Robotics and
Embedded Systems

5G Network Analysis

Project Report for the Lab Course Sensor Model-Based Autonomous Driving

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Contents

1. Introduction

In order to get a proper understanding of gigahertz network channel capacities (maximum data transfer rate) and ranges, a theoretical channel model will be derived subsequently. The channel model is further supposed highlight signal attenuations in various environments, with various factors affecting signal power.

The report starts with estabilishing a basic channel in chapter 2, introduces free-space signal losses and specific signal attenuators such as foliage and rainfall. The resulting channel model is plotted for a given rural scenario in 3 and channel capacities for a rural highway scenario discussed.

An outlook to further improvements to the model is given in chapter 4.

Furthermore, the channel model discussed in this report is implemented in the accompanying python script. Plots generated in chapter 3 can be generated for any given combination of channel parameters.

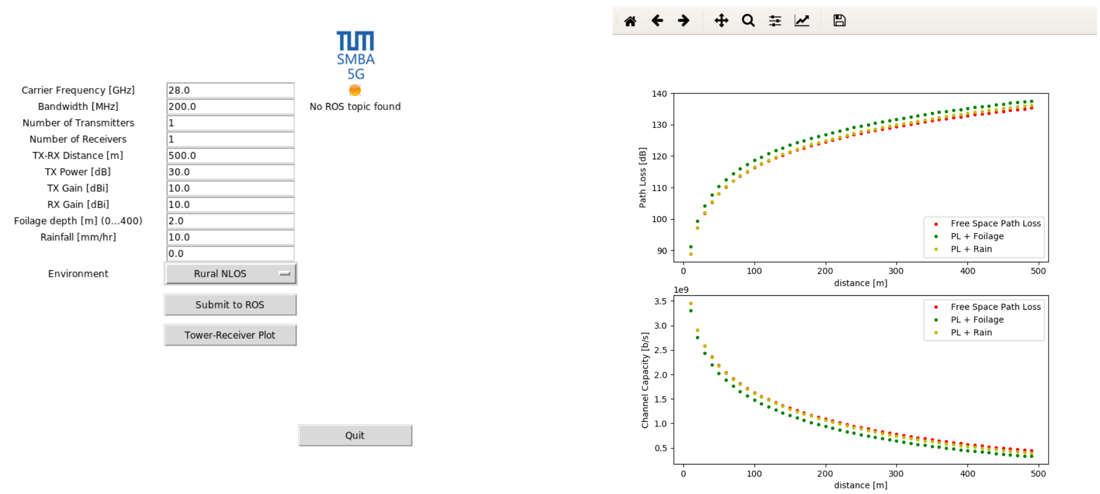

Figure 1 Python script GUI to simulate gigahertz channel models and generate path loss and channel capacity plots over distance.

2. Model

2.1. Channel Capacity, Noise and Signal Power

In order to estimate the radio propagation losses in a given environment, a loss model has to be established. Given the loss model, the available transmission bandwith can be inferred with the Shannon-Hatley theorem [2] as followed:

$$C = B\log_2(1 + \frac{S}{N}) \tag{2.1}$$

where C is the channel capacity (or bitrate), B the bandwidth of the communication channel, S the received signal power and N the signal noise. Signal power over signal noise yield a fractionless unit, commonly called the signal to noise ratio (SNR). The SNR is given by the fraction $\frac{S}{N}$ for powers in Watts or by following subtraction $SNR = P_R - P_N$ if powers are given in decibels.
For a given channel model the bandwidth B is known, leaving the SNR to be determined. While the signal power S is a more complex result of the recieved signal power minus transmission losses, the noise power N is dominated by thermal noise in the receiving antenna and can be model by John-Nyquist noise. John-Nyquist noise models the thermal agitation of charge carriers in an electric conductor [5], the antenna, and is given by:

$$P = k_B T \Delta f \tag{2.2}$$

where k_B is the Boltzmann constant, T the temperature of the receiver in Kelvin and Δf the bandwidth of the channel. Changes in temperature yield negligable effect on the noise floor for common environmental temperature of 0 to 30 degress Celsisus. One can thus simplify the formula for a temperature of 20 degress Celsisus and express the power in units of dBm (as will all upcoming formulas) to yield:

$$P_N = 10\log_{10}(k_B T * 1000) + 10\log_{10}(\Delta f) = 174 + 10\log_{10}(\Delta f) \tag{2.3}$$

The noise power is thus primarily affected on the channel bandwidth Δf.
The received signal power P_R is modeled, for any given receiver-transmitter pair of radio antennas, by the Friis transmission equation [1]:

$$P_R = P_T + G_T + G_R - 20\log_{10}(\frac{4\pi d}{\lambda}) \tag{2.4}$$

where P_T is the transmission power in decibels at the transmitting antenna, G_T and G_R the transmitting and receiving antenna gains respectively. The last term gives the free-space path loss that the signal undergoes, given receiver and transmitter and in the far field of each other ($d >> \lambda$), where d gives the transmitter-receiver distance and λ the carrier wavelength. For a 5 GHz signal, the wavelength equals 6 cm. Thus the far field assumption holds for the given case, as transmitter-receiver distances d of less then 1 m are not of interest.

2.2. Free-Space Path Loss

The free-space path loss ($FSPL$) term of the Friis transmission equation (last term,[7]) yields only the path loss due to the geometric spread of the tranmission signal over distance. To include further environmental scenarios, such as non line of sight (NLOS) cases, the FSPL is replaced with the path loss (PL) given by the log normal shadowing (or large-scale path loss) model ([6]), as:

$$PL_L = FSPL(f, 1m) + 10n\log_{10}(d) + \chi_\sigma \tag{2.5}$$

The path loss is given by the $FSPL$ at a receiver-transmitter distance of 1 m and extended by terms around the path loss exponent n (or PLE) and the fading deviation χ_σ. One may note that a PLE n of 2 would yield the same as the FSPL at distance d plus the deviation term χ_σ. PLE and χ_σ are found as results from experimental measurements. Figure **??** shows measurements under different environmental conditions and the marks the according trend lines for the respective path loss exponents n. Values for n and χ_σ are found in table 2 for urban and rural environemtns and line of sight and non line of sight scenarios.

Environment	Path Loss Exponent	Fading Deviation [dB]
Urban LOS	2.0	4.0
Urban NLOS	3.2	7.0
Rural LOS	2.2	4.0
Rural NLOS	2.8	8.0

Figure 2 Table of common path loss exponents and fading deviation values for given LOS and NLOS environments. Updated values taken from [8].

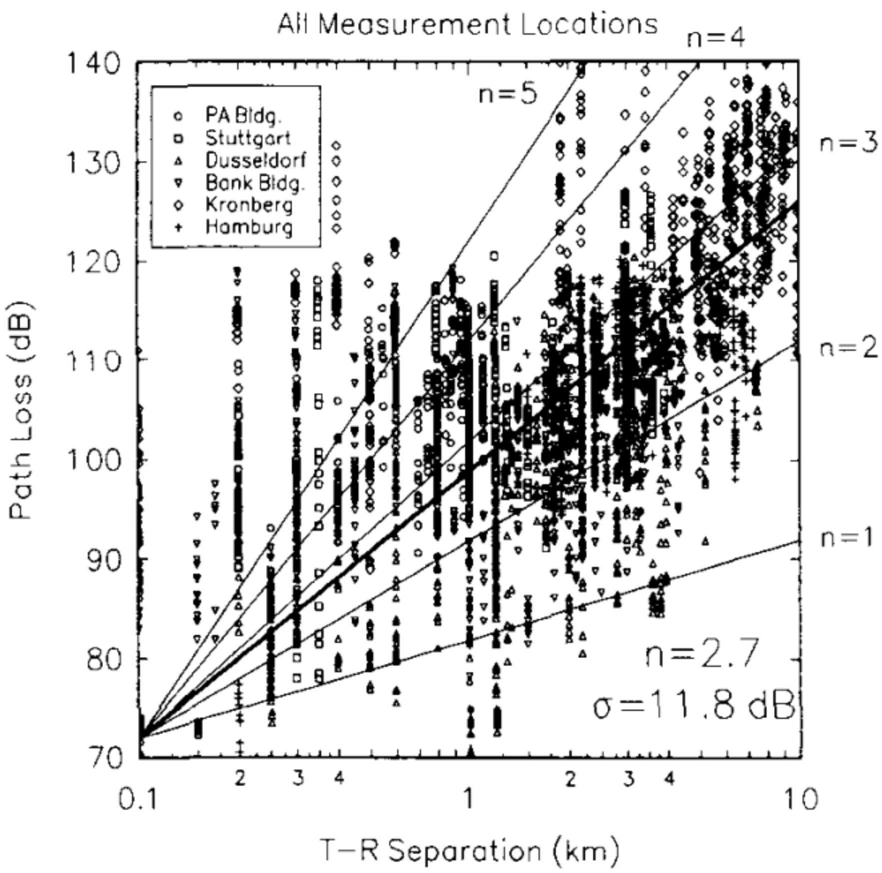

Figure 3 Experimentally determined path loss vs log transmitter-receiver distance for various environments. Trend lines indicate the path loss exponent for given scenarios [6].

2.3. Specific path losses

2.3.1. Foliage

Signal attenuation due to foliage can be described by Weissberger's model [11]. Based on experimental data, a formula is given for foliage depth d_f of up to 400m, for a given channel of carrier frequency f as followed:

$$PL_F = \begin{cases} 1.33 f^{0.284} d_f^{0.588} & \text{if } 14 < d \leq 400 \\ 0.45 f^{0.284} d_f & \text{if } 0 < d \leq 14 \end{cases} \tag{2.6}$$

Wiessberger's model is best for dense, dry tree foliage and only suitable for carrier frequencies between 230 MHz and 95 GHz. The frequency criteria is fullfilled in the channel models followingly investigated and the model sufficiently applicable to middle european vegetation.

2.3.2. Rainfall

A model for path loss due to rainfall is given by the International Telecommunications Union (ITU) in recommondation ITU-R P.838-3 [10]. The recommondation (based on [3]) specifies the specific attenuation γ_R in dB/km (transmitter-receiver distance) for a given rainfall rate R in mm/h as followed:

$$\gamma_R = kR^{\alpha} \tag{2.7}$$

whereby the coefficients k and α are given for linear or circular polarizations by:

$$k = [k_H + k_V + (k_H - k_V)\cos^2\theta\cos 2\tau]/2 \tag{2.8}$$

$$\alpha = [k_H\alpha_H + k_V\alpha_V + (k_H\alpha_H - k_V\alpha_V)\cos^2\theta\cos 2\tau]/2k \tag{2.9}$$

The recommondation provides lookup tables for the horizontal and vertical components of k and α for carrier frequencies f between 1 and 1000 GHz. For simplicity, only the values at 28 GHz are used in the following model, which avoids implementing a lookup table for the given coefficients. To get the path loss in dB, equation 2.7 must be multiplied by the distance d as followed:

$$PL_R = kR^{\alpha}d/1000 \tag{2.10}$$

As rainfall attentuation increases for carrier freuencies f below 100 GHz (as seen in figure 4, the choosen frequency provides us with an upper limit for the targeted 5G frequencies of 2 to 28 GHz. One may note, that for even for heavy rainfall, as assumed in figure 4, the path loss due to rainfall is below 1dB and thus negligably small.

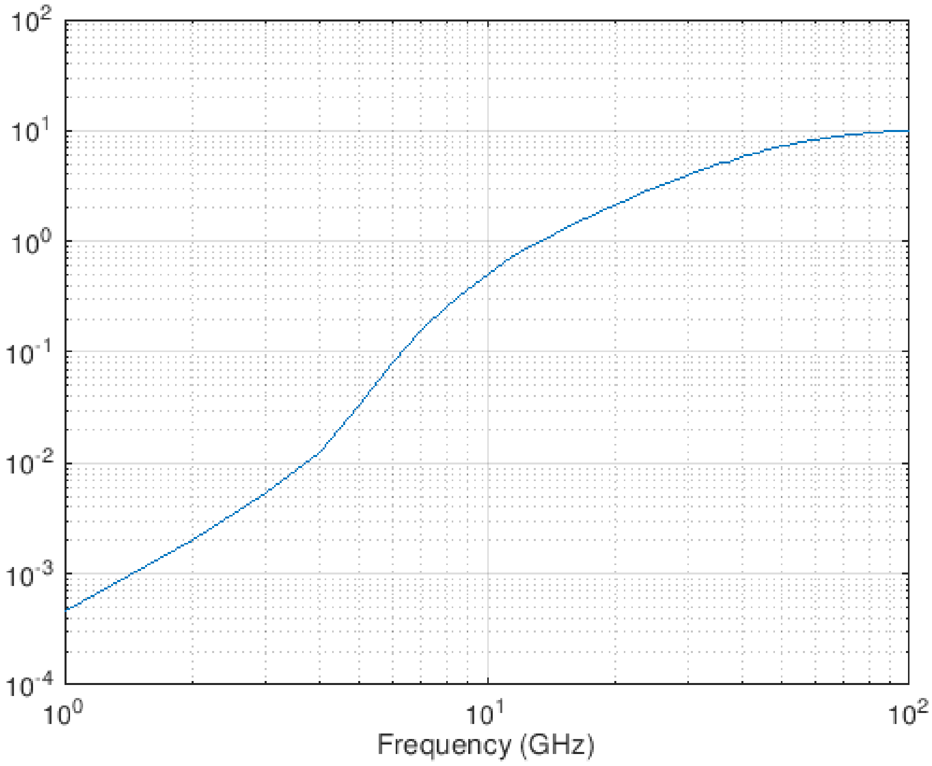

Figure 4 Plot of path loss (attenuation) due to heavy rainfall (20mm/h) for carrier frequencies between 1 and 100 GHz, given a transmitter receiver distance of 1000m. (MathWorks Matlab Phased Array System Toolbox)

2.4. Channel Model

Given all models for signal attenuation above, a final path loss can be constructed ([9]) from equations 2.5, 2.6 and 2.7 as:

$$\begin{aligned} PL &= PL_L + PL_F + PL_R \\ &= 20\log_{10}(\frac{4\pi f}{c}) + 10n\log_{10}(d) + \chi_\sigma \\ &\quad + 1.33 f^{0.284} d_f^{0.588} \\ &\quad + kR^\alpha d/1000 \end{aligned} \tag{2.11}$$

given $14 < d_f \leq 400$ for Weissenberg's model case. The accompanying python implementation of the channel model does account for both cases accordingly.

The final channel capacity can thus be obtained by substituting the path loss equation 2.11 into Friis transmission equation 2.4:

$$P_R = P_T + G_T + G_R - PL \tag{2.12}$$

Shannon-Nyquist (2.13) then yields the final capacity in bits/second through Friis (2.12) and the Nyquist noise (2.3) as:

$$C = B\log_2(1 + SNR) = B\log_2(1 + 10^{((P_R - P_N)/10)}) \tag{2.13}$$

Simulation results for various scenarios with channel model given above are presented in the next chapter.

3. Simulation

Given the path loss model established, we can plot the path loss and corresponding channel capacity over distance, to identify the maximum feasable transmitter-receiver distance d. For the following plots, a few channel assumptions have been made to reflect a likely 5G network scenario along a highway:

- Carrier frequency: 28 GHz
- Bandwidth: 800 MHz
- Transmission Power: 30 dBm
- Transmission Gain: 10 dBm
- Receiver Gain: 10 dBm
- Environment: Rural

These assumptions yield the path loss and capacity plots in figure 5 for short distances (1 - 400m) and figure 6 for long distances (400 - 2000m). As figure 5 shows, the lowest path loss occurs for direct line of sight (LOS) channels, where roughly a 30 dB difference between LOS and NLOS cases can be observed in the first 400 meters. Looking at specific factors, such as rainfall, it can be obsereved, that even heavy rainfall contributes an insignificant amount of attenuation when compared to NLOS path loss. Foliage however, 10 m in this case, does produce a significant path loss.
Overall, the LOS case yields roughly 100 Mbit/s channel capacity at 200m meters (fig. 5) and 3 Mbit/s at 1000m of transmitter-receiver distance.
Contrary, the NLOS case with foliage decays quickly to 100 Mbit/s of capacity in the first 10 meters. The 1 Mbit/s limit is reached after 50 meters and figure 7 shows only a mere 800 bits/s at 400m transmitter-receiver distance.
One can thus conclude, that for the choosen channel parameters, the NLOS case provides no signifcant data transfer in ranges over 100 meters. An application as a 5G base station thus seems extremly unlikely in rural settings, such as a highway. Solely LOS communication seems feasable.
Given a rural highway setting with direct LOS communication between base station and receiver and a medium car density of 4 cars every 25 meters (both directions), a simultaneous bandwidth of 3.25 Mbits/s could be available for every participant.

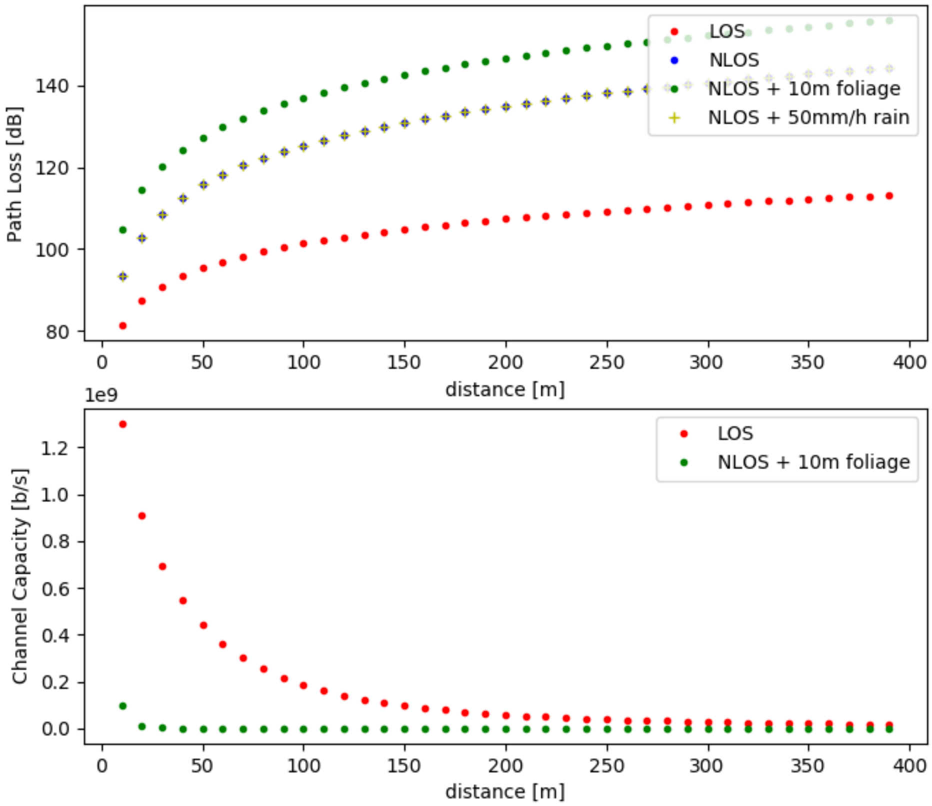

Figure 5 Path loss and channel capacity over 1 to 400 m distance for various environment scenarios, given channel parameter above.

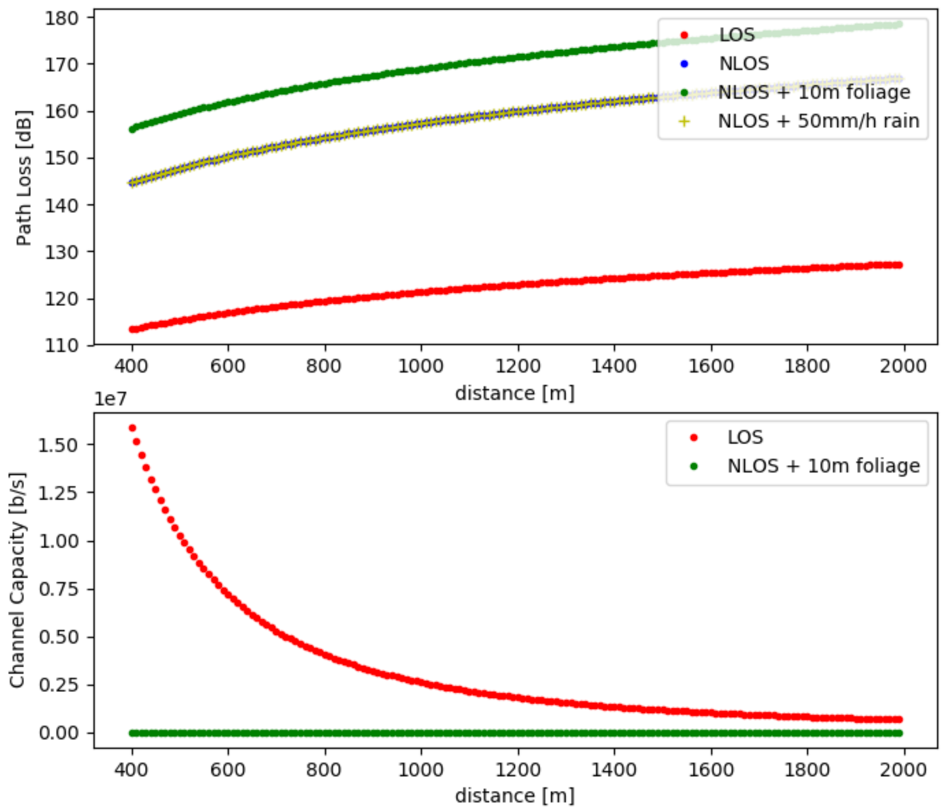

Figure 6 Path loss and channel capacity over 400 to 2000 m distance for various environment scenarios, given channel parameter above.

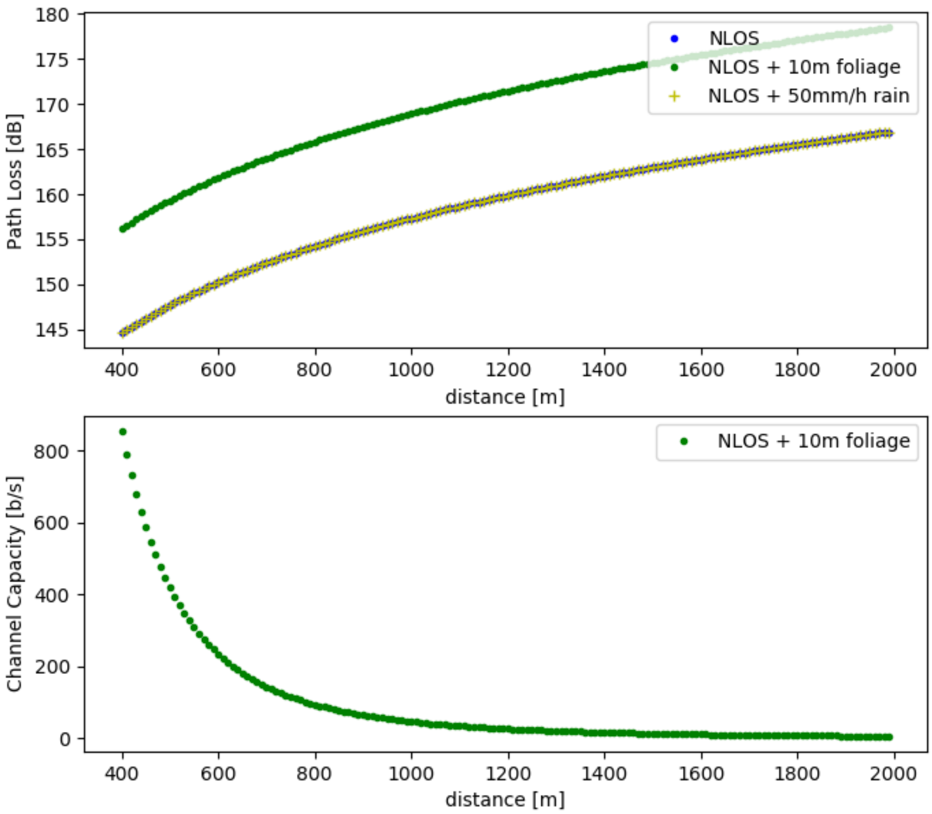

Figure 7 Path loss and channel capacity over 400 to 2000 m distance for NLOS environment scenarios, given channel parameter above.

4. Conclusion and Outlook

The channel model given in this report can be further expanded by including signal attenuation due to multipath. However, the mathematical model becomes non-trivial and the usage of existing implementations may be wise, such as Matlab's Phased Array System Toolbox. Multipath effects produce curious results in respect to transmiter and receiver heights, where signals can be attenuated or amplified [4].

Furthermore, a MIMO channel model with corresponding channel matrix may be of utter interest, given MIMO usage in LTE and especially 5G networks. With MIMO, it would be interesting to compare the effects of signal attenuation between different operating modes i.e. precoding (for maximum single channel signal strength) verses spatial multiplexing (for parallel channels on the same carrier frequency) [9].

Overall, the channel model and it's python implementation give a basic toolbox to generate channel capacity plots for various environments and influencing factors. Basic esimates about necessary base station density for given data rates in given environments can be made.

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