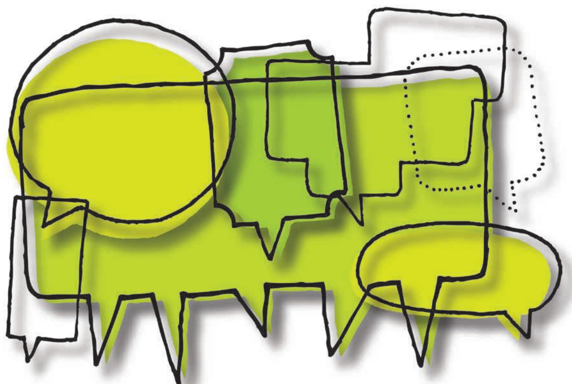
Speaker's Corner

Millimeter-Wave Propagation: Spectrum Management Implications—An Update for >100 GHz

■ Michael Marcus, Xavier Cantos Roman, and Josep Jornet

In the June 2005 issue of this magazine, a previous article on the spectrum management implications of millimeter-wave (mm-wave) propagation was published [1]. It was derived from a Federal Communications Commission report issued in 1997.



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Introduction

At the time the data in the original article were published, plans for the practical use of the spectrum above 50 GHz were vague, and it was difficult to focus on the spectrum management questions that would be most significant to the microwave community. The computation of propagation loss at these frequencies requires complex software that was not readily available at the time of this prior work. Now, the propagation model in ITU-R Recommendation P.676-12 (August 2019), "Attenuation by Atmospheric Gases and Related Effects" is widely accepted, and software to implement it is available from a variety of sources (see "Software Sources for the ITU-R P.676 Model"). Also, almost two decades later, the possible uses of this spectrum are clearer. This article focuses on issues not addressed in the original article that are also important in spectrum management decisions, especially now as the discussions on 6G have started and the upper mm-wave or subterahertz (sub-THz) spectrum (from 100 to 300 GHz) is envisioned as a key resource for the next generation of wireless networks.

Free Space and Absorption Losses

Propagation at mm-wave and sub-THz frequencies involves both free space loss as well as gaseous absorption, and for some paths, may involve path blockage. Depending on several factors, including frequency, distance, and elevation angle, either the free space loss or the absorption loss dominates as free space loss has a d^{-2} dependence on distance, while absorption has an exponential dependence of distance of the form $e^{-\alpha d}$, so for large distances, the absorption loss is much greater than the free space loss. However, as will be shown later, for some elevation angles, the major path loss mechanism can change several times as distance increases. These factors in path losses result in mm-wave paths being a complicated function of distance in some cases.

Figure 1 shows the plot of mm-wave propagation that is typically published. In this case, we have added two climate-related lines from the P.676 model.

Michael Marcus (mjmarcus@marcus-spectrum.com), Xavier Cantos Roman (cantosroman.x@northeastern.edu), and Josep Jornet (j.jornet@northeastern.edu) are with the Institute for the Wireless Internet of Things, Northeastern University, Boston, MA 02115 USA.

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Software Sources for the ITU-R P.676 Model

The P.676 model used for atmospheric absorption calculations is a complex one that cannot be handled with pencil and paper. (One of the sources given later has 25 pages of MATLAB coding.) The following software implements this model, and at the time of drafting this article, is available at no cost. Note that this model is only for atmospheric absorption, and generally, simpler free space loss must be added to obtain the total path loss prediction. Recommendation ITU-R P.525-4, "Calculation of Free-Space Attenuation," gives the formula for this part of path loss and can be found at https://www.itu.int/rec/R-REC-P.525-4-201908-I/en.

The software sources are as follows:

- Center National d'Etudes Spatiales (France): https://logiciels.cnes.fr/sites/default/files/usermanual.pdf
- MathWorks File Exchange: https://www.mathworks.com/matlabcentral/fileexchange/78865-atmospheric-absorption-loss-for-satellite-communications
- Naval Research Laboratory (USA): https://apps.dtic.mil/sti/pdfs/AD1122415.pdf.

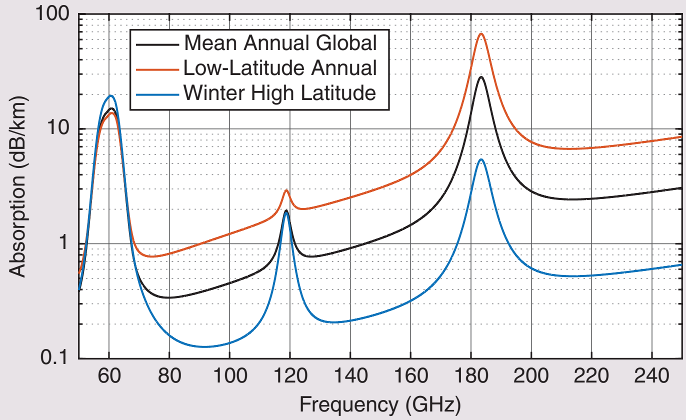

Figure 1. *The absorption path loss per ITU-R P.676-12 model.*

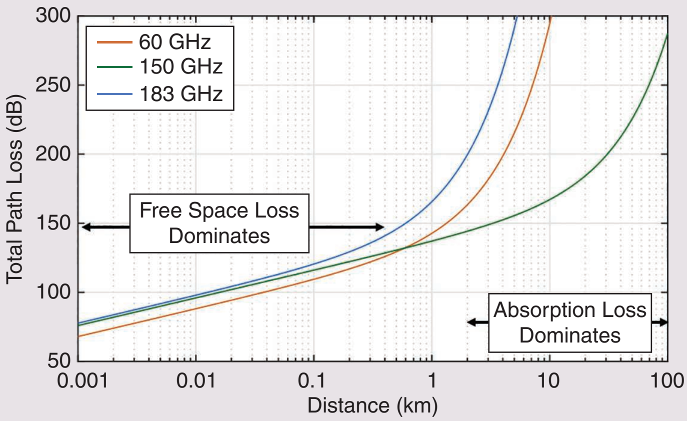

Figure 2. *Horizontal sea level total path loss versus distance for three bands: 60 GHz, which corresponds to an oxygen absorption line; 150 GHz, not on an absorption line; and 183 GHz, which corresponds to a water absorption line.*

mm-wave absorption propagation is affected by several climate-related parameters that are included in the P.676 model: local temperature; dry air pressure; and water vapor partial pressure profiles versus height. This model also includes six reference standard atmospheres from Recommendation ITU-R P.835: (i.e., the mean annual global reference atmosphere; the low-latitude reference atmosphere; the midlatitude summer reference atmosphere; the midlatitude winter reference atmosphere; the high-latitude summer reference atmosphere; or the high-latitude winter reference atmosphere) that may be used if detailed information on the parameters for the geographic location under consideration are not available.

The lines shown in Figure 1 are the mean annual global average and the highest and lowest absorption levels of the six reference standard atmospheres from Recommendation ITU-R P.835 to show how much variation is possible depending on the local climate. In a specific location with unusual weather conditions, action losses might vary more from the mean annual global reference atmosphere than any of these reference atmospheres, and the P.676 model can be used with more detailed climate data to check how these extremes might affect system performance as well as any interference potential.

For short distances at mm-wave frequencies, the free space loss, with its inverse square dependence on distance, dominates path loss, but as distance increases, absorption loss starts to dominate. This is shown in Figure 2 where the Total Path Loss is the sum of both loss factors.

Thus, for the case of 60 GHz where the absorption loss coefficient is large, it still really has no impact for distances less than about 1 km because free space loss is much greater at such shorter distances. The exact crossover point between the impact of these two types of losses depends on assumptions, including antenna size. To simplify this issue, we are defining the *crossover* or *inflection point* to be the distance at which the partial derivative of the loss with distance is equal for both loss mechanisms. Figure 3 then shows the regions where each of the two propagation mechanisms dominates under this definition.

Even at a fixed location area, path loss due to absorption can vary significantly with altitude. The decreasing density of the molecules as altitude increases causes the absorption coefficient to decrease. Figure 4 shows this change with the altitudes for three bands. In the case of the 60-GHz band, the absorption is due to oxygen molecules, while in the 150- and 183-GHz band, the absorption is due to water molecules, when not on an absorption peak and when exactly on an absorption peak, respectively. The density of water molecules decreases more rapidly with altitude than that of oxygen molecules, so the absorption of radio signals also lessens more rapidly with altitude in bands that contain water molecule resonances.

Case Study: Subterahertz Backhaul Links: Bridging the Digital Divide or Harming Passive Nongeostationary Orbit Satellites?

One potential use of the mm-wave spectrum is high-speed >1 Tb/s fixed-service links for backhaul in mobile communication systems in locations where optical fiber installation is either too expensive or too time consuming to be practical. To obtain a contiguous spectrum greater than 12.5 GHz, it would be necessary to overlap passive spectrum bands that must be protected to provide vital environmental sensing from nongeostationary orbit (NGSO) satellites. Such radio links might also be useful for the temporary restoration of optical fixer links that are damaged in a disaster. At lower frequencies, sharing such passive bands is impractical because of interference concerns resulting from satellite illumination from terrestrial antenna sidelobes. But almost all such communications links are near horizontal paths, and Figure 5

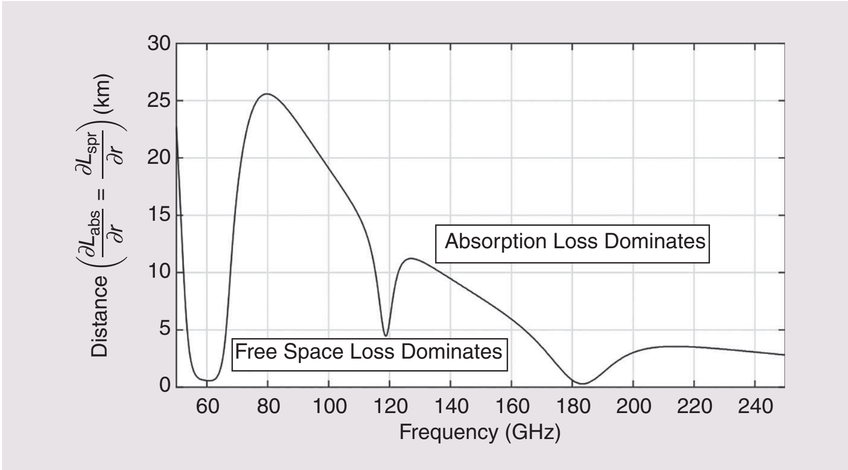

Figure 3. *The crossover distance. Above the curve absorption is the dominant loss, and below the free space, loss is dominant (sea level).*

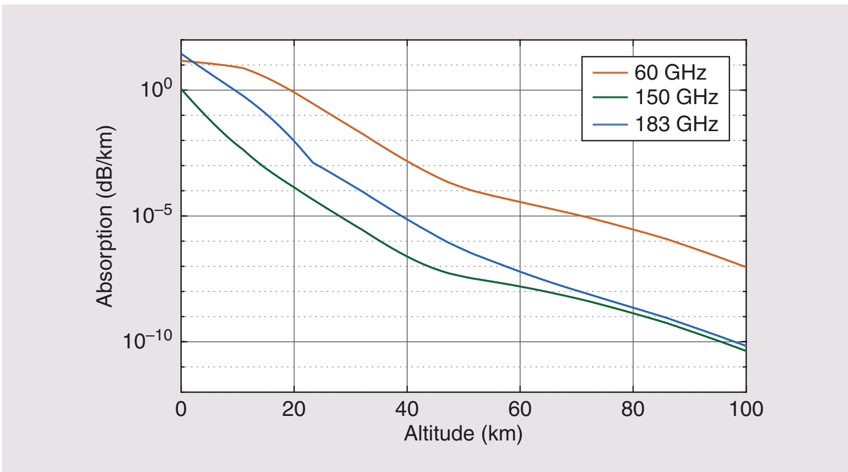

Figure 4. *The variation of absorption with altitude for mean annual global reference atmosphere.*

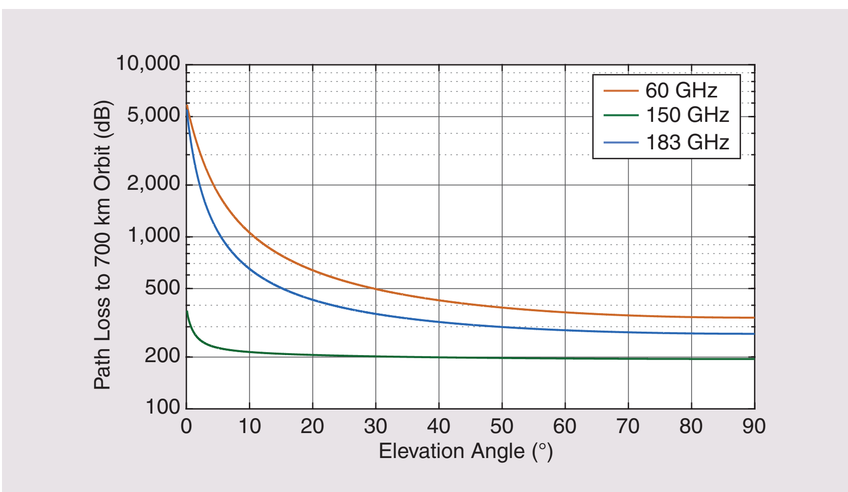

Figure 5. *The path loss to a typical NGSO satellite orbit as a function of elevation angle.*

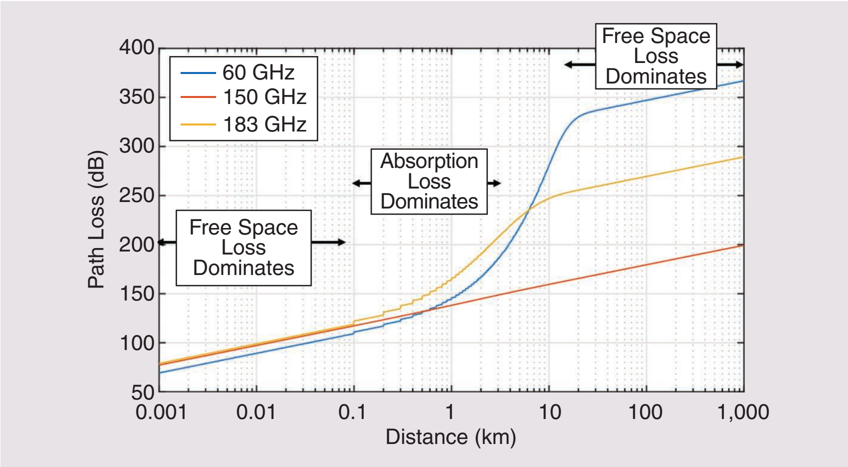

Figure 6. *Path loss versus distance for a 60° path showing the different loss mechanisms involved for slanted paths.*

shows the unusual dependence of path loss from terrestrial transmitters to satellites on elevation angles.

Note that for low elevation angles, path losses of literally thousands of decibels are possible for some passive bands. Thus, as NGSO satellites pass within view of such a transmitter, the main beam signal strength from the transmitter that impinges on the satellite would be highly attenuated and would not be as capable of causing interference as low elevation angles. At higher elevation angles, the path loss becomes much less, so successful sharing will depend on the ability to develop antennas for such links with low sidelobe levels at high elevation angles. Thus, a promising sharing mechanism for terrestrial use in passive satellite bands may be the development of terrestrial antennas with very low sidelobe levels at higher elevation angles.

Another way to look at the path loss on long paths at high elevation angles is to consider the path loss as a function of distance from the transmitter on such paths. While this calculation has no clear practical use, it does give insight into the complexity of mm-wave propagation in cases that involve both free space and absorption path losses as well as varying elevations. Figure 6 shows the case of a +60° elevation angle from a terrestrial transmitter in the case of three frequencies. For a distance less than about 0.5 km, free space loss dominates, and then absorption loss dominates. Finally, for distances greater than about 5 km from the transmitter on the slanted path, free space dominates again as the atmosphere has a much lower density of molecules, and thus absorption ceases to be significant.

Conclusion

Mm-wave and sub-THz propagation is very different than in lower bands due to the impact of absorption and its variation with many factors, such as climate and altitude. This article has shown some basic trends in the hope of developing better insight into this phenomenon. With the availability of software implementations of the P.676 model, researchers should be able to explore new system concepts that take advantage of this unusual propagation in practical systems.

Acknowledgment

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Reference

[1] M. Marcus and B. Pattan, "Millimeter wave propagation: spectrum management implications," *IEEE Micro. Mag.*, vol. 6, no. 2, pp. 54–62, Jun. 2005, doi: 10.1109/MMW.2005.1491267.