On the Mathematical Modeling of an Antenna in the 5G RF2 Range

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Abstract

The purpose of this research is to study the mathematical modeling of an antenna in the frequency range of 26-52 GHz (the 5G RF2 band) to be tested in an Over-The-Air (OTA) chamber and explore modification of the model to investigate radiation pattern output. This work is motivated by a project given to our independent study course by our industry partner OCELOTT. By literature review, we found that one of the important factors of antenna design is the path loss model. In this project, we experiment with how different environments generate different path loss models and present some examples of the environments and corresponding antennas. We also seek to make recommendations on the antennas to use based on a particular environment to minimize the path loss. We examine different types of antennas and their geometry, as well as creating simulations for the path loss to see how the signal would be affected.

Background

- An Over-The-Air (OTA) chamber is an electromagnetic shield system that are used to test the signals of electronic devices in a closed environment.
- The type of antenna we are studying is a double ridge horn antenna. This antenna is a good fit for the as it can better accommodate the 5G RF2 26-52 GHz band.
- Path loss (PL) is the attenuation of electromagnetic waves along a path from a transmitter to a receiver. Based on the frequency range, the path loss can measure the mmWave on a wider range and determine the rate of the received signal strength (RSS).
- For this research, a smaller antenna is needed as it can produce smaller mmWave wavelength and have a higher frequency spectrum bandwidth.

Goals

- Establish a clear relationship between path loss and received power.
- Demonstrate how path loss is affected by changes in frequency.
- Show how the radiation patterns of the receiving antenna vary with path loss.

Methods

Both Python and the Computer Simulation Technology (CST) Studio Suite were used to model the parameters of the antenna.

First, three different path loss models were investigated at a set distance of 20 centimeters through a range of frequencies that spanned the 5G RF2 band. In particular, we plotted each path loss model as a function of frequency, as well as a test power received model.

Beyond our initial approach, the CST Studio Suite allowed us to work with a more intuitive 3d modeling software, especially since it allowed us to specify the kind of antenna as a double ridge horn antenna. From this software, a number of radiation diagrams and gain profiles were generated.

$$\mathrm{PL}^{\mathrm{AGB}}(f,d)[\mathrm{dB}] = 10\alpha\log_{10}\left(\frac{d}{1\text{ m}}\right) + \beta + 10\gamma\log_{10}\left(\frac{f}{1\text{ GHz}}\right) + \chi_\sigma^{\mathrm{ABG}}\ ;\ (\text{for } d \geq 1\text{ m})$$

Table 1. Meaning of Each Term

Terms	Meaning	Units
$\mathrm{PL}^{\mathrm{ABG}}$	Path Loss	decibels [dB]
α	Distance Coefficient	decibels [dB]
β	Optimized Offset Value	decibels [dB]
γ	Frequency Coefficient	decibels [dB]
d	3-D T-R Separation Distance	meters [m]
f	Carrier Frequency	gigahertz [GHz]
$\chi_\sigma^{\mathrm{ABG}}$	Gaussian Random Variable[1]	decibels [dB]

[1] σ represents the standard deviation of $\chi_\sigma^{\mathrm{ABG}}$ in units of decibels [dB], describing large-scale signal fluctuations.

$$\mathrm{PL}^{\mathrm{CI}}(f,d)[\mathrm{dB}] = \mathrm{FSPL}(f,d_0)[\mathrm{dB}] + 10n\log_{10}\left(\frac{d}{d_0}\right) + \chi_\sigma^{\mathrm{CI}}\ ;\ (\text{for } d \geq d_0)$$

$$\mathrm{FSPL}(f,d_0)[\mathrm{dB}] = 20\log_{10}\left(\frac{4\pi f d_0 \times 10^9}{c}\right)$$

Table 1. Meaning of Each Term

Terms	Meaning	Units
$\mathrm{PL}^{\mathrm{CI}}$	Path Loss	decibels [dB]
FSPL	Free-Space Path Loss	decibels [dB]
f	Carrier Frequency	gigahertz [GHz]
d	3-D T-R Separation Distance	meters [m]
d_0	CI Free Space Reference Distance	meters [m]
n	Path Loss Exponent	decibels [dB]
c	Speed of Light	meters per second [m/s]

$$\mathrm{PL}^{\mathrm{CIF}}(f,d)[\mathrm{dB}] = \mathrm{FSPL}(f,d_0=1\text{ m})[\mathrm{dB}] + 10n\left(1 + b\left(\frac{f-f_0}{f_0}\right)\right)\log_{10}(d) + \chi_\sigma^{\mathrm{CIF}}\ ;\ (\text{for } d \geq 1\text{ m})$$

$$f_0 = \frac{\sum_{k=1}^{K} f_k N_k}{\sum_{k=1}^{K} N_k}$$

Table 3. Meaning of Each Term

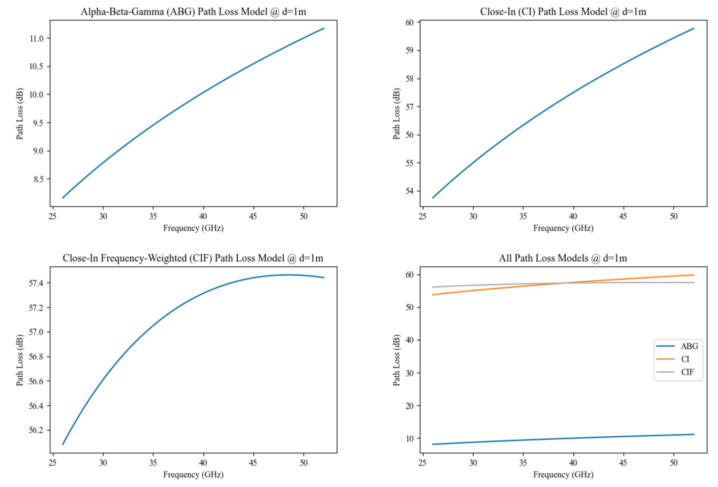
Terms	Meaning	Units
$\mathrm{PL}^{\mathrm{CIF}}$	Path Loss	decibels [dB]
FSPL	Free-Space Path Loss	decibels [dB]
f	Carrier Frequency	gigahertz [GHz]
f_0	Average Frequency	gigahertz [GHz]
d	3-D T-R Separation Distance	meters [m]
d_0	CI Free Space Reference Distance	meters [m]
n	Distance Coefficient	decibels [dB]
b	Linear Frequency Coefficient	no units [ ]
K	Number of Unique Frequencies	no units [ ]
N_k	Number of Path Loss Data Points	no units [ ]
$\chi_\sigma^{\mathrm{CIF}}$	Gaussian Random Variable[1]	decibels [dB]

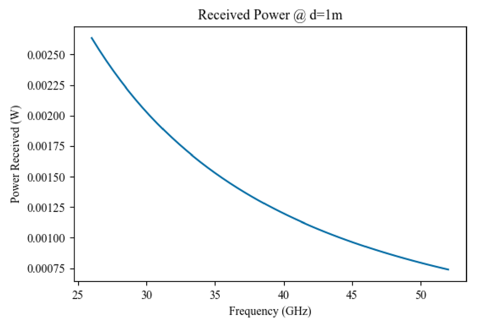
[1] σ represents the standard deviation of $\chi_\sigma^{\mathrm{CIF}}$ in units of decibels [dB] that describes large-scale shadowing.

Results

Path Loss Models and Received Power Test

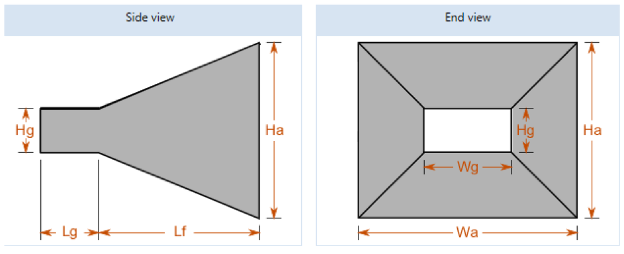
The path loss models are plotted below for a distance of 20 centimeters and other parameters set equal to 1 to see how path loss responds to change in frequency.

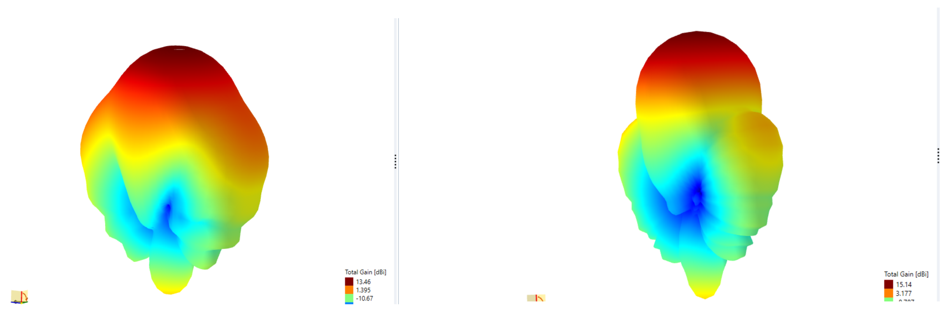


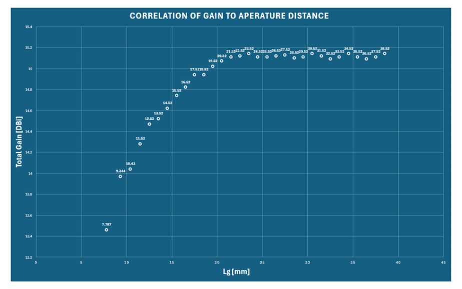


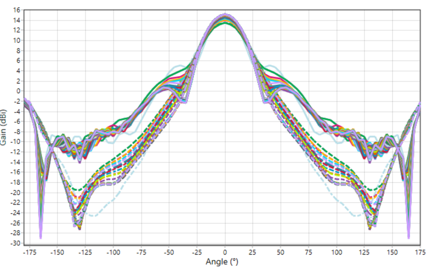
Radiation Diagrams and Gain Profiles

Following our research and Model making, we were able to access the Antenna Magus software to run simulations with varying dimensions of the antenna. Correlation was found between the aperture of the antenna and total gain (calculated by simulation). This simulation also gave radiation patterns for the set frequency of 38.5 GHz.









Continuing Work

Following the current results, there will be further development on the antenna itself as we continue to work with the industry partners and establish full access to the Antenna Magus software. In addition to this, we will continue to develop mathematical models and integrate them with the CST simulated Horn Antenna and optimize the final design for maximum gain and minimal loss.

Conclusion

- A double ridge horn antenna was confirmed to be a suitable antenna to accommodate the 5G RF2 26-52 GHz frequency band.
- The received power of an antenna is significantly affected by path loss, especially towards higher frequencies. However, the effect of antenna shape on received power can still be explored.
- There was found to be a correlation between the antenna aperture size and the total gain, leading to differences in radiation pattern according to antenna dimensions.

Acknowledgements

Faculty Mentor: Dr. Keshav Acharya

We extend our gratitude to Rodrigo Junqueira and Rodrigo Marques of OCELLOTT for proposing this project, and allowing us to work with them.