NetSim®

Accelerate Network R & D

Propagation Models

A Network Simulation & Emulation Software

By

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1 Introduction

Path loss calculations are carried out between a transmitter and a receiver using propagation models and other calculations related to radio wave propagation such as shadowing and fading. Propagation models are mathematical representations of the average loss in signal strength over distance. Shadowing and fading margins are added to this average loss to get more precise path loss values.

NetSim is a packet level network simulator, for answering questions such as: application throughputs, packet latencies, probability of packet delivery, rate of packet delivery, etc. For such a simulation it is sufficient and efficient to model the power attenuation over a channel. Sufficient, because the received power determines the probability of packet reception. Efficient, because a symbol-by-symbol model would require a channel model with a complex response function, and modelling of all the propagation paths; this will make the simulation very slow, defeating the very objective of packet-level modelling. Questions such as file transfer throughput, voice and video quality, the effect of network sizing, the comparisons between different wireless access technologies can all be answered by a packet level model, along with power loss models over the communication channels.

Propagation models are used to model power loss (signal attenuation) for all wireless links. These include WLAN – 802.11, Legacy Networks, ZigBee / IOT / WSN – 802.15.4, LTE, Cognitive radio – 802.22 and VANET. The 5G NR propagation models are described in the 5G NR technology library document.

1.1 Propagation Loss

Three different and mutually independent propagation phenomena influence the power of the received signal: path loss, shadowing and fading.

The different models available in NetSim are

1. **Path loss Models**
   - Friis Free Space Propagation (Default option in GUI)
   - Log Distance
   - HATA Suburban
   - HATA Urban
   - COST 231 HATA Suburban
   - COST 231 HATA Urban
   - Indoor Office

- Indoor Factory
- Indoor Home
- No Path Loss
- Two Ray
- Patloss Matrix File
- None

2. **Shadowing Models**
   - None
   - Constant
   - Lognormal

3. **Fading Models**
   - None
   - Rayleigh
   - Nakagami
   - Rician

2 Path loss

Path loss is the reduction in power density of an electromagnetic wave as it propagates through space. Path loss may be due to many effects, such as free reflection, aperture-medium coupling loss, and absorption. The general formula by which received power is calculated is

$$RX_{Power} = TX_{Power} + G_t + G_R - PL_{d0} - 10 \log D^\eta$$

Where η is the path loss exponent, whose value is normally in the range of 2 to 5, G_t is the transmitter antenna gain, and G_R is the receiver antenna again. In NetSim, the default value for path loss exponent η, is 2.

D is the distance between transmitter and the receiver, measured in meters. D is assumed to be greater than d_0, the far field reference distance. PL_{do} is the path loss at reference distance, d_0 (d_0 is assumed as 1m). PL_{do} depends on the protocol and is a user input available in the PHY layer of the radios. For 802.11b the default value is 40dB

Example: Calculate the received power at 2 due to node 1's transmission. The transmit power of node1 is 100mW (20dBm), frequency is 2412 MHz, and G_t and G_R are 0

$$RX_{power} \text{ (dbm)} = 20 \text{ dBm} + 0 + 0 - 40\text{dB} - 40\text{dB} = -60 \text{ dBm}$$

The default value for reference distance d_0 and path loss at reference distance PL_{d0} are

1. 802.11 a / b / g / n / ac / p
   a. 2.4 GHz: Default d_0 = 1m and PL_{d0} = 40dB
   b. 5 GHz: Default d_0 = 1m and PL_{d0} = 47 dB
2. 802.15.4
   a. Default d_0 = 8m and PL_{d0} = 58.5dB
3. In LTE and 5G NR the calculations are done for each carrier for uplink and download
   a. Default d_0 = 1m and PL_{d0} = 32dB

2.1 Path loss models

2.1.1 Friis Free space propagation model

The free space propagation model is used to predict received signal strength when the transmitter and receiver have a clear, unobstructed line-of-sight path between them. Satellite communication systems and microwave line-of-sight radio links typically undergo free space propagation. The free space power received by a receiver antenna which is separated from a radiating transmitter antenna by distance d, is given by the Friis free space equation.

$$P_r = P_t + G_t + G_r + 20\log_{10}\left(\frac{\lambda}{(4 * \pi * d_0)}\right) + \left(10 * 2 * \log_{10}\left(\frac{d_0}{d}\right)\right)$$

where P_t is the transmitted power, P_r is the received power, G_t is the transmitter antenna gain, G_r is the receiver antenna gain, d is the T-R separation distance in meters and λ is the wavelength in meters.

2.1.2 Log distance

The average received power logarithmically decreases with distance, whether in outdoor or indoor radio channels. The average large-scale path loss for an arbitrary T-R separation is expressed as a function of distance by using path loss exponent n.

$$P_r = P_t + G_t + G_r + 20\log_{10}\left(\frac{\lambda}{(4 * \pi * d_0)}\right) + \left(10 * \eta * \log_{10}\left(\frac{d_0}{d}\right)\right)$$

Where η is path loss exponent. NetSim allows users to set $2.0 \leq \eta \leq 5.0$

d_0 is the reference distance, and the model is applicable only for $d > d_0$

d is the Transmitter Receiver separation distance.

2.1.3 Hata Urban

The hata model is an empirical formulation of the graphical path loss data provided by Okumura. Hata presented the urban area propagation loss as a standard formula and supplied correction equations for applications to other situations. The standard formula for median path loss in urban areas is given by

$$Pr = [Pt] - L50\,(dB)$$

$$L_{50}(dB) = 69.55 + 26.16\log(f_c) - 13.82\log(h_{te}) - a(h_{re}) + (44.9 - 6.55\log(h_{te}))\log(d)$$

Where

L_{50} (dB) = 50th percentile (median) value of path loss

f_c = Frequency in MHz

h_{te} = Transmitter antenna height (Range 30m to 200m, default 30m)

h_{re} = Receiver antenna height (Range 1m to 10m, default 1m)

d = Separation distance in km. Since the input is in meters, it is divided by 1000 to convert to km

$a\,(h_{re})$ = correction factor for effective mobile antenna height which is a function of the size of coverage area.

$$a\,(hre) = 8.29\,(log\,1.54\,h\,re\,)2 - 1.1\,db \quad \text{for } f_c < 300\text{ MHz}$$

$$a\ (hre)\ =\ 3.2\ (log\ 11.74\ h\ re\ )2 - 4.97\ db \quad \text{for } f_c >= 300 \text{ MHz}$$

2.1.4 Hata Suburban

To obtain path loss in suburban area, the standard Hata urban formula is modified as

$$Pr\ =\ [Pt]\ -\ L50\ (dB)$$

$$L_{50}\ (dB)\ =\ L_{50}(urban)(dB) - 2\left[\frac{logf_c}{28}\right]^2 - 5.4$$

2.1.5 COST231 Hata Urban and COST231 Hata Suburban

The European Co-operative for Scientific and Technical Research (EURO-COST formed COST231 working committee to develop an extended version of the Hata model COST231 proposed the following formula to extend Hata's model. The proposed model for path loss is

$$Pr\ =\ [Pt]\ -\ L50\ (dB)$$

$$L50(dB) = 46.3\ +\ 33.9log\ (fc) - 13.82log\ (hte) - a(hre) +\ (44.9 - 6.55\log(hte))\log\ (d) + CM$$

$$\text{Where } C_M = \begin{cases} 3\ dB\ for\ Urban \\ 0\ dB\ for\ Suburban \end{cases}$$

2.1.6 Indoor office and Indoor factory

$$Pr\ =\ [Pt] + [Gt] + [Gr] + 20log10\left(\frac{\lambda}{(4*\pi*d_0)}\right) + \left(10*\eta*log10\left(\frac{do}{d}\right)\right)m$$

$$\text{Where } \eta = \begin{cases} 2.6\ \ \text{for Indoor\_office} \\ 2.1\ \ \text{for Indoor\_factory} \end{cases}$$

2.1.7 Indoor home

$$Pr\ =\ [Pt]\ +\ [Gt]\ +\ [Gr]\ +\ 20log10\left(\frac{\lambda}{(4*\pi*d_0)}\right) + \left(10*\eta*log10\left(\frac{do}{d}\right)\right)$$

Where η = 3

2.1.8 Two Ray

The Two-Rays Ground Reflected Model is a radio propagation model which predicts the path losses between a transmitting antenna and a receiving antenna when they are in LOS (line of sight). Generally, the two antenna each have different height. The received signal having two

components, the LOS component and the multipath component formed predominantly by a single ground reflected wave. The standard formula for Two-ray model is

$$Pr = [Pt] + [Gt] + [Gr] - 40\log_{10}(d) + 10\log_{10}(Gh_t^2 h_r^2)$$

Where

G= $G_t \times G_r$ = product of transmit and receive antenna gains

h_t = z coordinate of the transmitter plus transmitter antenna height

h_r= z coordinate of the receiver plus receiver antenna height

d = Distance between transmitter and receiver

2.1.9 Pathloss Matrix File

In Pathloss using matrix file, users can write their own custom pathloss models and define the pathloss for the wireless links. The name of the trace file generated should be kept as PathlossMatrix<Wireless Link Id>.txt and it should be in the **NetSim Pathloss Matrix File format**.

The propagation loss is fixed for each pair of nodes and does not depend on their actual positions. This model should be useful for synthetic tests. Note that by default the propagation loss is assumed to be symmetric. The value of pathloss for each pair of nodes is read from a file.

The name of the trace file generated should be kept as PathlossMetrics<Wireless Link Id>.txt and it should be in the NetSim Pathloss Metrics File format**.** The NetSim Pathloss Matrix File format is as follows

Step 1: Open node (Wireless_Link) properties -> select pathloss model as PATHLOSS_MATRIX_FILE and click on Configure Pathloss metrics.

Step 2: Inside the text file and write the code in format shown below

Commented lines

Empty lines will be ignored

Format for writing this file is

SNR value must be in increasing order

time(sec),tx,rx,loss(dB)

time <Time_in_Secs>, <Tx_Node_ID>, <Rx_Node_ID, <Pathloss(dB)>

2.1.10 Default value of pathloss exponent

The default value of path loss exponent for all path loss models in NetSim are as shown below **Table 2-1**.

Path loss model	Path loss exponent (default)
Friis free space	2
Log distance	2
COST231 Urban	-
COST231 Hata Suburban	-
Hata Urban	-
Hata Suburban	-
Indoor Office	2.6
Indoor Factory	2.1
Indoor Home	3

Table 2-1: Default value of path loss exponent for path loss models

3 Shadowing models

3.1 Log normal shadowing

Pathloss models predict the mean path loss as a function of transmission and reception parameters such as frequency, antenna heights, and distance, etc. Therefore, the predicted path loss between a transmitter and a receiver is constant, in a given environment and for a given distance.

However, in reality different types of clutter may exist in the transmitter-receiver path. Therefore, the path losses for the same distance could be different along paths that pass through different types of environments. The location of the receiver in different types of clutter causes variations with respect to the mean path loss values given by the path loss models. Some paths undergo more loss while others are less obstructed and may have higher received signal strength. The variation of path loss with respect to the mean path loss values predicted by the propagation models, depending on the type of environment is called shadow fading (Shadowing) or slow fading. "Slow" fading implies that the variations in the path loss due to shadow fading occur comparatively slower than the fast fading effect (Fading), which is due to the mobile receiving multipath copies of a signal.

Measurements have shown that at any value of d, the path loss PL (d) at a particular location is random and distributed log-normally about the mean distance-dependent value i.e.

$$PL(d)[dB] = PL(d) + X\sigma = PL_{d_0} + 10nlog\left(\frac{d}{d_0}\right) + X\sigma$$

Where Xσ is a zero-mean Gaussian distributed random variable (in dB) with standard deviation σ (in dB)

The log normal distribution describes random shadowing effects which occur over a large number of measurement locations which have the same T-R separation but have different levels on the clutter propagation path. This phenomenon is referred to as log-normal shadowing

The default values of standard deviation (dB) for all shadowing models in NetSim are as shown below **Table 3-1**.

Shadowing Model	Standard Deviation
Log Normal	5
Constant	5

Table 3-1: Default values of standard deviation (dB) for shadowing models

4 Fading models

Fading is caused by interference between two or more versions of transmitted signal which arrive at the receiver at slightly different times. These waves, called multipath waves, combine at the receiver antenna to give a resultant signal which can vary widely in amplitude and phase, depending on the distribution of the intensity and relative propagation time of the waves and the bandwidth of the transmitted signal.

In built-up urban areas, fading occurs because the height of the mobile antennas is well below the height of surrounding structures, so there is no single line-of-sight path to the base station. The code for calculating fading power is present in fn_NetSim_IEEE802_11_Phy_In() function in IEEE_802_11.c file inside IEEE802_11 project.

The default values of Fading parameters in NetSim are as shown below **Table 4-1**.

Fading Model	Parameter	Value
Rayleigh	Scale Parameter	1
Nakagami	Shape parameter	1
	Scale Parameter	1
Rician	Shape parameter	1
	Scale Parameter	1

Table 4-1: Default values of Fading parameters

4.1 Nakagami Fading

The Nakagami distribution is related to the gamma distribution. In particular, given a random variable

$$Y \sim \gamma(K, \Theta)$$

it is possible to obtain a random variable

$$X \sim Nakagami\ (m, \Omega)$$

by setting k = m, Θ= Ω/m and taking the square root of Y

$$X = \sqrt{y}$$

4.2 Rayleigh Fading

In mobile radio channels, the Rayleigh distribution is commonly used to describe the statistical time varying nature of the received envelope of a flat fading signal, or the envelope of an individual multipath component. It is well known that the envelope of the sum of two quadrature Gaussian noise signals obeys a Rayleigh distribution. The Rayleigh distribution has a probability density function (pdf) is given by

$$P(r) = \frac{r}{\sigma^2} exp\left(-\frac{r^2}{2\sigma^2}\right) \quad 0 <= r <= \infty$$

$$P(r) = 0 \quad\quad r < 0$$

Where σ = rms value of the received voltage signal before envelope detection

σ^2 = time-average power of the received signal before envelope detection

The probability that the envelope of the received signal does not exceed a specified value R is given y corresponding cumulative distribution function (CDF) is given by

$$P(R) = \Pr(r \leq R) = \int_0^R p(r)dr = 1 - exp\left(-\frac{R^2}{2\sigma^2}\right)$$

The mean value r_{mean} of the Rayleigh distribution is given by

$$rmean = E[R] = \int_0^\infty rp(r)dr = \sigma\sqrt{\frac{\pi}{2}} = 1.2533\sigma$$

And the variance of the Rayleigh distribution is given by σ_r^2 which represents the ac power in the signal envelope

$$\sigma r^2 = E[r^2] - E^2[r] = \int_0^\infty r^2 p(r)dr - \frac{\sigma^2 \pi}{2} = \sigma^2\left(2 - \frac{\pi}{2}\right)$$

4.3 Rician Fading

In communications theory, **Rician distributions** are used to model scattered signals that reach a receiver by multiple paths. Depending on the density of the scatter, the signal will display different fading characteristics. Rician distributions model fading with a stronger line-of-sight. The Rician distribution has a probability density function (pdf) is given by

$$f(x|v,\sigma) = \frac{x}{\sigma^2} \exp\left(\frac{-(x^2 + v^2)}{2\sigma^2}\right) I_0\left(\frac{xv}{\sigma^2}\right)$$

Where,

v= distance between the reference point and the center of the bivariate distribution,

σ=spread

The mean value of the Rician distribution is given by

$$mean = \sigma\sqrt{\frac{\pi}{2}} L_{1/2}\left(\frac{-v^2}{2\sigma^2}\right)$$

And the variance of the Rician distribution is given by

$$Variance = 2\sigma^2 + v^2 - \frac{\pi\sigma^2}{2} L_{\frac{1}{2}}^2\left(\frac{-v^2}{2\sigma^2}\right)$$

5 SINR Calculation

Analogous to the SNR used often in wired communications systems, the SINR is defined as the power of a certain signal of interest divided by the sum of the interference power (from all the other interfering signals) and the power of some background noise.

The interference power is the difference between the total power received by the receiver and the power received from one particular transmitter.

The background thermal noise in dBm at room temperature is given by:

$$P\ (in\ dBm) = -174 + 10 \times log_{10}(\varDelta f)$$

$$P\ (in\ mW) = 10^{\left(\frac{P\ (indBm)}{10}\right)}$$

Where $\varDelta f$ is the Bandwidth in Hz.

- 802.15.4, $\varDelta f$ = 2 MHz
- 802.11a, b, g, $\varDelta f$ = 20 MHz
- 802.11n, $\varDelta f$ = 20 MHz or 40 MHz
- 802.11 ac, $\varDelta f$ = 20 / 40 / 80 / 160 MHz

Therefore, SINR in dBm is calculated as:

$$SINR\ (in\ dBm) = log_{10}\left(\frac{Received\ power\ (in\ mW)}{Interference\ Noise\ (in\ mW)\ +\ Thermal\ Noise\ (in\ mW)}\right)$$

Note: Floating numbers may lose precision when converting from dbm to mw or viceversa (Ref: https://msdn.microsoft.com/en-us/library/c151dt3s.aspx). Hence

- If the received power (in mw) is less than 0.0001 then it's assumed to be zero.
- If the received power (in mw) is 0 then dbm value is -10000.0 not -∞
- While adding two powers, decimal points after fifth digit is ignored. Ex 2.0000005+3.0000012 = 5.0

6 Bit Error Rate (BER) Calculation

Note that the BER source codes are not open for user modification. If a user wishes to change the BER then they can comment NetSim's BER function call and write their own function. This can be written in C or it can be written in MATLAB (and a call made to MATLAB from NetSim).

$$SNR_{dB} = RxPower_{dB} - NoisePower_{dB}$$

$$Noise = kTB$$

$$SNR_{linear} = 10^{\frac{SNR_{dB}}{10}}$$

$$\frac{Eb}{N0} = SNR \times \frac{Bandwidth_{Hz}}{DataRate_{bitspersecond}}$$

6.1 BER Calculation for QAM

Computation of the exact bit error rate (BER) for square M-ary QAM (8, 16, 32, 64, 128 and 256 QAM)

$$P_b = \frac{1}{\log_2 \sqrt{M}} \sum_{k=1}^{\log_2 \sqrt{M}} P_b(k)$$

where

$$P_b = \frac{1}{\sqrt{M}} \sum_{j=0}^{(1-2^{-k}).\sqrt{M}-1} \left[(-1)^{\left\lfloor \frac{j.2^{k-1}}{\sqrt{M}} \right\rfloor} . \left(2^{k-1} - \left\lfloor \frac{j.2^{k-1}}{\sqrt{M}} - \frac{1}{2} \right\rfloor \right) . erfc \left((2.j+1) \sqrt{\frac{3(\log_2 M).r}{2(M-1)}} \right) \right]$$

and

$$r = \frac{E_b}{N_0}$$

6.2 BER Calculation for DQPSK, O-QPSK and QPSK

$$BER = 0.5 * ERFC \left(0.5 \times \frac{Eb}{N0} \right)^{\frac{1}{2}}$$

Note: The 802.15.4 2003 and 802.15.4 2006 standards used the formula BER = $\frac{8}{15} \times \frac{1}{16} \times \sum_k -1^k \binom{16}{k} e^{-20 \times SINR \times (\frac{1}{k}-1)})$ for O-QPSK which has since been changed

6.3 BER Calculation for DBPSK and BPSK

$$BER = 0.5 * ERFC \left(\frac{Eb}{N0}\right)^{\frac{1}{2}}$$

6.4 BER Calculation for LTE

In the case of LTE an SNR-BER table is looked up for each MCS.

7 References

- Ronell B. Sicat, "Bit Error Probability Computations for M-ary Quadrature Amplitude Modulation", EE 242 Digital Communications and Codings, 2009