Performance prediction for fixed microwave data links

RF wireless links are becoming a popular alternative to fiber. Getting solid numbers that will permit estimation of link performance with a high degree of certainty is a mandate.

By John S. Seybold

Millimeter-wave (MMW), also sometimes loosely referred to as microwave, data links are becoming an increasingly common means of providing carrier class service in dense urban areas. If a line-of-sight exists between two points and roof rights and licensing can be secured, a MMW link provides a cost-effective alternative to the slow and costly process of laying fiber. The carrier has two key factors that the link must satisfy if the link is going to provide fiber-like service: availability and bit error rate (BER). It is the job of the radio and the link designers to ensure that these requirements are met.

System parameters

A scan of Web sites of some of the equipment makers provides some insight into the various types of “specmanship.” Some manufacturers provide a sensitivity that is based on a residual (after correction) BER of 10^{-6} or 10^{-8}. For the data rates involved (100 Mb/s or greater), these kinds of error rates result in uncorrected errors occurring only seconds apart. That is hardly carrier-grade service. Thus, the first order of business is to determine the receiver threshold where the BER is at an acceptable level. This value may not be available from the manufacturer and may have to be estimated. Depending on the level of coding involved, an increase of 2 to 3 dB should move the system into the clear operating region where the BER will be 10 to 12 or better.

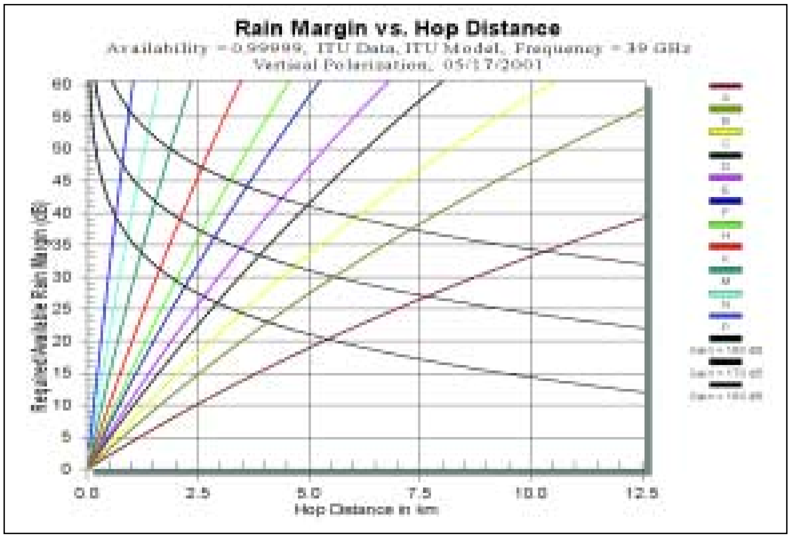

Figure 1. Five-nines hop distance chart, 39 GHz, ITU rain model.

Once a usable threshold has been determined, the next step is to determine the maximum transmit power. Again, the user must be aware of what is actually being specified. The number of interest is the maximum value of the average transmit power at the input to the antenna. The manufacturer may specify the maximum peak envelope power emitted from the transmitter or delivered to the antenna. Most systems using digital modulation and Nyquist filtering will require anywhere from 4 to 10 dB of output backoff (OBO) for linear operation[1]. Using the peak output power results in overstating the transmit capabilities of the radio, thereby overestimating the link performance. If the maximum average transmit power is not given, the user may want to assume a reduction from the peak power between 4 and 8 dB, to include OBO and any filter or waveguide insertion loss between the transmitter and the antenna.

The remaining hardware parameter to address is the antenna gain. For the 38 GHz band, the Federal Communications Commission (FCC) provides a minimum gain of 38 dB, which is generally met with a 1-foot diameter or larger antenna[2]. For the 28 GHz local multipoint distribution service (LMDS) band, there is no minimum gain requirement — only a maximum beamwidth requirement — so there is a greater likelihood of a data sheet containing a marketing or ‘typical’ gain number. In addition to removing any fluff in the antenna gain numbers, the link designer may also want to reduce the antenna gain by 1 dB to account for less-than-perfect alignment.

Once a satisfactory value for the antenna gain is determined, the hop distance and availability analysis can be performed. The system gain can be defined as the maximum average transmit power minus the receiver sensitivity expressed in dB or dBm. For dB, the formula is:

$$G_s = P_{T\max} - R_{thresh} \text{ dB} \tag{1}$$

The link gain, which may also be referred to as system gain, is defined as:

$$G_L = G_S = P_{T\max} + 2\,(G_{RxAnt}) - R_{thresh} \text{ dB} \tag{2}$$

For the remainder of this article, the term *system gain* will refer to Equation 2.

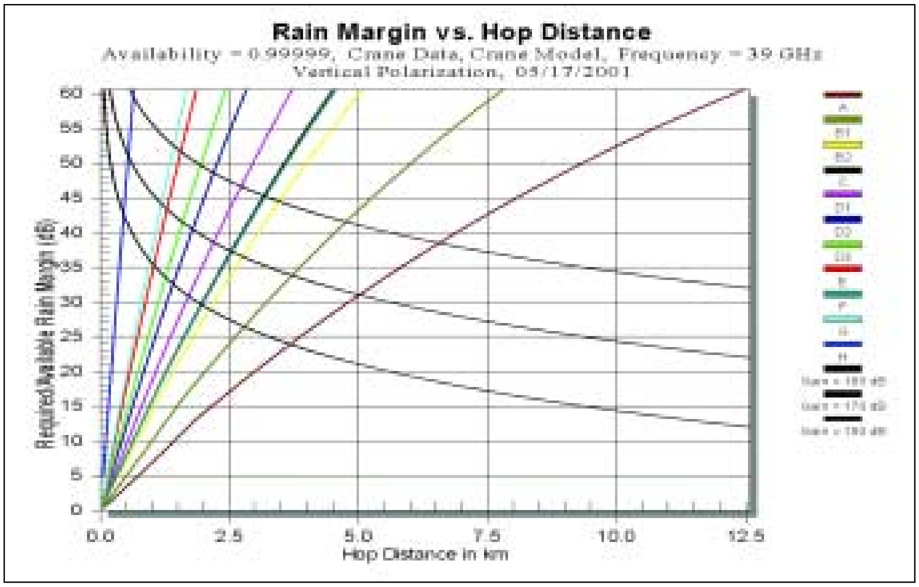

Figure 2. Five-nines hop distance chart, 39 GHz, Crane rain model.

This system gain determines how the radios, and thus the link, will perform during a rain fade. Depending on the environment that the link is deployed in, the designer may elect to reduce the system gain by another dB to provide an interference margin. A common definition of threshold-to-interference ratio uses a 1 dB degradation of the system threshold as the point where interference is considered a problem.

Availability is the percentage of time that the link will be operational. For wireless links, this is generally considered to be exclusively due to rain outages and does not usually budget for equipment failures. This is a shortcoming of the rain availability analysis for wireless links because wireless links actually have more equipment in the critical data path than a fiber link. For the remainder of this work, the term availability will be taken to apply exclusively to link outages due to rain, with the understanding that an additional analysis may be required to account for availability limitations due to equipment failures.

Note the concept of the two or three-sigma design as it applies to radio hardware. While this is a common method for system design, the concept must be addressed for the application to wireless data links. If a system has a three-sigma system gain, that means that it is only expected to meet the specification 99.87% of the time. The probability of having a system that does not meet the specification is not negligible when compared to a four- or five-nines link availability.

Therefore, it is important that the key system parameters be known with better than a three-sigma certainty. This is best achieved by careful acceptance testing either during production or immediately prior to deployment. If the uncertainty in the system gain is not addressed, then the availability of the link is likely to be less than the design target even if the rain models are correctly applied.

It should be stressed that having less than the required gain results in a reduction in availability. Thus, the link will operate properly the majority of the time, but it will fail during rain events that it should be able to handle.

Rain models

There are two popular rain models commonly used for MMW RF link planning: The International Telecommunications Union (ITU) model[3] and the Crane model[4]. Each has a corresponding set of empirical rain data with each model. While each model can be applied using the other set of rain data, that procedure is not discussed herein. Each set of rain data divides the globe into rain regions that characterize the rain conditions.

One recommendation for use of the ITU model uses the rain rate, which occurs 0.01% of the time, or the 0.9999 rain rate. Table 1 shows the 0.9999 or 0.01% rain rate data for use with the ITU model. The rain rate data for the desired rain region are then used to compute the path attenuation using the expression:

$$Atten_{0.01} = a * RR^{b} * d * r \quad \text{dB} \qquad (3)$$

Where: RR = the 0.9999 rain rate for the chosen region, in mm/hr and d is the hop distance in km.

Furthermore:

$$r = \frac{1}{\left(1 + \frac{d}{d_0}\right)} \qquad (4)$$

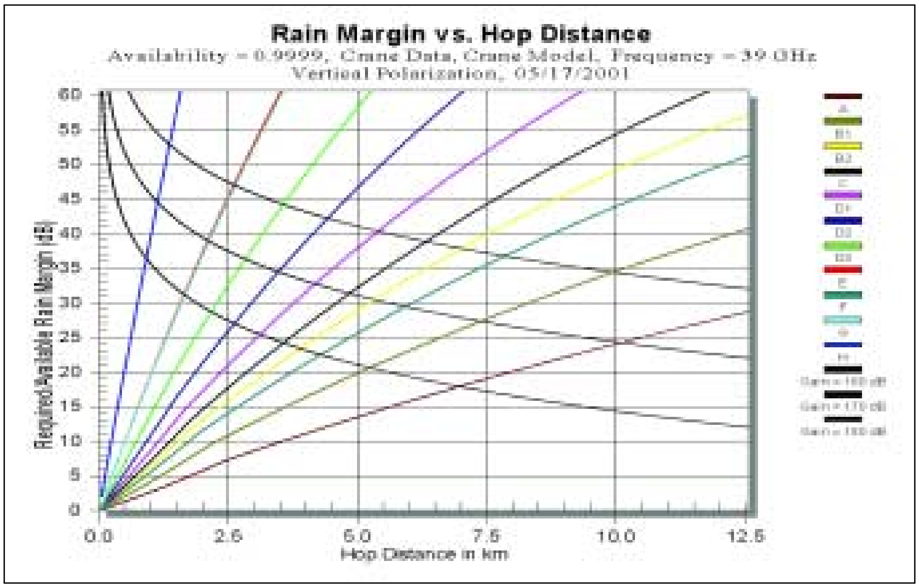

Figure 3. Four-nines hop distance chart, 39 GHz, Crane rain model.

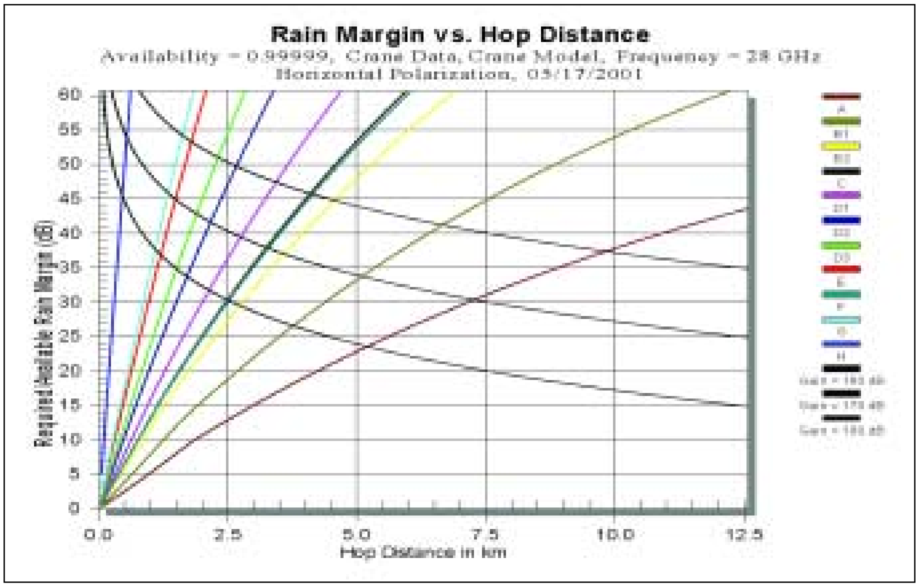

Figure 4. Five-nines hop distance chart, 28 GHz, Crane rain model.

With :

$$d_0 = 35e^{-0.015RR}\ \text{km} \qquad (5)$$

Equation 3 provides an estimate of the path attenuation that is only exceeded 0.01% of the time. The ITU model also provides an adjustment factor for availability that is applied to the path attenuation if availabilities other than 0.9999 are desired. The adjustment factor is applied to the attenuation (expressed in dB) that is computed by (3). The expression for the adjustment factor is:

A	B	C	D	E	F	G	H	J	K	L	M	N	P
8	12	15	19	22	28	30	32	35	42	60	63	95	145

Table 1. ITU rain rate data (mm/hr) for 0.9999 availability.

$$\frac{Atten}{Atten0.01} = 0.12p^{-(0.546+0.043\log(p))} \qquad (6)$$

Where p is the desired outage probability expressed as a percentage (p = 0.01 for 0.9999 availability). The adjustment factor is validated for availabilities from 0.99 to 0.99999.

The *a* and *b* factors are empirical values that have been tabulated in the references and are the same values for both Crane and ITU models. The values are a function of the frequency and polarization of interest. Parameter values for frequencies that are not tabulated can be computed by interpolation, using a logarithmic frequency scale and logarithmic scale for *a* and a linear scale for *b*.

The Crane model takes a different approach to modeling rain attenuation. Crane does not use an availability adjustment factor on the attenuation, but rather uses the rain data for a number of different availabilities — some of which are shown in Table 2 along with the rain rates. The rain rate data for the desired availability are then used in Crane's empirical model to determine the path attenuation as a function of range. The Crane model is divided into two segments, depending on the actual rain rate involved. The first segment is for distances between 0 and δ(*d*) where:

$$\delta(RR) = 3.8 - 0.6\ln(RR)\ \text{km} \qquad (7)$$

In this region, the rain attenuation is:

$$Atten = \frac{aRR^b(e^{yd}-1)}{y}\ \text{dB} \qquad (8)$$

where: $0 < d < \delta(RR)$

Where:

$$y = b\left[\frac{0.83-0.17\ln(RR)}{\delta(RR)}\right] \qquad (9)$$

For the other case, $\delta(RR) < d < 22.5$ km, the attenuation is given by:

$$Atten = aRR^b\left[\frac{(e^{y\delta(RR)}-1)}{y} + \frac{(e^{zd}-e^{z\delta(RR)})e^{0.83-0.17\ln(RR)}}{z}\right] \qquad (10)$$

Where:

$$z = b(0.026 - 0.03\ln RR) \qquad (11)$$

Hop charts and availability

Using the preceding expressions for either of the models, it is straightforward to plot the rain attenuation for a given frequency, polarization and availability as a function of hop distance. Once the frequency, polarization, availability and rain region are selected, the *a* and *b* coefficients, rain rate and

Availability	**A**	**B**	**B1**	**B2**	**C**	**D1**	**D2**	**D3**	**E**	**F**	**G**	**H**
0.99	0.2	1.2	0.8	1.4	1.8	2.2	3.0	4.6	7.0	0.6	8.4	12.4
0.999	2.5	5.7	4.5	6.8	7.7	10.3	15.1	22.4	36.2	5.3	31.3	66.5
0.9999	9.9	21.1	16.1	25.8	29.5	36.2	46.8	61.6	91.5	22.2	90.2	209.3
099995	13.8	29.2	22.3	35.7	41.4	49.2	62.1	78.7	112	31.9	118	283.4
0.99999	28.1	52.5	42.6	63.8	71.6	86.6	114.1	133.2	176	70.7	197	542.6

Table 2. Crane rain rate data in mm/hr vs. availability.

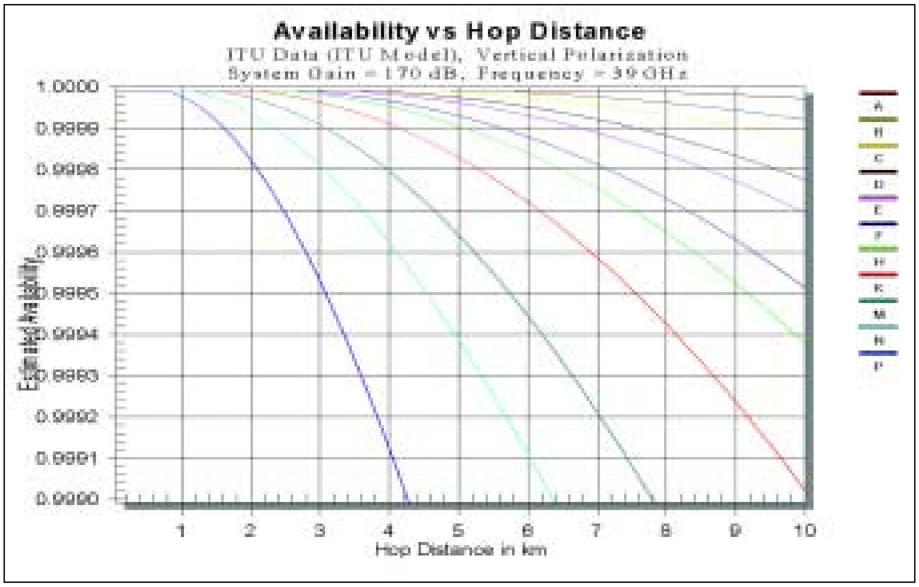

Figure 5. Availability vs. hop distance for vertical polarization, 39 GHz.

adjustment factor (if any) are fixed. The rain attenuation then becomes a function of the distance, *d*, only.

Figure 1 shows a plot of the expected rain fade for a 0.99999 rain vs. hop distance for several different rain regions. The colored curves represent the five-nines rain attenuation vs. distance for the respective rain regions. The black system gain curves represent the available fade margin for systems with different system gains.

The Friis equation gives the free-space loss as a function of distance.

$$L = 20\log\left(\frac{\lambda}{4\pi d}\right)\ \text{dB} \tag{12}$$

For terrestrial links at frequencies below about 55 GHz, gaseous absorption can be ignored unless the link distance is substantial. Multipath fading is usually minimal because the links are stationary and the antenna beams are relatively narrow. Thus, the free-space loss provides a good estimate of the path loss for a point-to-point link. The primary source of outages is precipitation. The available rain fade margin for a given link can then be computed as the system gain minus the free-space loss.

By superimposing a plot of the system gain minus the free-space loss as a function of range onto the rain attenuation curves, a hop distance chart is produced. Figure 1 shows a hop distance chart for a 39 GHz, vertical polarization link for three different system gains. The point where a system gain curve intersects a rain attenuation curve is the maximum 0.99999 availability link distance for that system in the selected rain region. The point where they intersect is the range where the rain fade margin of the link is equal to the 0.99999 rain-fade depth. For example, for a 170 dB system in rain region A, the five-nines hop distance is 7.6 km.

Figure 2 shows a similar hop distance chart using the Crane model and data. Because the rain regions for Crane and ITU are defined differently, it is not possible to make direct comparisons between the two models. It is possible to pick a particular city or geographic region and compare the predicted performance at that location. For instance, Orlando is in ITU region “N” and Crane region “E”, so a 170 dB system has an expected five-nines hop distance of 970 meters using ITU and 1000 meters using Crane. For values of system gains not shown, two curves can be linearly interpolated.

The hop distance chart provides a graphical means of determining at what hop distance the rain attenuation is equal to the fade margin. The intersection can be determined using iteration on a computer. Because the attenuation model minus the free-space loss is a transcendental function, it cannot be solved directly. While not as precise, the graphical solution provides more information than a numerical solution. For example, in the drier regions, where the rain attenuation curve has less slope, it can be seen that a small change in the system gain can result in a substantial change in the predicted hop distance. This becomes more apparent at lower availabilities such as the four-nines hop distance chart shown in Figure 3.

Figure 4 shows a five-nines hop chart at 28 GHz. At the lower frequency, the impact of rain attenuation is less severe than at 39 GHz, so the corresponding hop distances are longer. It is also noteworthy that the rain attenuation is slightly greater on horizontally polarized signals than on vertically polarized signals. The *a* and *b* factors in the attenuation model are different for horizontal and vertical polarization. This is a consideration for dual polarization systems because the performance in rain will be limited by the horizontally polarized signal.

A common question encountered by radio vendors is: “My hop distance is longer than the maximum five-nines hop distance. What will the actual availability be?” This is an important question. From an operational standpoint, 0.99997 is not profoundly different from 0.99999 availability. Using the ITU model (with the adjustment factor), a family of curves showing availability vs. hop distance can be generated for a given system gain. Figure 5 shows a sample availability chart for a system gain of 170 dB. It must be remembered that this curve is only valid for the stated system gain. Using such a curve, the availability can be estimated for any hop distance once the rain region and system gain have been established.

Summary

This article discussed how to look past typical marketing specifications and get to the solid numbers that will permit estimation of link performance with a high degree of certainty. Once a set of solid radio specifications are in hand, the dominant limitation of link availability is the rain fade. Two popular methods for modeling rain fade and how they relate to availability were examined. A hop distance chart was generated and discussed. Finally, a plot of expected availability vs. hop distance for a given system gain was presented.

RF

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References

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[2] Code of Federal Regulations, Title 47, Volume 5, 101.517, Revised as of October 1, 2000

[3] ITU Recommendation PN837-1, Rec838, Rec.ITU-R P.530-7

[4] "Electromagnetic Wave Propagation Through Rain," Robert Crane, John Wiley & Sons, February 1996.

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John S. Seybold received his B.S.E.E. from the University of Wisconsin in 1982, his M.S.E.E. from California State University, Fullerton, in 1986 and his Ph.D. from the University of Central Florida in 1995. Seybold is an associate professor of electrical engineering at Florida Institute of Technology in Melbourne, FL, where he also serves as the associate director of their Wireless Center of Excellence. Seybold held a variety of positions in the industry prior to joining the faculty at Florida Tech. Most recently, he was a senior RF systems analyst at Triton Network Systems, where he was responsible for RF network planning, link outage prediction and frequency re-use analysis. Seybold has also worked in radar systems, synthetic aperture radar (SAR) and communications systems, including spread spectrum. He is a licensed professional engineer in the state of Florida, a senior member of the IEEE and a member of Phi Kappa Phi and Tau Beta Pi. He can be contacted at: *jseybold@mpinet.net.*