

THE LAST-MILE SOLUTION: HYBRID FSO RADIO

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INTRODUCTION

Presently the “last mile” remains an unsolved dilemma for the world's telecommunications carriers, despite the many attempts at attacking the problem:

- DSL and cable modems can, to some extent, take advantage of existing wired networks; however, they cannot provide true broadband services in a deterministic way. DSL technology is plagued by the actual topology of the copper to which it is attached, and is limited in distance (from the central office) and capacity (several Mbps). Cable modems enjoy higher capacity, yet the channel is shared and the amount of bandwidth at any given time is not guaranteed.
- Unlicensed wireless RF technologies are also limited in capacity, and carriers are reluctant to install systems that might have interference issues. Licensed wireless RF technologies can provide very high capacity, but the nonrecurring initial capital expenditures for spectrum licenses usually makes the business model very difficult to implement. Additionally, in any given city the licenses permit only two carriers to participate.
- Free-space optical (FSO) technologies offer optical capacity but are typically deployed at lengths under a kilometer for reasonable availability. FSO has a major time-to-market advantage over fiber. Fiber builds often take 6 to 9 months, whereas an FSO link can be operational in a few days.
- Millimeter wave technology at 60 GHz is unlicensed due to oxygen absorption and is capable of higher capacity than frequencies at longer wavelengths. However, it is susceptible to outage in heavy rain regions and is thus limited in range (about 400 m or so).
- W-band technologies are just starting to come out of the lab and are being licensed on a link-by-link basis. However, they are likely to be licensed in the future due to their relatively good propagation characteristics.

**THE SOLUTION:
HYBRID FSO
RADIO**

A new solution to the last-mile problem uses the strengths of two of these technologies to mutually mitigate each other's weakness. Hybrid FSO Radio (HFR) combines free-space optical and 60 GHz millimeter wave (MMW) technologies to provide, for the first time, a true carrier grade (99.999%) wireless, redundant, unlicensed system capable of ranges greater than 1 km in **all** weather conditions. HFR is poised to be the disruptive technology that will help carriers liquidate bandwidth assets currently locked in fiber networks.

Free-Space Optics and Range Limitations

The link equation for a free-space optical system is actually very simple at a high level (leaving out optical efficiencies, detector noises, etc.). The equation, illustrated in Figure 1, shows that the amount of received power is proportional to the amount of power transmitted and the area of the collection aperture. It is inversely proportional to the square of the beam divergence and the square of the link range. It is also inversely proportional to the exponential of the product of the atmospheric attenuation coefficient (in units of 1/distance) and the link range.

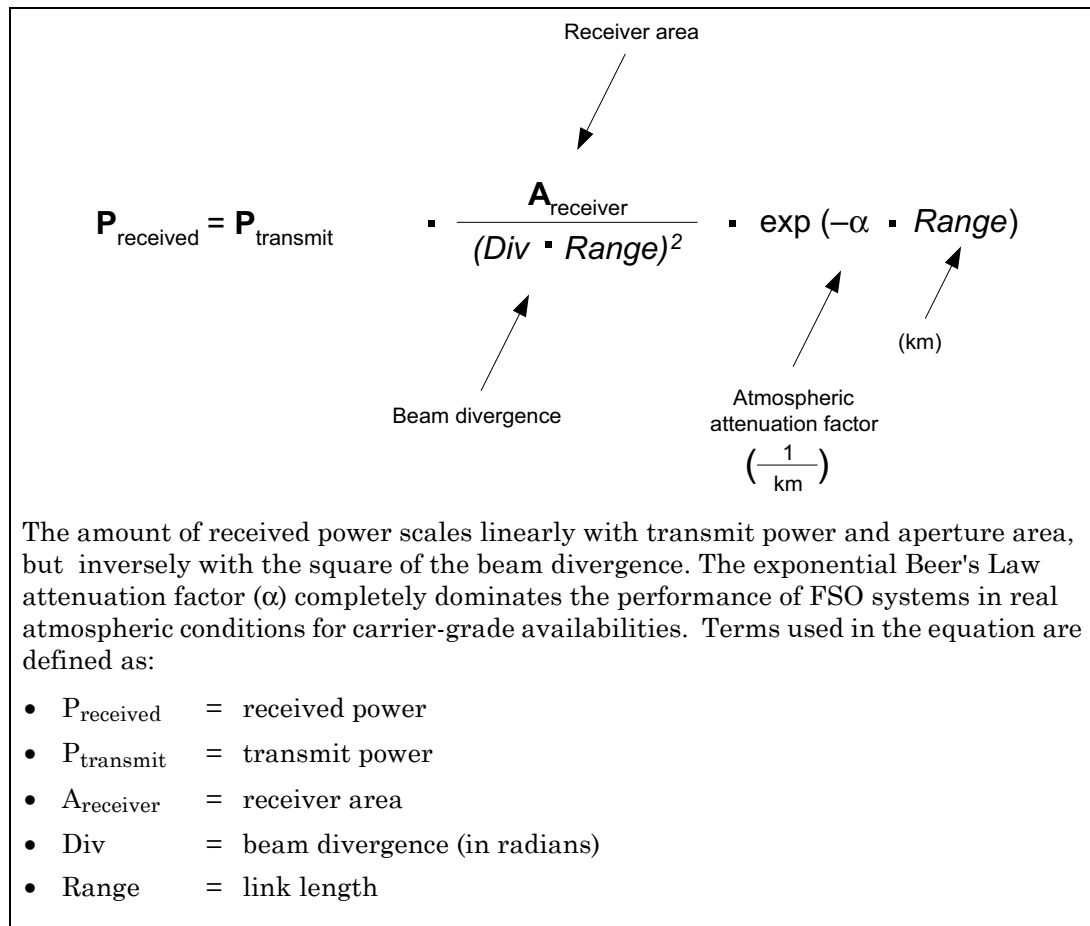


Figure 1. Basic FSO link equation

As shown in this equation, the variables that can be controlled are the transmit power, the receive aperture size, the beam divergence and the range of the link. The atmospheric attenuation coefficient is uncontrollable in an outdoor environment and is roughly independent of wavelength in heavy attenuation conditions. Unfortunately, the received power is exponentially dependent on the product of the atmospheric extinction coefficient and the range. In real atmospheric situations and for carrier-class products (i.e., availabilities at 99.9% or better), this term overwhelms everything else in the equation. What this means is that a system designer can choose to use huge transmit laser powers, design large apertures, and employ very tight beam divergences, yet the amount of received power will remain essentially unchanged.

In foggy conditions, the atmospheric loss component of the link equation dominates by many orders of magnitude, essentially overwhelming any system design choices that could affect availability. For connections that are intended to be carrier class using free-space optical systems, this fact needs to be accepted and must be taken into account for network design. The only other variable under the designer's control is link range, which must be kept short enough that atmospheric attenuation is not the dominant term in the link equation. As will be discussed in a later section, this implies that the link range **must** be less than 500 m for carrier-class availability. Under this constraint, efficient designs can be produced that provide economical, reliable operation.

Figure 2 shows a tabular link budget for the top five free-space optical system manufacturers. Most of the system parameters are freely available from manufacturers data sheets; however, where a parameter has been assumed, it is noted. The assumed atmospheric attenuation condition is 100 dB/km, which is a moderate fog. The link ranges were adjusted for each system such that the margins came out to approximately zero, representing the threshold of communication. It is interesting to note the wide variety of aperture size, wavelengths, transmit divergences and transmit power (all of the adjustable system parameters) employed in these systems. However, as previously discussed, the maximum link ranges are all about the same (about ± 30 m or so), illustrating the point that there is not a lot system designers can do to increase link range in realistic carrier-grade atmospheric conditions.

The key issue for carriers deploying free-space optical systems is system availability. System availability depends on many factors, such as equipment reliability and network design (redundancy for example), but these are well known and fairly quantifiable. The biggest unknown is the statistics of atmospheric attenuation. While almost all major airports around the world maintain visibility statistics (which can be converted to attenuation coefficients), the spatial scale of visibility measurements is rough (generally 100 m or so) and the temporal scale is infrequent (hourly in most cases). With the crude spatial and temporal scales, estimates of availability for carrier-grade equipment (99.9% or better) are limited to 99.9% or worse. These huge databases are therefore not useful except for estimating the lowest acceptable carrier grade of service. To permit carriers to write reasonable service-level agreements, better data is needed. AirFiber has deployed instruments capable of acquiring this data running continuously for several years. These instruments, which include a nephelometer and a weather benchmark system, provide data at the correct spatial and temporal resolution for accurate estimates of availability and link range to be made.

Even with a variety of design approaches:

- Transmit power
- Receive apertures
- Beam divergence

... when a modest 100 dB/km fog is encountered...

the net difference in link range is only about +/-30 m

	AirFiber	Vendor A	Vendor B	Vendor C	Vendor D	Vendor E	
Transmitter	AlGaAs	AlGaAs	EDFA	InGaAs	AlGaAs	AlGaAs	
Modulation Format	NRZ OOK	NRZ OOK	NRZ OOK	NRZ OOK	NRZ OOK	NRZ OOK	
Receiver	Si APD	Si APD	PIN	PIN	Si APD	Si APD	
PRODUCT SPECIFICATIONS							
Wavelength	785	850	1550	1550	850	910	nm
Data Rate	1250	1250	1250	155	1250	622	Mbps
Average Laser Power	18	30	1000	320	16	25	mW
Peak Laser Power	36	60	2000	640	31	50	mW
Transmit Aperture	8	5	40	5	5	15	cm
Transmit Divergence	0.5	2.0	2.0	4.3	2.0	11.0	mrad(1/e²)
Receive Aperture	8	20	40	20	19	17	cm
Optical Background	0	0	0	0	0	0	W/m ² /nm/sr
Receiver Field of View	3	3	3	3	3	3	mrad(1/e ²)
Receive Filter Width	25	25	25	25	25	25	nm
Receiver Sensitivity	1000	1000	1000	1000	1000	1000	nW
Bit Error Rate	1 x 10 ⁻¹²	1 x 10 ⁻¹²	1 x 10 ⁻¹²	1 x 10 ⁻¹²	1 x 10 ⁻¹²	1 x 10 ⁻¹⁰	
ATMOSPHERIC EFFECTS							
Attenuation - Moderate Fog	-100	-100	-100	-100	-100	-100	dB/km
Peak Laser Transmit Power	-14	-12	3	-2	-15	-13	dBW
Extinction Ratio Degradation	0	0	0	0	0	0	dB
Transmit Optics Degradation	0	0	-15	0	0	0	dBW
Pointing Loss	-1	-1	-1	-1	-1	-1	dB
Geometric Range Loss	-7	-10	-6	-18	-10	-22	dB
Atmospheric Loss	-34	-33	-38	-36	-30	-20	dB
Atmospheric Loss	-34	-33	-38	-36	-30	-20	dB
Atmospheric Scintillation Fade	-1	-1	-1	-1	-1	-1	dB
Receive Optics Attenuation	-1	-1	-1	-1	-1	-1	dB
Bandpass Filter Loss	-1	-1	-1	-1	-1	-1	dB
Miscellaneous Loss Elements	0	0	0	0	0	0	dB
ZERO RECEIVE POWER							
Received Peak Power at Detector	-60	-60	-60	-60	-60	-60	dBW
Required Peak Power at Detector	-60	-60	-60	-60	-60	-60	dBW
Link Margin at Range	0	0	0	0	0	0	dB
Range	341	331	381	361	305	203	m

The system design space of transmit power, receive aperture size, beam divergence, and wavelength has been fairly well explored by vendors, yet in a modest fog (100 dB/km) the range performance of all of the products is very similar.

Figure 2. FSO vendor performance comparison

Figure 3 plots this data for two cities, Tokyo and San Diego. The cumulative probability density functions for Tokyo and San Diego are represented by solid boxes and open boxes, respectively. Also plotted is the link budget equation for an AirFiber product (other vendors' products will have roughly the same link margin). The left vertical axis shows the percentage of time that attenuation is greater than or equal to a given value.

The horizontal axis is attenuation in dB/km, while the right vertical axis is the maximum link range at zero link margin. To use the chart, choose an availability, say 99.9% (as shown by the green dotted line); move horizontally to the desired city (Tokyo in this example); move vertically to the link budget equation; and finally move horizontally to the maximum link range (in the case of Tokyo, it is about 350 m). It is interesting to note that Tokyo is qualitatively in the top 10% of cities for clarity of the atmosphere and San Diego is in the bottom 10%. Therefore, for most deployments, the maximum range will fall somewhere in between these two cities, certainly less than 500 m in most cases.

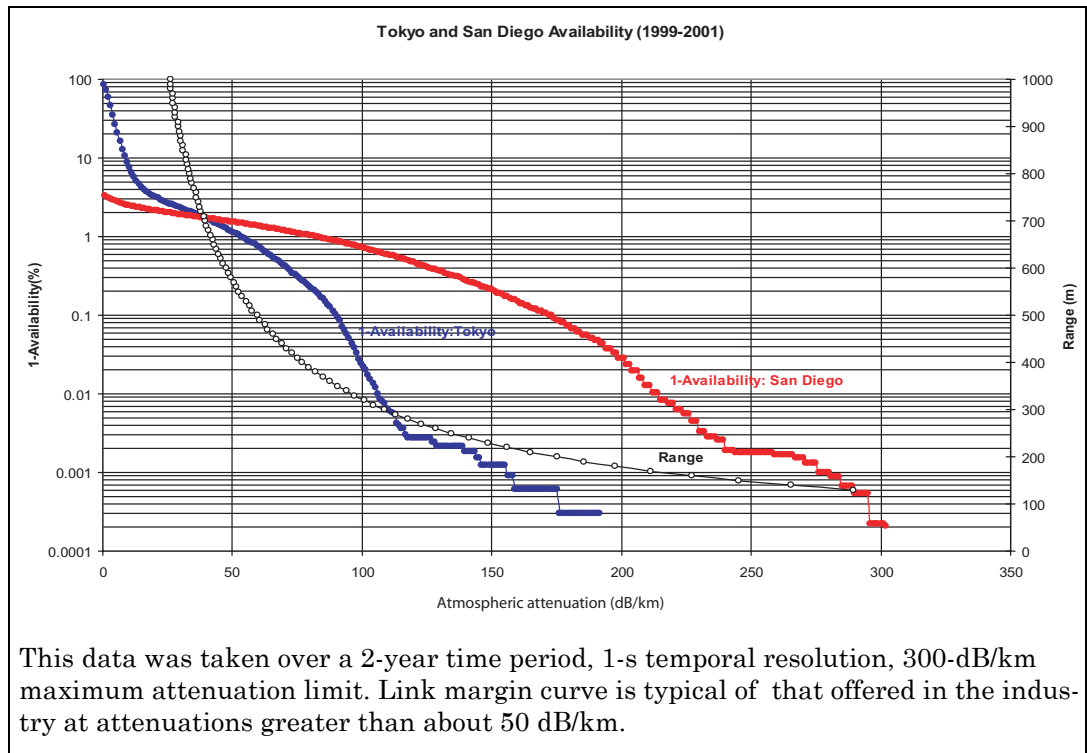


Figure 3. FSO availability examples

Another topic of frequent discussion concerning the performance of free-space optical systems is the issue of atmospheric propagation and wavelength. One generally held belief is that systems operating at longer wavelengths have better range performance than systems at shorter wavelengths. Figure 4 shows several calculations performed using MODTRAN—an industry standard atmospheric propagation modeling tool—for a 1 km path length for which the x-axis is wavelength. The conditions were a visibility range of 200 m, typical of an advection fog. The y-axis in the top panel is transmission from a minimum of 0 to a maximum of 1. The top panel shows the amount of absorption due to water only in the atmosphere. Here there are many wavelengths that propagate very poorly due to absorption by water vapor, particularly near 1.3–1.4 microns. The second panel shows absorption due to oxygen and carbon dioxide, which are relatively narrow lines and are easily avoided.

The third panel shows the effects of Mie scattering by water droplets in the fog. Clearly this is the dominant loss mechanism under these conditions and is basically independent of wavelength (it's actually a little worse at 1.5 microns than at 785 nm, for example). Finally the bottom panel shows the combined effects of all three loss mechanisms. Again the result is basically independent of wavelength. There is no advantage in propagation range by using longer wavelengths in any reasonably thick fog. Finally, the same calculations were carried out all the way to millimeter waves, as illustrated in Figure 5. This was done for completeness and to ensure that the attenuation reduced at RF frequencies to generally accepted values. Not until the wavelength reaches millimeter size (RF) is attenuation markedly reduced.

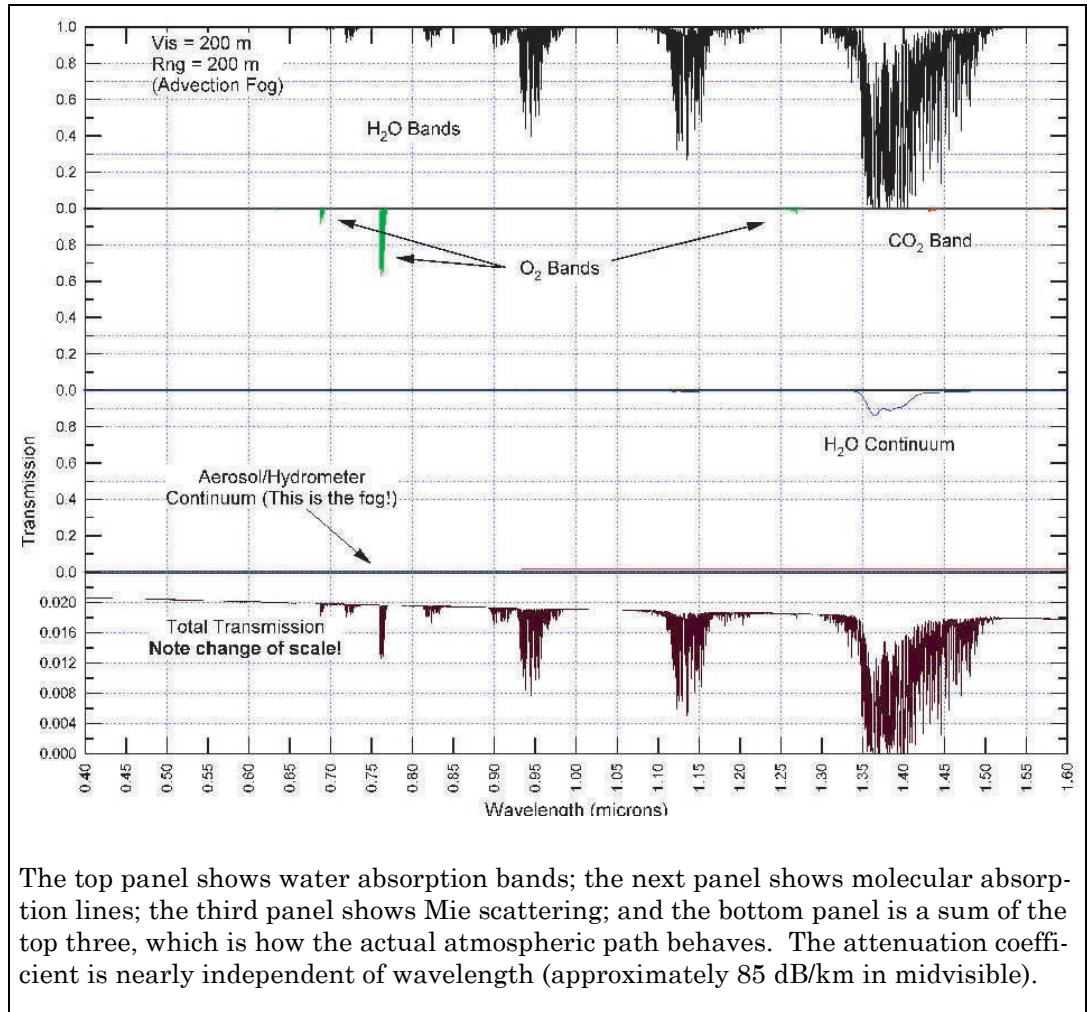


Figure 4. MODTRAN calculation of propagation versus wavelength in moderate fog

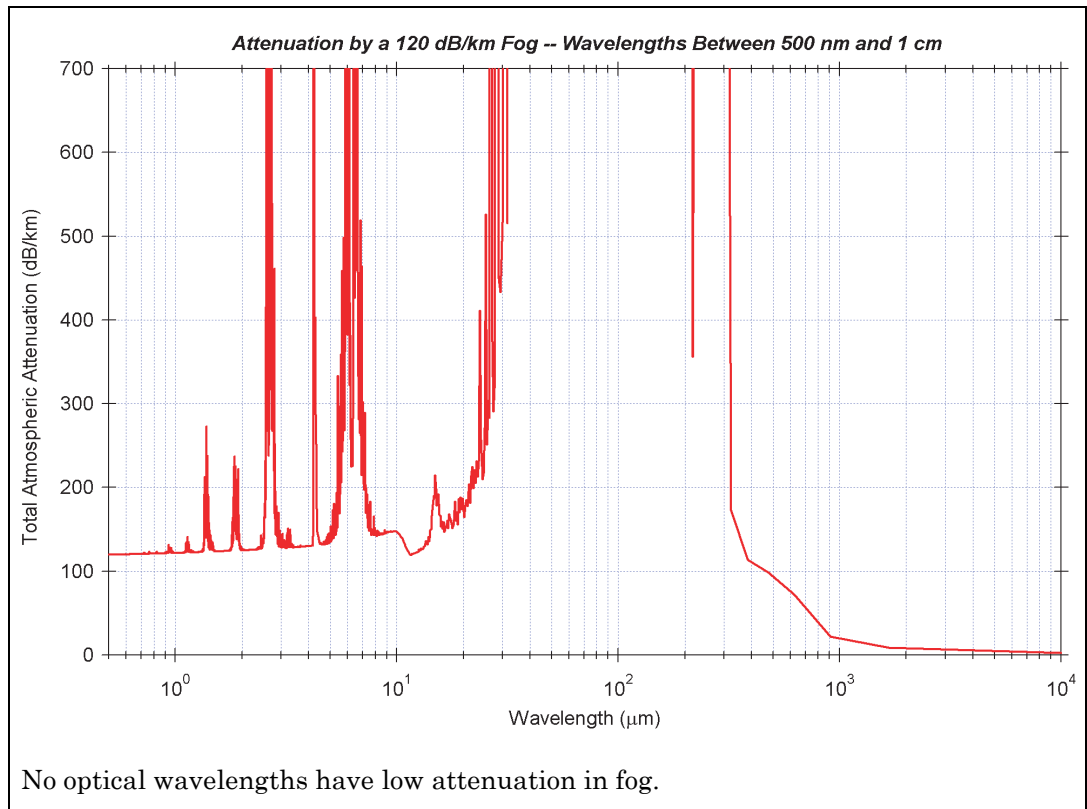


Figure 5. Same calculation as in Figure 4, extended to millimeter waves (and presented as attenuation rather than transmission)

In summary, we can clearly state that for the majority of cities around the world, the carrier-class distance (as defined by 99.9% availability or better) for FSO is less than 500 m. In addition, despite numerous claims, all free-space optics vendors have about the same range performance in carrier-grade conditions (99.9% or better) due to complete domination of the link budget equation by the atmospheric attenuation factor in high attenuation situations. Finally, wavelength has virtually no effect on propagation range under carrier-grade conditions for wavelengths from visible all the way up to millimeter wave (RF) scales.

60 GHz mm Waves and Rain Attenuation

The link equation for an MMW system can be written identically to that for an FSO system. There are three components of loss: free-space loss, gaseous loss, and loss due to particulate scattering, primarily from precipitation. Just as in FSO, free-space loss is driven by transmit power, receive aperture size, and beam divergence. MMW systems at 60 GHz are limited to output powers of about 500 mW (total radiated power) for license-free operation. System designers are free to choose the antenna size, which generally dictates its gain. The size of the antenna determines the amount of intercepted MMW energy and determines the beam divergence, since the system is diffraction limited.

The only gaseous molecular absorption of any significance at 60 GHz is oxygen, which is significant. Oxygen absorption at 60 GHz is about 16 dB/km (near sea level), which naturally attenuates the signal at all times, regardless of the weather. One might ask why choose this wavelength if it is limited in range? The answers are frequency reuse and licensing. Since the MMW energy is absorbed so readily, there is little chance of systems interfering with each other. This fact drove the decision to permit the 60 GHz band to be unlicensed; there is no need to share spectrum due to the nature of the atmosphere. For most reasonably sized systems with an antenna diameter of about 13 in., the clear air range is about 1500 m (Figure 6 shows the link budget parameters for this particular system).

Transmit Power	Pt	10	dBm
Transmit Gain	Gt	43	dBi
Receive Gain	Gr	43	dBi
Wavelength	Lambda	0.005	m
Range	Range	1500	m
Oxygen Absorption	Losses Clear Air	0.016	dB/m
	Losses other (rain)	0	dB/m
Received Power	Pr	-59.52662237	dBm
Noise Eq Input Pwr	Nein	-78.20381423	dBm
Signal/Noise	S/N	18.67719185	dB
	Min S/N	18	dB
	Margin	0.67719185	dB
Noise Factor	NF	11	dB
Bandwidth	BW	300000000	Hz
	temperature	290	K
Boltzmann	k	1.3807E-23	J/K
	Nein	-78.20381423	dBm

The maximum range is about 1500 m primarily due to oxygen absorption.

Figure 6. Simple link budget for a 60 GHz MMW system

Unfortunately, rain does affect the performance of 60 GHz systems, especially in heavy rain regions such as Crane D and E. Figure 7 shows rain rates and attenuation as a function of frequency in the MMW regime. Figure 8 shows the range performance of a typical 60 GHz system for various rain regions. In heavy rain regions the carrier-grade range is limited to less than 500 m, similar in value to fog-imposed limitations on FSO.

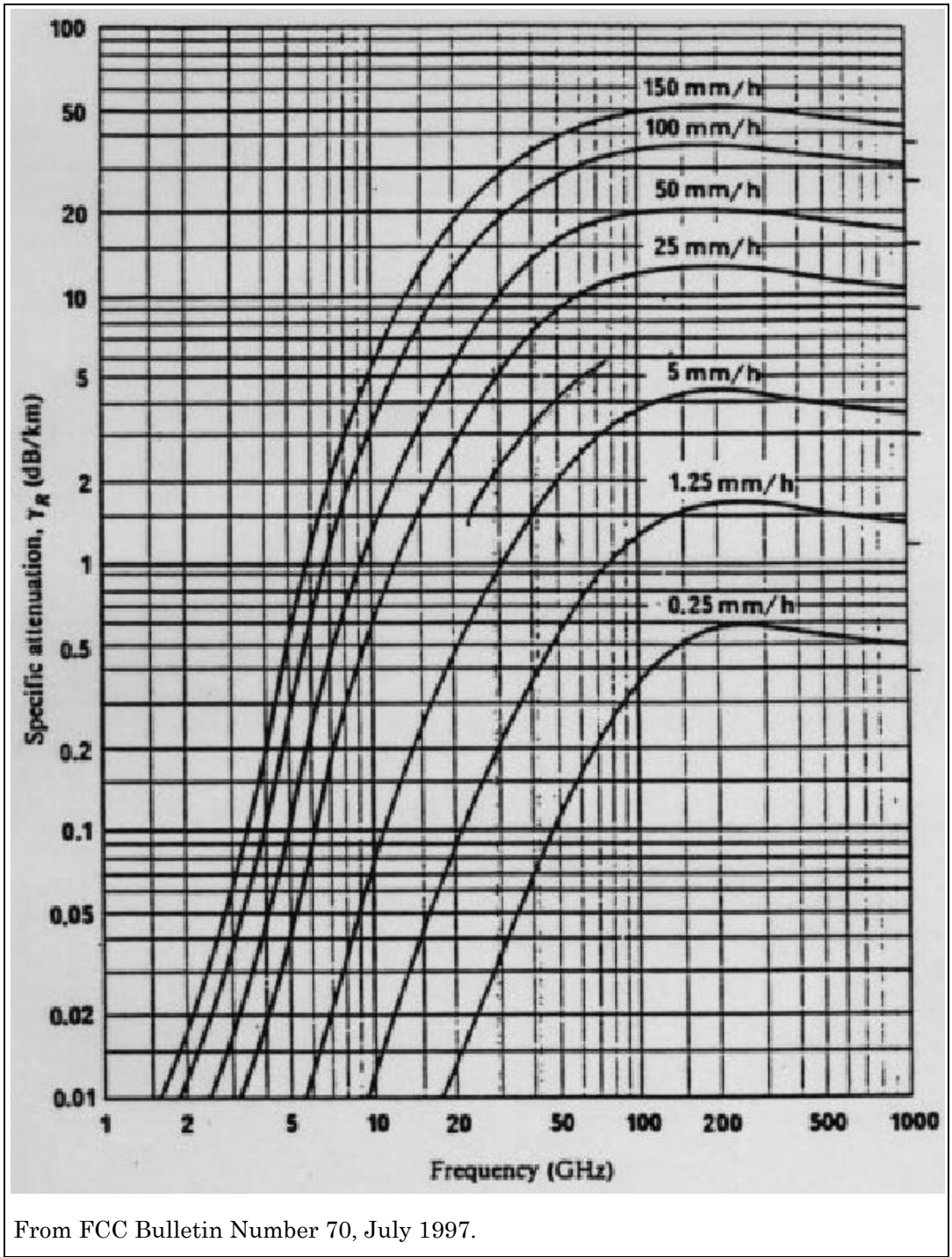


Figure 7. Rain rate and attenuation at MMW frequencies

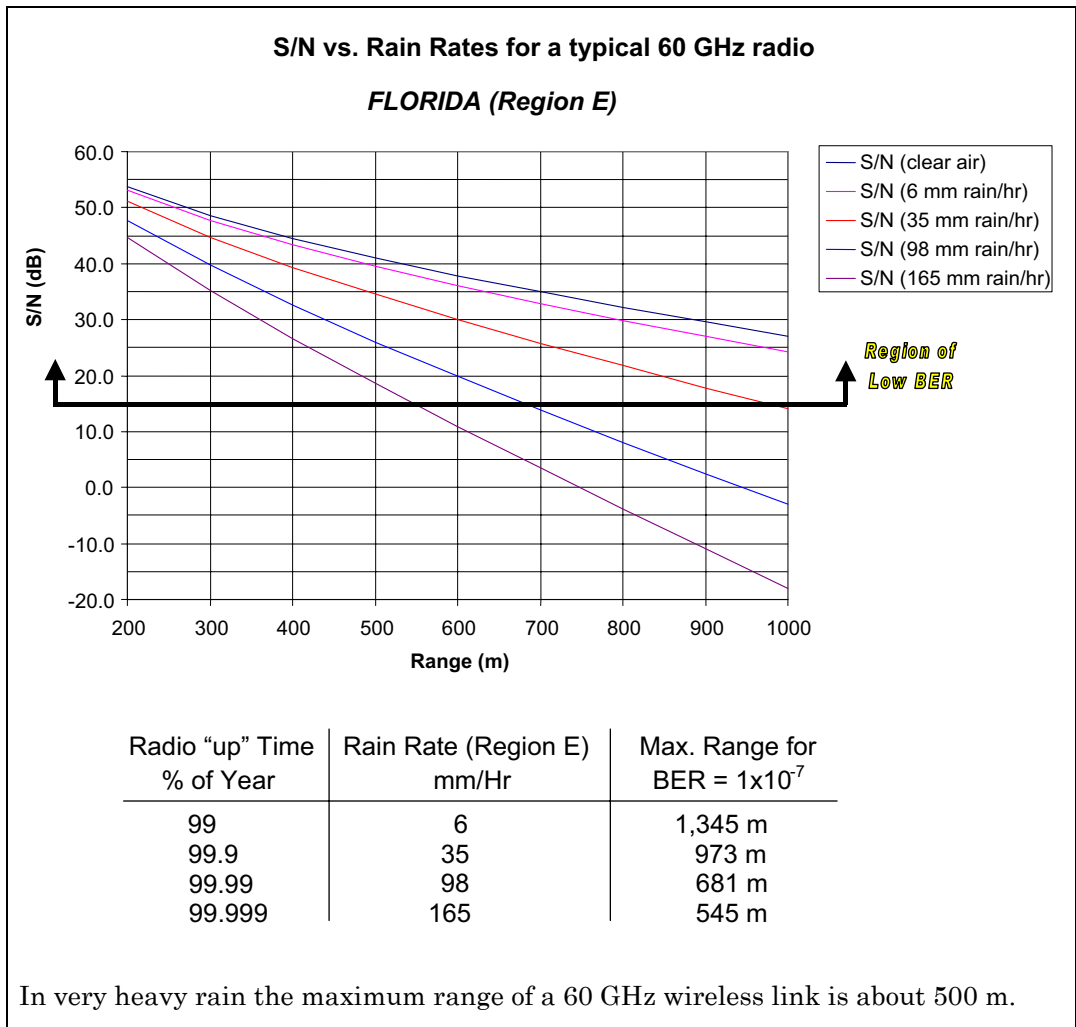


Figure 8. Range performance of a 60 GHz system in a heavy rain region

**ONE + ONE
EQUALS FIVE
(9s): HFR**

Typically, nature can be cruel; however, sometimes she permits symbiotic relationships where the whole is greater than the sum of the parts. This is the case with an HFR system. It turns out that fog has virtually no impact on the propagation distance of 60 GHz radios, as shown by Figure 9. The arrow at the 60 GHz frequency indicates that attenuation due to fog is less than 0.2 dB/km, essentially lost in the noise for link range calculations. Fortunately it also turns out that rain does not cause a major problem for FSO systems.

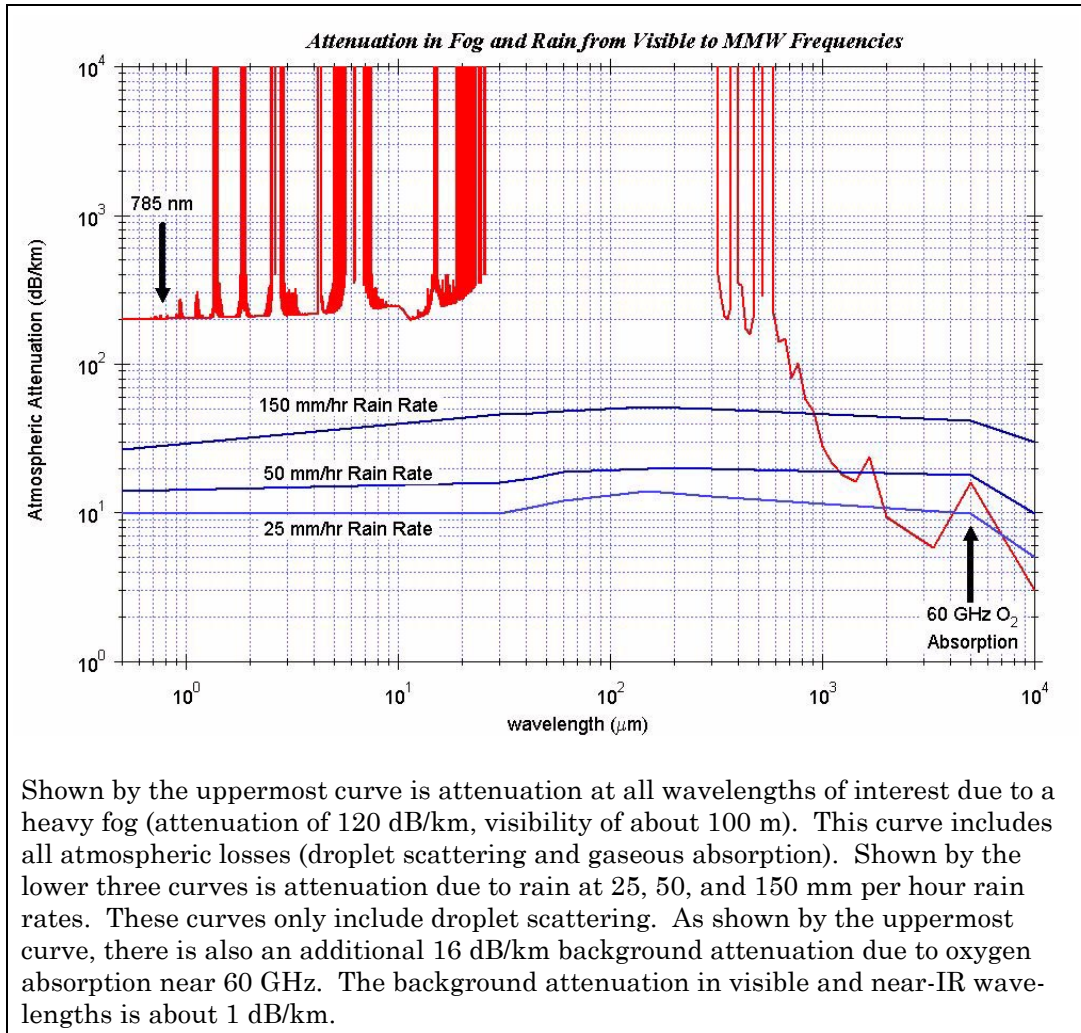


Figure 9. Attenuation by wavelength for fog and rain conditions from visible to millimeter wavelengths

Figure 10 shows aggregated nephelometer data collected in 13 locations over roughly 2 years. We believe that the black curve, which is a fit to **all** of the data—measured and theoretical—shown on the figure, represents actual field conditions on average. Because these calculations are very sensitive to rain drop size distributions, an average over actual data plus theoretical values provides a realistic picture of what is seen in the field. For very heavy rain regions (>150 mm/hr), where the MMW system will be down, the curves predict FSO attenuation around 30 dB/km. This supports our belief that a 1-km range HFR system will operate at very high availability. If the raindrop size distribution leans towards larger droplets (4 mm or so) the attenuation at a rain rate of 150 mm/hr will be about 16 dB/km; if the droplet size is more like 2 mm, the attenuation could be as high as 35 dB/km.

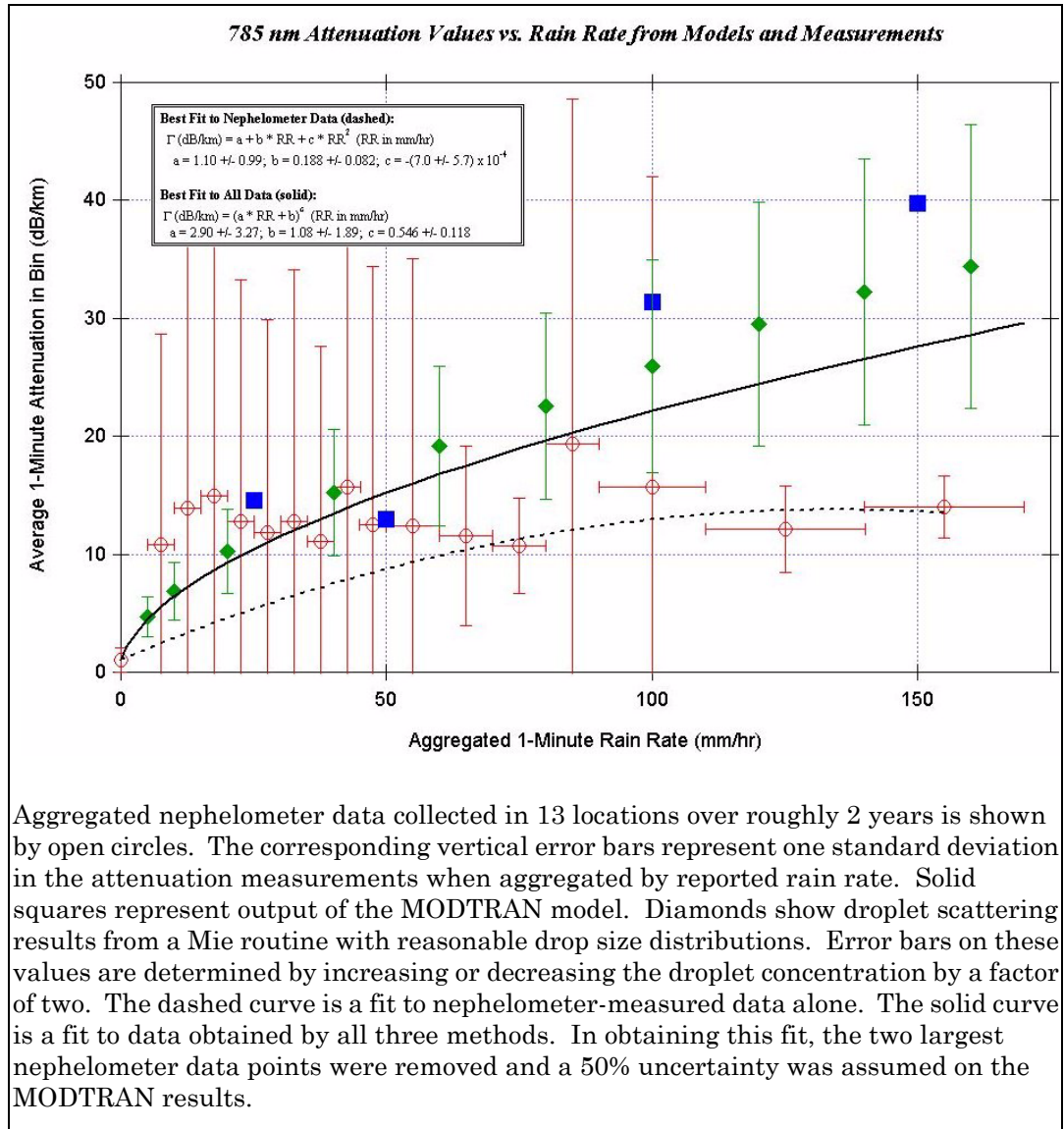
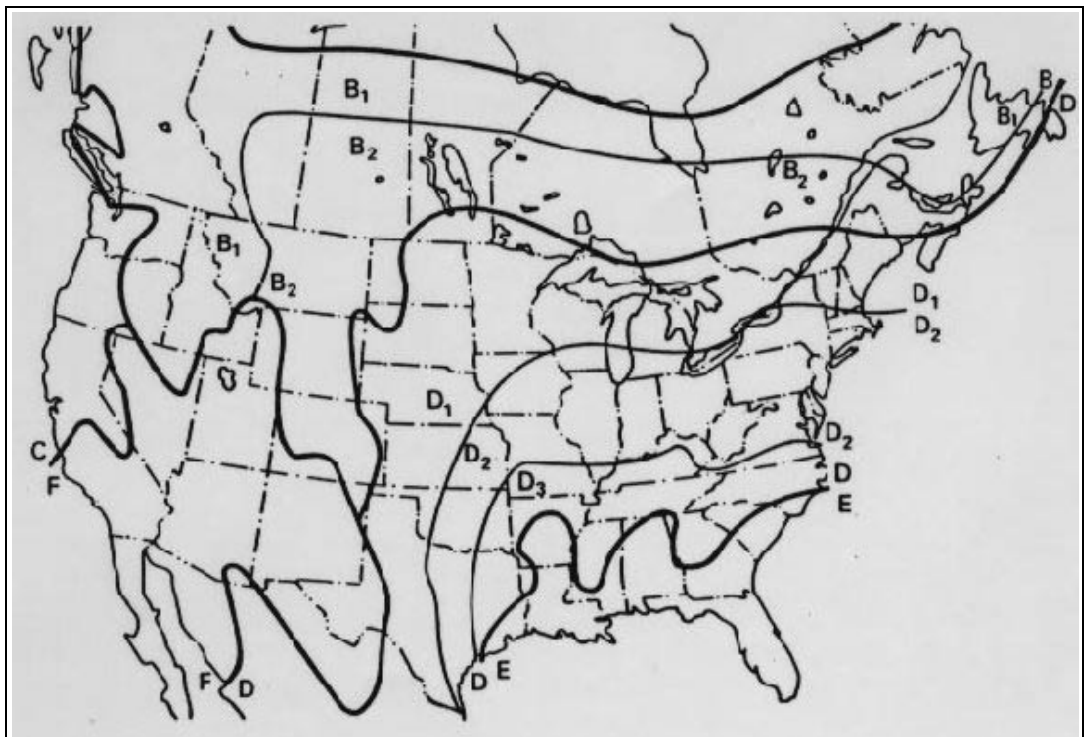


Figure 10. AirFiber nephelometer and theoretical data—rain rate versus attenuation

Symbiosis between the two technologies means that a combined system, where the path data is switched hitlessly between the two paths in a protocol-independent manner, has a greatly extended range at carrier grade (99.999%) availability. Figure 11 shows the Crane model rain regions for the United States, while Figure 12 shows the associated rain rate and CDF of rain rate for all the defined rain regions. Using these statistical models for rain rate in the various regions, along with detailed models of FSO and MMW subsystem performance, highly accurate availability predictions for an HFR system are possible. Figures 13–15 are bar graphs of range at a given availability (99.999%, 99.995%, 99.99%); the 60 GHz system alone is shown in gray and an HFR system is shown in black. Qualitatively the HFR has about twice the range of the 60 GHz subsystem alone. For North America, the **shortest** 99.999% distance for the HFR (E rain region) is between 800 m to 1 km. For 99.995% availability, the distance for an HFR system in all of North America is over 1 km. The HFR system offers the best data rate, range performance, and statistical availability of any unlicensed wireless system built to date.



FCC Bulletin Number 70, July 1997.

Figure 11. Rain regions for the United States

Percent of Year	RAIN CLIMATE REGION												Minutes per Year	Hours per Year
	A	B ₁	B	B ₂	C	D ₁	D ₂	D ₃	E	F	G	H		
0.001	28.5	45	57.5	70	78	90	108	126	165	66	185	253	5.26	0.09
0.002	21	34	44	54	62	72	89	106	144	51	157	220.5	10.5	0.18
0.005	13.5	22	28.5	35	41	50	64.5	80.5	118	34	120.5	178	26.3	0.44
0.01	10.0	15.5	19.5	23.5	28	35.5	49	63	98	23	94	147	52.6	0.88
0.02	7.0	11.0	13.5	16	18	24	35	48	78	15	72	119	105	1.75
0.05	4.0	6.4	8.0	9.5	11	14.5	22	32	52	8.3	47	86.5	263	4.38
0.1	2.5	4.2	5.2	6.1	7.2	9.8	14.5	22	35	5.2	32	64	526	8.77
0.2	1.5	2.8	3.4	4.0	4.8	6.4	9.5	14.5	21	3.1	21.8	43.5	1052	17.5
0.5	0.7	1.5	1.9	2.3	2.7	3.6	5.2	7.8	10.6	1.4	12.2	22.5	2630	43.8
1.0	0.4	1.0	1.3	1.5	1.8	2.2	3.0	4.7	6.0	0.7	8.0	12.0	5260	87.7
2.0	0.1	0.5	0.7	0.8	1.1	1.2	1.5	1.9	2.9	0.2	5.0	5.2	10520	175
5.0	0.0	0.2	0.3	0.3	0.5	0.0	0.0	0.0	0.5	0.0	1.8	1.2	26298	438

From FCC Bulletin Number 70, July 1997.

Figure 12. Rain rates cumulative probability density function in various rain regions

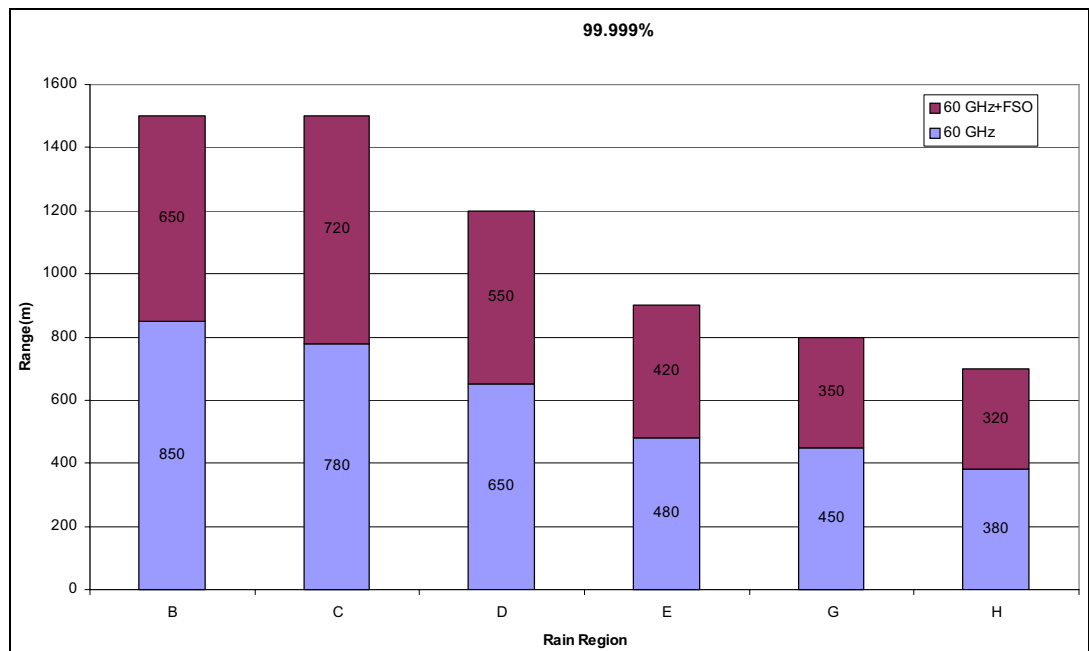


Figure 13. Predicted MMW and HFR maximum ranges in various rain regions for 99.999% statistical path availability

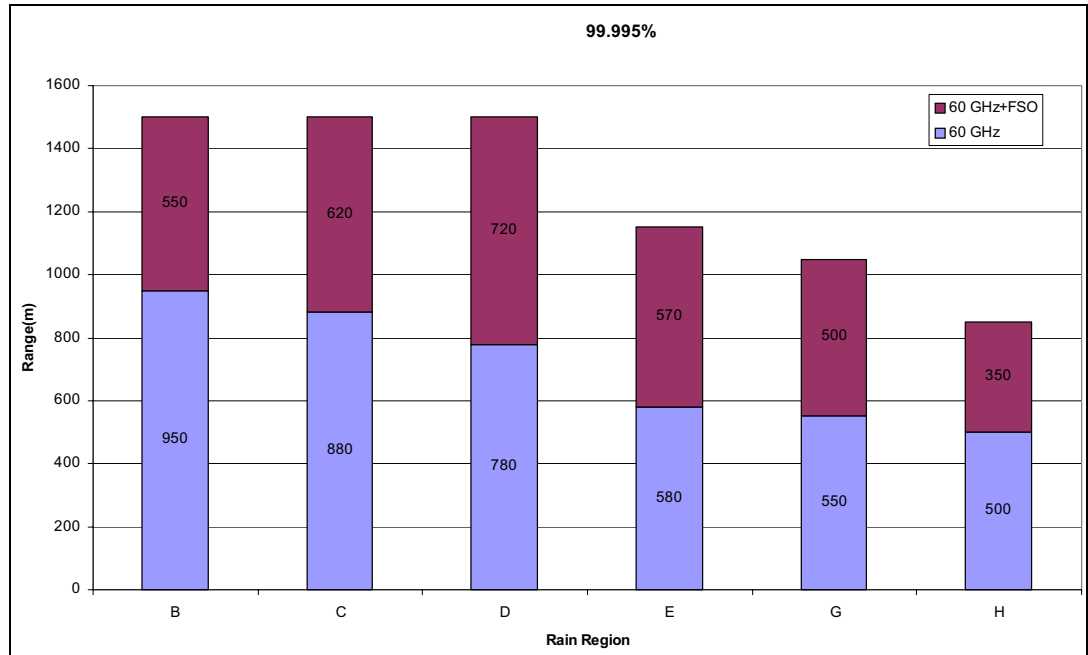


Figure 14. Predicted MMW and HFR maximum ranges in various rain regions for 99.995% statistical path availability

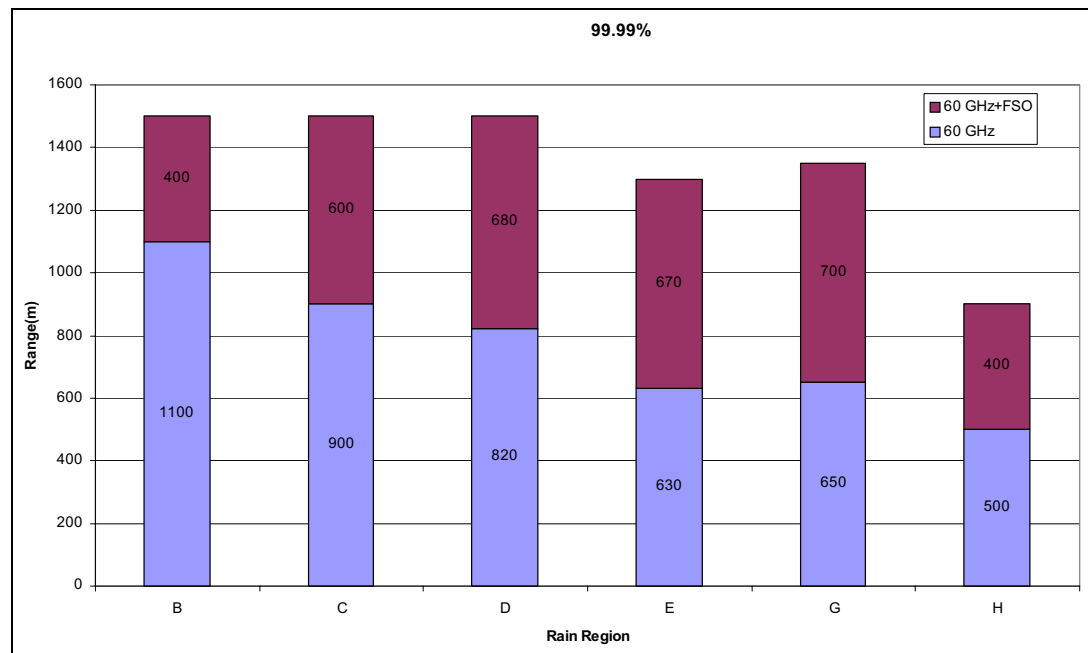


Figure 15. Predicted MMW and HFR maximum ranges in various rain regions for 99.99% statistical path availability

The other benefit the RLC provides is true equipment and path redundancy. If one piece of the HFR system failed or required servicing, in almost all cases it could be removed from the system with **no** bit loss to the customer. (In the rare event that the RLC electronics themselves failed, the second RLC takes over, potentially resulting in a 50-ms outage.) Figure 17 shows the fail-over scenario using an RLC. A passive 3 dB combiner/splitter combines the signal outputs from each RLC to provide true redundancy, even in the event of an RLC failure.

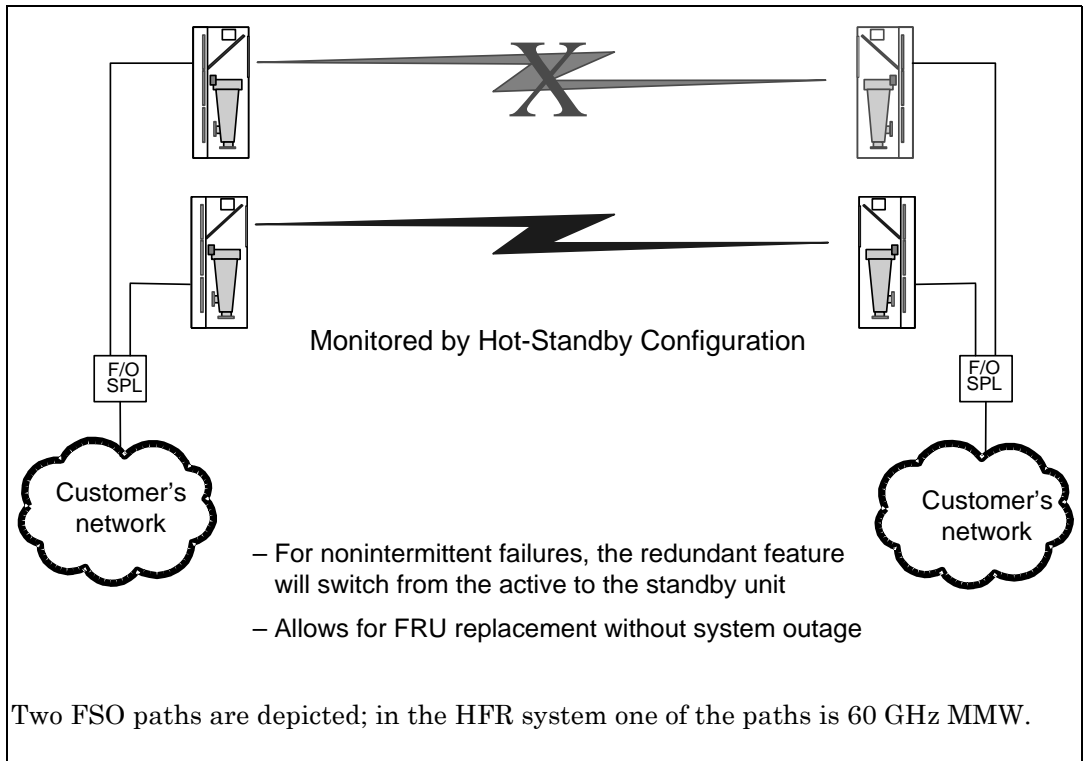


Figure 17. Redundant paths and failover capability using the RLC

This unique solution utilizes links running at the same capacity to provide a consistent and guaranteed data rate at all times during all weather conditions. This approach is significantly different than previous attempts to marry FSO with microwave, and it is not considered a “backup” system. Microwave backups utilize lower capacity microwave systems to handle communications during foggy conditions. Typically, this would result in loss of data during the switchover and a dramatically lower capacity during fog events.

Real HFR Results for a Massive 300 dB/km Fog Event

Figure 18 is a photograph of the HFR system developed by AirFiber. Figure 19 shows a time series of data recorded by a nephelometer mounted on the rooftop next to an HFR system. The nephelometer measures the attenuation of the atmosphere as a function of time. In this case, a massive fog that lasted over 6 hours and reached a peak attenuation of 300 dB/km is depicted. There were several FSO-only systems operating at the time, with link ranges of 300 to 800 m. **All** the FSO-only systems were out for nearly the entire duration of the fog event. The remarkable thing is that an HFR system at 800 m range performed flawlessly, switching seamlessly between FSO and 60 GHz as necessary depending on the atmospheric conditions. The user saw **no** lost bits during this massive fog event due to path attenuation. Similarly if the same system were operating in rain the system would switch to FSO as soon as the rain attenuation caused errors on the 60 GHz link, again with no bit errors to the user. Figure 20 is a summary of error statistics taken during this fog event. The small residual bit errors are due to a low-level error rate on the 60 GHz equipment caused by a temporary issue in overspeeding the MMW unit beyond its design range—they are not due to losses incurred during RLC switching.



Figure 18. HFR prototype system

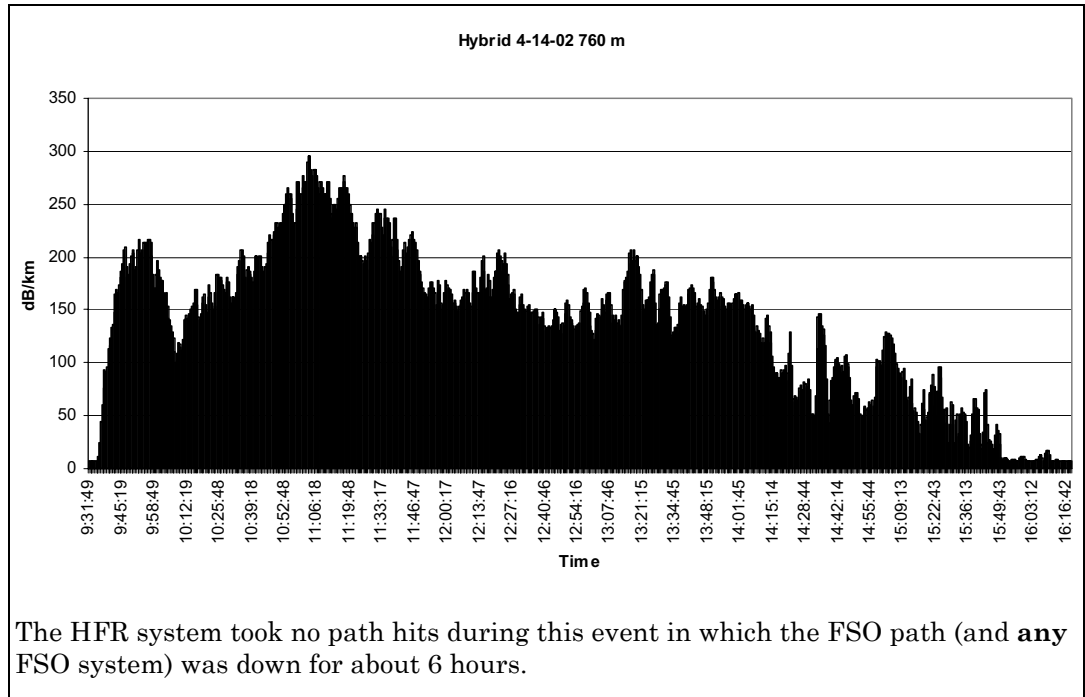


Figure 19. A deep fog fade in Poway, CA at the AirFiber, Inc. 760-m range outdoor test facility

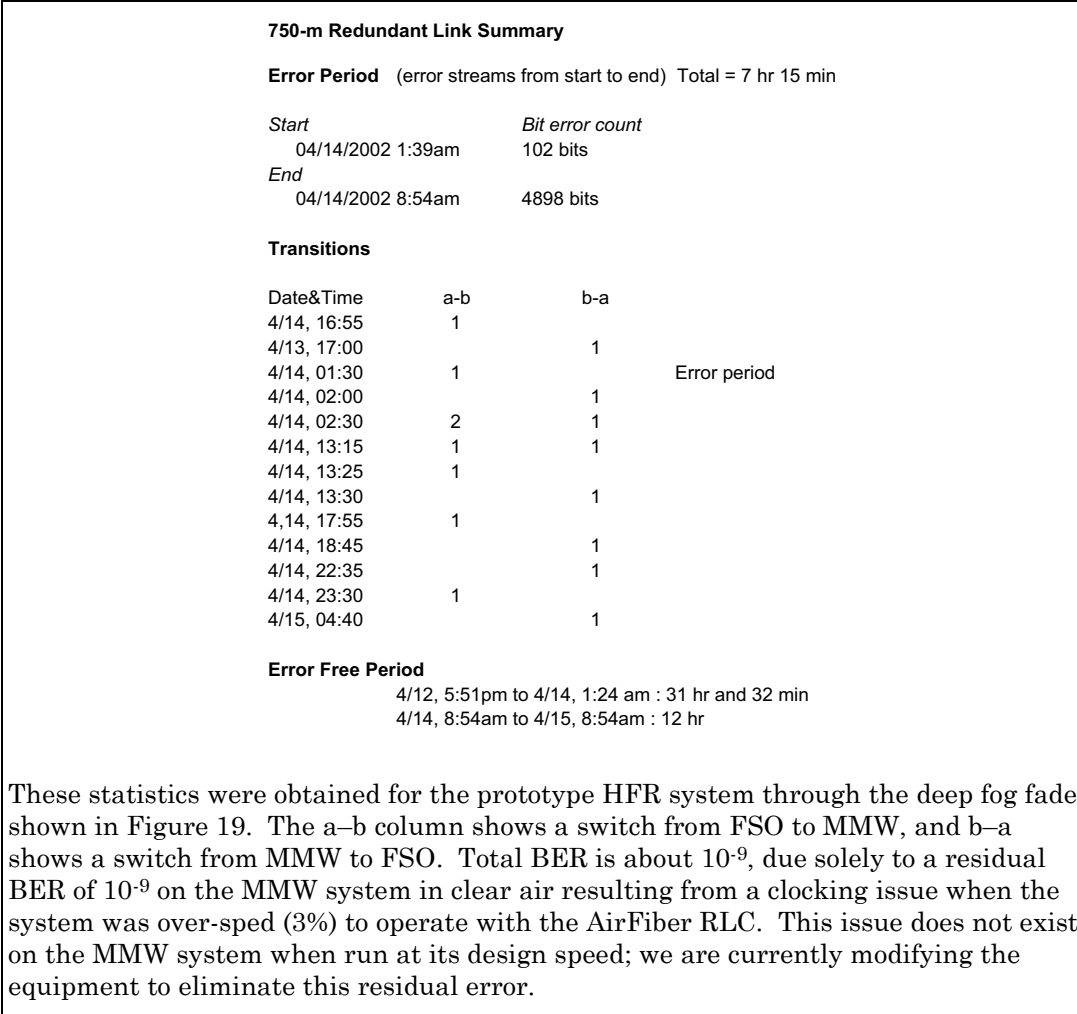


Figure 20. Some BER statistics for the prototype HFR system

CONCLUSIONS

For carriers to unlock the value in their very substantial fiber assets, they need to solve the last-mile problem. The only solution, other than burying fiber everywhere, is to use an HFR system. With HFR, carriers can sell to a customer and deliver fiber-like speeds and availabilities in days at a fraction of the cost of running fiber. An HFR system is unlicensed, which means multiple customers can enjoy deployment of these systems without having to pay up-front for spectrum rights. HFR is truly the last-mile solution that can allow carriers to greatly increase revenues while reducing costs associated with building that revenue base.

References

- *The Physics of FSO* white paper, AirFiber, Inc., December 2001
- FCC Bulletin Number 70, July 1997