on FSL links ranges from 50 to 315 dB /km, depending on the denseness of the fog. The atmospheric attenuation is typically slow or medium varying. The extensive atmospheric attenuation would introduce intolerable level of bit error over a period of several minutes to a few hours. The second atmospheric impairment is scintillation, light intensity fluctuation in the received optical signal. The scintillation occurs during hot and dry days when temperature gradients originate atmospheric turbulence. Scintillation can cause bit error bursts to an FSL link. The third atmospheric impairment is the optical signal dispersion or waveform distortion. The dispersion is not a practical concern to an OC-3 or OC-12 FSL link. But it can be a dominant factor limiting data rate of a very high capacity FSL link. For the same FSL communication system, the usable link distance can be more than 8 km in a clear weather. But the usable link distance shrinks to 300 meters in the presence of heavy fog.

Fibre optic communication systems have earned a reputation of high availability. However, the availability of a FSL link is highly dependent on the link distance of interest and historical local weather or meteorological data. Without knowing the local weather history, the safe distance of a FSL link is only about 300 meters if an availability of 99.95% is required. This is because the heavy fog attenuation introduces an enormous atmospheric attenuation up to 315 dB /km. For a given FSL communication system configuration and a specific location, the maximum FSL link distance could be roughly estimated, based on the historical visibility probability data at the location and the general atmospheric attenuation model as a function of visibility conditions.

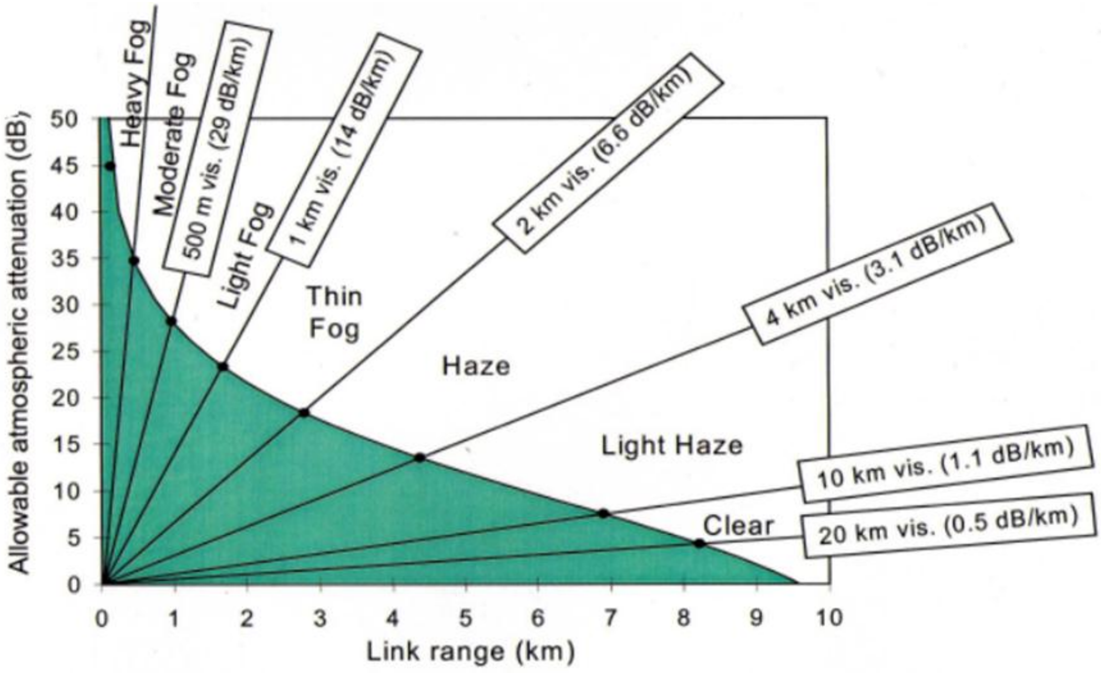

Figure 8: An example of allowable FSL link margin curve for atmospheric impairments, intercepted with atmospheric attenuation under different weather conditions [11].

The maximum link margin allowable for atmospheric loss is inversely proportional to the square of link distance, as illustrated in Figure 8. The intercept points suggest the link range under the specific weather conditions. However, atmospheric attenuation coefficient (dB/km) starts increasing exponentially to the desired link availability when the link availability exceeds 98%. This means that it is a lot harder to increase link availability above 98% than to extend the link range, while maintaining the link availability.

TOTAL ATTENUATION AT 60 GHZ VERSUS 70 / 80/ 90 GHZ BANDS

In this section we compare the total attenuation for Zones K and N at 60 GHz band with the licensed bands at 70, 80 and 90 GHz for 4-nine and 5-nine availability. While the atmospheric absorption is significant in the 60 GHz bound, it is insignificant in the other bands. The difference is compensated with a relative increase in the rain attenuation at the higher frequency bands. It is worth noticing that the total

International Journal of Applied Engineering Research ISSN 0973-4562 Volume 12, Number 11 (2017) pp. 2635-2646

attenuation at 57 GHz and 64 GHz is almost similar to that at 94 GHz. With the high antenna gain (narrow beamwidth) and careful radio link planning, cochannel interference can be significantly minimized at the 60 GHz band.

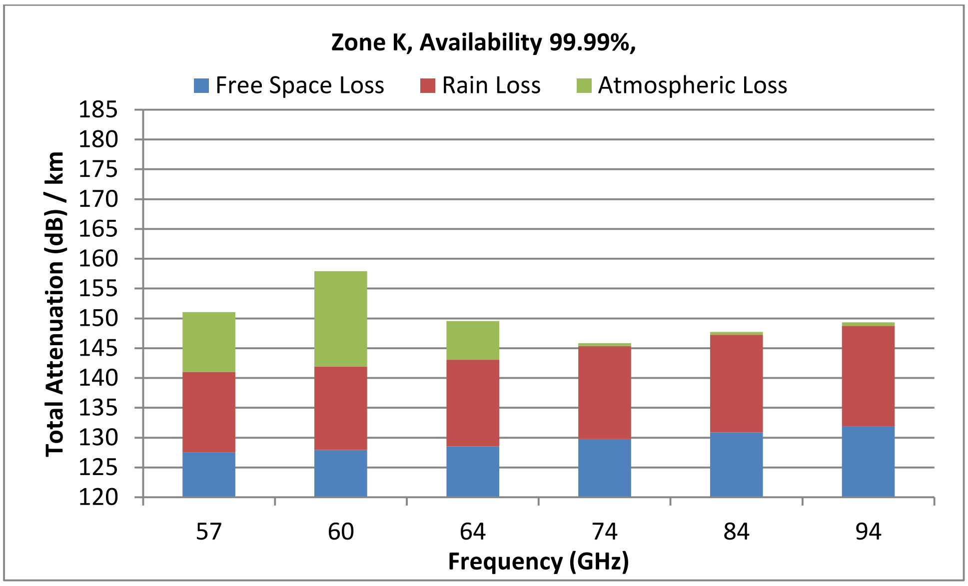

Figure 9: Total attenuation (dB) / km breakdown at various frequencies V-band and E-band frequencies for rain Zone K with 99.99% link availability

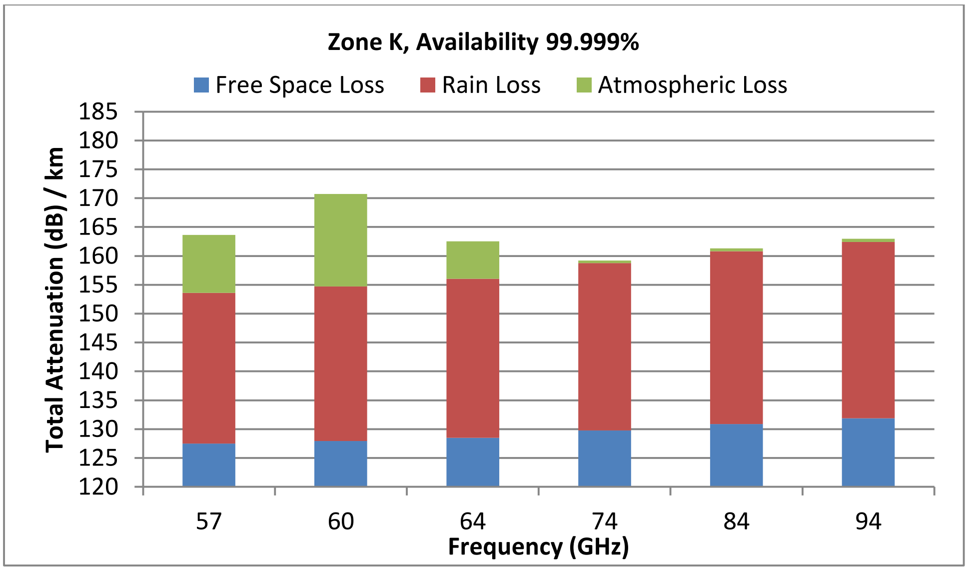

Figure 10: Total attenuation (dB) / km breakdown at various frequencies V-band and E-band frequencies for rain Zone K with 99.999% link availability

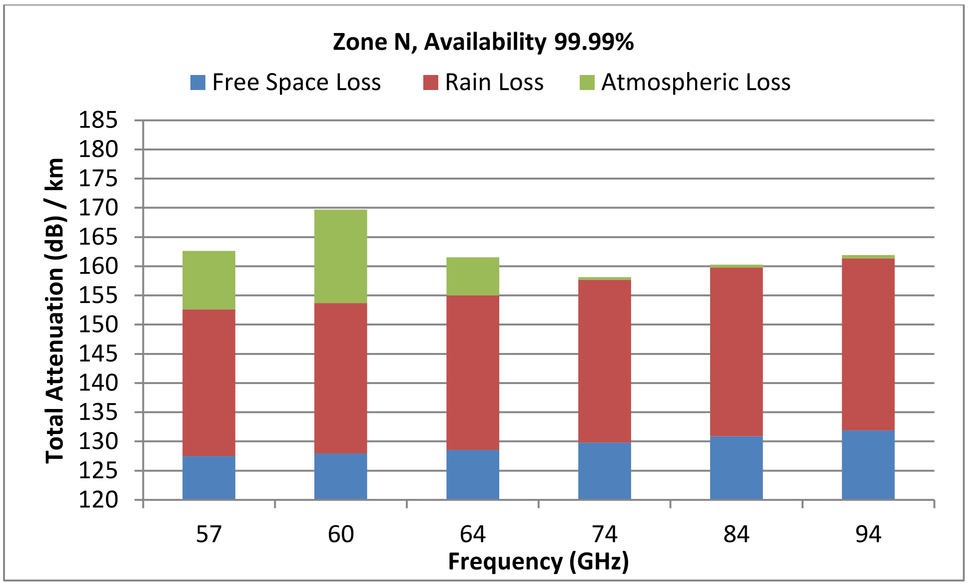

Figure 11: Total attenuation (dB) / km breakdown at various frequencies V-band and E-band frequencies for rain Zone N with 99.99% link availability

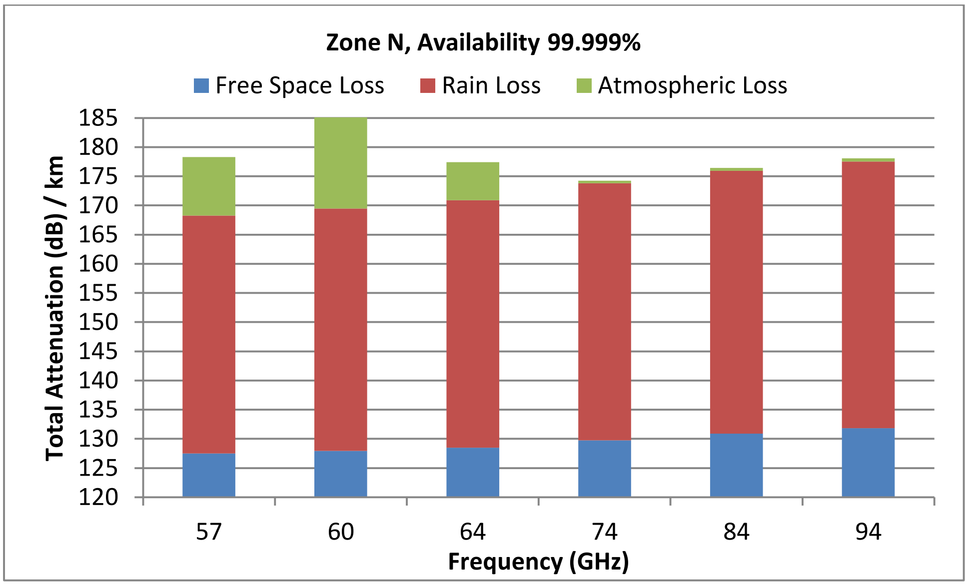

Figure 12: Total attenuation (dB) / km breakdown at various frequencies V-band and E-band frequencies for rain Zone N with 99.999% link availability

DISCUSSION OF RESULTS

Analysis of results reveal important points to take into consideration, when it comes to the deployment of 60 GHz radios. The maximum range is less than 2 km for all rain zones for data rates equal to OC-3 and 4-nine link availability or higher, respectively. The maximum range, is however, limited to the considered EIRP of 60 dBm. The maximum allowed EIRP by FCC recommendation is 82 dBm. The extra 22 dB in EIRP promises even an extension beyond the 2 km range. This would provide a competitive edge over the higher licensed frequency bands, particularly at the 80/90 GHz. The findings could motivate the ETSI to look into increasing the EIRP beyond the current maximum of 55 dBm; particularly for suburban areas. The 60 GHz band would be attractive to the future deployment of 5G networks, particularly in urban cities; where cellular ranges would be relatively smaller, data rates would be relatively higher and link availabilities would fall between 4-nines and 5-nines. The continued improvement in power transmitters at 60 GHz band with higher gain and reduced noise figure would undoubtedly contribute towards the improvement of radio link performance and quality. One more thing to add is that rain attenuation within a rain zone and it effect on link availability, as results show, is not uncertain, when it comes to deployment. Unlike 60 GHz radio links, FSL link availability is highly uncertain due to the high variability of denseness of fog, throughout the hours of the day, which makes the FSL maximum range lower than 300 m at 99.95% link availability. Furthermore eye safety remains an issue, particularly at low altitudes.

60 GHz VERSUS FSL TECHNOLOGIES

FSL and 60 GHz radios are two promising wireless alternatives for Broadband access. They have large cost saving advantage over leasing OC-3 /OC-12/ OC-24 links. They are unlicensed with easy installation and maintenance, as long as roof rights are assured. Table 5 compares the two technologies. Link availability precision, certainty and cost are what distinguishes 60 GHz links from FSO, if relative short distance is considered [12]. The 70 GHz licensed link provides a very high link availability at medium distances but at a relatively medium cost [12]. The 80/90 link performance can be similar to the performance of the 60 GHz radio link. Notably, 60 GHz could offer one order of magnitude of information transfer density; 16 Mbps/m2 [13] than Ultra wideband (UWB) could offer. Further capacity enhancements can be relatively easily obtained by application of MIMO techniques, since at 60 GHz and higher frequencies, antenna dimensions and mutual distances can be relatively small.

Table 5: Comparison between 60 GHz and FSL Technologies

60 GHz Wireless	Feature	Free Space Laser
460 to 740 m for 99,999% availability 580 to 870 m for 99.99% availability for Continental United States	Range for OC-24 link	less than 300 m for 99.95% availability for most US cities
OC-3, OC-12, (OC-24 recent)	Throughput	OC-3, OC12, OC-24
Free	Spectrum License	Free
Yes	LOS solution	Yes
Yes (both max EIRP and MPE)	TX Power Limit Compliance	Yes (eye safety)
Path loss, oxygen absorption, heavy rain	Range Limiting Factors	Fog, heavy snow, heavy rain
Low	Interference Risk	Very low
Easy install, auto-tracking not required	Link installation and maintenance	Easy install, auto-tracking often required
330x200x330 mm (11 kg)	Size and weight (transceiver)	610x381x394 mm (20 kg)
< $60/Mbps for OC-12	Link cost per link	< $170 /Mbps for OC-3 < $ 90 /Mbps for OC-12
Relatively new	Maturity of technology	Matured technology

Optical fibre is clearly the optimum capacity solution but from a time to market and cost of deployment (rights of way, trenching) point of view, wireless definitely has the edge. Alternative wireless technologies that circumvent these existing problems and provide broadband access are required. FSL and 60 GHz both provide this solution. They are flexible technologies that increase the number of methods of access for the service provider. They each have their niche applications and can be deployed whenever and wherever appropriate in their natural zone of advantage.

There also seems to be a trend towards differentiating the availability guaranteed to customers on the core network compared to a lowering of the same for local access. This is a change in paradigm for most service providers. But if this were to become a reality, alternative technologies like FSL could be widely deployed.

Both FSL and 60 GHz have many potential applications:

- Metropolitan area networks/MAN extension: The use of wireless links for point to point roof top links is a viable application of this technology. The reduced time to market is paramount importance in adding customers or reconfiguring the network.
- Campus area networks: The short hops up to 1 km are an ideal range for campus wide applications. Corporate and educational institutions could be the ideal target.

As additional capacity is required over time, growth of the availability for up to OC12 capacity could be expected. This technology can be applied in may scenarios, including but not limited to MAN extension, campus applications access and network protection. Its high capacity (up to 1 Gbps) at a low link wireless network can be achieved with the placement of new links.

- Temporary deployments while awaiting fibre termination: Since these are unlicensed, it could be used for temporary solutions while awaiting fibre terminations. This would increase customer satisfaction in getting a link up in a timely fashion while waiting fibre install.
- Network protection: These links could also be used for last mile fibre protection in presence of fibre cut. They may also be used together as hybrid FSL/60 GHz solution to provide operational diversity. This hybrid solution could complement each other in maintaining the link range under adverse weather conditions without compromising the link availability.

Some companies, such as [14] have seized the advantages of both bands to manufacture hybrid products; combining FSL and RF millimetre wave radios in the 60 GHz and 70/80/90 GHz bands that would make wireless communication possible in any weather.

At this point, and considering the future fifth generation (5G) backhaul network, it is worth saying the most viable solution is to use optical fiber (OF) together with millimeter-wave radio frequency (mmWave RF) links [15-16]. In ultra-dense cellular networks however, the mmWave RF interference issue may arise, and the mmWave RF capacity, in some cases, may not be enough for the 5G requirements. In addition, installation of OF is sometimes limited due to the high cost, especially in ultra-dense environment, or even impossible because of the restriction on cable installation. A hybrid FSL/mmWave RF technology, which is able to offer a vast bandwidth (comparable to that of OF) over flexible and cost-effective free-space links, therefore can be an effective alternative to both OF and mmWave RF [17-18].

CONCLUSION

FSL and 60 GHz are viable potential alternative broadband access methods that would provide new service opportunities for service providers. Since this technology is unlicensed, their fast and cost effective deployment will allow the service provider to quickly respond to the changing needs of business. FSL is the technology of choice if high capacity is demanded (OC-12 and higher), while lower availabilities (99.5%) can be tolerated and the range (< 300 m) required is small. 60 GHz on the other hand would provide a longer range (960 m, 730 m, 580 m) for OC-3 data rate and 5-nines availability in rain zone D, K and N, respectively, with ease of installation. However, the biggest technical challenge faced, is that the limited range to less than 1 km in most circumstances, unless link availability is relaxed to 4 nines or below. Rooftop rights are a large practical issue that could limit quick deployment. But an intelligent deployment of these technologies for their niche applications will add another powerful tool in the portfolio for low-cost access to customers. Finally 5G hybrid networks; suitable for 5G backhaul networks would witness a good promise for the demanding increase in system capacity and ultra-dense cells at all weather conditions.

REFERENCES

[1] *Propagation data and prediction methods required for the design of terrestrial line-of-sight systems*, Recommendation ITU-R P.530-9, 2001.

[2] *Specific attenuation model for rain for use in prediction methods*, Recommendation ITU-R P.838-3, 2005.

[3] *Characteristics of Precipitation for Propagation Modeling*, Recommendation ITU-R P.837-1ITU, 1994.

[4] T. S. Rappaport, *Wireless Communications*, 3rd ed. Singapore: Pearson Education Inc, 2002.

[5] M.G. Frecassetti, “E-Band and V-Band-Survey on status of worldwide regulation,” ETSI White Paper No. 9 [Online], Jun 2015. Available: http://www.etsi.org/images/files/ETSIWhitePapers/etsi_wp9_e_band_and_v_band_survey_20150629.pdf

[6] Gayan de Alwis, Murray Delahoy, “60 GHz band millimeter wave technology,” Doc. 3/04[Online], Australian Communications Authority, Dec 2004. Available: http://www.acma.gov.au/webwr/radcomm/frequency_planning/radiofrequency_planning_topics/docs/sp3_04_60%20ghz%20mwt%20-%20discussion%20paper-final.pdf

[7] Mathuranathan Viswanathan, “Performance comparison of digital modulation techniques”, Published by Mathuranathan [Online], Apr 2010. Available: http://www.gaussianwaves.com/2010/04/performance-comparison-of-digital-modulation-techniques-2/

[8] J.G. Proakis, *Digital Communications*, 3rd ed. New York: McGraw-Hill, 1995.

[9] P. Adhikari, “Understanding Millimeter Wave Wireless Communication,” US Federal white paper L1104-WP. ©2008 Loea Corporation [Online], Leoa corporation, San Diego, CA, USA, 2008. Available: http://www.loeacom.com/pdf%20files/L1104-WP_Understanding%20MMWCom.pdf

[10] J. C. Palais, *Fibre Optic Communications*, 4th ed. Harlow: Prentice Hall, 1998.

[11] Isaac I. Kim, Joseph Koontz, Harel Hakakha, Prasanna Adhikari, Ron Stieger, Carter Moursund, Micah Barclay, Alyssa Stanford , Richard Ruigrok,

John J. Schuster, Eric J. Korevaaret, "Measurement of scintillation and link margin for the TerraLink laser communication system, " *in Proc. SPIE 3232, Wireless Technologies and Systems: Millimeter-Wave and Optical,* Dallas, TX, Jan 1998, pp.100-118.

[12] Bridgewave. (2016). *Comparison Chart: Advantages and disadvantages of today's point-to-point high-capacity (several hundred Mbps to Gbps) link solutions* [Online]. Available:http://www.bridgewave.com /products/comp_chart.cfm

[13] P.F. Smudlers, "60 GHz radio: prospects and future directions," *in Proceedings Symposium IEEE Benelux Chapter on Communications and Vehicular Technology*, vol. 8, pp.1-8, Nov 2003,

[14] OpenPR. (Aug 2011). *Lightpointe introduces hybrid optical-RF wireless series, enabling next generation ultra-reliable gigabit Ethernet connectivity* [Online]. Available: http://www.openpr.com/news/search result.html

[15] X. Ge, S. Tu, G. Mao, C.-X. Wang, T. Han, "5G ultra-dense cellular networks," *IEEE Wireless Com*., vol. 23, no. 1, pp. 72–79, Feb 2016.

[16] C. Dehos, J. L. Gonzalez, A. D. Domenico, D. Ktenas, L. Dussopt, "Millimeter-wave access and backhauling: the solution to the exponential data traffic increase in 5G mobile communications systems," *IEEE Com. Mag*., vol. 52, no. 9, pp. 88–95, Sep 2014.

[17] H. Dahrouj, A. Douik, F. Rayal, T.Y. Al-Naffouri, M.S. Alouini, "Cost-effective hybrid RF / FSO backhaul solution for next generation wireless systems," *IEEE Wireless Com*., vol. 22, no. 5, pp. 98-104, Oct 2015.

[18] D. Schulz, V. Jungnickel, C. Alexakis, M. Schlosser, J. Hilt, A. Paraskevopoulos, L. Grobe, P. Farkas, R. Freund, "Robust optical wireless link for the backhaul and fronthaul of small radio cells," *IEEE/OSA J. Lightw. Technol.*, vol. 34, no. 6, pp. 1523–1532, Mar 2016.