NetSim®

Accelerate Network R & D

Propagation Models

A Network Simulation & Emulation Software

By

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Contents

1 Introduction **4**
1.1 Propagation Loss . . . 4
2 Path loss **5**
2.1 Path loss models . . . 6
2.1.1 Free space propagation model . . . 6
2.1.2 Log distance . . . 6
2.1.3 Hata Urban . . . 6
2.1.4 Hata Suburban . . . 7
2.1.5 COST231 Hata Urban and COST231 Hata Suburban . . . 7
2.1.6 Indoor office and Indoor factory . . . 8
2.1.7 Indoor home . . . 8
2.1.8 Two Ray . . . 8
2.1.9 Range Based . . . 8
2.1.10 Pathloss Matrix File . . . 10
2.1.11 Default value of pathloss exponent . . . 11
3 Shadowing models **11**
3.1 Log normal shadowing . . . 11
4 Fading models **12**
4.1 Nakagami Fading . . . 12
4.2 Rayleigh Fading . . . 12
4.3 Rician Fading . . . 13
5 SINR Calculation **13**
6 Bit Error Rate (BER) Calculation **14**
6.1 BER Calculation for QAM . . . 15
6.2 BER Calculation for DQPSK, O-QPSK and QPSK . . . 15
6.3 BER Calculation for DBPSK and BPSK . . . 15
6.4 BER Calculation for BFSK . . . 15
6.5 BER Calculation for LTE . . . 16
6.6 SINR-PER Curves for 802.11g . . . 16
7 References **17**

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

The three different and mutually independent propagation phenomena influence the power of the received signal are (a) path loss, (b) shadowing, and (c) fading. The different models available in NetSim are:

1. **Path loss Models**
    - 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
    - Range Based
    - Pathloss 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

$$Rx_{Power} = Tx_{Power} + G_t + G_R - PL_{d0} - 10\log(D^{\eta}) \quad (1)$$

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 gain. 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_{d0} is the path loss at reference distance, d_0 (d_0 is assumed as 1m). PL_{d0} depends on the protocol and is a user input available in the PHY layer of the radios. For 802.11b the default value of PL_{d0} is 40dB.

Example: Calculate the received power at node 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. The distance between the nodes is 100m and η is assumed as 2

$$Rx_{power}\ (dBm) = 20 + 0 + 0 - 40 - 10 \times 2 \times \log_{10}(100) \quad (2)$$

$$= 20 - 40 - 40 = -60 \text{ dBm} \quad (3)$$

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

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2.1 Path loss models

2.1.1 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 free space equation.

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

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.

$$P_r = P_t + G_t + G_r + 20\log_{10}\left(\frac{\lambda}{4\pi d_0}\right) + 10 \times \eta \times \log_{10}\left(\frac{d_0}{d}\right) \quad (5)$$

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

λ is the wavelength and is equal to $\frac{c}{f}$ where c is the speed of light and f is the frequency

Default settings in NetSim

$$G_t = G_r = 0 \text{ dB} \quad (6)$$
$$d_0 = 1 \text{ m} \quad (7)$$

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

$$Pr = [Pt] - L_{50} \text{ (dB)} \quad (8)$$

$$L_{50}(\text{dB}) = 69.55 + 26.16 \times \log(f_c) - 13.82 \times \log(h_{te}) - a(h_{re}) + (44.9 - 6.55 \times \log(h_{te})) \times \log(d) \quad (9)$$

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.

$$a(h_{re}) = 8.29 \times (\log_{10}(1.54 \times h_{re}))^2 - 1.1 \quad \text{in dB for } f_c < 300 \text{ MHz} \quad (10)$$

$$a(h_{re}) = 3.2 \times (\log_{10}(11.74 \times h_{re}))^2 - 4.97 \quad \text{in dB for } f_c \geq 300 \text{ MHz} \quad (11)$$

2.1.4 Hata Suburban

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

$$Pr = [Pt] - L_{50} \text{ (dB)} \quad (12)$$

$$L_{50}(\text{dB}) = L_{50}(\text{urban})(\text{dB}) - 2\left[\log_{10}\left(\frac{f_c}{28}\right)\right]^2 - 5.4 \quad (13)$$

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

$$Pr = [Pt] - L_{50} \text{ (dB)} \quad (14)$$

$$L_{50}(\text{dB}) = 46.3 + 33.9\log(f_c) - 13.82\log(h_{te}) - a(h_{re}) + (44.9 - 6.55\log(h_{te}))\log(d) + C_M \quad (15)$$

$$\text{Where } C_M = \begin{cases} 3 \text{ dB} & \text{for Urban} \\ 0 \text{ dB} & \text{for Suburban} \end{cases} \quad (16)$$

2.1.6 Indoor office and Indoor factory

$$Pr = [Pt] + [Gt] + [Gr] + 20\log_{10}\left(\frac{\lambda}{4\pi d_0}\right) + 10 \times \eta \times \log_{10}\left(\frac{d_0}{d}\right) \tag{17}$$

$$\text{Where } \eta = \begin{cases} 2.6 & \text{for Indoor_office} \\ 2.1 & \text{for Indoor_factory} \end{cases} \tag{18}$$

2.1.7 Indoor home

$$Pr = [Pt] + [Gt] + [Gr] + 20\log_{10}\left(\frac{\lambda}{4\pi d_0}\right) + 10 \times \eta \times \log_{10}\left(\frac{d_0}{d}\right) \tag{19}$$

Where $\eta = 3$

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

$$Pr = [Pt] + [Gt] + [Gr] - 40\log_{10}(d) + 10\log_{10}(G \times h_t^2 \times h_r^2) \tag{20}$$

Where

G_t, G_r = 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 Range Based

The propagation loss depends only on the distance (range) between transmitter and receiver. There is a single Range attribute that determines the path loss. This is not a real-world loss model but a theoretical model useful for experimentation.

Receivers at or within Range meters see a 0 dB pathloss. Hence received power equals transmit power. Receivers beyond Range see a 1000 dB pathloss. Hence received power will be close to -1000 dBm i.e., zero in linear units.

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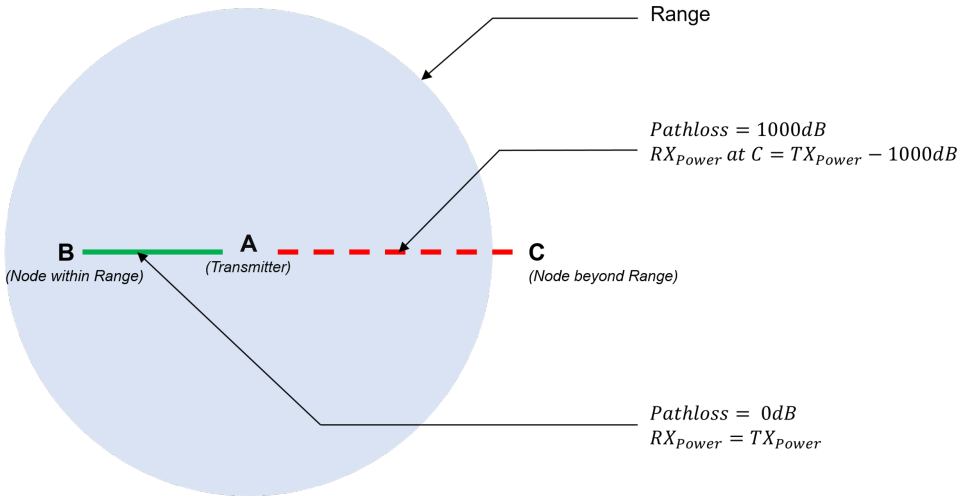

Figure 2-1: *This figure explains a typical range based pathloss model. In this example, Node A and B are in transmission range with each other which is denoted by a blue circle where the pathloss is 0dB i.e, successful transmission. And Node C is beyond the range i.e, pathloss is 1000dB all packets are errored and dropped. In NetSim, user has to specify the range of the node in meters in the links.*

This is a link-level property and would apply to all devices connected to that point-to-multipoint or multi-point-to-multipoint link. Thus, users can have AP1 and associated Wireless nodes set to Range based pathloss, and AP2 and its wireless nodes set to a different pathloss model.

This pathloss is applied not just for transmissions but for Carrier sensing and Interference calculations also. For example, as shown in Figure 2-2, consider a scenario with A transmitting to B and C transmitting to D. Let B be within range of A, D be within range of C and B also be within range of C. In this case, if there is a simultaneous transmission from A and C, the transmission from A will fail at B due to interference of the C to D transmission.

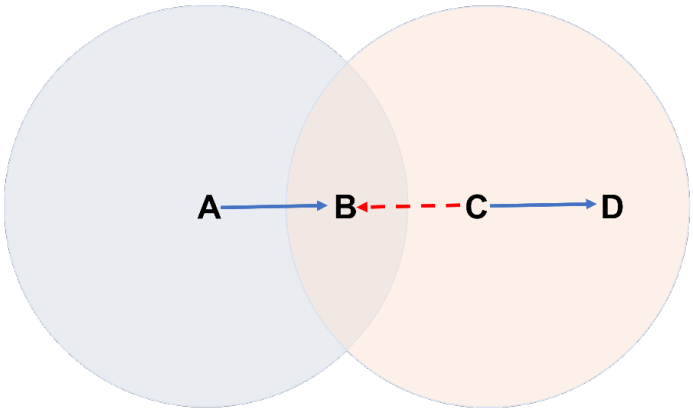

Figure 2-2: *Transmission failure due to interference from neighbouring transmissions. In this case A > B transmission fails due to interfering signal from C, when C transmits to D. This occurs because B is within range of C.*

Similarly let us consider another example as shown in Figure 2-3, where B is within the range of A, D is within the range of C. Further, A and C are within range of one another. In this case if there is a transmission from A, C detects the medium to be busy and vice versa which leads to carrier sense blocking at transmitters.

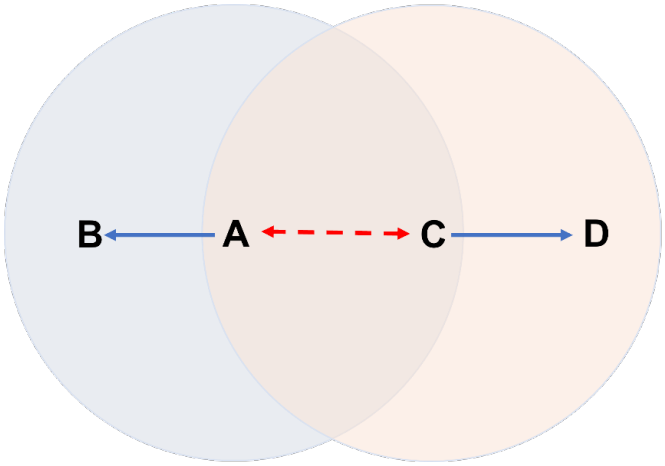

Figure 2-3: *Carrier sense (CS) blocking due to neighbouring transmissions. If A transmits, then C is CS blocked and if C transmits then A is CS blocked.*

Given below in Table 2-1 are the lower bound, upper bound, and default values for the Range (m) parameter in the GUI for different protocols.

Table 2-1: *Min, Max, and Default values of Range(m) for Range Based pathloss model*

Network	Min	Max	Default
Wi-Fi (Internetworks, MANET, VANET), TDMA, Pure Aloha, Slotted Aloha, Cognitive Radio	1	1000000	50
WSN, IoT	1	1000000	20
UWAN	100	1000000	10000

2.1.10 Pathloss Matrix File

With this option users can define the pathloss for the wireless links. The name of the trace file generated should be PathlossMatrix⟨Wireless Link Id⟩.txt and it should be per 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. 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 PathlossMatrix⟨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)>
```

2.1.11 Default value of pathloss exponent

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

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

Path loss model	Path loss exponent (default)
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

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, 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.

$$PL(d)\ [\text{dB}] = PL_{d_0} + 10 \times \eta \times \log\left(\frac{d}{d_0}\right) + \chi \tag{21}$$

Where χ is a zero-mean Gaussian distributed random variable (in dB) with standard deviation σ (in dB). The default value for σ is 5 dB, and the range of σ (in dB) is $5 \leq \sigma \leq 12$.

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

Table 4-1: *Default values of Fading parameters*

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

4.1 Nakagami Fading

In Nakagami fading, amplitude gain is Nakagami distributed. We know that when a variable is Nakagami distributed its square is Gamma distributed. Hence the power gain is Gamma distributed. The Gamma PDF, with shape parameter α and scale parameter β is given by

$$f(x) = \frac{1}{\beta^{\alpha}\,\Gamma(\alpha)}\, x^{\alpha-1}\, e^{-(x/\beta)} \quad \text{where } \Gamma(\alpha) = \int_0^{\infty} t^{\alpha-1} e^{-t}\, dt \text{ is the Gamma function} \tag{22}$$

NetSim uses a numerical method to generate a Gamma Random variate quickly based on [1]. The GUI takes shape parameter (m) and scale parameter (w) as input and a gamma distribution is generated with $\alpha = m$ and $\beta = \frac{w}{m}$. The values obtained in linear scale are then converted into dB. The default values for m and w are both 1.

4.2 Rayleigh Fading

In Rayleigh fading, the amplitude gain is Rayleigh distributed and the square of the amplitude is the power gain. Now we know that when a variable is Rayleigh distributed its square is exponentially distributed. The exponential distribution's PDF is given as

$$f(x) = \lambda\, e^{-\lambda x} \tag{23}$$

An exponential random variate is generated in NetSim using

$$T = -\frac{\log_e(R)}{\lambda} \tag{24}$$

where R is a uniform random number on (0, 1). λ is $\frac{1}{w}$ where w is the scale parameter that a user can set in the GUI. The default value of w is 1, and hence the default value of λ is also 1. The value of T is obtained in linear scale which is then converted to dB.

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 is circularly-symmetric bivariate normal random variable. The Rician distribution has a probability density function (pdf) given by

$$f(x,\, \nu,\, \sigma) = \frac{x}{\sigma^2}\ \exp\left(\frac{-(x^2+\nu^2)}{2\sigma^2}\right)\ I_0\left(\frac{x\nu}{\sigma^2}\right) \tag{25}$$

where, ν is the mean, σ is the standard deviation and $I_0(z)$ is the modified Bessel function of first kind with order zero. Rician fading also takes shape parameter (m) and scale parameter (w) as GUI inputs with default values set to 1. The shape parameter, defined as the ratio of the power contributions by line-of-sight path to the remaining multipaths is given by $m = \frac{v^2}{2\sigma^2}$ and scale parameter, defined as the total power received in all paths as $w = \nu^2 + 2\sigma^2$. Using shape and scale parameters, we can determine the value of ν and σ as $\sigma = \sqrt{\frac{w}{m+1}}$ and $\nu = \sqrt{\frac{m \cdot w}{2(m+1)}}$. We thus, get fading loss (in linear scale) as $R = X^2 + Y^2$, from $X \sim N(\nu \cos\theta,\ \sigma^2)$ and $Y \sim N(\nu \sin\theta,\ \sigma^2)$ where θ is any real number, $N(\nu,\ \sigma^2)$ stands for Normal Distribution with mean ν and standard deviation σ.

5 SINR Calculation

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. NetSim models an ideal receiver whose noise figure (NF) is zero.

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

$$P\ (\text{dBm}) = -174 + 10 \times \log_{10}(\Delta f) \tag{26}$$

$$P\ (\text{mW}) = 10^{\left(\frac{P\ (\text{dBm})}{10}\right)} \tag{27}$$

Where Δf is the Bandwidth in Hz.

- 802.15.4, Δf = 5 MHz
- 802.11a, b, g, Δf = 20 MHz
- 802.11n, Δf = 20 MHz or 40 MHz
- 802.11 ac, Δf = 20 / 40 / 80 / 160 MHz

Therefore, SINR is calculated as:

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$$SINR\ [\text{dB}] = 10 \times \log_{10}\left(\frac{\text{Received power [mW]}}{\text{Interference Noise [mW]} + \text{Thermal Noise [mW]}}\right) \quad (28)$$

NOTE: Floating numbers may lose precision when converting from dBm to mW or vice versa (Ref: https://msdn.microsoft.com/en-us/library/c151dt3s.aspx). Hence

- If the received power (in mW) is less than 0.0001 then it is assumed to be zero.
- If the received power (in mW) is 0 then dBm value is -10000.0 not $-\infty$
- While adding two powers, decimal points after fifth digit is ignored. Ex: $2.0000005+3.0000012 = 5.0$

6 Bit Error Rate (BER) Calculation

Receiver sensitivity is the minimum signal strength that a receiver can detect. In NetSim, if the received signal power is higher than the receiver sensitivity, then the signal is decoded with its BER calculated from the SINR-BER formulas/tables given in this section.

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).

$$SINR\ (\text{dB}) = RxPower\ (\text{dBm}) - (Noise + Interference)\ (\text{dBm}) \quad (29)$$

$$Noise = k \times Temp \times Bandwidth \quad (30)$$

$$SINR\ (\text{linear}) = 10^{\frac{SINR\ (\text{dB})}{10}} \quad (31)$$

$$\frac{E_b}{N_0} = \frac{\left(\frac{P \times T_s}{M}\right)}{\left(\frac{N+I}{W}\right)} = \frac{SINR \times W}{\left(\frac{M}{T_s}\right)}$$

$$= SINR(\text{Linear}) \times \frac{\text{ChannelBandwidth (Hz)}}{\text{ChannelDataRate (bps)}} \quad (32)$$

Thus,

$$\frac{E_b}{N_0} = \frac{SINR(\text{Linear}) \times \text{ChannelBandwidth}}{\text{DataSymbolRate (kBd)} \times \text{ModulationOrder} \times \text{CodeRate}} \quad (33)$$

Where P is the received power, T_s is the symbol duration, M is the modulation order, N is noise, I is interference and W is the channel bandwidth. An implication of this calculation is that the coding gain equals the reciprocal of the code rate. This is an approximation.

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) is based on [2]

$$P_b = \frac{1}{\log_2(\sqrt{M})} \sum_{k=1}^{\log_2(\sqrt{M})} P_b(k) \tag{34}$$

where

$$P_b(k) = \frac{1}{\sqrt{M}} \sum_{j=0}^{(1-2^{-k})\sqrt{M}-1} \left\lfloor (-1)^{\left\lfloor \frac{j\cdot 2^{k-1}}{\sqrt{M}} \right\rfloor} \cdot \left(2^{k-1} - \left\lfloor \frac{j\cdot 2^{k-1}}{\sqrt{M}} - \frac{1}{2} \right\rfloor\right) \cdot \operatorname{erfc}\left((2j+1)\sqrt{\frac{3(\log_2 M)\cdot r}{2(M-1)}}\right) \right\rfloor \tag{35}$$

and

$$r = \frac{E_b}{N_0} \tag{36}$$

6.2 BER Calculation for DQPSK, O-QPSK and QPSK

$$BER = 0.5 \times \operatorname{erfc}\left(\sqrt{0.5 \times \frac{E_b}{N_0}}\right) \tag{37}$$

NOTE: The 802.15.4 2003 and 802.15.4 2006 standards used the formula

$$BER = \frac{8}{15} \times \frac{1}{16} \times \sum_k (-1)^k \binom{16}{k} e^{-20\times SINR\times(1/k-1)} \tag{38}$$

for O-QPSK which has since been changed.

6.3 BER Calculation for DBPSK and BPSK

$$BER = 0.5 \times \operatorname{erfc}\left(\sqrt{\frac{E_b}{N_0}}\right) \tag{39}$$

6.4 BER Calculation for BFSK

For BFSK, NetSim uses the following BER expressions:

1. Modulation_BFSK_Coherent

$$BER = 0.5 \times \operatorname{erfc}\left(\sqrt{0.5 \times \frac{E_b}{N_0}}\right) \tag{40}$$

2. Modulation_BFSK_NonCoherent

$$BER = 0.5 \times e^{-0.5 \times \frac{E_b}{N_0}} \tag{41}$$

6.5 BER Calculation for LTE

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

6.6 SINR-PER Curves for 802.11g

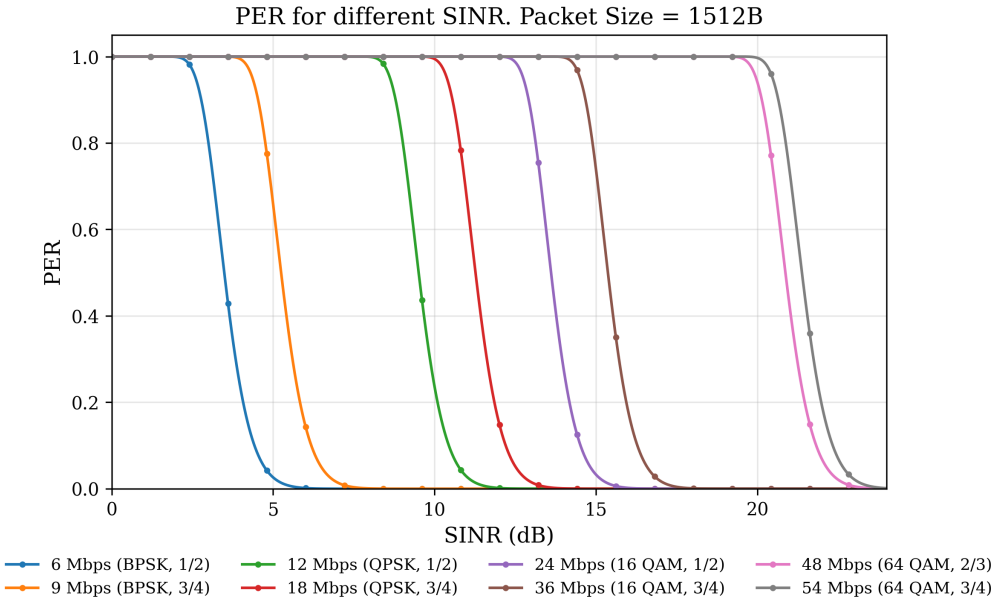

Figure 6-1: *PER – SINR Combined Curve for all PHY rates*

We get the BER by looking up the SINR-PER curves. Then $PER = 1 - (1 - BER)^L$ where $L = 1512 \times 8$. The Figure 6-1 plot was obtained from the NetSim function used to calculate BER in IEEE 802.11 Phy.c

```
Calculate_ber_by_calculation (double sinr, PHY_MODULATION modulation,
double dataRate_mbps, double bandwidth_mHz)
```

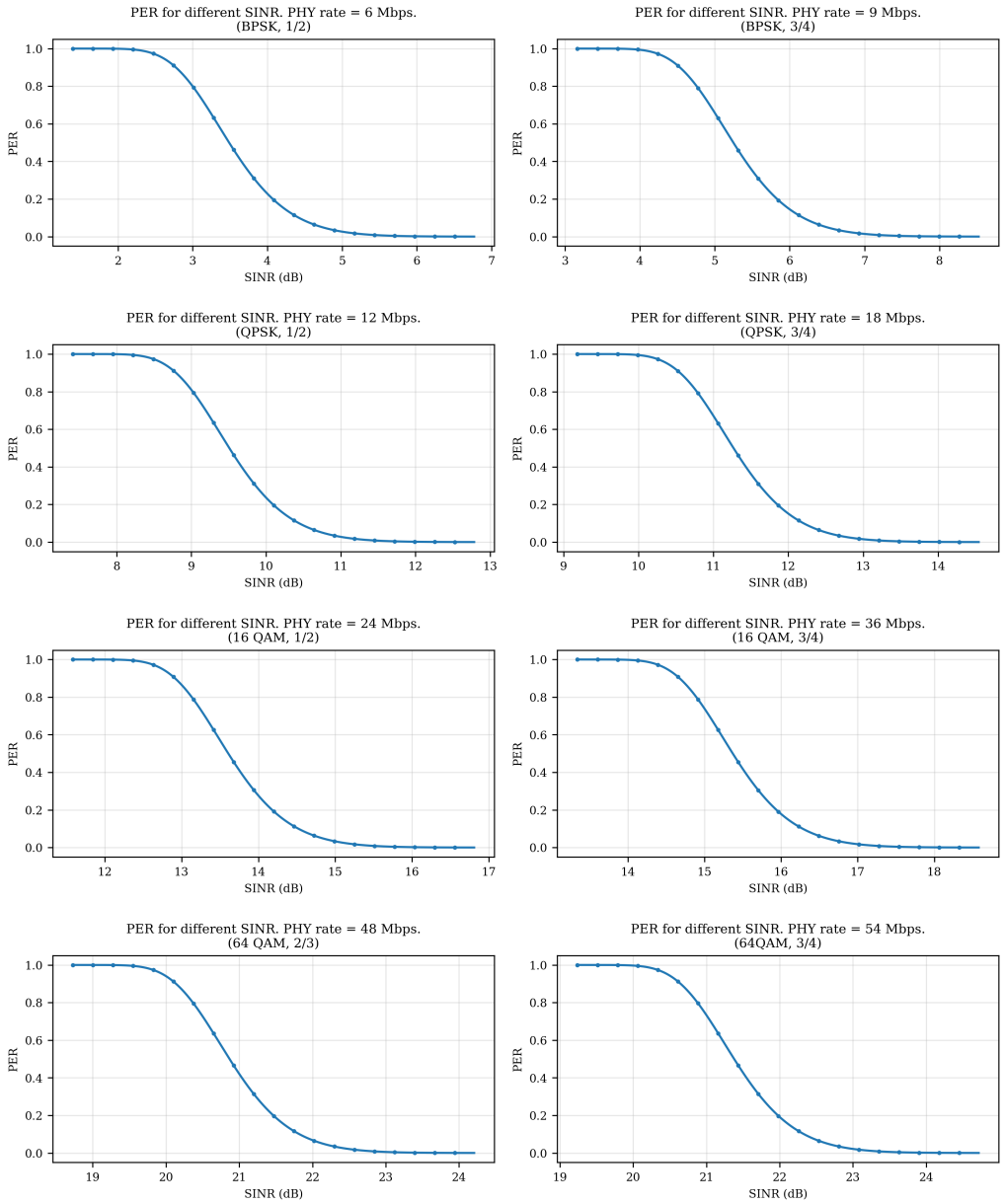

Figure 6-2: *802.11g/n PER – SINR Individual Curves for each PHY rate (MCS)*

7 References

[1] G. Marsaglia and W. W. Tsang, "A Simple Method for Generating Gamma Variables," *ACM Transactions on Mathematical Software*, 2000.

[2] Y. Dongweon, K. Cho and J. Lee, "Bit Error Probability of M-ary Quadrature Amplitude Modulation," in *IEEE Vehicular Technology Conference Fall 2000*, Boston, 2000.