TUNABLE MILLIMETER-WAVE COMMUNICATIONS

Stanley Becker
Consultant
Applied Electronics Division
AIL Division of Eaton Corporation
Walt Whitman Road
Melville, New York

ABSTRACT

A communication link operating at 5 millimeters can be designed to take advantage of the properties of the oxygen absorption band to provide relatively interference free and secure communications. A tunable transmitter and receiver were developed to demonstate the adaptability of such a link to varying propagation and potentially hostile EMI conditions.

INTRODUCTION

Communication link designs optimize the link parameters of radiated power, receiver sensitivity, antenna gains, and propagation losses for maximum signal-to-noise ratio at the receiver. When there is an added requirement to provide communications security, directive antennas are often used and radiated power is reduced. For some short-range applications, the spatial security offered by these antennas (a restriction of look angle) is not sufficient. High gain antennas do not limit the overreach of the transmitter emanations beyond the receiver terminal in line with the antenna main beam or in diverse directions from reflectors in the field of view.

Attenuation of a transmitter signal in free space is inversely proportional to the square of the range from the transmitter. Additional attenuation, increasing exponentially with range, is possible in frequency bands where molecular absorption of radiated power is prominent. Such enhanced attenuation of radiated signal power will reduce the overreaching of the transmitter signal. Conversely, a receiver tuned to an incoming signal in an absorption band is less susceptible to radiated interference for a given interfering transmitter power and separation from the receiver. An experimental tunable transmitter and receiver[*] designed to operate on the skirt of the 5- mm oxygen line band is described, and some of the novel features that attend tunability in this band are described.

---

[*] The transmitter and receiver were built on Government Contract No. DAAB07-77-C-0118.

SIGNAL PROPAGATION

The signal power propagated to the receiver terminal of a communications link is:

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi R)^2} \times 10^{-\alpha R} \tag{1}$$

where P_r is the received signal power, P_t is the transmitted signal power, G_t is the transmitter antenna gain, G_r is the receiver antenna gain, λ is the signal wavelength, R is the range, and α is the absorption factor (a function of λ).

We see that received signal strength is inversely proportional to R^2. When α is not zero, the signal strength is inversely proportional to a factor with a value of αR in its exponent.

The 5-mm band is characterized by an oxygen absorption band shown in Figure 1 (1). The absorption coefficient, α, is plotted in dB per nautical mile. Converted to dB/km, the maximum absorption is about 15 dB/km, obtained at the surface at a frequency of about 60.5 GHz. Figure 1 also shows how absorption decreases with increasing altitude, and how the individual resonance lines are evident when broadening due to atmospheric pressure is diminished. Rain is also a very significant attenuation factor at millimeter wavelengths (2). Figure 2 shows that the absorption coefficient at 60 GHz is somewhat less than 4 dB/NM or about 2 dB/km for a moderate rainfall.

5-mm COMMUNICATIONS LINK

By operating in the 5-mm band, terrestrial, airborne, and spaceborne communication links can be designed to minimize the effects of radiated jamming power and to reduce the undesired overreaching of a transmitted signal. The scenarios are different for links totally within or between each of the propagation media. In this paper, we will discuss the terrestrial link application.

Setting up a 5-mm terrestrial link over a given range requires consideration and allowance for:

a) available radiated power
b) modulation bandwidth
c) receiver sensitivity
d) practical aperture size
e) propagation conditions

The highest power 5- mm solid-state sources that can be used for communications will provide up to about 0.2 W (InP Gunn) to 1.2 W (Impatt) in CW operation. With externalcooling, the InP Gunn output power can be increased to about 0.4 W. Hard-tube sources with output power extending through the kilowatt range are possible using cooled TWT's and magnetrons.

Modulation bandwidth and receiver sensitivity are intimately related. Depending on the application, the reliability of the link will dictate a given error rate, which will prescribe a minimum signal-to-noise ratio. For the purpose of this discussion, we will examine a 4-km link with a compatible modulation/receiver noise bandwidth of 200 kHz, receiver noise figure of 15 dB, signal-to-noise ratio of 10 dB, and a transmitter power of 50 mW.

If we were to set up a terrestrial link in a given geographic area, we would need to analyze the rainfall records in the area and compile statistics on rainfall rate versus probability of occurrence. Operation of the link during the day, night, or on a 24-hour basis would have to be factored into the analysis. Having compiled the rainfall data for the operational situation and with an acceptable percentage down-time decided upon, we can establish a maximum attenuation factor for rainfall. For this discussion we will use a maximum rain-attenuation factor of 5 dB/km (moderate to heavy rainfall). In Washington, D. C., this rainfall would be exceeded about 10 hours per year or about 0.1 percent of the time.

If we select antennas that are well within the manufacturing state of the art and ones that can readily be aligned, we would limit ourselves to an aperture of about 12 inches. Such antennas would have a 3-dB beam width of about 1.1 degrees and a gain of about 43 dB.

The signal-to-noise ratio for the terrestrial link is:

$$\mathrm{SNR} = \frac{P_r}{FkTB} \tag{2}$$

At an operating frequency of 60 GHz we use the following values (expressed in the dB scale): F = 15 dB, kTB = -121 dBm, P_t = +17 dBm, $G_t = G_r$ = 43.5 dB, R = 4 km, a = 15 dB/km, λ = 5 mm, and we obtain an SNR of 10 dB in clear weather.

DETECTION AND INTERFERENCE SUSCEPTIBILITY

The degree of severity of overreach is a function of the sensitivity of the intercept receiver, or listener, and the propagation path between the intercept receiver and the link transmitter. For this example, we assume a receiver sensitivity/antenna-gain advantage of 10 dB for the intercept receiver. The overreach of the link signal in the direction of the main beam and in other directions, due to inadvertent reflection from surrounding terrain or reflectors, is a function of the factors $1/R^2$ and $10^{-\alpha R}$ as was previously shown. In a frequency band where α is insignificant, the interceptor could be at a range of more than three times the link range; equivalent to an overreach of 8 km. However, a link operating at a frequency of 60 GHz would have an overreach of only 0.7 km.

The susceptibility of a 60 GHz receiver to interference is not inherently different from those in other bands, but the oxygen absorption band may be considered as a selective shield around the link receiver. By much the same way that an intercept receiver is at a disadvantage beyond the range of the link transmitter, an interfering transmitter must overcome an additional attenuation of 15 dB/km beyond the link range.

ACCOMMODATION FOR RAIN

Operating the communications link in a moderate-to-heavy rainfall would result in an additional 5 dB/km or 20 dB additional loss over that for the free-space path. Such a condition would reduce the SNR in the example discussed to -10 dB. It is not practical to increase transmitter power, aperture sizes (for convenience), or receiver sensitivity to make up for such a loss of signal strength. It is feasible, however, to retune the link to a frequency of say 64 GHz, thereby reducing the oxygen-line absorption coefficient from 15 0dB/km to about 9 dB/km. Such a retuning would recoup 20 dB of signal attenuation over the 4 km link range, restoring the initial 10 dB signal-to-noise ratio. Furthermore, the susceptibility to detection and interference would be essentially the same as it was in clear weather.

TUNABLE TRANSMITTER AND RECEIVER

The tunable 5-mm transmitter and receiver (3) that were built (Figures 3 and 4) incorporated several novel designs for the mixer, tunable oscillator and VCO (4 and 5). A summary of the component and system characteristics are shown in Tables I and II.

TABLE I. Millimeter-Wave Component Performance Characteristics

• Mechanically Tunable Oscillators	
Frequency Range/Output Power	55 to 63 GHz/26 to 60 mW
	64 to 70 GHz/20 to 40 mW
• Varactor-Controlled Oscillators	
Frequency Range/Output Power	60 to 62.5 GHz/8 to 25 mW
	63 to 66.5 GHz/3 to 25 mW
• Millimeter-Wave Mixer	
Frequency Range	61 to 72 GHz
Conversion Loss	6.6 ±1 dB
Noise Figure* (DSB)	10 dB
IF	Dc to 12 Ghz

* Including 4-dB IF amplifier noise figure

TABLE II. Transmitter and Receiver Performance

• Transmitter	
Antenna (3-inch diameter)	
Gain	1400
Beam Width	4.5 degrees
Polarization	Linear
Tuning Range	
Low Channel	60.8 to 61.5 GHz
High Channel	64.3 to 65.8 GHz
Output Power	
Low Channel	22 ±6 mW
High Channel	11 ±8 mW
Modulator Sensitivity	20 MHz/volt
• Receiver	
Antenna (3-inch diameter)	
Gain	1400
Beam Width	4. 5 degrees
Polarization	Linear
Tuning Range	5 GHz
Noise Figure	10 to 15 dB
Predetection Bandwidth (3 Db)	50 MHz
Baseband	Up to 10 MHz*
Discriminator Sensitivity	0.2 volt/MHz

*Transmitter supplied with low-pass filter, reducing baseband to 100 kHz.

RANGE CUTOFF MEASUREMENTS

Some measurements of the effect of oxygen-line absorption were made in Melville, NY between a rooftop and line-of -sight points 1.0 and 1.5 km distant. Data were taken at 61 and 65 GHz on a clear day. Analysis of the measurement data show that a somewhat greater range cutoff factor was obtained than would have been predicted by the range equation given in this paper.

As the range is increased from 1 to 1.5 km, the theoretical difference in signal strength at 61 GHz is:

$$20 \log \frac{1.5}{1.0} + 0.5 \times 15 \text{ dB} = 11 \text{ dB} \tag{3}$$

and at 65 GHz the differential is:

$$20 \log \frac{1.5}{1.0} + 0.5 \times 6 \text{ dB} = 6.5 \text{ dB} \tag{4}$$

The field measurements showed a difference of 14.5 dB and 13 dB for the 61 and 65 GHz measurements, respectively. The greater than expected falloff of signal power cannot be explained except for possible site and environment anomalies, which were not measured or evaluated.

SUMMARY

The use of a tunable transmitter and receiver in the 5-mm band can effect a decrease in susceptibility to radiated interference and a reduction of transmitter signal overreach. For a specified link reliability, the use of a tunable system can offset the effects of rain attenuation in a short-range communications application.

A tunable transmitter and receiver, developed for CORADCOM, were used in a field experiment to verify predictions of range cutoff as a function of frequency. The effects of increasing the range produced a greater than anticipated signal attenuation, but this might be attributed to anomalous site or propagation conditions.

ACKNOWLEDGEMENTS

The development of the tunable transmitter and receiver was performed for the U.S. Army's CORADCOM under the direction of E. Fliegler. Major contributors to the millimeter-wave design at AIL were L. Cohen and P. Meier. Assistance for the measurements described was given by D. Baird and S. Fung of AIL.

REFERENCES

1. Vignali, J. A., "Millimeter Waves and Naval Communications," NRL Report 7165, 10 December 1970.
2. Vignali, J. A. and Decker, K. M., "The Application of Microwaves to Low-Intercept Short-Haul Communication," NRL Report 6187, 8 February 1965.
3. Becker, S., "Tunable Planar Hybrid Millimeter-Wave Transmitter and Receiver," DoD ARPA Millimeter Wave Conference, Eglin AFB, FL, April 1979.
4. Meier, P. J., "4 and 5 mm Band Printed Circuit Balanced Mixers," Microwave Journal, August 1979.
5. Cohen, L. D. and Meier, P. J., "E-Plane Millimeter-Wave Circuits," Microwave Journal, August 1978.

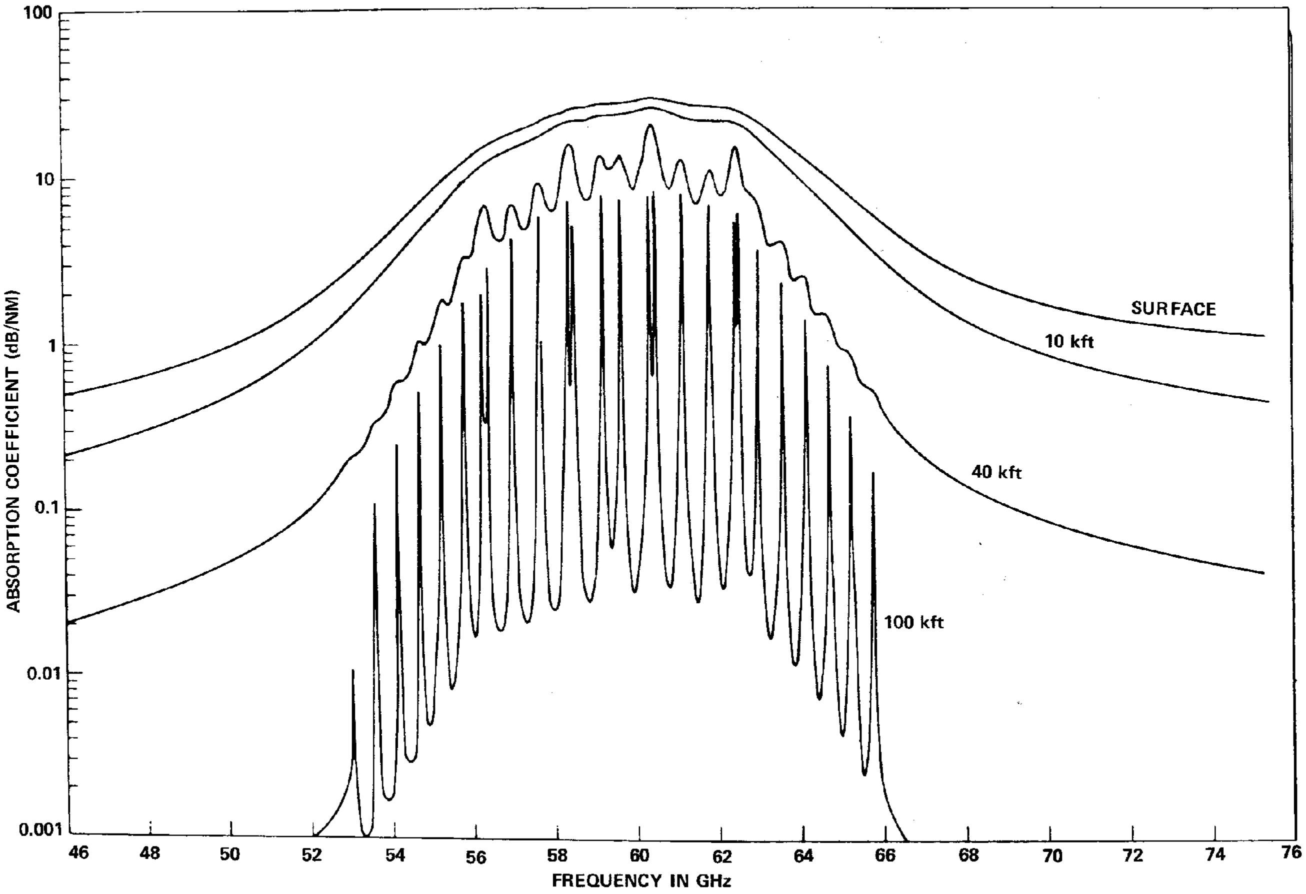

Figure 1 - Atmospheric Absorption in the 60-GHz Region at Various Altitudes

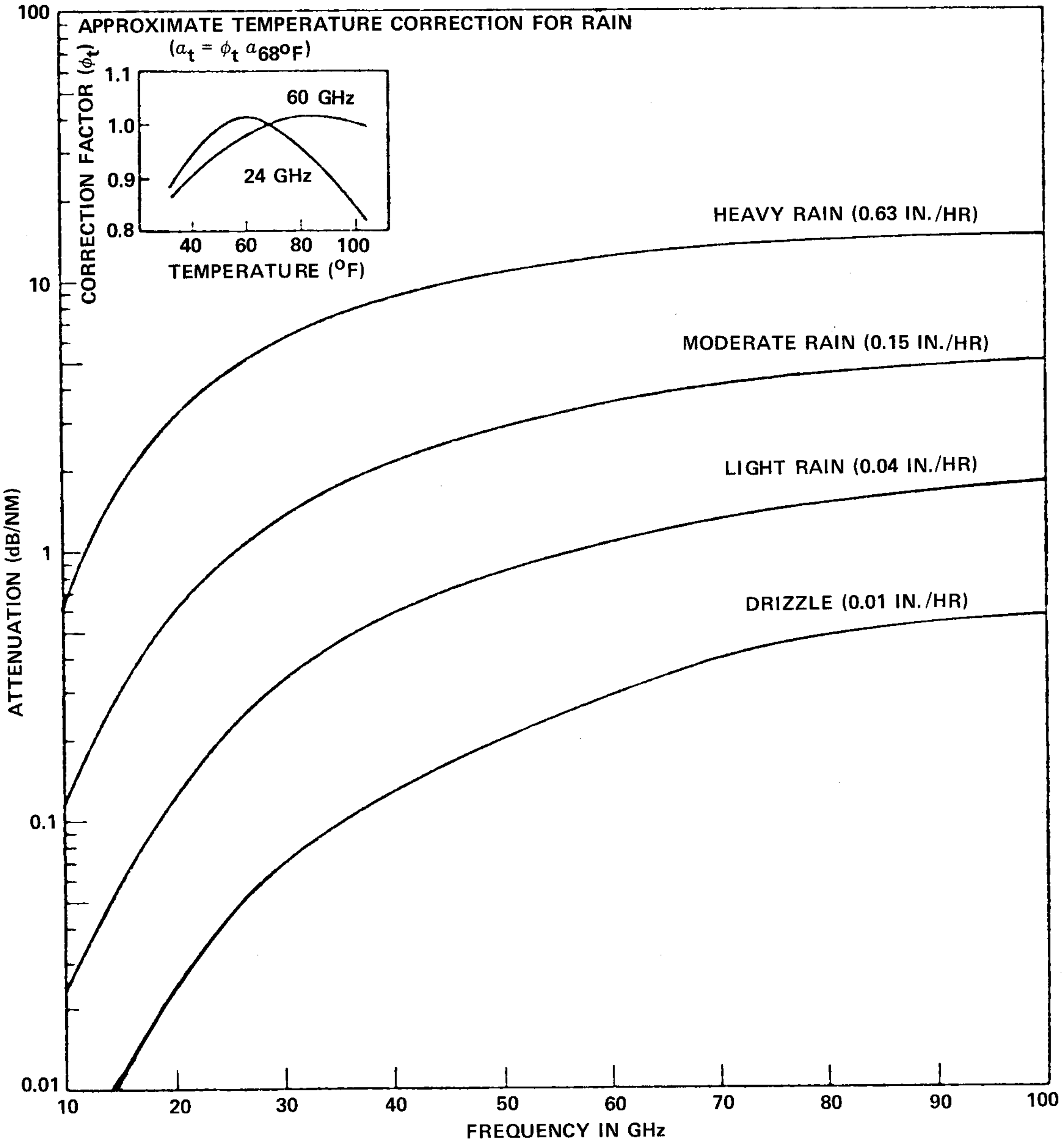

Figure 2 - Attenuations Due to Rain at Sea Level, 68°F

Figure 3a - Tunable Millimeter-Wave Transmitter, Panel Side

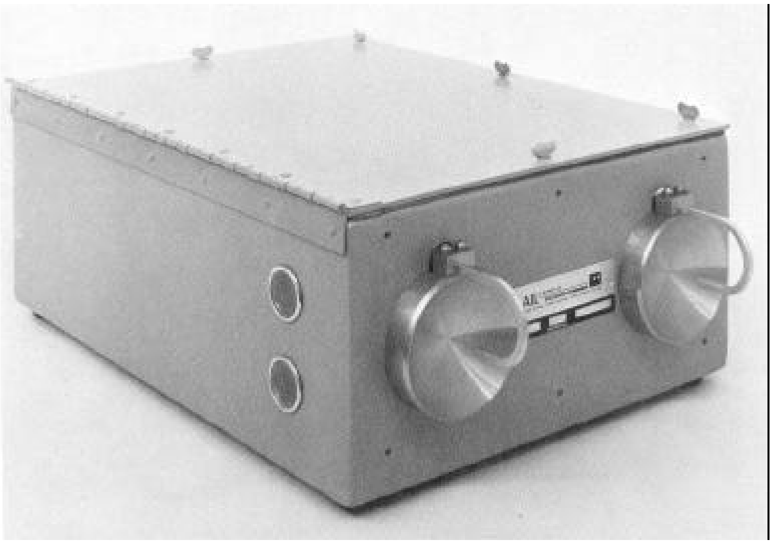

Figure 3b - Tunable Millimeter-Wave Transmitter, Antenna Side

Figure 4a - Tunable Millimeter-Wave Receiver, Panel Side

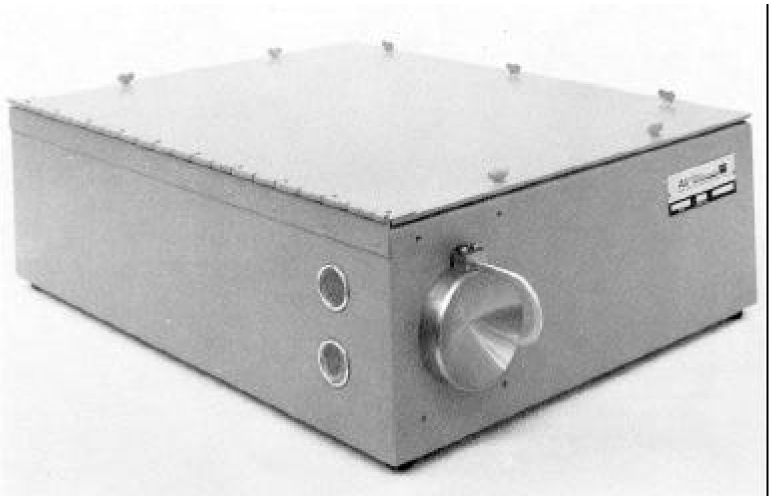

Figure 4b - Tunable Millimeter-Wave Receiver, Antenna Side