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Development of a Wireless Model Incorporating Large-Scale Fading in a Rural, Urban and Suburban Environment

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DEVELOPMENT OF A WIRELESS MODEL INCORPORATING LARGE-SCALE FADING IN A RURAL, URBAN AND SUBURBAN ENVIRONMENT

THESIS

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Roger A. Illari

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Abstract

The goal of this research is to develop a more realistic estimate of received signal strength level as calculated by OPNET. The goal is accomplished by replacing the existing free-space pathloss model used by OPNET with the Hata and COST-231 pathloss models. The calculated received signal strength using the new models behaves similarly to the measured values, with a 0.245 dB difference for 880 MHz and a 1.365 dB difference for 1922 MHz between the pathloss slopes. There is an 11.3 dBm difference between the initial starting signal strength from the calculated values and the measured values.

An important aspect of a wireless communication system is the planning process. The planning phase of a wireless communication system will determine the number of necessary transmitting antennas, the frequency to be used for communications, and ultimately the cost of the entire project. Because of the possible expense of these factors it is important that the planning stage of any wireless communications project produce an accurate calculation of the coverage area.

DEVELOPMENT OF A WIRELESS MODEL INCORPORATING LARGE-SCALE FADING IN A RURAL, URBAN AND SUBURBAN ENVIRONMENT

I. Introduction

1.1 Background

The propagation of a radio signal is affected by three main factors; reflection, scattering and diffraction [Rap02]. Reflection occurs when the signal impinges upon an object much larger than the signal wavelength, e.g., the earth or a large building. Scattering occurs when the traveling wave front encounters objects much smaller than the wavelength with sharp edges, e.g., lampposts and stop signs. The result is multiple smaller wave fronts are created. Diffraction is the apparent bending or spreading of a signal/wave when it impinges upon an object [Rap02].

Due to these factors, a received radio signal level is subject to fading. Large-scale fading is mainly due to the transmitter receiver pair (T-R) separation. The further a receiver gets from a transmitter, the more the received signal will decrease. Small-scale fading is also known as multipath fading because the main cause is the arrival of multiple copies of the same signal at the receiver. If the copies are in phase they will have an additive effect on the average signal strength; if the signals are out of phase, there will be a destructive effect on the signal strength [Rap02]. Over a small distance such as a 25 m T-R separation, the value of a received signal fluctuates very little due to large-scale fading. On the other hand, small-scale fading can cause the signal to fluctuate by as much as 30 dB over the same distance [Skl97].

The need for accurate signal strength prediction spurred the creation of radio signal propagation models. Propagation models are either empirical, theoretical or a mix of the two. The empirical model is based on measurements and takes into account all factors that affect radio propagation. Theoretical models are based on the fundamental principles of the radio wave phenomenon [NNP00].

OPNET modeler is a comprehensive network research and development tool used to plan and design wireless communications networks. The wireless module for OPNET has a radio transceiver pipeline that accounts for radio communications link such as transmit (TX) and receive (RX) antenna gain, signal to noise ratio (SNR) and received power.

1.2 Motivation and Goal

Military bases all over the world have wireless communication systems located on each of them. The limited resources available to organizations such as the Air Force Communications Agency (AFCA) mean they rely heavily on computer simulators to plan any changes to existing systems or create new ones. Therefore, the models should be as accurate as possible. This means the pathloss model used by OPNET should model the environment the system will operate in with maximum fidelity.

The goal of this research is to replace the free space pathloss model used by OPNET to calculate wireless links characteristics with a pathloss model that more accurately accounts for the different types of environments that a signal will travel through.

1.3 Thesis Layout

This chapter introduces the factors which can interfere with wireless communications; it also discusses the goals and motivation for the research. Chapter II discusses the different factors that affect radio signal propagation in detail as well as some different outdoor pathloss models. Chapter II discusses the operation of OPNET's transceiver pipeline. Chapter III discusses the methodology used to conduct the research and the factors and parameters being used in the research, the number of simulations being performed, how the simulations are setup and what data is being collected from each simulations. Chapter IV presents the analysis of the results and Chapter V presents conclusions drawn from the research and provides ideas for future research.

II. Literature Review

2.1 Chapter Overview

This chapter illustrates the complications and tools associated with planning a wireless communication system. It also discusses current research into effective and realistic planning of a wireless communication system.

One of the main obstacles encountered when planning a wireless communication system are factors that reduce the received signal strength such as large-scale fading and small-scale fading [Rap96]. Aiding the planner of a wireless communication system is a research and development tool called OPNET. OPNET Modeler is an environment for network modeling and simulation, which supports the design and study of communication networks, devices, protocols, and applications. [Opn05]. Current research illustrates the need to incorporate the fading factors into modern network modelers such as OPNET and NS to provide a more realistic assessment of the performance of a proposed wireless communication system [Acl03], [Acr03] and [Pun00]. The research in [Acl03], [Acr03] and [Pun00] each attempt to replace the original pathloss model used by OPNET and NS with pathloss models that more accurately reflect real world conditions.

Section 2 provides background and current issues in wireless communications. Section 3 discusses the factors that affect radio signal propagation. Section 4 and 5 discusses the details of large-scale and small-scale fading of the radio signal. Section 6 discusses some of the outdoor propagation models currently being used to predict wireless signal coverage. Section 7 explains each stage of the radio transceiver pipeline of OPNET. Section 8 discusses relevant research concerning wireless signal propagation.

2.2 Background

2.2.1 History

In 1897, Guglielmo Marconi demonstrated the importance of radio by maintaining constant contact with a ship as it crossed the English Channel [Rap96]. What Marconi did not realize at the time was how rapidly wireless communication system would pervade modern society. With the advancements in technology, wireless communication has become a part of modern society faster than any other invention of the 20th century as seen in Figure 1 [Rap96].

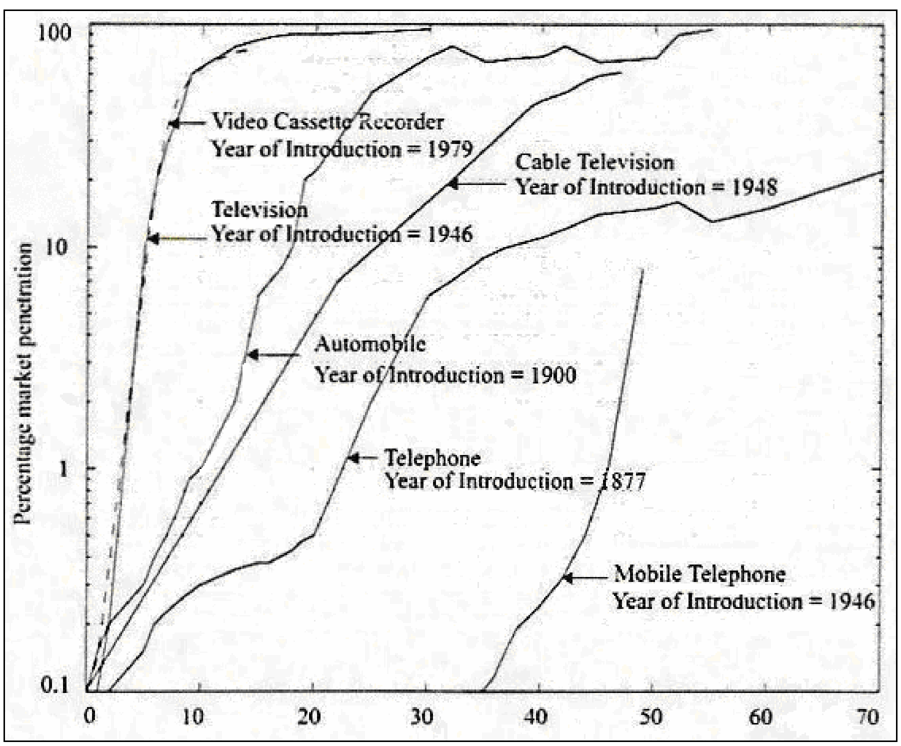

Figure 1. Consumer Market Percentage of Mobile Telephony [Rap96]

Figure 1 shows that Mobile Telephony which does not include paging systems, amateur radio, dispatch radio, citizens band (CB) radio, public service radio, cordless phones, or terrestrial microwave radio systems have become increasingly popular in the consumer sector. For 35 years following their introduction, mobile telephones were not prevalent in modern society due to the expense of the service and equipment. But during the 1980's, there is a marked increase in mobile telephones acceptance in modern society compared to the television and the videocassette recorder. The increased acceptance of mobile telephones is attributed to the increase in technological advances, which reduced the expense associated with the service and equipment, and in turn made mobile telephones more affordable for consumers [Rap96].

2.3 Current Issues

With the popularity of mobile telephone came issues inherent in the planning of a wireless communication system. In 1974 the Federal Communications Commission (FCC) allocated a 40 MHz of bandwidth in the 800 to 900 MHz frequency range which was divided into a total of 666 duplex channels for mobile telephone use [Lee97] as shown in Figure 2.

Base Transmit	Mobile Transmit	Number of Channels	Channel Spacing	Total Bandwidth
870-890 MHz	825-845 MHz	666	30 kHz	40 MHz

Figure 2. Frequency Range Allocated in 1974 [Lee97]

In 1989, the FCC granted an additional 166 channels (10 MHz) to accommodate the rapid growth and demand. The rapid growth coupled with the limited number of channels available (832 total) caused wireless communications system planners to develop schemes for frequency reuse and allocation. To meet the demand with the limited amount of frequency channels available, wireless system planners developed a technique for frequency reuse by allocating a group of radio channels to be used within a small geographic area called a cell [Rap02]. The cell is a hexagonal-shaped geographic area as seen in Figure 3.

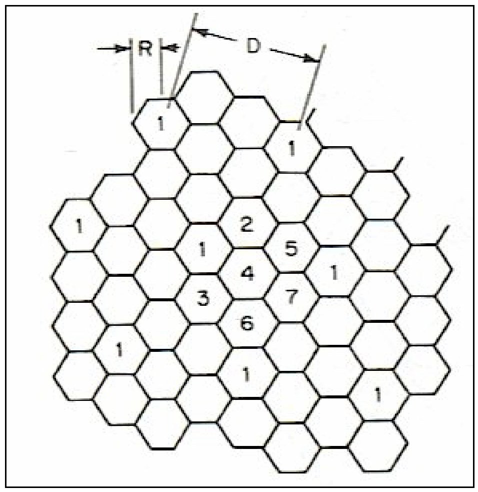

Figure 3. Basic Cell Block [Rap02]

The different numbered individual cells seen in Figure 3 are allocated a different group of frequencies for use in that cell, and cells with the same numbers are using the same group of frequencies. The number of cells in each block *K* is calculated from Equation (2.1).

$$K = \frac{(D/R)^2}{3} \tag{2.1}$$

where D is the distance between two adjacent frequency-reuse cells and R is the radius of each cell. For a *D/R* equal to 4.6, *K* is equal to 7. For the number of cells in the block in Figure 3 this means the frequencies can be divided into 7 groups (cells).

2.4 Mobile Radio Propagation Factors

Predicting the received signal strength at a mobile receiver from a stationary transmitter has become one of the most difficult aspects of planning for a wireless communication system [Rap02]. The varied environments in which wireless communications systems are used pose different challenges that hinder wireless signal propagation. To predict the average signal strength at a receiver, planners must account for obstacles between the transmitter and mobile receiver that affect radio wave propagation. The signal can travel over a path that can vary from a line of sight (no obstacles), to mountains, to buildings. The three mechanisms that influence signal propagation in a mobile communication system are reflection, diffraction, and scattering.

2.4.1 Reflection

Reflection occurs when a propagating electromagnetic wave impinges upon an object that has very large dimensions compared to the wavelength of the incident wave [Rap02]. A reflected wave can either increase or decrease a signal level at the reception point [NNP00]. Figure 4, below, illustrates the phenomenon of refection as it pertains to radio signal propagation. The signal level can be increased if a large proportion of the reflected waves are reflected toward the receiver and decreased if the reflected wave is directed away from the receiver. Buildings, walls and the surface of the earth are causes of reflection.

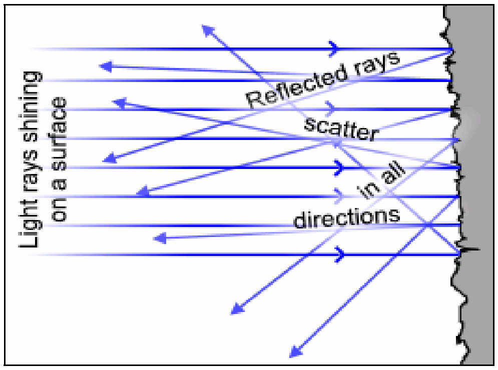

Figure 4. Reflection of an Incoming Wave [Wir06]

2.4.2 Diffraction

Diffraction occurs when a large opaque body whose dimensions are considerably larger than the signal wavelength obstructs the signal path between the transmitter and receiver. Diffraction occurs at the obstacle's edges where some scattering may also occur as well as additional attenuation [NNP00]. Figure 5 below illustrates the phenomenon of diffraction.

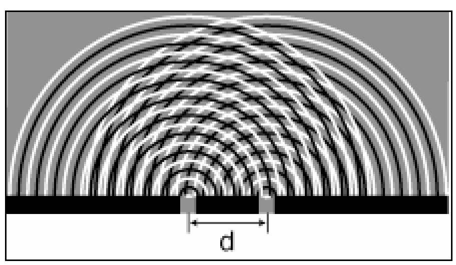

Figure 5. Effects of Diffraction [Wid06]

When a crest, the section of a wave that rises above an undisturbed position, overlaps with another crest or a trough, the low point of the wave, overlaps with another trough constructive interference occurs, and the signal strength will increase. If a crest overlaps with a trough, then they cancel each out, and the interference is destructive. [Wid06] The creation of the secondary wave front allows the receiver to receive a signal even though the line-of-sight (LOS) path is obstructed; this phenomenon is sometimes called shadowing [Skl97].

2.4.3 Scattering

Scattering occurs when the medium in which the signal is propagating has many objects that are smaller than or comparable to the wavelength of the radio signal. This phenomenon is similar to diffraction except the radio wave is scattered in a greater number of directions [NNP00]. In urban settings foliage, stop signs and lampposts are examples of objects that cause scattering [Skl97].

2.5 Large-Scale Fading

The factors affecting wireless communication can be categorized into two main categories; large-scale fading and small-scale fading [Skl97]. Large-scale fading is useful in determining a transmit antenna coverage area. Large-scale fading or large-scale pathloss is useful for predicting the average received signal strength at a given distance from the transmit antenna. In Figure 6, the effects of large-scale fading are shown as the distance between the transmitter and receiver increases.

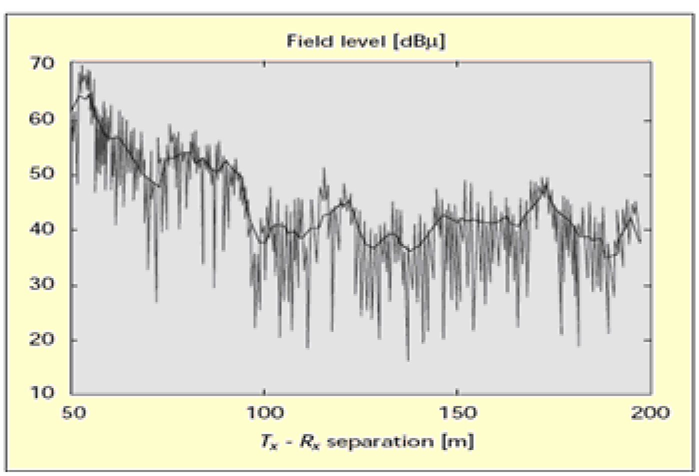

Figure 6. Measured Signal Strength [NNP00]

The graph shows as the separation of the receiver from the transmitter increases, the average signal level i.e., (solid dark line) decreases. The measured signal level at 50 meters is approximately 62dBμ; at the ending distance of 200 meters, the received average signal strength is approximately 40dBμ.

2.6 Small–Scale Fading

Unlike large-scale fading that measures the average received signal strength, small-scale fading is a rapid fluctuation in signal strength measured over a small distance or period of time [Rap02]. The effects of small-scale fading are shown in Figure 6 by the gray line. It can be seen in Figure 6 the transmitter and receiver distances of 100-150 meters shows great fluctuation in the received signal strength, from a maximum value of approximately 52dBμ to a minimum value of 15dBμ. The four main physical factors which influence small-scale fading in the radio propagation channel are multipath propagation, speed of the mobile receivers, speed of surrounding objects and transmission bandwidth of the signal [Rap02].

2.6.1 Multipath Propagation

Multipath propagation results from the presence of reflectors and scatterers in the propagation channel that cause multiple versions of the transmitted signal to arrive at the receiver, each distorted in amplitude, phase and angle of arrival. Small-scale fading is also known as multipath fading [Mat05]. Due to the increased time required to receive the baseband portion of the signal, intersymbol interference can occur resulting in signal smearing [Rap02]. Intersymbol interference is a disturbance caused by extraneous energy from the signal in one or more keying intervals that interferes with the reception of the signal in another keying interval [Wii06].

2.6.2 Speed of the Mobile

The relative motion between a base station and a mobile receiver results in random frequency modulation due to the different Doppler shifts on each of the multipath components (waves arriving at the receiver). The Doppler shifts can be either negative or positive depending on whether the mobile receiver is moving towards or away from the base station [Rap02].

2.6.3 Speed of the Surrounding Objects

This phenomenon occurs if the objects surrounding a mobile receiver are moving much faster in relation to the mobile receiver. For example, if a mobile receiver is adjacent to a highway, the speed and multitude of the vehicles near the mobile receiver will induce a Doppler shift upon the signals being received [Rap02].

2.6.4 Signal Transmission Bandwidth

This physical factor is concerned with the transmitted signal bandwidth compared to the "bandwidth" of the multipath channel. If the transmitted signal bandwidth is much greater than the "bandwidth" of the multipath channel, then the received signal strength will not fade much over the local area because of small-scale fading factors. Otherwise, if the transmitted signal bandwidth is narrow relative to the "bandwidth" of the multipath channel, then the signal amplitude can change rapidly while the signal structure is not itself distorted in time [Rap02].

2.7 Propagation Models

Because of the numerous factors involved in the radio signal propagation and the difficulty in predicting short-term fading, nearly all propagation models estimate either the average or median values of the signal level [NNP00]. A propagation model is a set of mathematical expressions, diagrams and/or algorithms used to represent the environment a radio signal will travel through [NNP00]. These models can be either empirical (statistical) or theoretical (deterministic) or a combination of the two. The empirical model is based on measurements while theoretical models use the fundamental principles of radio wave propagation phenomena [NNP00].

2.7.1 Outdoor Propagation Models

Radio transmissions in a mobile communication system often take place over irregular terrain. The terrain profile must be taken into account to determine the pathloss and will vary from an unobstructed line of sight (LOS) to a simple curvature of the earth to a highly mountainous profile. The presence of trees, buildings and other obstacles must all be taken into account when predicting signal strength coverage. A few of the more commonly used outdoor propagation models are discussed.

2.7.2 Free Space Propagation Model

The free-space propagation model is used when the transmitter-receiver (T-R) pair have an unobstructed clear LOS between them. Satellite communications and microwave LOS radio communication typically experience free-space pathloss [Rap02]. When the receive antenna gain is isotropic, the power received is given by the Friis free-space equation (equation (2.2)).

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \qquad (2.2)$$

where d in equation 2.2 is the T-R distance in meters, P_t is the transmitted power which is a function of the T-R seperation, G_t is the gain of the transmit antenna, G_r is the gain of the receive antenna, λ is the free-space wavelength in meters and L accounts for all system losses not related to propagation ($L \geq 1$) [Rap02]. This model assumes that the path between the T-R pair is free of obstructions that might reflect or absorb any radio frequency (RF) energy and is mainly a function of the transmitter and receiver separation [Skl96].

2.7.3 Okumura Model

The Okumura model is one of the most widely used models for signal prediction in urban areas [Rap02]. The Okumura model is the result of empirical data collected in detailed propagation tests over various situations of an irregular terrain and environmental clutter [NNP00]. Okumura developed a set of curves which describe median attenuation denoted as $L_{50}(dB)$, relative to free-space in an urban area over a quasi-smooth terrain with a base station effective antenna height of 200 m and mobile antenna height of 3 m. To determine pathloss with Okumura's model, free-space pathloss is first calculated between the points of interest. The value of median attenuation relative to free-space ($A_{mu}(f,d)$) is then read from curves in Figure 7. Finally, the correction factors for the type of terrain and the height of the receive and transmit antennas is added [Oku68]. The resultant model is shown in equation (2.3).

$$L_{50}(dB) = L_F + A_{mu}(f,d) - G(h_{te}) - G(h_{re}) - G_{AREA} \tag{2.3}$$

where L_F is the free-space propagation loss in decibels, $A_{mu}(f,d)$ is the median attenuation relative to free-space obtained from the graph in Figure 7 in decibels, $G(h_{te})$ is the base station antenna height gain factor in decibels, $G(h_{re})$ is the mobile antenna height gain factor in decibels and G_{AREA} is the gain due to the type of environment [Oku68].

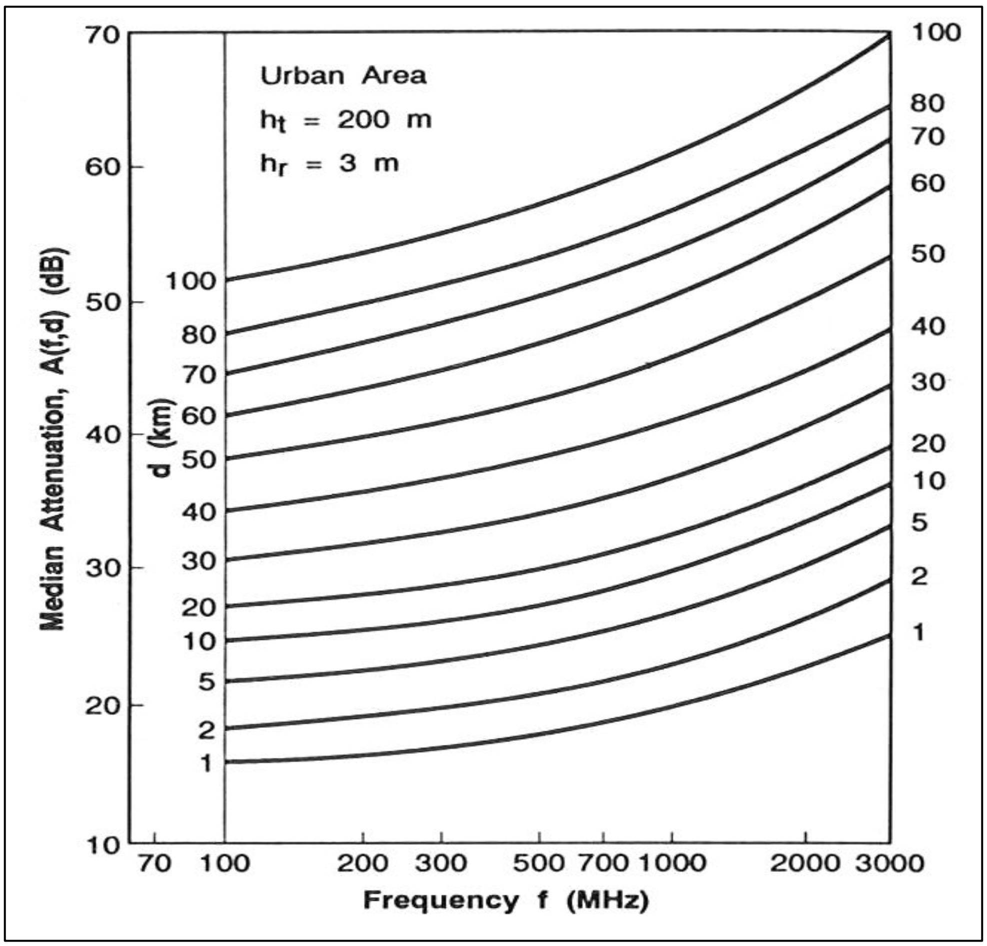

Figure 7. Median Attenuation Relative to Free Space [Oku68]

For transmit antenna heights h_{te} from 30 m to 1000 m, $G(h_{te})$ is obtained from equation (2.4).

$$G(h_{te}) = 20\log\left(\frac{h_{te}}{200}\right) \tag{2.4}$$

If the antenna height is less than or equal to 3 m, $G(h_{re})$ is obtained from equation (2.5).

$$G(h_{re}) = 10\log\left(\frac{h_{re}}{3}\right) \tag{2.5}$$

where h_{re} is the receiver antenna height in meters. If the antenna height is greater than 3 m and less than 10 m $G(h_{re})$ is obtained using equation (2.6).

$$G(h_{re}) = 20\log\left(\frac{h_{re}}{3}\right). \tag{2.6}$$

G_{AREA} is obtained from Figure 8. G_{AREA} is dependent on the type of environment and the frequency being used. Okumura's model is considered to be among the simplest and best in terms of accuracy for pathloss prediction for a mature cellular and land mobile radio system in cluttered environments [Rap02]. The model developed by Okumura is solely based on measured data and does not provide any analytical explanation. The model is valid for the frequencies in the range of 150 MHz to 1920 MHz, T-R distances of 1 km to 100 km, base station antenna heights of 30 m to 1000 m and receiver antenna heights of 3 m to 10 m [Rap02].

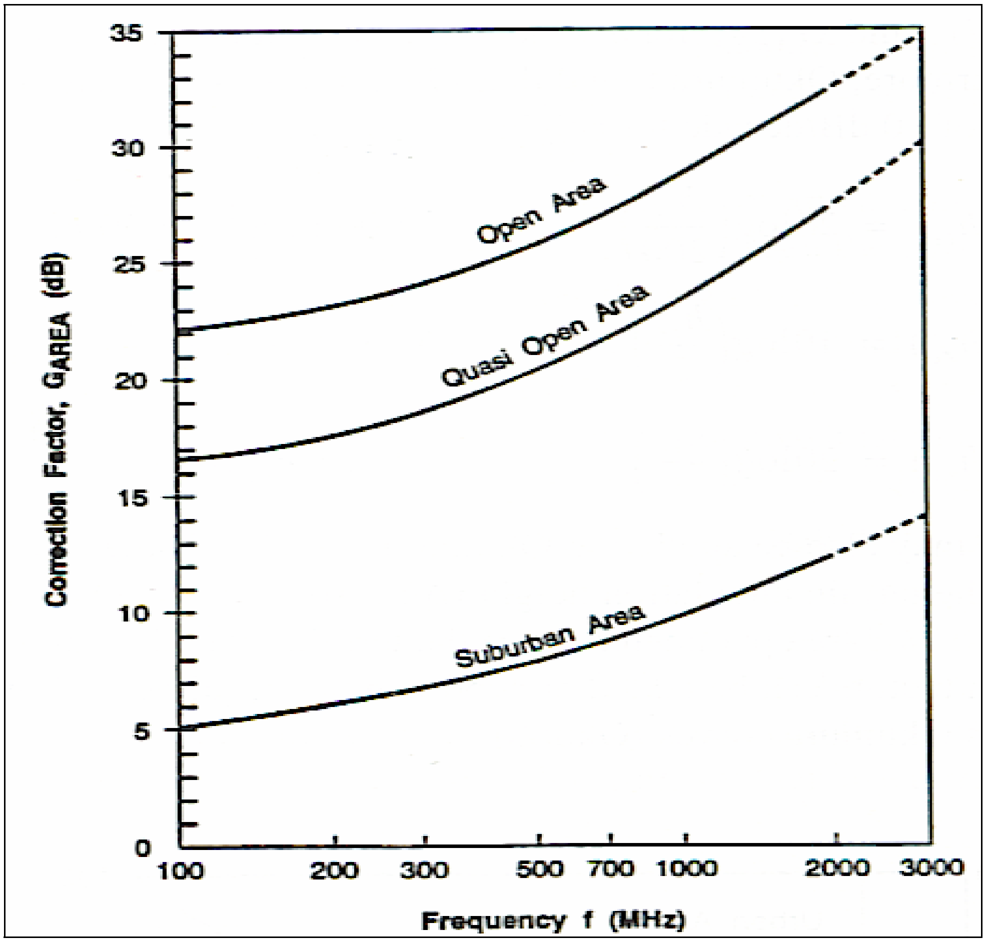

Figure 8. G_{AREA} Graph

2.7.4 Hata Model

The Hata model is an empirical formulation of the graphical pathloss data provided by Okumura. The model is valid for frequencies between 150 MHz to 1500 MHz, transmit antenna heights of 30 m to 200 m, receiver antenna heights of 1 m to 10 m and distances of 1 km to 100 km. Hata developed a standard formula for propagation loss in an urban environment (see equation (2.7)).

$$\begin{aligned} L_{50}(urban)(dB) = 69.55 + 26.16\log f_c - 13.82\log h_{te} \\ - a(h_{re}) + (44.9 - 6.55\log h_{te})\log d \end{aligned} \tag{2.7}$$

where f_c is the frequency in MHz, h_{te} is the transmit antenna height in meters, h_{re} is the receiver antenna height in meters, d is the T-R separation in km and $a(h_{re})$ is the correction factor for effective mobile antenna height which is a function of the size of the coverage area. $a(h_{re})$ is calculated for a large city using equations (2.8) and (2.9).

$$a(h_{re}) = 8.29(\log 1.54 h_{re})^2 - 1.1\, dB \qquad for\ f_c \leq 300 MHz \text{ , or} \tag{2.8}$$

$$a(h_{re}) = 3.2(\log 11.75 h_{re})^2 - 4.97\, dB \qquad for\ f_c \geq 300 MHz \text{ .} \tag{2.9}$$

Medium to small sized cities have a smaller number of tall buildings i.e. skyscrapers. Manhattan would be characterized as a large city where as downtown Dayton, OH would be characterized as a small city. Equation (2.10) is used to calculate $a(h_{re})$ for small to medium sized cities.

$$a(h_{re}) = (1.1 \log f_c - 0.7) h_{re} - \left(1.56 \log f_c - 0.8\right) dB \tag{2.10}$$

To obtain the pathloss in a suburban area the Hata formula becomes equation (2.11).

$$L_{50}(suburban)(dB) = L_{50}(urban) - 2\left(\log\left(f_c / 28\right)\right)^2 - 5.4 \tag{2.11}$$

where the $a(h_{re})$ is calculated using the equation (2.10). The pathloss in a rural area is obtained using equation (2.12).

$$L_{50}(rural)(dB) = L_{50}(urban) - 4.78\left(\log f_c\right)^2 + 18.33 \log f_c - 40.94 \tag{2.12}$$

where $a(h_{re})$ is calculated using equation (2.10). The prediction's of Hata's model are very close to the graphs of Okumura's model, with both providing a practical means to planning for large cell mobile systems [Hat90].

2.7.5 COST-231 Model

The COST-231 model is an empirical formula that was proposed by the European Cooperative for Scientific and Technical research to extend Hata's model to 2 GHz [Rap02]. The COST-231 pathloss model given by equation (2.13).

$$\begin{aligned} L_{50}(urban) &= 46.3 + 33.9\log f_c - 13.82\log h_{te} \\ &\quad - a(h_{re}) + (44.9 - 6.55\log h_e)\log d + C_M \end{aligned} \tag{2.13}$$

where f_c is the frequency in MHz, h_{te} is the transmit antenna height in meters, d is the T-R separation in km and $a(h_{re})$ is the correction factor for effective mobile antenna height which is a function of the size of the coverage area and h_{re} which is the receiver antenna height in meters. $a(h_{re})$ is defined in equations (2.8), (2.9) and (2.10). C_M is equal to 0 dB for a medium sized city and suburban area or 3 dB for a metropolitan center. The COST-231 model is valid for frequencies between 1500 MHz to 2000 MHz, transmit antenna heights of 30 m to 200 m, receiver antenna heights of 1 m to 10 m and distances of 1 km to 20 km [EUR91].

2.8 OPNET Wireless Module

The OPNET wireless module is model that allows realistic and accurate modeling of wireless networks. The wireless module uses a Radio Transceiver Pipeline (RTP) to model wireless transmissions of packets. An "execution" of the pipeline is performed for each eligible receiver. Figure 9 depicts the 14 stages of the Radio Transceiver Pipeline.

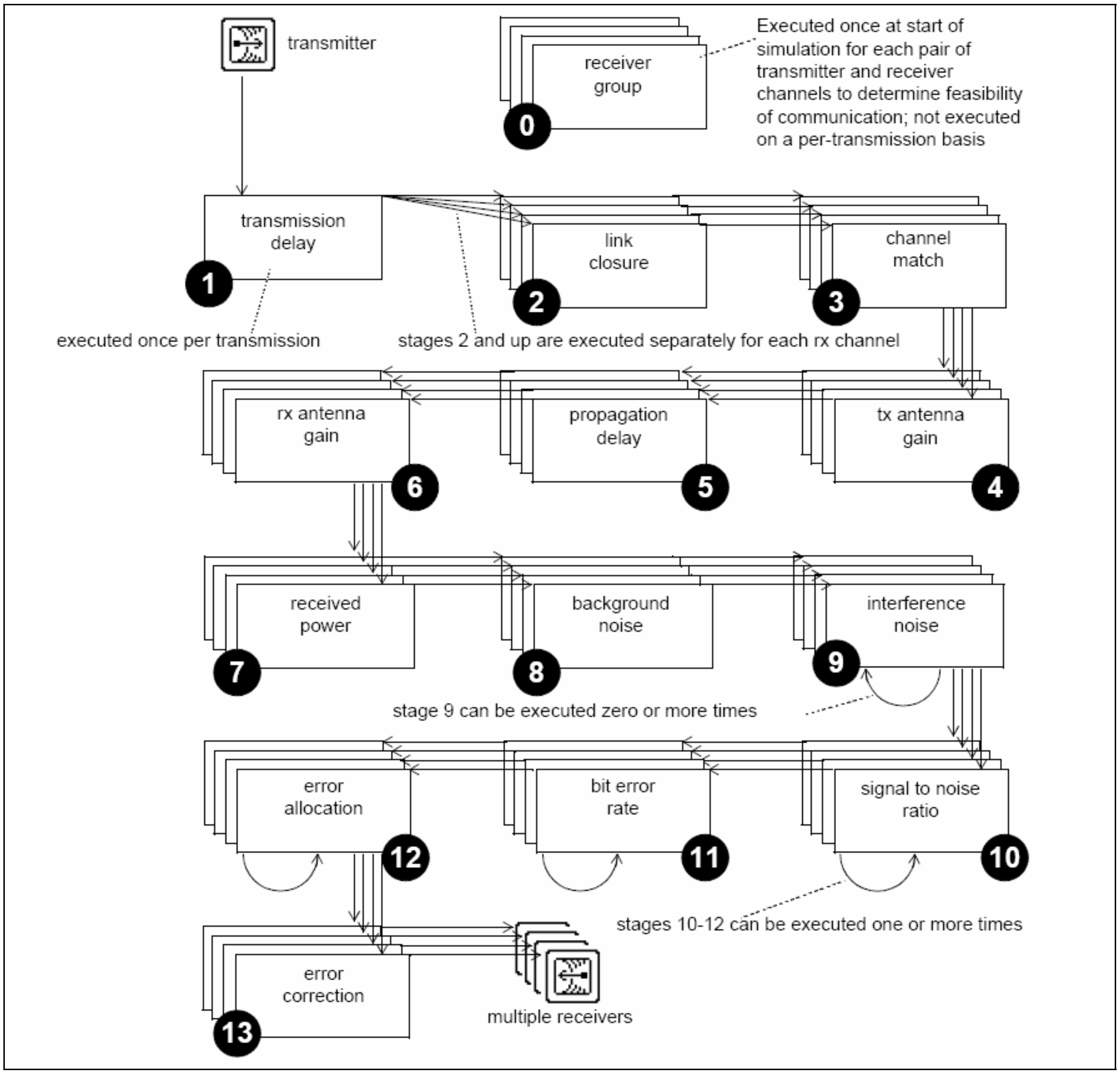

Figure 9. Radio Transceiver Pipeline Execution [Opn05]

Because radio links are carried over a broadcast medium, one transmission can have multiple receivers or one receiver can receive multiple transmissions. Thus some receivers can require multiple executions of various stages of the pipeline because they are part of multiple transmission-receiver channels. The following subsections describe OPNET's Radio Transceiver pipeline stages.

2.8.1 Receiver Group

During a radio transmission, this stage calculates the possible transmission channel - receiver channel pairs that form the receiver groups. This information forms an initial list of possible receivers for the transmission object. This is not actually a part of the dynamic pipeline but it is included because the results of this pipeline stage will influence the behavior of the radio transmissions. This stage is only executed once at the start of a simulation for each transmitter and receiver channels.

2.8.2 Transmission Delay

This is the only stage for which a single execution is performed to support all subsequent pipeline stages. This stage calculates the time an entire packet takes to complete transmission. The result is the simulation difference between the transmission of the first bit of a packet and the last bit of a packet. The result of this stage is used in conjunction with the propagation delay stage to determine the time for the last bit of a packet arrived at a link's destination (receiver).

2.8.3 Link Closure

This stage is invoked once per receiver channel for each transmitter channel. The goal of this stage is to determine if a receiver can be affected by the transmitter signal by determining if transmission signal can physically reach the receiver. Physical considerations such as occlusion by obstacles and/or the surface of the earth are used to make this determination.

2.8.4 Channel Match

This stage is invoked once per receiver channel to classify the transmission with respect to the receiver. This stage uses the result from the Link Closure stage to assign one of three possible categories to the packet. "Valid" means that the packets will be accepted and possibly forwarded to other modules. "Noise" identifies these packets as having data content that cannot be received. The "Ignored" category means that a transmission will have no effect on a receiver channels performance or state.

2.8.5 TX Antenna Gain

This stage is executed separately for each destination channel. This stage computes the gain of the transmitter's associated antenna based on a directional vector from the transmitter to the receiver [Opn05]. The antenna gain is used in stage 7 of the pipeline to calculate the received power.

2.8.6 Propagation Delay

This stage is invoked for each receiver channel that has successfully passed the previous two stages. This stage calculates the time required for a packet's signal to travel from the radio transmitter to the radio receiver. The result is distance dependent and is used by the simulation kernel to schedule the beginning of reception event for the receiver channel. Additionally, the result is used in conjunction with the transmission delay result to determine the time the packet completes reception.

2.8.7 RX Antenna Gain

This is the earliest stage executed that is associated with the receiver and is executed separately for eligible destination channels as determined by the link closure stage. The purpose of this stage is to calculate the gain provided by the receiver antenna. This stage's operation is similar to that of the TX antenna gain stage and the result of this stage is used in stage 7 to calculate the received power.

2.8.8 Received Power

This stage is executed separately for each eligible destination channel. This stage calculates the received power of the arriving packet's signal (in watts). For a "valid" packet, the received power is used to determine if a receiver can correctly capture all the information contained within a packet. The received power is used to determine the relative strengths of a packet marked as either "valid" or "noise" which is used by later stages (Signal-to-Noise Ratio) of the pipeline.

2.8.9 Background Noise

This stage represents the effect of all noise sources on the receiver except for other concurrently arriving transmissions. The result is the sum of power (in watts) of noise sources measured at the receiver's location and in the receiver channel bandwidth. This quantity is stored for later use in stage 10 where it is added to other noise sources to compute a total noise level.

2.8.10 Interference Noise

This stage may be invoked for a packet if either of two conditions occurs, either the packet is valid and other packets arrive at a destination at the same time, or the packet is valid and is already being received when another packet occur at the destination. The pipelines of the two packets share the results of this stage if the packets are both "valid". This stage tries to account for the interactions between transmissions that arrive concurrently at the same receiver channel. The result of this stage determines the current level of noise from all interfering transmissions.

2.8.11 Signal-to-Noise Ratio (SNR)

This stage is executed for a valid packet under three circumstances: the packet arrives at a destination; a packet is being received when another packet arrives at the destination, or a packet is being received when another packet is being completed. The purpose of this stage is to compute the current average signal power to average noise power ratio (SNR) result for the arriving packet. It takes into account values obtained from the previous stages, received power, background noise and interference noise, to determine if the receiver can correctly receive the packet contents. The result is used by the kernel to update standard output results of receiver channels and by the Bit Error Rate stage of the pipeline.

2.8.12 Bit Error Rate (BER)

The three circumstances in which this stage is executed are: the packet completes reception at its destination channel, the packet is already being received and another packet (valid or invalid) arrives, the packet is already being received and another packet (valid or invalid) completes reception. This stage derives the probability of bit error during the previous interval of constant SNR. This is an expected rate, not an empirical rate as it is usually based on the SNR, and is a function of the type of modulation used by the transmitted signal. The result from this stage is a computed bit error rate (BER) which is a double-precision floating-point number between zero and one (inclusive).

2.8.13 Error Allocation

This stage is always executed and estimates the number of bit errors in a packet segment where the bit error probability has been calculated and is constant. Bit error count estimation is based on the bit error probability from the previous stage and the length of the affected segment. The result from this stage is the number of new errors added to the total number of errors found per packet. The value should be between zero and the number of bits in the packet.

2.8.14 Error correction

This stage is invoked when a packet completes reception. Only one invocation of this stage occurs per valid packet. The purpose of this stage is to determine if the arriving packet can be forwarded via the channel's corresponding output stream to one of the receiver's neighboring modules in the destination node. This is usually dependent upon whether the packet has experienced collisions, the result computed in the error allocation stage, and the ability of the receiver to correct the errors affecting the packet [Opn05]. The kernel will either destroy the packet or allow it to proceed based upon the result from this stage.

2.9 Relevant Research

In the past few years there has been some research done on modifying OPNET's transceiver pipeline by incorporating new standards [Acl03] or by adding a more realistic fading model [Acr03]. Research incorporated Ricean and Rayleigh fading into the ns network simulator [Pun00].

2.9.1 IEEE 802.16 Pathloss Replacement

In [Acl03], The free-space pathloss model used by OPNET's received power stage is modified. The original pathloss formula is replaced with the IEEE 802.16 pathloss formula obtained from [Erc01]. The new formula accounts for large-scale pathloss [Acl03].

2.9.2 Rayleigh Fading Incorporation

The received power stage of the wireless module of OPNET is modified to account for wireless fading in addition to the original calculation of distance attenuation [Acr03]. Time correlated flat Rayleigh fading is incorporated into the pipeline stage. Rayleigh fading is caused by the effects of multipath include constructive and destructive interference, and phase shifting of the signal [Wif06]. Figure 10 below illustrates the effects of Rayleigh fading on a radar system. Rayleigh fading can cause the appearance of multiple ghost targets in a radar system [Wif06].

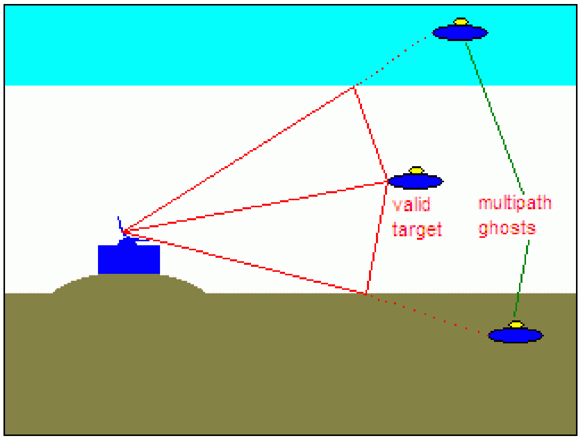

Figure 10. Rayleigh Fading in Radar System [Wif06]

2.9.3 Ricean and Rayleigh Fading Incorporation in NS Network Simulator

In [Pun00] Ratish J. Punnoose, Pavel V. Nikitin, and Daniel D. Stancil model the effects of small-scale fading within the ns network simulator. Their model accounted for time-correlation when computing packet error probability without adding to the complexity of the computation. The model uses a simple table lookup for an efficient implementation. The fading models statistics and time correlation properties are obtained from the Doppler spectrum. This method of implementation allows for the faithful simulation of a complete fading envelope [Pun00].

2.10 Summary

This chapter introduces some of the history of wireless communications and it shows how quickly wireless communication devices have become popular. It also describes some of the characteristics of the mobile propagation channel. Radio propagation models that exist and are used to plan wireless communication systems are described. The chapter discusses the OPNET network simulator used to plan wireless communication systems. The chapter concludes with a discussion of relevant research done on the subject of modeling radio propagations.

III. Methodology

3.1 Problem Definition

3.1.1 Goals and Hypothesis

The goal of this research is to develop a more accurate received signal strength model for a wireless communication network using a more realistic outdoor propagation model.

OPNET calculates the pathloss P_L between a T-R pair using the free-space pathloss formula

$$P_L = \left(\frac{\lambda}{4\pi d} \right)^2 \tag{3.1}$$

where d is the distance between the T-R pair in meters and λ is the wavelength of the center frequency in meters. This formula is accurate for calculations of pathloss between a T-R pair under line-of-sight (LOS) conditions. However, this formula does not account for environments with a large number of reflectors, scatterers and/or diffractors. By replacing the free-space pathloss formula with an empirical pathloss formula, which provides accurate pathloss calculations in urban, suburban and rural environments, the calculation of received signal strength should more accurately reflect measured values.

3.1.2 Approach

OPNET calculates the pathloss in the received power stage of the radio transceiver pipeline. The default receiver power pipeline stage, dra_power, uses the free-space pathloss formula. Replacing the formula used by the radio transceiver pipeline stage with a more realistic empirical formula should result in a more realistic and accurate prediction for received signal strength levels. The default empirical formulas for free-space pathloss are replaced with the Hata formula [Hat90] and the COST-231 extension to the Hata model [Eur91]. Hata models are empirical formulas derived from the tables used in the Okumura outdoor propagation model [Oku68]. The Okumura models are widely used for signal prediction in urban areas [Rap02]. Hata models reduce the complexity of calculating pathloss and the COST-231 extends the range of frequencies for which the Hata model is valid [Rap02].

3.2 System boundaries

The System under Test (SUT) is the radio transceiver pipeline of OPNET's wireless module which consists of 14 stages. Each stage performs a specific wireless communications link function. Each of the stages is executed once for a receiver and may be executed a number of times depending on the situation. The Component under Test (CUT) is the received power stage, stage 7 because it calculates the received power of the arriving packet. The pathloss is calculated in this stage.

3.3 System Services

The services provided by the radio transceiver pipeline is the characterization of a wireless communications link incorporating TX/RX antenna gain, propagation delay, interference noise, bit error rate, signal to noise ratio and received power. Pathloss is the inverse of received power. Therefore, if OPNET provides accurate prediction of pathloss, it can provide a realistic and accurate value for received signal strength.

3.4 Workload

The system workload are the packets transmitted from transmitter to receiver. OPNET calculates the pathloss for each packet arriving at the receiver. The calculation of pathloss is independent of the quantity or type of traffic being received by receiver. That is, the system invokes the same radio transceiver pipeline every time a packet is received independent of the quantity or type of traffic. An increase in packets may affect interference calculations and result in the Bit Error Rate (BER) of the packet increasing. An increase in the BER reduces the throughput of the wireless link. However, an examination of the throughput of the system is outside of the scope of this research.

3.5 Performance Metrics

The performance metric for the research is received signal power level in decibels. Pathloss is defined as the attenuation undergone by an electromagnetic wave in transit between a transmitter and a receiver. Pathloss is one factor that affects the signal strength at a receiver. For validation, the calculated received signal strength is compared to actual measured received signal strength levels found in [HTJ93].

3.6 Parameters

A parameter is a characteristic of a system that affects performance if changed or a user request to the system that if changed affects the performance. The parameters below impact system performance.

3.6.1 System

- Antenna Characteristics

   - o Antenna Gain – Antenna gain determines how much of a signal level will be received. It also allows a signal to be received at greater distances from the transmitter.
   - o Antenna Type – An Omni directional antenna transmits in a circular pattern, while a directional antenna is an antenna, which transmits or receives maximum power in a particular direction [Wia06].

- Transmitted Traffic Level – The number of packets being transmitted to a receiver can increase the interference at a receiver. This increases the background and noise interference which, in turn, increase the BER and SNR.

- Transmitter and Receiver Separation – The distance between the transmitter and receiver inversely affects the received signal level. The further a receiver is from the transmitter, the less power it receives.

- Signal Propagation Environment – The number of reflectors, diffractors and scatterers in the path between the transmitter and receiver effects the amount of received power at the receiver.

- Signal Frequency – The frequency of the signal determines how much of the signal is absorbed into different types of material, and it also determines how far the signal propagates.

3.7 Factors

Factors are parameters that are varied during the simulations for analysis purposes.

Table 1. List of Factors and Values Used

Factor	Values Used
Signal Frequency	880 MHz for Hata model, except for Suburban environment 894 MHz is used 1922 MHz, for COST-231 model
Signal Propagation Environment	Large City Urban, Urban, Suburban and Rural for Hata model only
Antenna Gain	6.5 dBi Large City and Urban TX antennas 9 dBi Suburban and Rural TX antennas 5.2 dBi RX antenna
Antenna Height	136 meters for Large City Urban TX antenna 34 meters for Urban TX antenna 57 meters for Suburban TX antenna 37 meters for Rural TX antenna 3.35 meters for RX antenna (0.61 meters for actual antenna height and 2.74 meters for van height)

- Signal Frequency – The frequencies of 880 and 894 MHz is used to test the Hata model and 1922 MHz is used to test the COST-231 model.

- Signal Propagation Environment – The environment in which a signal travels is classified into four categories; Urban Large City, Urban Medium City, Suburban and Rural for the Hata and three categories; Urban Large City, Urban Medium City and Suburban for the COST-231 models. Each category is characterized by the number of reflectors, diffractors and scatterers found in the environment. The Large City Urban environment contains the most obstructions (large number of skyscrapers). The Urban environment is characterized by mainly having 3 to 4 story buildings. The Suburban environment contains residential and small business buildings. The Rural or Open Space environment is characterized by open spaces and farmland. All four environments are tested for both propagation models [HTJ93].

- Antenna Height – The models are valid for TX antenna heights of 30 m to 200 m and RX antenna heights of 1 m to 10 m. The antenna heights listed in Table 1 were obtained from [HTJ93] and these are the values tested.

3.8 Evaluation Technique

The evaluation of the SUT is performed in three steps. The factors listed in Table 1 are used to evaluate the system during each step. The first step ensures that OPNET is correctly calculating the pathloss using the Hata model and the COST-231 model. The pathloss calculated by OPNET is compared to a manual calculation of the pathloss using the model formulas. There should be no difference between the two calculated pathlosses. The second evaluation compares the received signal strength manually calculated using the free-space pathloss and using the original pipeline stage, dra_power, against the modified versions of dra_power_urban_large, dra_power_urban, dra_power_suburban and dra_power_rural. The final step in the evaluation compares the received signal strength calculated using the "modified" pipeline stages with measured received signal strength levels obtained from [HTJ93].

3.9 Experimental Design

The simulations are performed using OPNET Modeler 10.5. There are four different scenarios including Large City Urban, Urban, Suburban and Rural. Each scenario consists of a stationary base station, two mobile nodes and a mobility configuration component. Figure 11 below shows the experiment setup for the Large City Urban scenario.

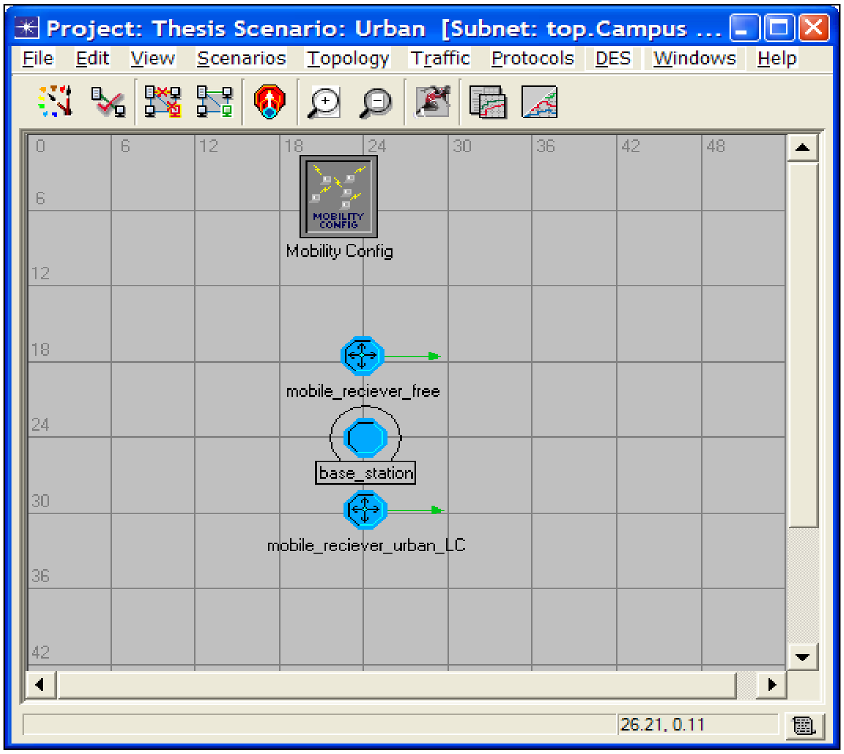

Figure 11. Experiment Scenario Setup

The mobile nodes travel in a straight line along the arrow at a rate of 60 km/hr, which means that after 20 minutes the nodes will have traversed 20 km. At the beginning of each simulation, the mobile nodes are placed at the same location as the base transmitter. Figure 12 depicts the initial node placement, speed of the mobile nodes and the direction of travel.

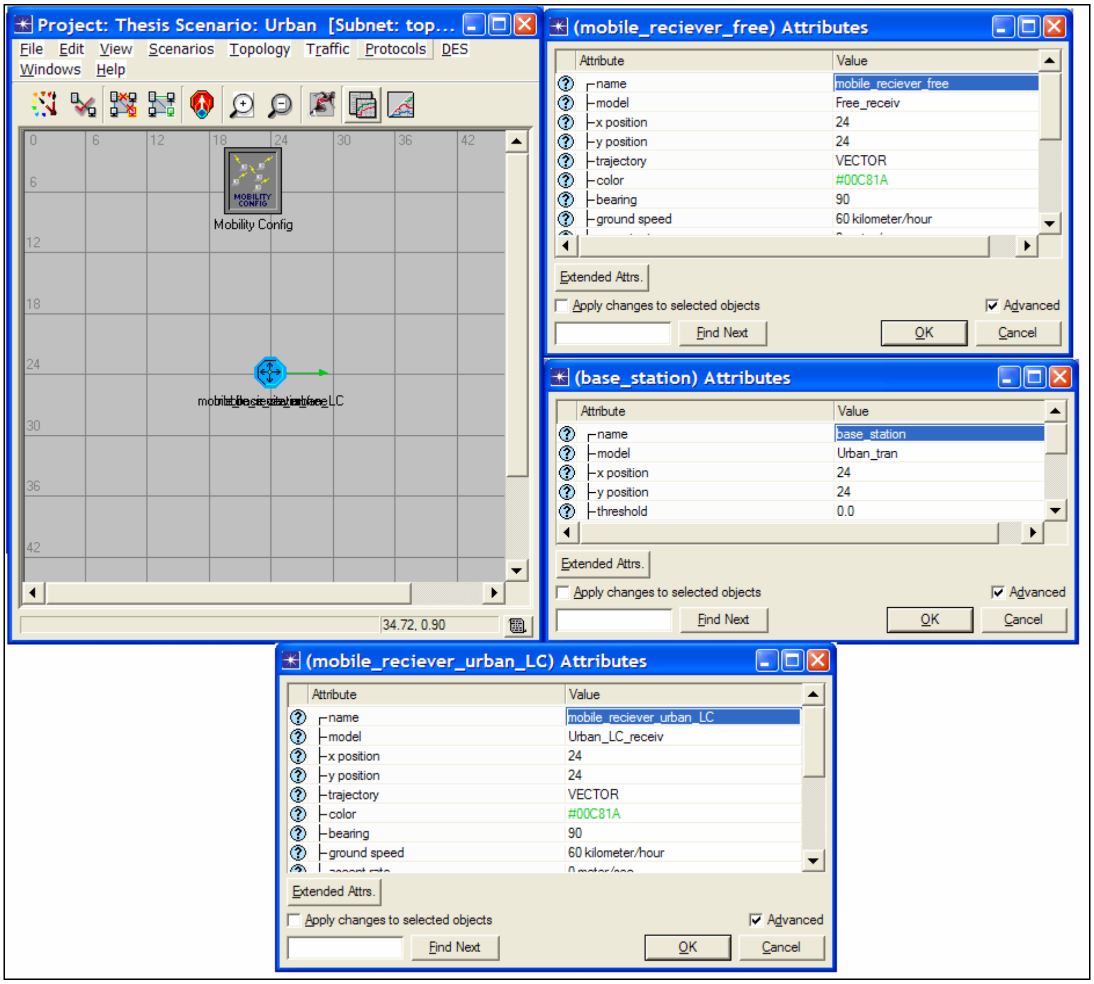

Figure 12. Initial Node Location and Speed

The upper left-hand corner of Figure 12 shows the initial scenario setup for each simulation. The two blocks on the right-hand side and at the bottom of Figure 12 are the attributes for each node in the scenario. The three blocks show that the three nodes are placed at the same x and y position in the scenario. The top right and bottom middle block show that the mobile nodes are traveling at the same rate of speed, 60 km/hr, and in the same direction (bearing = 90). The mobile nodes travel the same path at the same speed to avoiding introducing any variance in the collected data.

Each node consists of a processor component, a point-to-point transmitter/receiver, an antenna component and a packet stream connecting all three components together as seen in Figure 13.

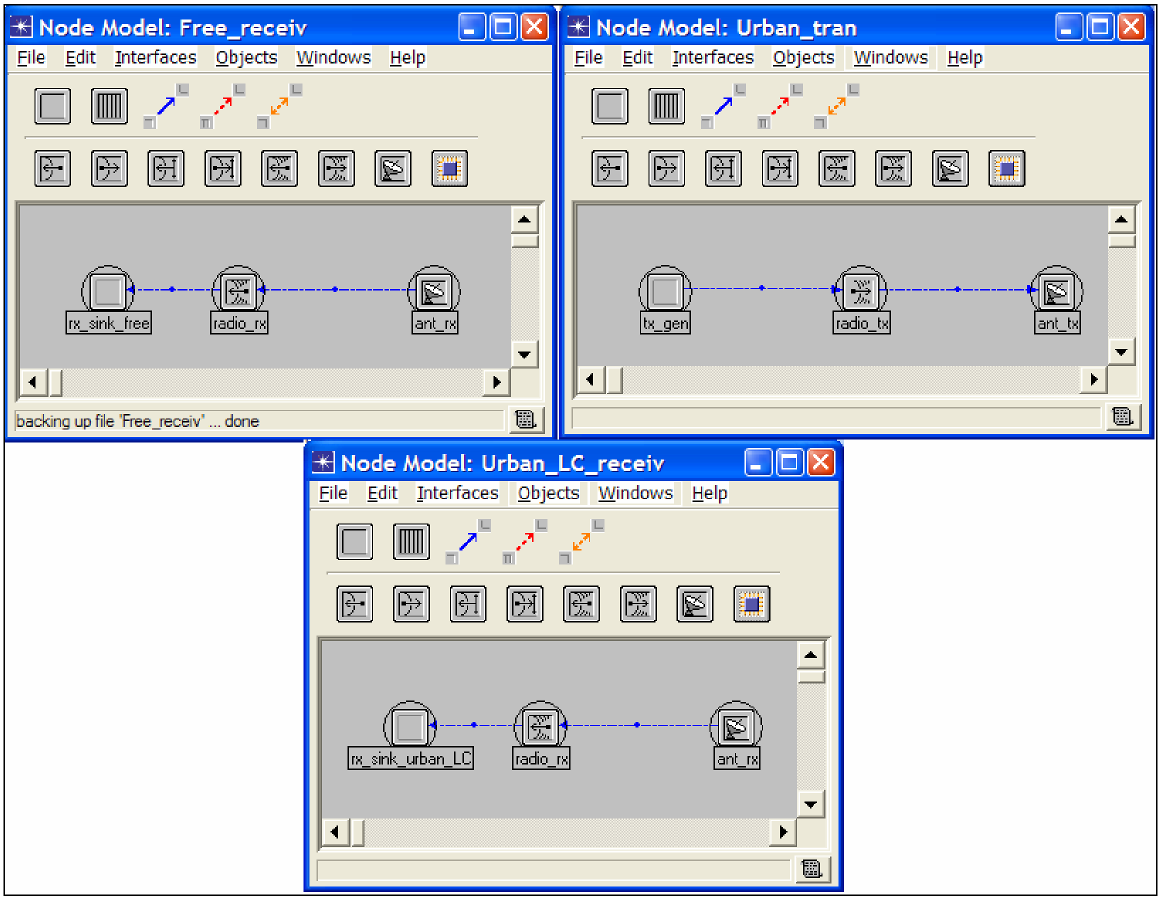

Figure 13. Node Models

In Figure 13 the processor component for the transmitter in the upper right hand corner is a simple source, labeled *tx_gen*, outputting packets 1024 bits long every 0.025 seconds. The packets are sent to the radio transmitter, labeled *radio_tx*, via the packet stream. The packets are passed to transmitting antenna, labeled *ant_tx*, via the packet stream for broadcast to the receiver. The receiver nodes are in the blocks located in the upper left and bottom center of Figure 13. The packets are received through the receiver antennas then the packets are passed via the packet stream to the radio receiver, *radio_rx*. The packets are then sent to the sink processors, *rx_sink_free* and *rx_sink_urban_LC* where the statistical information from the packets is collected and the packets are destroyed.

To implement the pathloss changes in the transceiver pipeline, the original C/C++ code for the received power stage (dra_power) is modified. The modified pipeline stages are located in Appendix A. The pipeline stages are modified to use the new formulas in equation 2.7 and 2.13 for pathloss calculation and to calculate the statistic of received power in decibels. The mobile node in each simulation using the original free-space pathloss model has its' dra_power pipeline code modified to calculate received power in decibels and in watts. The C/C++ pipeline code being utilized by the mobile nodes is changed in the attributes for each *radio_rx* in Figure 13.

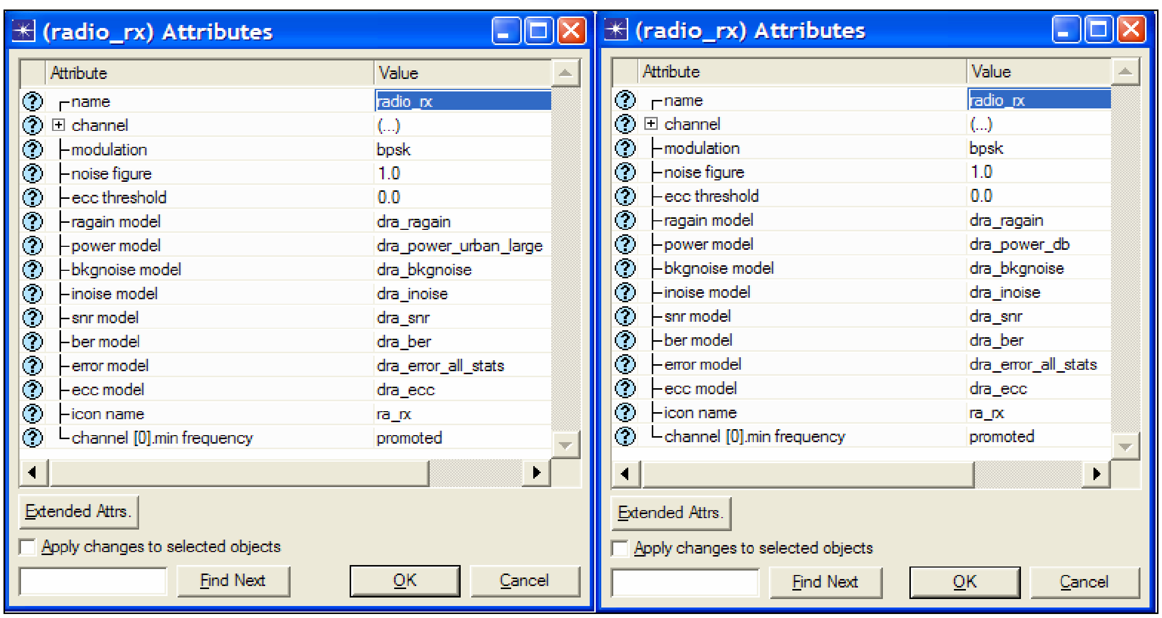

Figure 14. C/C++ Pipeline Stage Used

Figure 14 shows the attributes for the free-space mobile receiver on the left and the mobile receiver with the "modified" pipeline code on the right. The value for the power model, seventh row from the top, determines which pipeline code is used for the received power stage in the radio transceiver pipeline.

Using the above setup, seven simulations are run for all four of the environment types to test the Hata model and the COST-231 model. The first set of simulations is used to collect the pathloss values being calculated by the new pipeline stage. A second set of simulations with five replications are performed to collect the received power statistic for analysis. Ideally, only one run is sufficient for the analysis of the output but five replications are being utilized to ensure that there is not an anomaly in the operation of the transceiver pipeline with the modified pipeline stage. The total number of simulations performed is {5 replications * [4 (Hata) + 3 (COST-231)]} (for received power analysis) + 7 (for pathloss comparison) = 42.

Table 2. Simulation Parameters

Model	Environments	Frequency (MHz)	Tx antenna height (m)	Rx antenna height (m)	Distance (km)
Hata	Urban Large City	880	136	3.35	1 to 20
	Urban Medium City	880	34	3.35	1 to 20
	Suburban	880	57	3.35	1 to 20
	Rural	880	37	3.35	1 to 20
COST-231	Urban Large City	1922	136	3.35	1 to 20
	Urban Medium City	1922	34	3.35	1 to 20
	Suburban	1922	57	3.35	1 to 20

3.10 Analysis and Interpretation of Results

Because the pathloss formulas are not time varying, an ANOVA analysis of the data will not be performed. When comparing the OPNET calculated pathloss and the pathloss using the Hata and COST-231 models there should be no difference between the two calculations given the same input parameters. When comparing the received powerr using the original pipeline C/C++ code and the modified code there should be significant difference between the two calculations. The final analysis compares the signal strength calculated from the modified pipeline code and the measured received signal strength data obtained from [HTJ93]. The modified results should more closely resemble the actual data than the original pipeline code.

3.11 Summary

The frequency, distance, TX/RX antenna heights and the propagation environment will be set to specified values to analyze the data. An ANOVA approach will not be used because the formulas are not time varying.

IV. Analysis and Results

4.1 Pathloss Calculation Comparison

The first step in evaluating the modifications is to ensure OPNET calculates the correct pathloss. The actual output from the OPNET debugger is listed is Appendix B. Table 3 lists the results and factors being used for the Urban Large City simulation.

Table 3. Urban Large City Pathloss Calculation

OPNET PL	Distance (km)	Formula PL	Difference	Parameter Settings	
114.066	1.011	114.066	0.000	Fc (MHz)=	880
114.288	1.028	114.288	0.000	ht (m)=	136
114.506	1.045	114.506	0.000	hr (m)=	3.35
114.721	1.061	114.721	0.000	a(hr)=	114.721

OPNET PL	Distance (km)	Formula PL	Difference	Parameter Settings	
128.107	1.011	128.107	0.000	Fc (MHz)=	1922
128.329	1.028	128.329	0.000	ht (m)=	136
128.548	1.045	128.548	0.000	hr (m)=	3.35
128.763	1.061	128.763	0.000	a(hr)=	3.172

The first column shows the pathloss calculated by OPNET and obtained from the debugger output. The third column shows the value calculated by the formula from Chapter 2. The parameters being used are listed in the last column. The fourth column shows that there is no difference between the two calculated values.

Table 4 lists the pathloss values calculated during the Urban Medium City simulation.

Table 4. Urban Medium City Pathloss Calculation

OPNET PL	Distance (km)	Formula PL	Difference	Parameter Settings	
120.745	1.003	120.745	0.000	Fc (MHz)=	880
120.995	1.020	120.995	0.000	ht (m)=	34
121.241	1.036	121.241	0.000	hr (m)=	3.35
121.484	1.053	121.484	0.000	a(hr)=	4.712

OPNET PL	Distance (km)	Formula PL	Difference	Parameter Settings	
131.065	1.003	131.065	0.000	Fc (MHz)=	1922
131.316	1.020	131.316	0.000	ht (m)=	34
131.562	1.036	131.562	0.000	hr (m)=	3.35
131.804	1.053	131.804	0.000	a(hr)=	5.433

Table 4 shows that OPNET is calculating the correct value for the Urban Medium City simulation. Table 5 lists the calculations and values for the Suburban simulation.

Table 5. Suburban Pathloss Calculation

OPNET PL	Distance (km)	Formula PL	Difference	Parameter Settings	
107.907	1.005	107.907	0.000	Fc (MHz)=	894
108.147	1.021	108.147	0.000	ht (m)=	57
108.383	1.038	108.383	0.000	hr (m)=	3.35
108.615	1.055	108.615	0.000	a(hr)=	4.727

OPNET PL	Distance (km)	Formula PL	Difference	Parameter Settings	
127.988	1.005	127.988	0.000	Fc (MHz)=	1922
128.228	1.021	128.228	0.000	ht (m)=	57
128.464	1.038	128.464	0.000	hr (m)=	3.35
128.696	1.055	128.696	0.000	a(hr)=	5.433

The results found in Table 5 show that there is no difference between the two calculations for the suburban model using the factors shown. Table 6 lists the results for the Rural simulation.

Table 6. Rural Pathloss Calculation

OPNET PL	Distance (km)	Formula PL	Difference	Parameters Settings	
91.830	1.003	91.830	0.000	Fc (MHz)=	880
92.079	1.020	92.079	0.000	ht (m)=	37
92.324	1.037	92.324	0.000	hr (m)=	3.35
92.564	1.053	92.564	0.000	a(hr)=	4.712

Table 6 shows that there is no difference between the two calculated pathloss values.

4.2 Pipeline Stage Comparison

The second comparison is between the original pipeline code using the OPNET implementation of the free-space pathloss formula and the “modified” pipeline code. The goal is to show that the “modified” pipeline code results are different from the original pipeline code. The received signal strength obtained from the simulations using the two different models is compared. The values are collected for T-R separation distances of 1 km to 20 km. The received signal strength in dBm is plotted verses the log distance in kilometers. The data from all five repetitions is plotted to ensure that OPNET does not produce any anomalies during calculations. If there were, any anomalies in the data collected, more than one line would appear in the graphs.

The manual calculation of the received signal strength using equation 2.2 with the pathloss obtained from the free-space model is compared with the Urban Large City signal strength values calculated from OPNET in Figure 15. The Friis free-space equation implies that the received power will decrease as the square of the T-R separation distance increases. This implies that the power drops off at a rate of 20 dB/decade [Rap02]. The graphs on the left in Figure 15 behave as predicted at d = 1 km the initial signal strength is – 32.7 dBm and at d = 10 km the value is – 52.7 dBm for 880 MHz. The initial signal strength level for 1922 MHz is – 39.5 dBm at d = 1 km and – 59.5 dBm at d = 10 km. The free-space model and Hata/COST-231 models have calculated signal strength values that behave logarithmic.

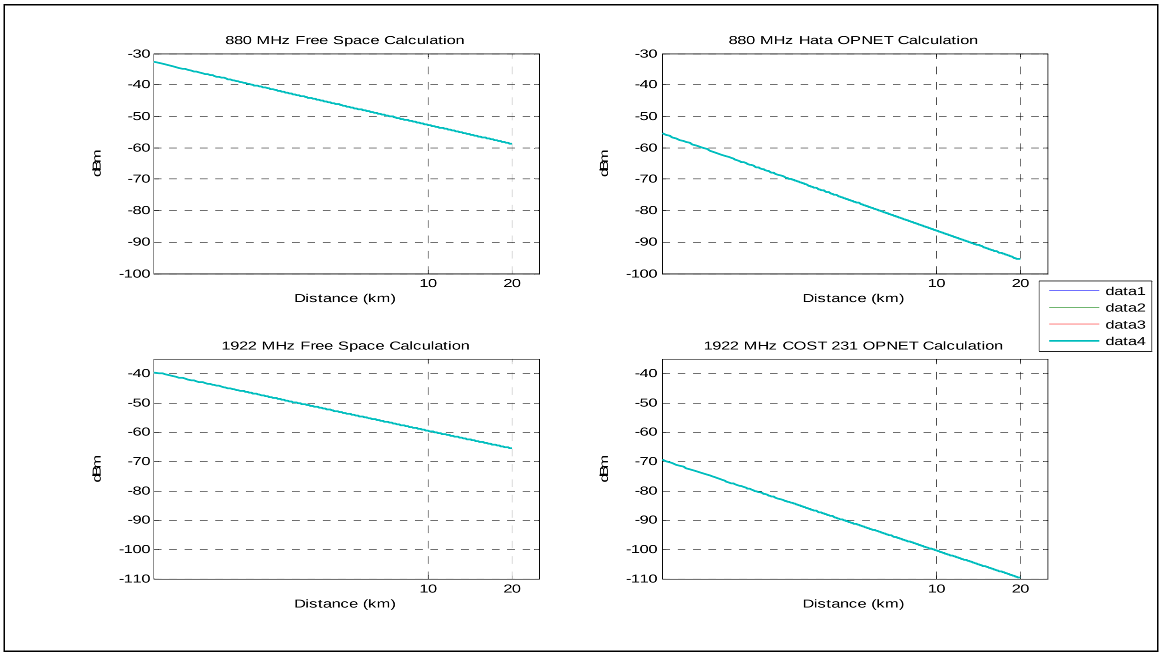

Figure 15. Urban Large City and Free-Space Comparison

The main difference between the values calculated using the free-space model and the Hata/COST-231 models is the signal strength at d = 1 km. The Hata has an initial signal strength of -55.4 dBm at d = 1 km and the COST-231 has an initial signal strength of –69.4 dBm.

The graphs in Figure 16 compare the received signal strength calculated by OPNET using the free-space pathloss model. The graphs on the left side of Figure 16 are using the original pipeline code and on the right side are the graphs from the "modified" Urban Large City pipeline code. One difference between the two pipeline codes is that the signal strength calculated using the "modified" pipeline code decreases in a logarithmic fashion, consistent with (2.7) for the Hata model and (2.13) for the COST-231 model.

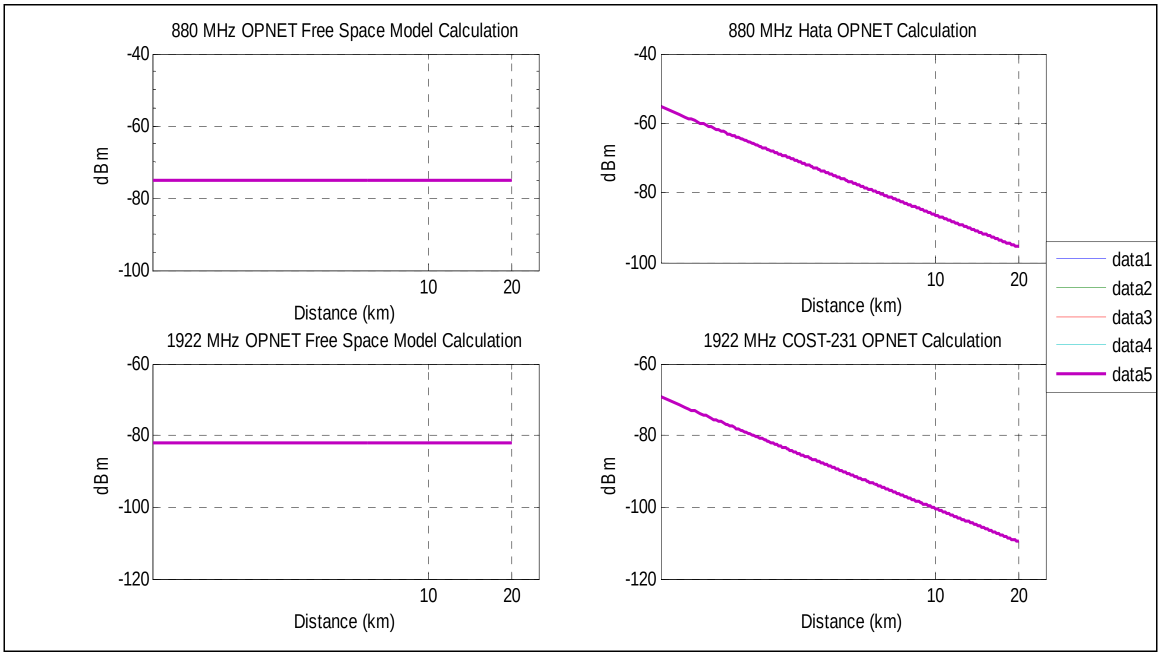

Figure 16. Urban Large City Received Signal Strength Comparison

Whereas the signal strength from the original pipeline code is almost constant until the ten kilometer mark at which point it begins to decrease. Another difference between the two pipeline codes is the initial signal strengths at d = 1 km. The signal strength using the original pipeline code starts at approximately -75.1 dBm and -81.9 dBm for 880 MHz and 1922 MHz, respectively. The simulation results using the Hata and COST-231 models have a starting signal strength level of -55.37 dBm and -69.41 dBm respectively. In Figures 18, 20 and 22 similar trends can be seen for the Urban Medium City, Suburban and Rural cases, respectively.

Figure 17 compares the Friis calculation using the Urban Medium City parameters with the OPNET calculation using the Hata/COST-231 models. The same differences can be seen in Figure 17 that is evident in Figure 15. The two models behave in a logarithmic manner and have different initial signal strengths at d = 1 km.

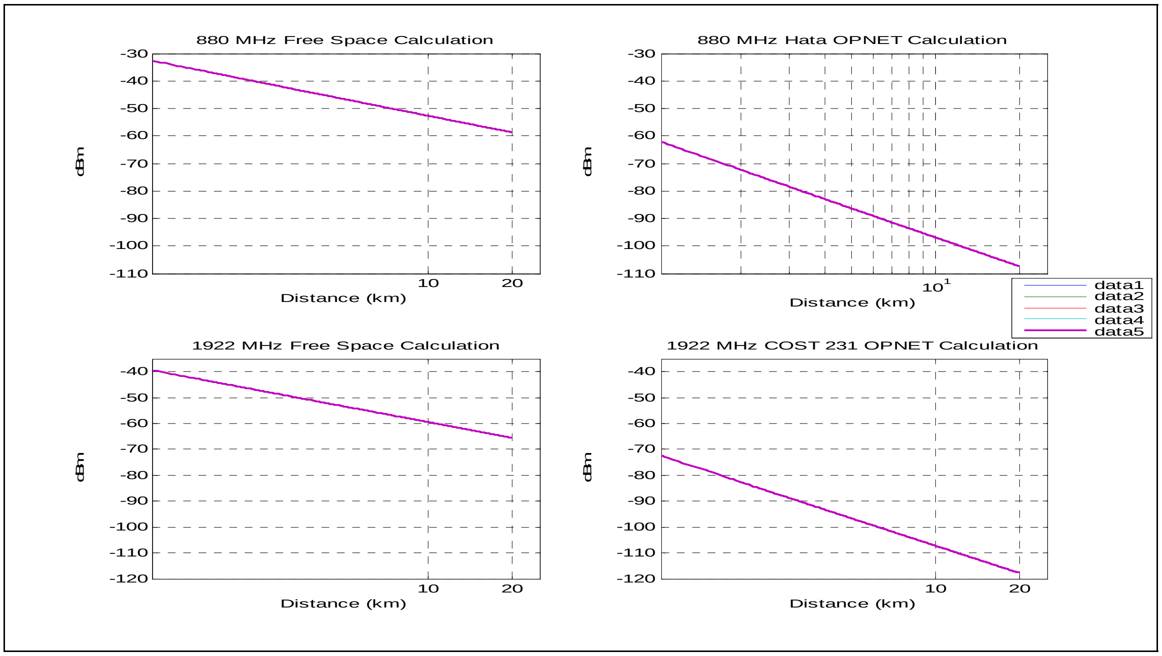

Figure 17. Urban Medium City and Free-Space Comparison

There is – 29.4 dBm difference between the free-space model calculation and the Hata model and a – 33.0 dBm difference at the 1922 MHz.

The results from the Urban Medium City Received Signal Strength Comparison are seen in Figure 16. The simulation results from the free-space model and Hata/COST-231 models show similar characteristics to the results found in Figure 15. The free-space model is almost constant until the ten kilometer mark and the "modified" pipeline code is logarithmic in appearance. The initial signal strength values for d = 1 km are similar for the free-space model at 880 MHz and the Hata model, approximately -62.4 dBm and -62.05 dBm respectively.

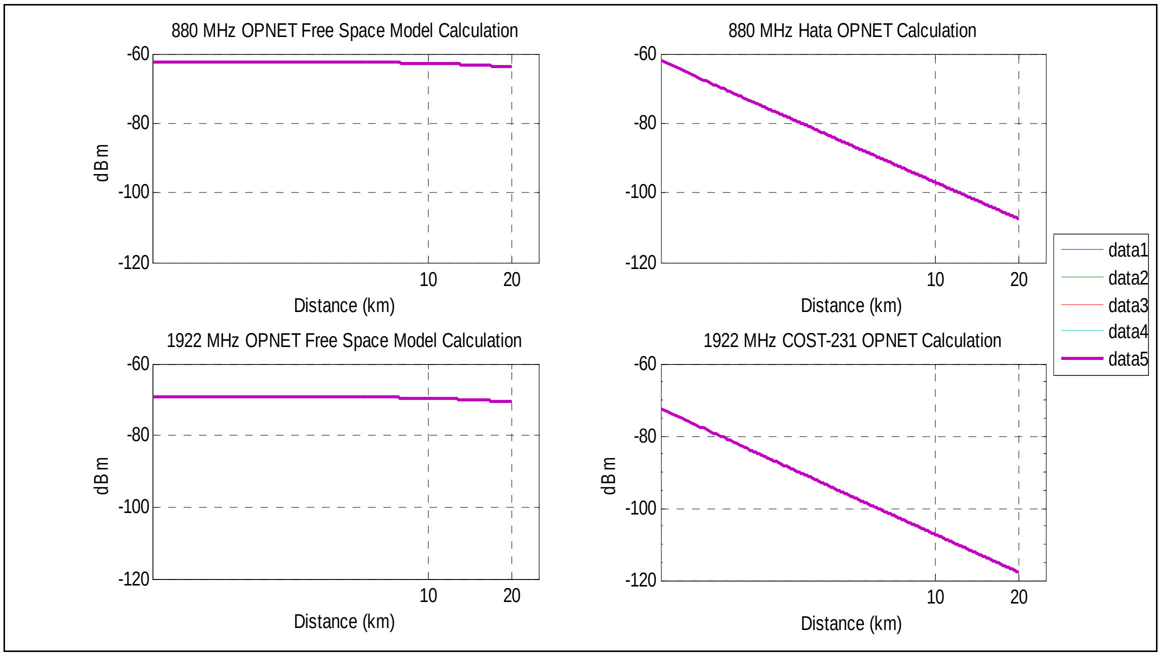

Figure 18. Urban Medium City Received Signal Strength Comparison

But the starting signal strengths are different for the 1922 MHz results, approximately -69.2 dBm for the Free-space model and -72.37 dBm for the COST-231 model.

In Figure 19 the free-space model and the Hata/COST-231 models are compared using the suburban environment settings. The free-space model and Hata/COST-231 models behave logarithmic manner. The initial signal strength at d = 1 km is different between the two models for the different frequencies. At 894 MHz the difference is – 16.4 dBm and at 1922 MHz the difference is – 29.8 dBm.

The results for the Suburban Received Signal Strength Comparison are seen in Figure 20. The trend continues with the received signal strength levels calculated by the Free-space model appearing almost constant and then decreasing at the ten kilometer point.

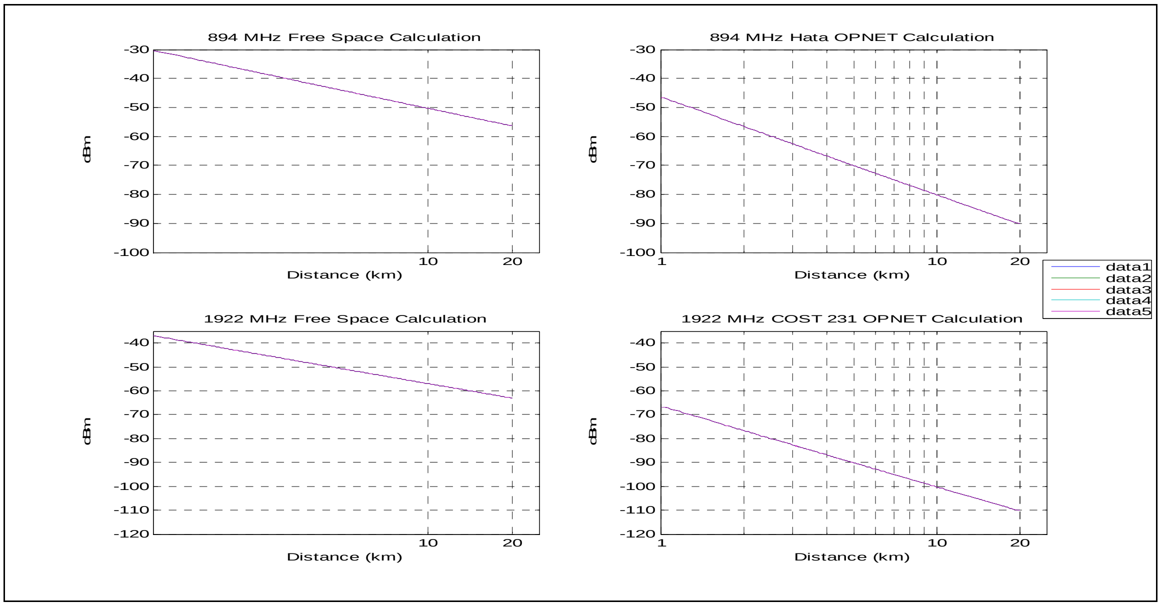

Figure 19. Suburban and Free Space Comparison

The "modified" pipeline models have a logarithmic decrease in received signal strength.

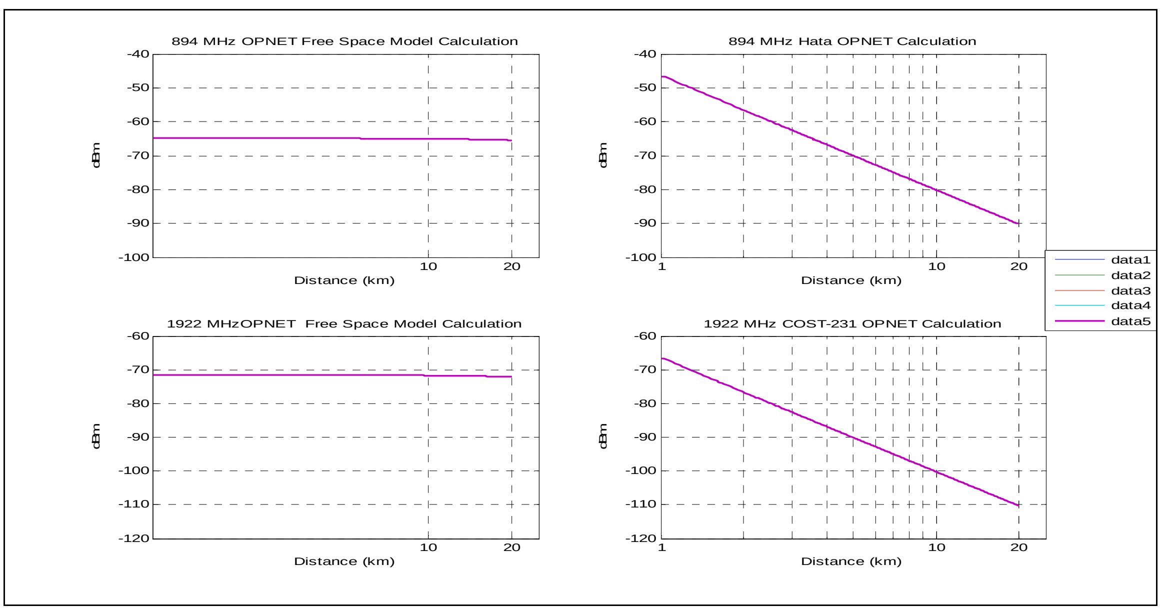

Figure 20. Suburban Received Signal Strength Comparison

Unlike the results in Figure 18, the starting signal strength levels in Figure 20 are different. At 880 MHz the starting values are approximately -64.9 dBm and -46.71 dBm for the Free-space model and Hata model respectively. At 1922 MHz the values are approximately -71.5 dBm and -66.79 dBm for the Free-space model and COST-231 models respectively.

The parameters for the Rural environment are used to compare the free-space model with the Hata/COST-231 models in Figure 21.

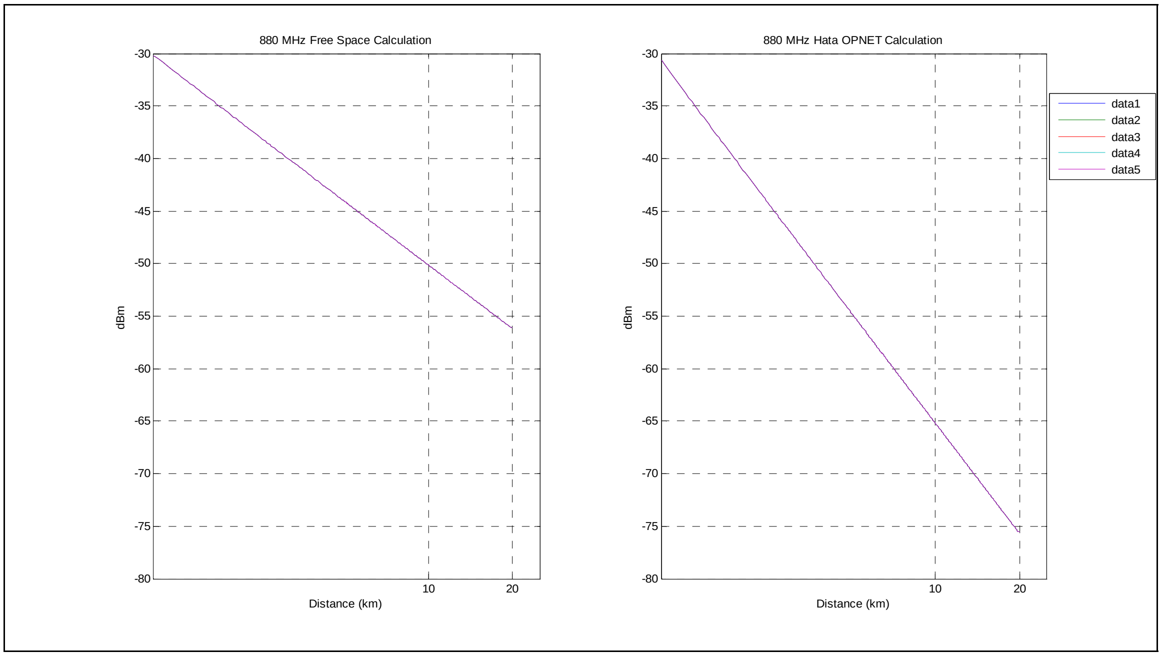

Figure 21. Rural and Free-Space Comparison

Both models behave in a logarithmic manner but, they have very similar initial signal strength levels. The free-space model has a signal strength value of – 30.2 dBm at d = 1 km and the Hata model has a – 30.6 dBm at d = 1 km, a – 0.4 dBm difference.

The graphs in Figure 22 are for the Rural Received Signal Strength Comparison using the Hata model and the Free-space model. The free-space model has a received signal strength level of approximately -60.5 dBm; where as the Hata model has a received signal strength level of approximately -31 dBm.

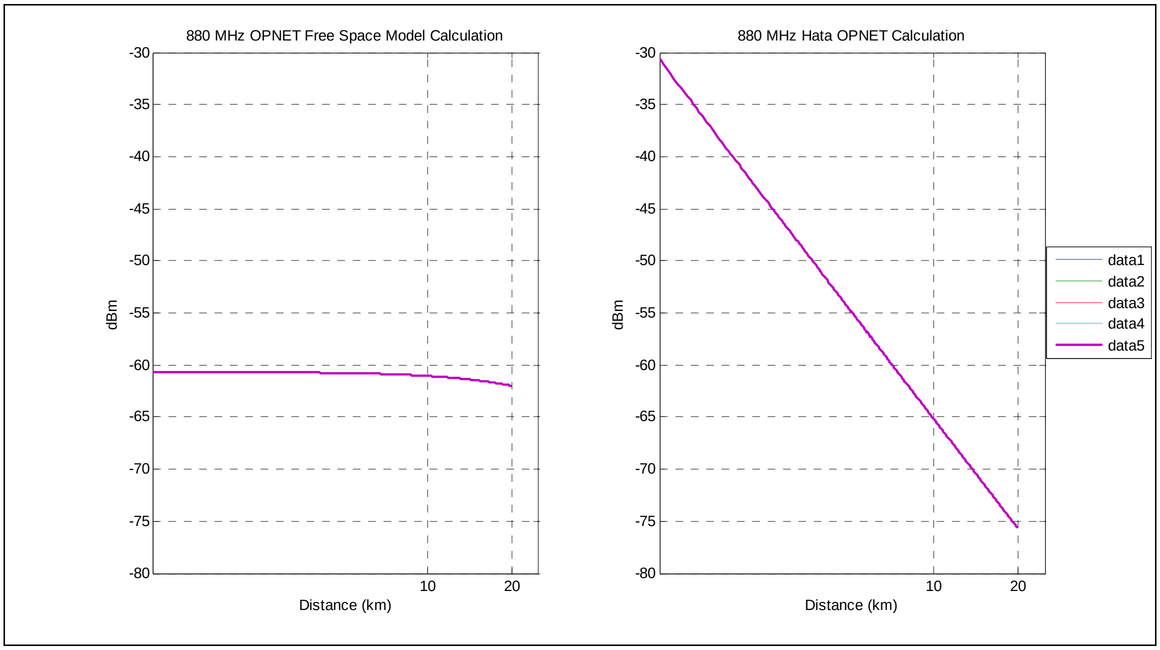

Figure 22. Rural Received Signal Strength Comparison

As with the previous results, the signal strength levels are almost constant until the d = 10 km point for the Free-space model and are logarithmic for the Hata model.

In Figures 16, 18, 20 and 22 the signal strength levels for the free-space model are minimally impacted by the increase in T-R separation. This is observed by the small decrease in signal strength from 1 km to 20 km. Yet the Hata model and COST-231 exhibit a logarithmic decrease as the T-R separation increases.

4.3 Measured Received Signal Strength Comparison

The final comparison is between the measured received power levels that are obtained using the new models and measured received signal strength levels obtained from [HTJ93]. The pathloss slope of all seven simulations will be compared and the measured received signal strength values for the suburban environment will be compared with the suburban simulation results. The measured slopes for the pathloss of [HTJ93] are shown in Table 7.

Table 7. Measured Pathloss Slope [HTJ93]

Site	Pathloss Slope (dB/decade)	
	880 MHz	1922 MHz
Cell 13 (semi rural)	-30.5	-26.7
Cell 5 (suburban)	-38.2	-34.4
Cell 100 (urban)	-37.4	-36.3
Cell 19 (heavy urban)	-28.7	-29.4
Average	-33.7	-31.7

The pathloss slopes for each simulation are shown in Table 7. The pathloss slope for the simulations is calculated by converting the time axis that is used by OPNET to a distance in kilometers. The mobile nodes are traveling at 60 km/hr therefore the time in seconds is divided by sixty to obtain the distance in km. The log of the distance is calculated by taking the common log of the distance in kilometers. Then the slope is calculated by subtracting the received signal strength value at the zero log starting distance (1 km) from the one log ending distance (10 km) to obtain a dB/decade pathloss slope.

Table 8. Simulation Pathloss Slopes for Hata / COST-231 Model (dB/decade)

Sim. Environment	880 MHz	1922 MHz
Rural	- 34.628	N/A
Suburban	- 33.399	- 33.399
Urban Med.	- 34.868	- 34.869
Urban LC	- 30.926	- 30.926
Average	- 33.455	- 33.065

The pathloss slopes from the simulations are similar to the measured slopes presented in Table 7 with the average simulation pathloss being nearly identical to the measured pathloss slope. The 880 MHz has a 0.245 dB difference and the 1922 MHz has a 1.365 dB difference between averages. The pathloss slopes for each individual environment: Suburban, Urban Medium and Urban Large City is identical for both frequencies. Using the graphs in Figure 23, the signal strengths from the suburban simulation are compared with the measured signal strength at 1 km. The measured signal strength data of the suburban simulation is found in Appendix C.

The value of the average received signal strength at 1 km is estimated from the graphs in Figure 23 [HTJ93] as -58 dBm for 894 MHz and -78 MHz for 1922 MHz. The simulated values from Figure 17 at 1 km are -46.7 dBm at 880 MHz (Hata Model) and -66.7 dBm at 1922 MHz (COST-231 Model). Therefore, there is a difference (simulated-measured) of + 11.3 dBm for both the 880 MHz and 1922 MHz cases. The significance of this is that the average received signal strength calculated by the Hata and COST-231 models are going to behave similar to an actual received signal because pathloss slopes are identical. However, the simulated signal strength is going to be greater than an actual received signal.

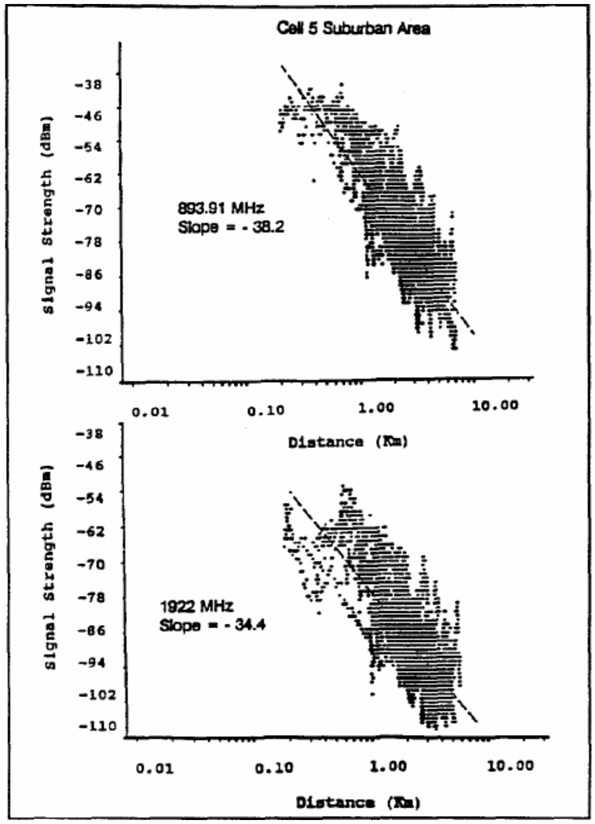

Figure 23. Pathloss Slopes for 894 MHz and 1922 MHz [HTJ93]

4.4 Summary

The pipeline stages have been modified correctly because the calculation that is performed for pathloss is the same as the value calculated by the formula. The manually calculated received signal strength is similar to the received signal strength calculated using the Hata/COST-231 models but, it is different from the original OPNET calculation using the free-space pathloss model. The free-space model used in the original pipeline code appears to be unaffected by the increase in distance between the transmitter and receiver. The Hata model and COST-231 models exhibit a logarithmic relationship between the signal strength levels and T-R separation. The initial signal strength values differ from the free-space model and the Hata and COST-231 models. When compared to measured data, the values for the pathloss slope are similar to the simulation results. The signal strength value at 1 km for the suburban environment simulation was greater than the measured value by approximately 11 dBm. The results produced by the modified pipeline stages are more similar to the actual measured values than the original pipeline stages.

V. Conclusions and Recommendations

5.1 Chapter Overview

This chapter provides a summary of the research conclusions, the significance of the research and recommendations for future research.

5.2 Conclusions and Significance of Research

Altering the pathloss model being used by OPNET produces results that are more realistic than the original OPNET implementation. The original pathloss model does not account for the diffractors, scatterers and reflectors found in typical communication environments. In addition, the implementation of the free-space model by OPNET produce results that do not reflect the decay associated with using the free-space pathloss model. The OPNET implementation of the free-space model uses the propagation distance between the transmitter and receiver. The propagation distance is the three dimensional distance or vector distance between the transmitter and receiver (LOS). The propagation distance is appropriate for non-terrestrial calculations but produce results that are depicted in Figures 16, 18, 20 and 22, which are insensitive (to the T-R separation) and inaccurate for terrestrial communications systems in OPNET. The additions of the new pathloss models (Hata and COST 321) produces signal strength results that are similar to actual measured values.

With the modification of the OPNET pipeline stage, dra_power, the output from the wireless model can now be trusted to produce a more accurate/realistic result.

5.3 Recommendations for Future Research

In this research, the models used produced realistic results; unfortunately, the models were not completely accurate when compared to actual measured data. In addition, the models were limited to a certain range of frequencies, transmitter-receiver separation and antenna heights.

For future research, modifications can be made to the current pathloss model to account for the -11 dBm difference between the calculated signal strength and the measured signal strength. Additional models can be incorporated which will overcome the limits imposed by the frequency range, transmitter-reciever separation, and antenna heights on the current model.

Appendix A: Modified Pipeline Code

Modified dra_power pipeline stage for Urban Large City environment:

```
/* dra_power_large.ps.c */
/* Default received power model for radio link Transceiver  */
/* Pipeline. This model uses the receiver channel state             */
/* information to check and update the signal lock status   */
/* of the channel. It relies on the rxgroup stage model for */
/* the creation and initialization of the channel state             */
/* information.                                                                                                                  */

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/*      Bethesda, MD 20814, U.S.A.      */
/*                    All Rights Reserved.                          */
/****************************************/

#include "opnet.h"
#include "dra.h"
#include <math.h>
#include <stdlib.h>
#include <stdio.h>


/***** constants *****/

#define C                                        3.0E+08                     /* speed of light (m/s) */
#define SIXTEEN_PI_SQ                    157.91367           /* 16 times pi-squared */


/***** pipeline procedure *****/

#if defined (__cplusplus)
extern "C"
#endif

void
dra_power_urban_large_mt (OP_SIM_CONTEXT_ARG_OPT_COMMA Packet * pkptr)
          {
          double                                            prop_distance, rcvd_power, path_loss;
          double                                            tx_power, tx_base_freq, tx_bandwidth, tx_center_freq;
          double                                            lambda, rx_ant_gain, tx_ant_gain;
          Objid                                             rx_ch_obid;
          double                                            in_band_tx_power, band_max, band_min;
          double                                            rx_base_freq, rx_bandwidth;
          DraT_Rxch_State_Info*          rxch_state_ptr;
          double                                            tx_ant_height, rx_ant_height;                                             /* Antenna
heights for TX,RX*/
          double                                            tx_MHz_freq;
                    /* TX freq in Mega Hertz*/
          double                                            km_distance;
                    /* Distance converted to Kilometers*/
          double                                            a_hm, rcvd_power_dbm;
          /* Correction factor for mobile antenna*/
          double                                            path_loss_db = 0, in_band_tx_power_db;                            /* decible value of
pathloss and in band transmission power*/
          int                                                         prop_model = 0;
                              /* determines which pathloss formula to use*/
          double                                            rx_ant_gain_db, tx_ant_gain_db;                                                      /*
db values of the ant. gains */


          /** Compute the average power in Watts of the               **/
          /** signal associated with a transmitted packet.  **/
          FIN_MT (dra_power_urban_large_mt (pkptr));


          /* If the incoming packet is 'valid', it may cause the receiver to    */
          /* lock onto it. However, if the receiving node is disabled, then     */
          /* the channel match should be set to noise.                                        */
          if (op_td_get_int (pkptr, OPC_TDA_RA_MATCH_STATUS) == OPC_TDA_RA_MATCH_VALID)
                    {
                    if (op_td_is_set (pkptr, OPC_TDA_RA_ND_FAIL))
                              {
                              /* The receiving node is disabled.  Change        */
                              /* the channel match status to noise.             */
                              op_td_set_int (pkptr, OPC_TDA_RA_MATCH_STATUS, OPC_TDA_RA_MATCH_NOISE);
                              }
                    else
                              {
                              /* The receiving node is enabled.  Get  */
                              /* the address of the receiver channel. */
                              rx_ch_obid = op_td_get_int (pkptr, OPC_TDA_RA_RX_CH_OBJID);

                              /* Access receiver channels state information.          */
                              rxch_state_ptr = (DraT_Rxch_State_Info *) op_ima_obj_state_get (rx_ch_obid);

                              /* If the receiver channel is already locked,           */
                              /* the packet will now be considered to be noise. */
                              /* This prevents simultaneous reception of multiple         */
                              /* valid packets on any given radio channel.            */
                              if (rxch_state_ptr->signal_lock)
                                        op_td_set_int (pkptr, OPC_TDA_RA_MATCH_STATUS, OPC_TDA_RA_MATCH_NOISE);
                              else
                                        {
```

```
                              /* Otherwise, the receiver channel will become    */
                              /* locked until the packet reception ends.                  */
                              rxch_state_ptr->signal_lock = OPC_TRUE;
                              }
                    }
          }

          /* Get power allotted to transmitter channel. */
          tx_power = op_td_get_dbl (pkptr, OPC_TDA_RA_TX_POWER);

          /* Get transmission frequency in Hz. */
          tx_base_freq = op_td_get_dbl (pkptr, OPC_TDA_RA_TX_FREQ);
          tx_bandwidth = op_td_get_dbl (pkptr, OPC_TDA_RA_TX_BW);
          tx_center_freq = tx_base_freq + (tx_bandwidth / 2.0);

          /*Convert the transmit frequency to Mega Hertz*/
          tx_MHz_freq = tx_center_freq/1000000;
          printf("freq = %f\n",tx_MHz_freq);

          /* Caclculate wavelength (in meters). */
          lambda = C / tx_center_freq;
          /*printf("lambda = %f\n",lambda);*/

          /* Get distance between transmitter and receiver (in meters). */
          prop_distance = op_td_get_dbl (pkptr, OPC_TDA_RA_START_DIST);
          m_distance = (km_distance * 1000);
          /*printf("prop = %f\n",prop_distance);*/


          /* Get the height of the transmit and recieve antennas.*/
          tx_ant_height = (op_td_get_dbl (pkptr, OPC_TDA_RA_TX_ALT))/1000;
          rx_ant_height = (op_td_get_dbl (pkptr, OPC_TDA_RA_RX_ALT))/1000;
          printf("tx_height = %f\n",tx_ant_height);
          printf("rx_height = %f\n",rx_ant_height);

          /* Calculate the distance using the TDA sart_dist*/

          km_distance = sqrt(pow((prop_distance/1000),2)- pow((tx_ant_height-rx_ant_height),2));
          printf("dist_z = %f\n",km_distance);

// Calculate a_hm for Hata and COST-231
          if (tx_MHz_freq <= 300)
                    {
                              a_hm = 8.29*(pow(log10(1.54*rx_ant_height),2)) - 1.1;
                    }
          else
                    {
                              a_hm = 3.2*(pow(log10(11.75*rx_ant_height),2)) - 4.97;
                    }



          /* When using TMM, the TDA OPC_TDA_RA_RCVD_POWER will already         */
          /* have a raw value for the path loss. */
          if (op_td_is_set (pkptr, OPC_TDA_RA_RCVD_POWER))
                    {
                    path_loss = op_td_get_dbl (pkptr, OPC_TDA_RA_RCVD_POWER);
                    }
          else
                    {
                    /* Compute the path loss for this distance and wavelength. */
                    if (prop_distance > 0.0)
                              {
                    /* Determine which propagation model to use and use value in the db form*/

                               if ((tx_MHz_freq >= 150 && tx_MHz_freq <= 2000) && (km_distance >= 1 && km_distance <= 100)
                                        && (tx_ant_height >= 30 && tx_ant_height <= 200) && (rx_ant_height >= 1 && rx_ant_height <= 10))

                                        {
                                                  if ((tx_MHz_freq >= 150 && tx_MHz_freq <= 1500) && (km_distance >= 1 && km_distance <= 100))
                                                            {
                                                                      path_loss_db = 69.55 + 26.16*log10(tx_MHz_freq) - 13.82*log10(tx_ant_height) - a_hm
                                                                                + (44.9 - 6.55*log10(tx_ant_height))*log10(km_distance);
                                                                      prop_model = 1;
                                                            }
                                                  else if ((tx_MHz_freq > 1500 && tx_MHz_freq <= 2000) && (km_distance >= 1 && km_distance <= 20))
                                                            {
                                                                      path_loss_db = 46.3 + 33.9*log10(tx_MHz_freq) - 13.82*log10(tx_ant_height) - a_hm
                                                                      + (44.9 - 6.55*log10(tx_ant_height))*log10(km_distance) + 3;
                                                                      prop_model = 1;
                                                            }


                                                  else if ((tx_MHz_freq > 1500 && tx_MHz_freq <= 2000) && (km_distance > 20))
                                                            {
                                                                      path_loss = (lambda * lambda) /
                                                                      (SIXTEEN_PI_SQ * m_distance * m_distance);
                                                                      prop_model = 0;
                                                                      printf("Using Free-space PL\n\n",path_loss);
                                                            }

                                                            printf("Hata/COST_PL = %f\n\n",path_loss_db);
                                        }

                              else
                                        {
                                                  path_loss = (lambda * lambda) /
                                                  (SIXTEEN_PI_SQ * m_distance * m_distance);
                                                  prop_model = 0;
                                                  printf("Using Free Space PL\n\n",path_loss);
                                        }
                    }

          else
                    {
```

```
                    if (prop_model == 1)path_loss_db = 0.0;

                    else path_loss = 1;

          }
}


printf("prop_model = %i\n",prop_model);
/* Determine the receiver bandwidth and base frequency. */
rx_base_freq = op_td_get_dbl (pkptr, OPC_TDA_RA_RX_FREQ);
rx_bandwidth = op_td_get_dbl (pkptr, OPC_TDA_RA_RX_BW);

/* Use these values to determine the band overlap with the transmitter.         */
/* Note that if there were no overlap at all, the packet would already          */
/* have been filtered by the channel match stage.                                                    */

/* The base of the overlap band is the highest base frequency. */
if (rx_base_freq > tx_base_freq)
          band_min = rx_base_freq;
else
          band_min = tx_base_freq;

/* The top of the overlap band is the lowest end frequency. */
if (rx_base_freq + rx_bandwidth > tx_base_freq + tx_bandwidth)
          band_max = tx_base_freq + tx_bandwidth;
else
          band_max = rx_base_freq + rx_bandwidth;

/* Compute the amount of in-band transmitter power. */
in_band_tx_power = tx_power * (band_max - band_min) / tx_bandwidth;
in_band_tx_power_db = 10*log10(in_band_tx_power);

/* Get antenna gains. */
tx_ant_gain = pow (10.0, op_td_get_dbl (pkptr, OPC_TDA_RA_TX_GAIN) / 10.0);
rx_ant_gain = pow (10.0, op_td_get_dbl (pkptr, OPC_TDA_RA_RX_GAIN) / 10.0);
tx_ant_gain_db =  op_td_get_dbl (pkptr, OPC_TDA_RA_TX_GAIN);
rx_ant_gain_db =  op_td_get_dbl (pkptr, OPC_TDA_RA_RX_GAIN);

printf("tx gain = %f\n",tx_ant_gain_db);
printf("rx_gain = %f\n",rx_ant_gain_db);

/* Calculate received power level (in db). */



if(prop_model == 1) rcvd_power = pow(10.0, ((in_band_tx_power_db + tx_ant_gain_db  + rx_ant_gain_db - path_loss_db) / 10.0));

else
          {
          rcvd_power = in_band_tx_power * tx_ant_gain * path_loss * rx_ant_gain;
          printf("using normal rcvd power \n");
          }


/* The received power is stored in the packet as a decible value*/

rcvd_power_dbm = 10*log10(rcvd_power/.001);

op_td_set_dbl (pkptr, OPC_TDA_RA_RCVD_POWER_DBM, rcvd_power_dbm);

printf("rcvd_power_dbm = %f\n",rcvd_power_dbm);




printf("rcvd_power = %f\n",rcvd_power);

/* Assign the received power level (in Watts) */
/* to the packet transmission data attribute. */
op_td_set_dbl (pkptr, OPC_TDA_RA_RCVD_POWER, rcvd_power);

FOUT
}
```

Modified dra_power pipeline stage for Urban Medium City environment:

```
/* dra_power.ps.c */
/* Default received power model for radio link Transceiver  */
/* Pipeline. This model uses the receiver channel state               */
/* information to check and update the signal lock status   */
/* of the channel. It relies on the rxgroup stage model for */
/* the creation and initialization of the channel state               */
/* information.                                                                                                                     */

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/****************************************/

#include "opnet.h"
#include "dra.h"
#include <math.h>


/***** constants *****/

#define C                                        3.0E+08                    /* speed of light (m/s) */
#define SIXTEEN_PI_SQ                    157.91367           /* 16 times pi-squared */


/***** pipeline procedure *****/

#if defined (__cplusplus)
extern "C"
#endif

void
dra_power_urban_mt (OP_SIM_CONTEXT_ARG_OPT_COMMA Packet * pkptr)
          {
          double                                            prop_distance, rcvd_power, path_loss;
          double                                            tx_power, tx_base_freq, tx_bandwidth, tx_center_freq;
          double                                            lambda, rx_ant_gain, tx_ant_gain;
          Objid                                             rx_ch_obid;
          double                                            in_band_tx_power, band_max, band_min;
          double                                            rx_base_freq, rx_bandwidth;
          DraT_Rxch_State_Info*        rxch_state_ptr;
          double                                            tx_ant_height, rx_ant_height;                                       /* Antenna
heights for TX,RX*/
          double                                            tx_MHz_freq;
                    /* TX freq in Mega Hertz*/
          double                                            km_distance;
                    /* Distance converted to Kilometers*/
          double                                            a_hm;
                              /* Correction factor for mobile antenna*/
          double                                            path_loss_db = 0, in_band_tx_power_db;                    /* decible
value of pathloss and in band transmission power*/
          int                                                         prop_model = 0;
                                        /* determines which pathloss formula to use*/
          double                                            rx_ant_gain_db, rcvd_power_dbm, tx_ant_gain_db;
          /* db values of the ant. gains */

          /** Compute the average power in Watts of the              **/
          /** signal associated with a transmitted packet.  **/
          FIN_MT (dra_power_urban_large_mt (pkptr));

          /* If the incoming packet is 'valid', it may cause the receiver to    */
          /* lock onto it. However, if the receiving node is disabled, then     */
          /* the channel match should be set to noise.                                     */
          if (op_td_get_int (pkptr, OPC_TDA_RA_MATCH_STATUS) == OPC_TDA_RA_MATCH_VALID)
                    {
                    if (op_td_is_set (pkptr, OPC_TDA_RA_ND_FAIL))
                              {
                              /* The receiving node is disabled.  Change        */
                              /* the channel match status to noise.            */
                              op_td_set_int (pkptr, OPC_TDA_RA_MATCH_STATUS, OPC_TDA_RA_MATCH_NOISE);
                              }
                    else
                              {
                              /* The receiving node is enabled.  Get  */
                              /* the address of the receiver channel. */
                              rx_ch_obid = op_td_get_int (pkptr, OPC_TDA_RA_RX_CH_OBJID);

                              /* Access receiver channels state information.             */
                              rxch_state_ptr = (DraT_Rxch_State_Info *) op_ima_obj_state_get (rx_ch_obid);

                              /* If the receiver channel is already locked,              */
                              /* the packet will now be considered to be noise. */
                              /* This prevents simultaneous reception of multiple         */
                              /* valid packets on any given radio channel.               */
                              if (rxch_state_ptr->signal_lock)
                                        op_td_set_int (pkptr, OPC_TDA_RA_MATCH_STATUS, OPC_TDA_RA_MATCH_NOISE);
                              else
                                        {
                                        /* Otherwise, the receiver channel will become     */
                                        /* locked until the packet reception ends.                 */
                                        rxch_state_ptr->signal_lock = OPC_TRUE;
                                        }
                              }
                    }

          /* Get power allotted to transmitter channel. */
          tx_power = op_td_get_dbl (pkptr, OPC_TDA_RA_TX_POWER);
```

```
/* Get transmission frequency in Hz. */
tx_base_freq = op_td_get_dbl (pkptr, OPC_TDA_RA_TX_FREQ);
tx_bandwidth = op_td_get_dbl (pkptr, OPC_TDA_RA_TX_BW);
tx_center_freq = tx_base_freq + (tx_bandwidth / 2.0);

/*Convert the transmit frequency to Mega Hertz*/
tx_MHz_freq = tx_center_freq/1000000;
/*printf("freq = %f\n",tx_MHz_freq);*/

/* Caclculate wavelength (in meters). */
lambda = C / tx_center_freq;
/*printf("lambda = %f\n",lambda);*/

/* Get distance between transmitter and receiver (in meters). */
prop_distance = op_td_get_dbl (pkptr, OPC_TDA_RA_START_DIST);
m_distance = (km_distance * 1000);
/*printf("prop = %f\n",prop_distance);*/


/* Get the height of the transmit and recieve antennas.*/
tx_ant_height = (op_td_get_dbl (pkptr, OPC_TDA_RA_TX_ALT))/1000;
rx_ant_height = (op_td_get_dbl (pkptr, OPC_TDA_RA_RX_ALT))/1000;
printf("tx_height = %f\n",tx_ant_height);
printf("rx_height = %f\n",rx_ant_height);


/* Calculate the distance using the TDA start_dist*/

km_distance = sqrt(pow((prop_distance/1000),2)- pow((tx_ant_height-rx_ant_height),2));
printf("dist_z = %f\n",km_distance);

// Calculate a_hm for Hata and COST-231

a_hm = (1.1*log10(tx_MHz_freq) - 0.7)*rx_ant_height - (1.56*log10(tx_MHz_freq) - 0.8);


/* When using TMM, the TDA OPC_TDA_RA_RCVD_POWER will already         */
/* have a raw value for the path loss. */
if (op_td_is_set (pkptr, OPC_TDA_RA_RCVD_POWER))
          {
          path_loss = op_td_get_dbl (pkptr, OPC_TDA_RA_RCVD_POWER);
          }
else
          {
          /* Compute the path loss for this distance and wavelength. */
          if (prop_distance > 0.0)
                    {
                    /* Determine which propagation model to use and use value in the db form*/

                     if ((tx_MHz_freq >= 150 && tx_MHz_freq <= 2000) && (km_distance >= 1 && km_distance <= 100)
                              && (tx_ant_height >= 30 && tx_ant_height <= 200) && (rx_ant_height >= 1 && rx_ant_height <= 10))

                              {
                                        if ((tx_MHz_freq >= 150 && tx_MHz_freq <= 1500) && (km_distance >= 1 && km_distance <= 100))
                                                  {
                                                            path_loss_db = 69.55 + 26.16*log10(tx_MHz_freq) - 13.82*log10(tx_ant_height) - a_hm
                                                            + (44.9 - 6.55*log10(tx_ant_height))*log10(km_distance);
                                                            prop_model = 1;
                                                  }
                                        else if ((tx_MHz_freq > 1500 && tx_MHz_freq <= 2000) && (km_distance >= 1 && km_distance <= 20))
                                                  {
                                                            path_loss_db = 46.3 + 33.9*log10(tx_MHz_freq) - 13.82*log10(tx_ant_height) - a_hm
                                                            + (44.9 - 6.55*log10(tx_ant_height))*log10(km_distance);
                                                            prop_model = 1;
                                                  }


                                        else if ((tx_MHz_freq > 1500 && tx_MHz_freq <= 2000) && (km_distance > 20))
                                                            {
                                                                      path_loss = (lambda * lambda) /
                                                                      (SIXTEEN_PI_SQ * m_distance * m_distance);
                                                                      prop_model = 0;
                                                                      printf("Using Free Space PL\n\n",path_loss);
                                                            }

                              printf("Hata/COST_PL = %f\n\n",path_loss_db);
                              }

                    else
                                        {
                                        path_loss = (lambda * lambda) /
                                        (SIXTEEN_PI_SQ * m_distance * m_distance);
                                        prop_model = 0;
                                        printf("Using Free Space PL\n\n",path_loss);
                                        }
          }

else
          {
                    if (prop_model == 1)path_loss_db = 0.0;

                    else path_loss = 1;

          }
}


/* Determine the receiver bandwidth and base frequency. */
rx_base_freq = op_td_get_dbl (pkptr, OPC_TDA_RA_RX_FREQ);
rx_bandwidth = op_td_get_dbl (pkptr, OPC_TDA_RA_RX_BW);

/* Use these values to determine the band overlap with the transmitter.         */
/* Note that if there were no overlap at all, the packet would already          */
/* have been filtered by the channel match stage.                                                  */
```

```
/* The base of the overlap band is the highest base frequency. */
if (rx_base_freq > tx_base_freq)
          band_min = rx_base_freq;
else
          band_min = tx_base_freq;

/* The top of the overlap band is the lowest end frequency. */
if (rx_base_freq + rx_bandwidth > tx_base_freq + tx_bandwidth)
          band_max = tx_base_freq + tx_bandwidth;
else
          band_max = rx_base_freq + rx_bandwidth;

/* Compute the amount of in-band transmitter power. */
in_band_tx_power = tx_power * (band_max - band_min) / tx_bandwidth;
in_band_tx_power_db = 10*log10(in_band_tx_power);

/* Get antenna gains. */
tx_ant_gain = pow (10.0, op_td_get_dbl (pkptr, OPC_TDA_RA_TX_GAIN) / 10.0);
rx_ant_gain = pow (10.0, op_td_get_dbl (pkptr, OPC_TDA_RA_RX_GAIN) / 10.0);
tx_ant_gain_db =  op_td_get_dbl (pkptr, OPC_TDA_RA_TX_GAIN);
rx_ant_gain_db =  op_td_get_dbl (pkptr, OPC_TDA_RA_RX_GAIN);

/* Calculate received power level (in db). */
if(prop_model == 1) rcvd_power = pow(10.0, ((in_band_tx_power_db + tx_ant_gain_db  + rx_ant_gain_db - path_loss_db) / 10.0));

else
          rcvd_power = in_band_tx_power * tx_ant_gain * path_loss * rx_ant_gain;


printf("rcvd_power = %f\n",rcvd_power);

/* The received power is stored in the packet as a decible value*/

rcvd_power_dbm = 10*log10(rcvd_power/.001);

op_td_set_dbl (pkptr, OPC_TDA_RA_RCVD_POWER_DBM, rcvd_power_dbm);

printf("rcvd_power_dbm = %f\n",rcvd_power_dbm);


/* Assign the received power level (in Watts) */
/* to the packet transmission data attribute. */
op_td_set_dbl (pkptr, OPC_TDA_RA_RCVD_POWER, rcvd_power);

FOUT
}
```

Modified dra_power pipeline stage for Suburban environment:

```
/* dra_power.ps.c */
/* Default received power model for radio link Transceiver  */
/* Pipeline. This model uses the receiver channel state                */
/* information to check and update the signal lock status   */
/* of the channel. It relies on the rxgroup stage model for */
/* the creation and initialization of the channel state                */
/* information.                                                                                              */

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/***************************************/

#include "opnet.h"
#include "dra.h"
#include <math.h>


/***** constants *****/

#define C                                         3.0E+08                     /* speed of light (m/s) */
#define SIXTEEN_PI_SQ                    157.91367          /* 16 times pi-squared */


/***** pipeline procedure *****/

#if defined (__cplusplus)
extern "C"
#endif

void
dra_power_suburban_mt (OP_SIM_CONTEXT_ARG_OPT_COMMA Packet * pkptr)
          {
          double                                            prop_distance, rcvd_power, path_loss;
          double                                            tx_power, tx_base_freq, tx_bandwidth, tx_center_freq;
          double                                            lambda, rx_ant_gain, tx_ant_gain;
          Objid                                             rx_ch_obid;
          double                                            in_band_tx_power, band_max, band_min;
          double                                            rx_base_freq, rx_bandwidth;
          DraT_Rxch_State_Info*         rxch_state_ptr;
          double                                            tx_ant_height, rx_ant_height;                                           /* Antenna
heights for TX,RX*/
          double                                            tx_MHz_freq;
                    /* TX freq in Mega Hertz*/
          double                                            km_distance;
                    /* Distance converted to Kilometers*/
          double                                            a_hm;
                              /* Correction factor for mobile antenna*/
          double                                            path_loss_db = 0, in_band_tx_power_db;                                  /* decible
value of pathloss and in band transmission power*/
          int                                                         prop_model = 0;
                                        /* determines which pathloss formula to use*/
          double                                            rx_ant_gain_db, rcvd_power_dbm, tx_ant_gain_db;
          /* db values of the ant. gains */

          /** Compute the average power in Watts of the              **/
          /** signal associated with a transmitted packet.  **/
          FIN_MT (dra_power_urban_large_mt (pkptr));

          /* If the incoming packet is 'valid', it may cause the receiver to    */
          /* lock onto it. However, if the receiving node is disabled, then     */
          /* the channel match should be set to noise.                              */
          if (op_td_get_int (pkptr, OPC_TDA_RA_MATCH_STATUS) == OPC_TDA_RA_MATCH_VALID)
                    {
                    if (op_td_is_set (pkptr, OPC_TDA_RA_ND_FAIL))
                              {
                              /* The receiving node is disabled.  Change        */
                              /* the channel match status to noise.             */
                              op_td_set_int (pkptr, OPC_TDA_RA_MATCH_STATUS, OPC_TDA_RA_MATCH_NOISE);
                              }
                    else
                              {
                              /* The receiving node is enabled.  Get  */
                              /* the address of the receiver channel. */
                              rx_ch_obid = op_td_get_int (pkptr, OPC_TDA_RA_RX_CH_OBJID);

                              /* Access receiver channels state information.             */
                              rxch_state_ptr = (DraT_Rxch_State_Info *) op_ima_obj_state_get (rx_ch_obid);

                              /* If the receiver channel is already locked,              */
                              /* the packet will now be considered to be noise. */
                              /* This prevents simultaneous reception of multiple         */
                              /* valid packets on any given radio channel.               */
                              if (rxch_state_ptr->signal_lock)
                                        op_td_set_int (pkptr, OPC_TDA_RA_MATCH_STATUS, OPC_TDA_RA_MATCH_NOISE);
                              else
                                        {
                                        /* Otherwise, the receiver channel will become     */
                                        /* locked until the packet reception ends.                  */
                                        rxch_state_ptr->signal_lock = OPC_TRUE;
                                        }
                              }
                    }

          /* Get power allotted to transmitter channel. */
          tx_power = op_td_get_dbl (pkptr, OPC_TDA_RA_TX_POWER);
```

```
/* Get transmission frequency in Hz. */
tx_base_freq = op_td_get_dbl (pkptr, OPC_TDA_RA_TX_FREQ);
tx_bandwidth = op_td_get_dbl (pkptr, OPC_TDA_RA_TX_BW);
tx_center_freq = tx_base_freq + (tx_bandwidth / 2.0);

/*Convert the transmit frequency to Mega Hertz*/
tx_MHz_freq = tx_center_freq/1000000;
/*printf("freq = %f\n",tx_MHz_freq);*/

/* Caclculate wavelength (in meters). */
lambda = C / tx_center_freq;
/*printf("lambda = %f\n",lambda);*/

/* Get distance between transmitter and receiver (in meters). */
prop_distance = op_td_get_dbl (pkptr, OPC_TDA_RA_START_DIST);
/*printf("prop = %f\n",prop_distance);*/

/* Get the height of the transmit and recieve antennas.*/
tx_ant_height = (op_td_get_dbl (pkptr, OPC_TDA_RA_TX_ALT))/1000;
rx_ant_height = (op_td_get_dbl (pkptr, OPC_TDA_RA_RX_ALT))/1000;
printf("tx_height = %f\n",tx_ant_height);
printf("rx_height = %f\n",rx_ant_height);


/* Calculate the distance using the TDA sart_dist*/

km_distance = sqrt(pow((prop_distance/1000),2)- pow((tx_ant_height-rx_ant_height),2));
m_distance = (km_distance * 1000);
printf("dist_z = %f\n",km_distance);


// Calculate a_hm for Hata and COST-231

a_hm = (1.1*log10(tx_MHz_freq) - 0.7)*rx_ant_height - (1.56*log10(tx_MHz_freq) - 0.8);



/* When using TMM, the TDA OPC_TDA_RA_RCVD_POWER will already         */
/* have a raw value for the path loss. */
if (op_td_is_set (pkptr, OPC_TDA_RA_RCVD_POWER))
          {
          path_loss = op_td_get_dbl (pkptr, OPC_TDA_RA_RCVD_POWER);
          }
else
          {
          /* Compute the path loss for this distance and wavelength. */
          if (prop_distance > 0.0)
                    {
          /* Determine which propagation model to use and use value in the db form*/

           if ((tx_MHz_freq >= 150 && tx_MHz_freq <= 2000) && (km_distance >= 1 && km_distance <= 100)
                    && (tx_ant_height >= 30 && tx_ant_height <= 200) && (rx_ant_height >= 1 && rx_ant_height <= 10))

                    {
                              if ((tx_MHz_freq >= 150 && tx_MHz_freq <= 1500) && (km_distance >= 1 && km_distance <= 100))
                                        {
                                                  path_loss_db = 69.55 + 26.16*log10(tx_MHz_freq) - 13.82*log10(tx_ant_height) - a_hm
                                                  + (44.9 - 6.55*log10(tx_ant_height))*log10(km_distance) - 2*pow(log10(tx_MHz_freq/28),2) -
5.4;
                                                            prop_model = 1;
                                        }
                              else if ((tx_MHz_freq > 1500 && tx_MHz_freq <= 2000) && (km_distance >= 1 && km_distance <= 20))
                                        {
                                                  path_loss_db = 46.3 + 33.9*log10(tx_MHz_freq) - 13.82*log10(tx_ant_height) - a_hm
                                                  + (44.9 - 6.55*log10(tx_ant_height))*log10(km_distance);
                                                  prop_model = 1;
                                        }

                              else if ((tx_MHz_freq > 1500 && tx_MHz_freq <= 2000) && (km_distance > 20))
                                        {
                                                  path_loss = (lambda * lambda) /
                                                  (SIXTEEN_PI_SQ * m_distance * m_distance);
                                                  prop_model = 0;
                                                  printf("Using Free Space PL\n\n",path_loss);
                                        }

                                                  printf("Hata/COST_PL = %f\n\n",path_loss_db);
                    }

          else
                    {
                              path_loss = (lambda * lambda) /
                              (SIXTEEN_PI_SQ * m_distance * m_distance);
                              prop_model = 0;
                              printf("Using Free Space PL\n\n",path_loss);
                    }
          }

else
          {
                    if (prop_model == 1)path_loss_db = 0.0;

                    else path_loss = 1;

          }
}


/* Determine the receiver bandwidth and base frequency. */
rx_base_freq = op_td_get_dbl (pkptr, OPC_TDA_RA_RX_FREQ);
rx_bandwidth = op_td_get_dbl (pkptr, OPC_TDA_RA_RX_BW);

/* Use these values to determine the band overlap with the transmitter.        */
/* Note that if there were no overlap at all, the packet would already         */
```

```
/* have been filtered by the channel match stage.                                                     */

/* The base of the overlap band is the highest base frequency. */
if (rx_base_freq > tx_base_freq)
          band_min = rx_base_freq;
else
          band_min = tx_base_freq;

/* The top of the overlap band is the lowest end frequency. */
if (rx_base_freq + rx_bandwidth > tx_base_freq + tx_bandwidth)
          band_max = tx_base_freq + tx_bandwidth;
else
          band_max = rx_base_freq + rx_bandwidth;

/* Compute the amount of in-band transmitter power. */
in_band_tx_power = tx_power * (band_max - band_min) / tx_bandwidth;
in_band_tx_power_db = 10*log10(in_band_tx_power);

/* Get antenna gains. */
tx_ant_gain = pow (10.0, op_td_get_dbl (pkptr, OPC_TDA_RA_TX_GAIN) / 10.0);
rx_ant_gain = pow (10.0, op_td_get_dbl (pkptr, OPC_TDA_RA_RX_GAIN) / 10.0);
tx_ant_gain_db =  op_td_get_dbl (pkptr, OPC_TDA_RA_TX_GAIN);
rx_ant_gain_db =  op_td_get_dbl (pkptr, OPC_TDA_RA_RX_GAIN);

/* Calculate received power level (in db). */
if(prop_model == 1) rcvd_power = pow(10.0, ((in_band_tx_power_db + tx_ant_gain_db  + rx_ant_gain_db - path_loss_db) / 10.0));

else
          rcvd_power = in_band_tx_power * tx_ant_gain * path_loss * rx_ant_gain;


printf("rcvd_power = %f\n",rcvd_power);

/* The received power is stored in the packet as a decible value*/

rcvd_power_dbm = 10*log10(rcvd_power/.001);

op_td_set_dbl (pkptr, OPC_TDA_RA_RCVD_POWER_DBM, rcvd_power_dbm);

printf("rcvd_power_dbm = %f\n",rcvd_power_dbm);



/* Assign the received power level (in Watts) */
/* to the packet transmission data attribute. */
op_td_set_dbl (pkptr, OPC_TDA_RA_RCVD_POWER, rcvd_power);

FOUT
}
```

Modified dra_power pipeline stage for Rural environment:

```
/* dra_power.ps.c */
/* Default received power model for radio link Transceiver  */
/* Pipeline. This model uses the receiver channel state              */
/* information to check and update the signal lock status   */
/* of the channel. It relies on the rxgroup stage model for */
/* the creation and initialization of the channel state              */
/* information.                                                                                                                           */

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/****************************************/

#include "opnet.h"
#include "dra.h"
#include <math.h>


/***** constants *****/

#define C                                          3.0E+08                     /* speed of light (m/s) */
#define SIXTEEN_PI_SQ                    157.91367           /* 16 times pi-squared */


/***** pipeline procedure *****/

#if defined (__cplusplus)
extern "C"
#endif

void
dra_power_rural_mt (OP_SIM_CONTEXT_ARG_OPT_COMMA Packet * pkptr)
          {
          double                                            prop_distance, rcvd_power, path_loss;
          double                                            tx_power, tx_base_freq, tx_bandwidth, tx_center_freq;
          double                                            lambda, rx_ant_gain, tx_ant_gain;
          Objid                                             rx_ch_obid;
          double                                            in_band_tx_power, band_max, band_min;
          double                                            rx_base_freq, rx_bandwidth;
          DraT_Rxch_State_Info*         rxch_state_ptr;
          double                                            tx_ant_height, rx_ant_height;                                                  /* Antenna
heights for TX,RX*/
          double                                            tx_MHz_freq;
                    /* TX freq in Mega Hertz*/
          double                                            km_distance;
                    /* Distance converted to Kilometers*/
          double                                            a_hm;
                              /* Correction factor for mobile antenna*/
          double                                            path_loss_db = 0, in_band_tx_power_db;                                 /* decible value of
pathloss and in band transmission power*/
          int                                                         prop_model = 0;
                              /* determines which pathloss formula to use*/
          double                                            rx_ant_gain_db, rcvd_power_dbm, tx_ant_gain_db;            /* db values of the ant. gains */

          /** Compute the average power in Watts of the              **/
          /** signal associated with a transmitted packet.  **/
          FIN_MT (dra_power_urban_large_mt (pkptr));

          /* If the incoming packet is 'valid', it may cause the receiver to    */
          /* lock onto it. However, if the receiving node is disabled, then     */
          /* the channel match should be set to noise.                                              */
          if (op_td_get_int (pkptr, OPC_TDA_RA_MATCH_STATUS) == OPC_TDA_RA_MATCH_VALID)
                    {
                    if (op_td_is_set (pkptr, OPC_TDA_RA_ND_FAIL))
                              {
                              /* The receiving node is disabled.  Change        */
                              /* the channel match status to noise.             */
                              op_td_set_int (pkptr, OPC_TDA_RA_MATCH_STATUS, OPC_TDA_RA_MATCH_NOISE);
                              }
                    else
                              {
                              /* The receiving node is enabled.  Get  */
                              /* the address of the receiver channel. */
                              rx_ch_obid = op_td_get_int (pkptr, OPC_TDA_RA_RX_CH_OBJID);

                              /* Access receiver channels state information.            */
                              rxch_state_ptr = (DraT_Rxch_State_Info *) op_ima_obj_state_get (rx_ch_obid);

                              /* If the receiver channel is already locked,             */
                              /* the packet will now be considered to be noise. */
                              /* This prevents simultaneous reception of multiple         */
                              /* valid packets on any given radio channel.              */
                              if (rxch_state_ptr->signal_lock)
                                        op_td_set_int (pkptr, OPC_TDA_RA_MATCH_STATUS, OPC_TDA_RA_MATCH_NOISE);
                              else
                                        {
                                        /* Otherwise, the receiver channel will become    */
                                        /* locked until the packet reception ends.                  */
                                        rxch_state_ptr->signal_lock = OPC_TRUE;
                                        }
                              }
                    }

          /* Get power allotted to transmitter channel. */
          tx_power = op_td_get_dbl (pkptr, OPC_TDA_RA_TX_POWER);
```

```
/* Get transmission frequency in Hz. */
tx_base_freq = op_td_get_dbl (pkptr, OPC_TDA_RA_TX_FREQ);
tx_bandwidth = op_td_get_dbl (pkptr, OPC_TDA_RA_TX_BW);
tx_center_freq = tx_base_freq + (tx_bandwidth / 2.0);

/*Convert the transmit frequency to Mega Hertz*/
tx_MHz_freq = tx_center_freq/1000000;
/*printf("freq = %f\n",tx_MHz_freq);*/

/* Caclculate wavelength (in meters). */
lambda = C / tx_center_freq;
/*printf("lambda = %f\n",lambda);*/

/* Get distance between transmitter and receiver (in meters). */
prop_distance = op_td_get_dbl (pkptr, OPC_TDA_RA_START_DIST);
m_distance = (km_distance * 1000);
/*printf("prop = %f\n",prop_distance);*/


/* Get the height of the transmit and recieve antennas.*/
tx_ant_height = (op_td_get_dbl (pkptr, OPC_TDA_RA_TX_ALT))/1000;
rx_ant_height = (op_td_get_dbl (pkptr, OPC_TDA_RA_RX_ALT))/1000;
printf("tx_height = %f\n",tx_ant_height);
printf("rx_height = %f\n",rx_ant_height);

/* Calculate the distance using the TDA sart_dist*/

km_distance = sqrt(pow((prop_distance/1000),2)- pow((tx_ant_height-rx_ant_height),2));
printf("dist_z = %f\n",km_distance);


/* When using TMM, the TDA OPC_TDA_RA_RCVD_POWER will already         */
/* have a raw value for the pathloss. */
if (op_td_is_set (pkptr, OPC_TDA_RA_RCVD_POWER))
          {
          path_loss = op_td_get_dbl (pkptr, OPC_TDA_RA_RCVD_POWER);
          }
else
          {
          /* Compute the pathloss for this distance and wavelength. */
          if (prop_distance > 0.0)
                    {
          /* Determine which propagation model to use and use value in the db form*/

                    if ((tx_MHz_freq >= 150 && tx_MHz_freq <= 1500) && (km_distance >= 1 && km_distance <= 100)
                              && (tx_ant_height >= 30 && tx_ant_height <= 200) && (rx_ant_height >= 1 && rx_ant_height <= 10))
                    {

                              a_hm = (1.1*log10(tx_MHz_freq) - 0.7)*rx_ant_height - (1.56*log10(tx_MHz_freq) - 0.8);

                              path_loss_db = 69.55 + 26.16*log10(tx_MHz_freq) - 13.82*log10(tx_ant_height) - a_hm
                              + (44.9 - 6.55*log10(tx_ant_height))*log10(km_distance) - (4.78*pow(log10(tx_MHz_freq),2) +
                                        18.33*log10(tx_MHz_freq) - 40.94);

                              prop_model = 1;
                              printf("HataPL = %f\n",path_loss_db);
                    }
                    else

                    {
                              path_loss = (lambda * lambda) /
                              (SIXTEEN_PI_SQ * m_distance * m_distance);
                              prop_model = 0;
                              printf("path_loss = %f\n",path_loss);
                    }


                    }
          else
                    {
                              if (prop_model == 1)path_loss_db = 0.0;

                              else
                                        path_loss = 1;
                    }
          }


/* Determine the receiver bandwidth and base frequency. */
rx_base_freq = op_td_get_dbl (pkptr, OPC_TDA_RA_RX_FREQ);
rx_bandwidth = op_td_get_dbl (pkptr, OPC_TDA_RA_RX_BW);

/* Use these values to determine the band overlap with the transmitter.         */
/* Note that if there were no overlap at all, the packet would already          */
/* have been filtered by the channel match stage.                                                   */

/* The base of the overlap band is the highest base frequency. */
if (rx_base_freq > tx_base_freq)
          band_min = rx_base_freq;
else
          band_min = tx_base_freq;

/* The top of the overlap band is the lowest end frequency. */
if (rx_base_freq + rx_bandwidth > tx_base_freq + tx_bandwidth)
          band_max = tx_base_freq + tx_bandwidth;
else
          band_max = rx_base_freq + rx_bandwidth;

/* Compute the amount of in-band transmitter power. */
in_band_tx_power = tx_power * (band_max - band_min) / tx_bandwidth;
in_band_tx_power_db = 10*log10(in_band_tx_power);

/* Get antenna gains. */
tx_ant_gain = pow (10.0, op_td_get_dbl (pkptr, OPC_TDA_RA_TX_GAIN) / 10.0);
rx_ant_gain = pow (10.0, op_td_get_dbl (pkptr, OPC_TDA_RA_RX_GAIN) / 10.0);
```

```
tx_ant_gain_db =  op_td_get_dbl (pkptr, OPC_TDA_RA_TX_GAIN);
rx_ant_gain_db =  op_td_get_dbl (pkptr, OPC_TDA_RA_RX_GAIN);

/* Calculate received power level (in db). */
if(prop_model == 1) rcvd_power = pow(10.0, ((in_band_tx_power_db + tx_ant_gain_db  + rx_ant_gain_db - path_loss_db) / 10.0));

else
          rcvd_power = in_band_tx_power * tx_ant_gain * path_loss * rx_ant_gain;


printf("rcvd_power = %f\n",rcvd_power);

/* The received power is stored in the packet as a decible value*/

rcvd_power_dbm = 10*log10(rcvd_power/.001);

op_td_set_dbl (pkptr, OPC_TDA_RA_RCVD_POWER_DBM, rcvd_power_dbm);

printf("rcvd_power_dbm = %f\n",rcvd_power_dbm);


/* Assign the received power level (in Watts) */
/* to the packet transmission data attribute. */
op_td_set_dbl (pkptr, OPC_TDA_RA_RCVD_POWER, rcvd_power);

FOUT
}
```

Modified dra_power pipeline stage for dB collection:

```
/* dra_power_db.ps.c */
/* Default received power model for radio link Transceiver  */
/* Pipeline. This model uses the receiver channel state             */
/* information to check and update the signal lock status   */
/* of the channel. It relies on the rxgroup stage model for */
/* the creation and initialization of the channel state             */
/* information.                                                                                                                  */

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/***************************************/

#include "opnet.h"
#include "dra.h"
#include <math.h>


/***** constants *****/

#define C                                          3.0E+08                    /* speed of light (m/s) */
#define SIXTEEN_PI_SQ                    157.91367          /* 16 times pi-squared */


/***** pipeline procedure *****/

#if defined (__cplusplus)
extern "C"
#endif

void
dra_power_db_mt (OP_SIM_CONTEXT_ARG_OPT_COMMA Packet * pkptr)
          {
          double                                                 prop_distance, rcvd_power, path_loss;
          double                                                 tx_power, tx_base_freq, tx_bandwidth, tx_center_freq;
          double                                                 lambda, rx_ant_gain, tx_ant_gain;
          Objid                                                  rx_ch_obid;
          double                                                 in_band_tx_power, band_max, band_min;
          double                                                 rx_base_freq, rx_bandwidth;
          DraT_Rxch_State_Info*         rxch_state_ptr;
          double                                                 rcvd_power_dbm;                                                              /*
Correction factor for mobile antenna*/

          /** Compute the average power in Watts of the             **/
          /** signal associated with a transmitted packet.  **/
          FIN_MT (dra_power (pkptr));

          /* If the incoming packet is 'valid', it may cause the receiver to    */
          /* lock onto it. However, if the receiving node is disabled, then     */
          /* the channel match should be set to noise.                                    */
          if (op_td_get_int (pkptr, OPC_TDA_RA_MATCH_STATUS) == OPC_TDA_RA_MATCH_VALID)
                    {
                    if (op_td_is_set (pkptr, OPC_TDA_RA_ND_FAIL))
                              {
                              /* The receiving node is disabled.  Change        */
                              /* the channel match status to noise.             */
                              op_td_set_int (pkptr, OPC_TDA_RA_MATCH_STATUS, OPC_TDA_RA_MATCH_NOISE);
                              }
                    else
                              {
                              /* The receiving node is enabled.  Get  */
                              /* the address of the receiver channel. */
                              rx_ch_obid = op_td_get_int (pkptr, OPC_TDA_RA_RX_CH_OBJID);

                              /* Access receiver channels state information.             */
                              rxch_state_ptr = (DraT_Rxch_State_Info *) op_ima_obj_state_get (rx_ch_obid);

                              /* If the receiver channel is already locked,              */
                              /* the packet will now be considered to be noise. */
                              /* This prevents simultaneous reception of multiple        */
                              /* valid packets on any given radio channel.               */
                              if (rxch_state_ptr->signal_lock)
                                        op_td_set_int (pkptr, OPC_TDA_RA_MATCH_STATUS, OPC_TDA_RA_MATCH_NOISE);
                              else
                                        {
                                        /* Otherwise, the receiver channel will become     */
                                        /* locked until the packet reception ends.                 */
                                        rxch_state_ptr->signal_lock = OPC_TRUE;
                                        }
                              }
                    }

          /* Get power allotted to transmitter channel. */
          tx_power = op_td_get_dbl (pkptr, OPC_TDA_RA_TX_POWER);

          /* Get transmission frequency in Hz. */
          tx_base_freq = op_td_get_dbl (pkptr, OPC_TDA_RA_TX_FREQ);
          tx_bandwidth = op_td_get_dbl (pkptr, OPC_TDA_RA_TX_BW);
          tx_center_freq = tx_base_freq + (tx_bandwidth / 2.0);

          /* Caclculate wavelength (in meters). */
          lambda = C / tx_center_freq;

          /* Get distance between transmitter and receiver (in meters). */
          prop_distance = op_td_get_dbl (pkptr, OPC_TDA_RA_START_DIST);
          m_distance = (km_distance * 1000);
```
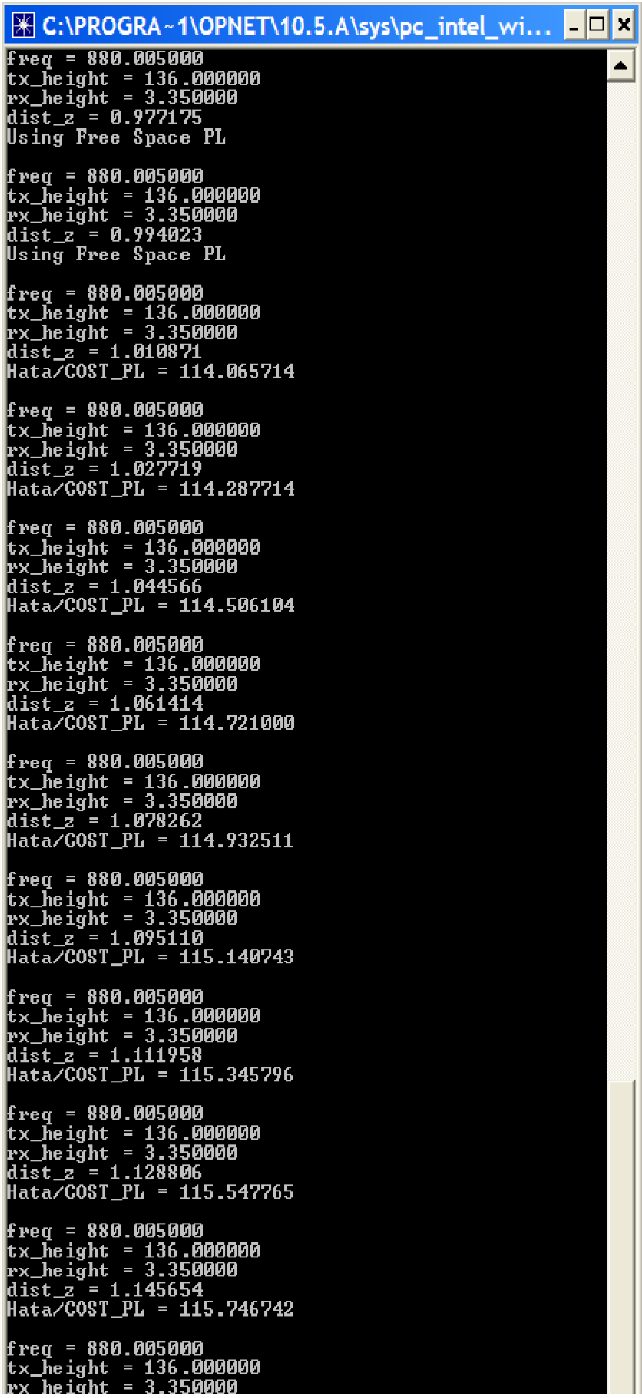
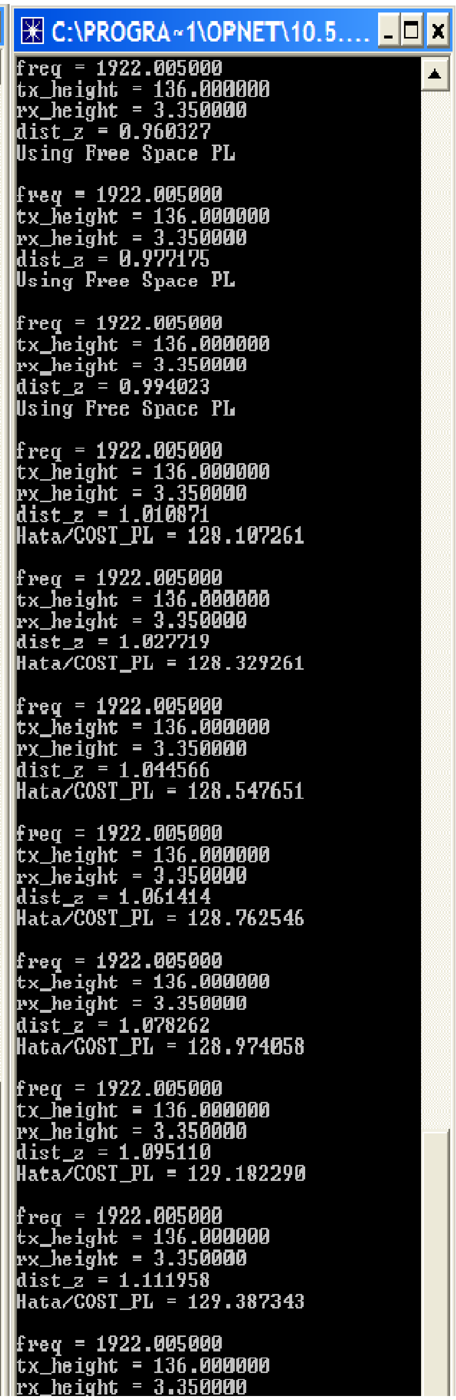

```
/* When using TMM, the TDA OPC_TDA_RA_RCVD_POWER will already         */
/* have a raw value for the pathloss. */
if (op_td_is_set (pkptr, OPC_TDA_RA_RCVD_POWER))
          {
          path_loss = op_td_get_dbl (pkptr, OPC_TDA_RA_RCVD_POWER);
          }
else
          {
          /* Compute the pathloss for this distance and wavelength. */
          if (prop_distance > 0.0)
                    {
                    path_loss = (lambda * lambda) /
                              (SIXTEEN_PI_SQ * m_distance * m_distance);
                    }
          else
                    path_loss = 1.0;
          }

/* Determine the receiver bandwidth and base frequency. */
rx_base_freq = op_td_get_dbl (pkptr, OPC_TDA_RA_RX_FREQ);
rx_bandwidth = op_td_get_dbl (pkptr, OPC_TDA_RA_RX_BW);

/* Use these values to determine the band overlap with the transmitter.         */
/* Note that if there were no overlap at all, the packet would already          */
/* have been filtered by the channel match stage.                                                    */

/* The base of the overlap band is the highest base frequency. */
if (rx_base_freq > tx_base_freq)
          band_min = rx_base_freq;
else
          band_min = tx_base_freq;

/* The top of the overlap band is the lowest end frequency. */
if (rx_base_freq + rx_bandwidth > tx_base_freq + tx_bandwidth)
          band_max = tx_base_freq + tx_bandwidth;
else
          band_max = rx_base_freq + rx_bandwidth;

/* Compute the amount of in-band transmitter power. */
in_band_tx_power = tx_power * (band_max - band_min) / tx_bandwidth;

/* Get antenna gains (raw form, not in dB). */
tx_ant_gain = pow (10.0, op_td_get_dbl (pkptr, OPC_TDA_RA_TX_GAIN) / 10.0);
rx_ant_gain = pow (10.0, op_td_get_dbl (pkptr, OPC_TDA_RA_RX_GAIN) / 10.0);

/* Calculate received power level. */
rcvd_power = in_band_tx_power * tx_ant_gain * path_loss * rx_ant_gain;


/* The received power is stored in the packet as a decible value*/

rcvd_power_dbm = 10*log10(rcvd_power/.001);

op_td_set_dbl (pkptr, OPC_TDA_RA_RCVD_POWER_DBM, rcvd_power_dbm);


/* Assign the received power level (in Watts) */
/* to the packet transmission data attribute. */
op_td_set_dbl (pkptr, OPC_TDA_RA_RCVD_POWER, rcvd_power);

FOUT
}
```

Appendix B: OPNET Debugger Output

Urban Large City output using the Hata and COST-231 model:

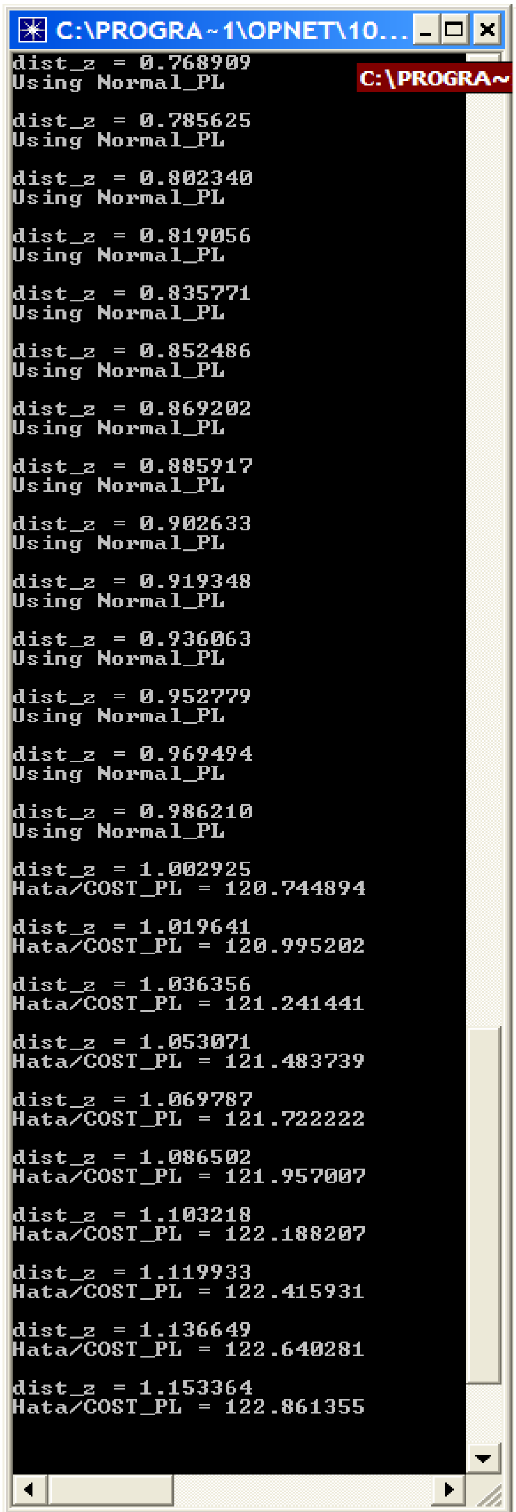

C:\PROGRA~1\OPNET\10.5.A\sys\pc_intel_wi...

```
freq = 880.005000
tx_height = 136.000000
rx_height = 3.350000
dist_z = 0.977175
Using Free Space PL

freq = 880.005000
tx_height = 136.000000
rx_height = 3.350000
dist_z = 0.994023
Using Free Space PL

freq = 880.005000
tx_height = 136.000000
rx_height = 3.350000
dist_z = 1.010871
Hata/COST_PL = 114.065714

freq = 880.005000
tx_height = 136.000000
rx_height = 3.350000
dist_z = 1.027719
Hata/COST_PL = 114.287714

freq = 880.005000
tx_height = 136.000000
rx_height = 3.350000
dist_z = 1.044566
Hata/COST_PL = 114.506104

freq = 880.005000
tx_height = 136.000000
rx_height = 3.350000
dist_z = 1.061414
Hata/COST_PL = 114.721000

freq = 880.005000
tx_height = 136.000000
rx_height = 3.350000
dist_z = 1.078262
Hata/COST_PL = 114.932511

freq = 880.005000
tx_height = 136.000000
rx_height = 3.350000
dist_z = 1.095110
Hata/COST_PL = 115.140743

freq = 880.005000
tx_height = 136.000000
rx_height = 3.350000
dist_z = 1.111958
Hata/COST_PL = 115.345796

freq = 880.005000
tx_height = 136.000000
rx_height = 3.350000
dist_z = 1.128806
Hata/COST_PL = 115.547765

freq = 880.005000
tx_height = 136.000000
rx_height = 3.350000
dist_z = 1.145654
Hata/COST_PL = 115.746742

freq = 880.005000
tx_height = 136.000000
rx_height = 3.350000
```

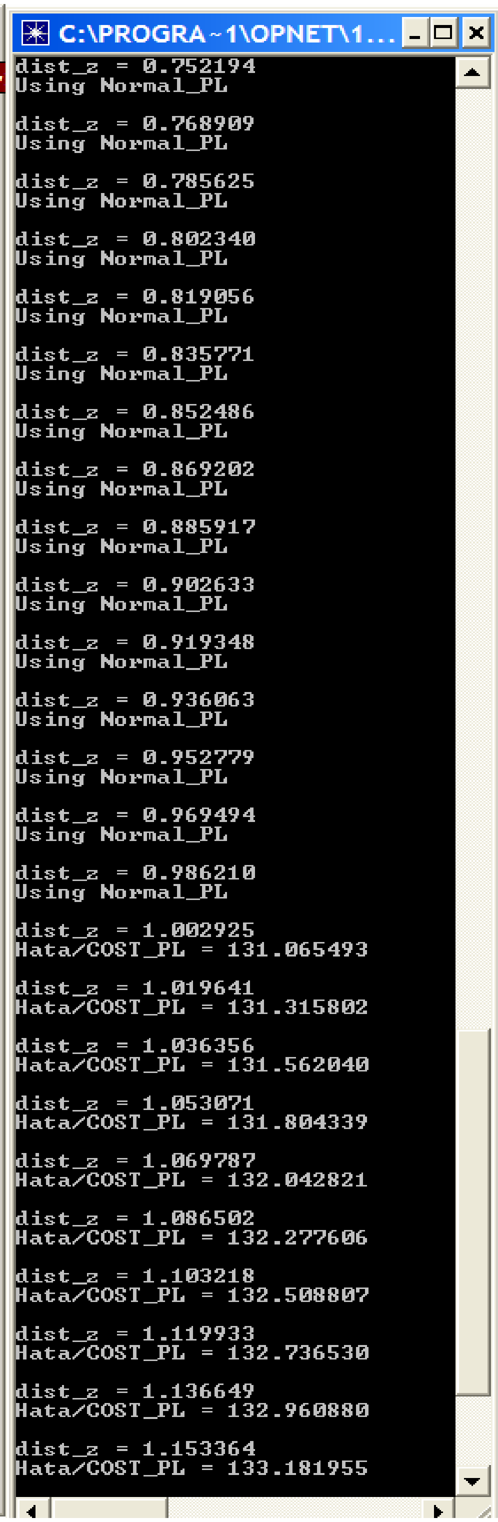

C:\PROGRA~1\OPNET\10.5....

```
freq = 1922.005000
tx_height = 136.000000
rx_height = 3.350000
dist_z = 0.960327
Using Free Space PL

freq = 1922.005000
tx_height = 136.000000
rx_height = 3.350000
dist_z = 0.977175
Using Free Space PL

freq = 1922.005000
tx_height = 136.000000
rx_height = 3.350000
dist_z = 0.994023
Using Free Space PL

freq = 1922.005000
tx_height = 136.000000
rx_height = 3.350000
dist_z = 1.010871
Hata/COST_PL = 128.107261

freq = 1922.005000
tx_height = 136.000000
rx_height = 3.350000
dist_z = 1.027719
Hata/COST_PL = 128.329261

freq = 1922.005000
tx_height = 136.000000
rx_height = 3.350000
dist_z = 1.044566
Hata/COST_PL = 128.547651

freq = 1922.005000
tx_height = 136.000000
rx_height = 3.350000
dist_z = 1.061414
Hata/COST_PL = 128.762546

freq = 1922.005000
tx_height = 136.000000
rx_height = 3.350000
dist_z = 1.078262
Hata/COST_PL = 128.974058

freq = 1922.005000
tx_height = 136.000000
rx_height = 3.350000
dist_z = 1.095110
Hata/COST_PL = 129.182290

freq = 1922.005000
tx_height = 136.000000
rx_height = 3.350000
dist_z = 1.111958
Hata/COST_PL = 129.387343

freq = 1922.005000
tx_height = 136.000000
rx_height = 3.350000
```

Urban Medium City output using the Hata and COST-231 model respectively:

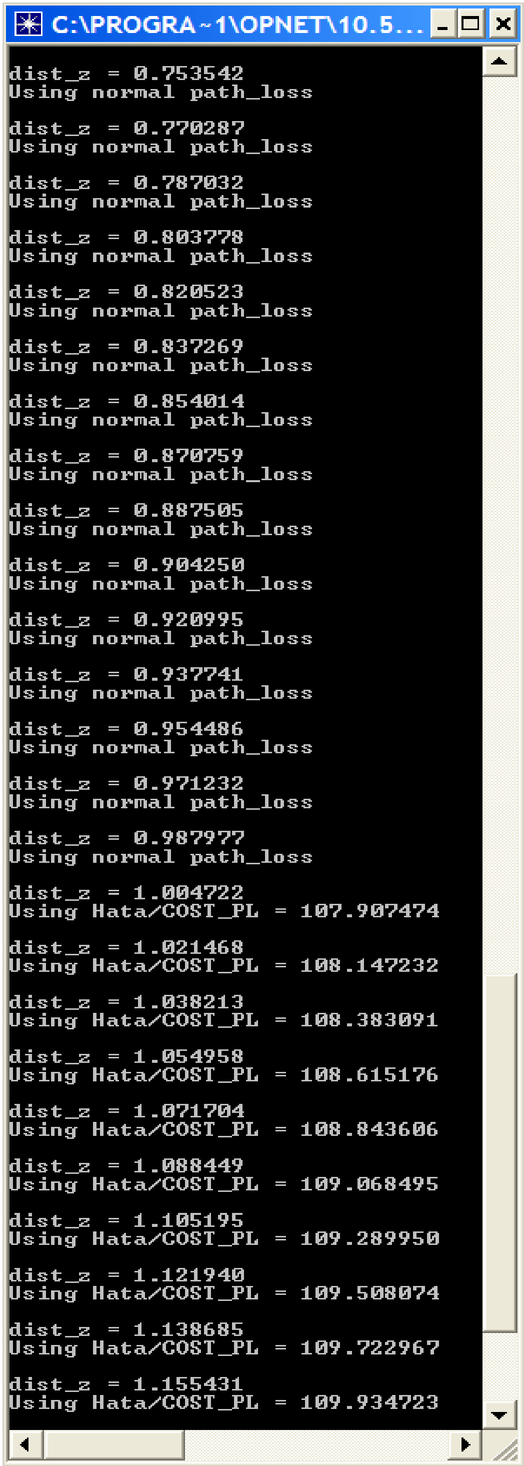


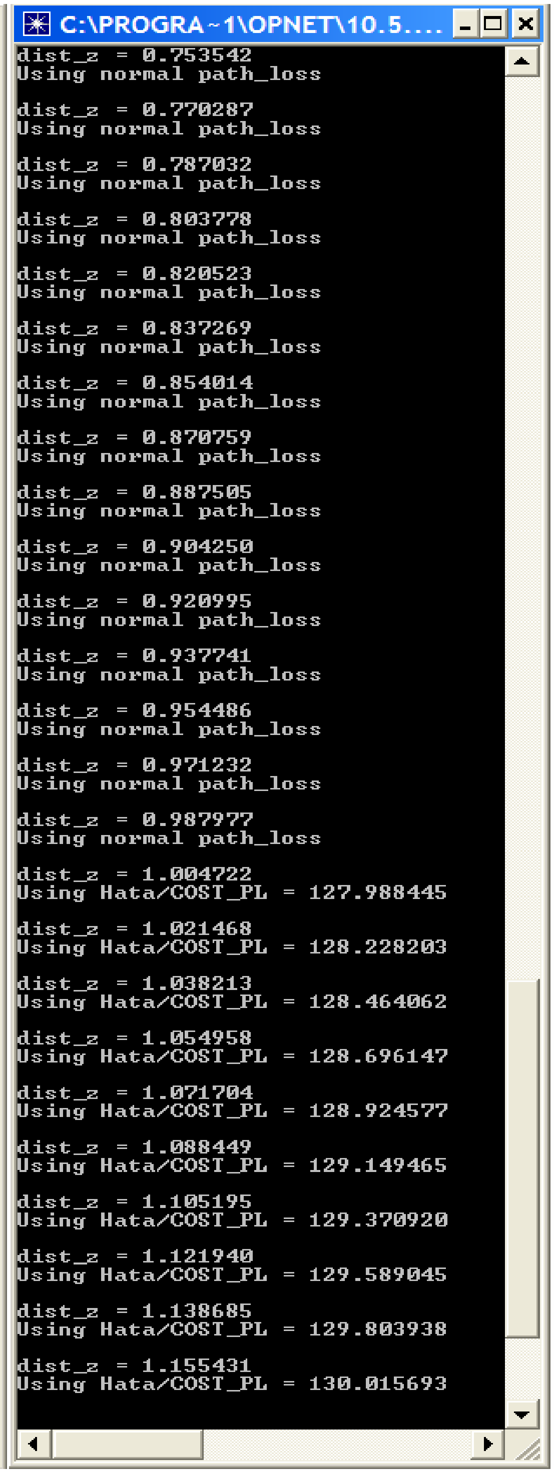
```
C:\PROGRA~1\OPNET\10...
dist_z = 0.768909
Using Normal_PL

dist_z = 0.785625
Using Normal_PL

dist_z = 0.802340
Using Normal_PL

dist_z = 0.819056
Using Normal_PL

dist_z = 0.835771
Using Normal_PL

dist_z = 0.852486
Using Normal_PL

dist_z = 0.869202
Using Normal_PL

dist_z = 0.885917
Using Normal_PL

dist_z = 0.902633
Using Normal_PL

dist_z = 0.919348
Using Normal_PL

dist_z = 0.936063
Using Normal_PL

dist_z = 0.952779
Using Normal_PL

dist_z = 0.969494
Using Normal_PL

dist_z = 0.986210
Using Normal_PL

dist_z = 1.002925
Hata/COST_PL = 120.744894

dist_z = 1.019641
Hata/COST_PL = 120.995202

dist_z = 1.036356
Hata/COST_PL = 121.241441

dist_z = 1.053071
Hata/COST_PL = 121.483739

dist_z = 1.069787
Hata/COST_PL = 121.722222

dist_z = 1.086502
Hata/COST_PL = 121.957007

dist_z = 1.103218
Hata/COST_PL = 122.188207

dist_z = 1.119933
Hata/COST_PL = 122.415931

dist_z = 1.136649
Hata/COST_PL = 122.640281

dist_z = 1.153364
Hata/COST_PL = 122.861355
```



```
C:\PROGRA~1\OPNET\1...
dist_z = 0.752194
Using Normal_PL

dist_z = 0.768909
Using Normal_PL

dist_z = 0.785625
Using Normal_PL

dist_z = 0.802340
Using Normal_PL

dist_z = 0.819056
Using Normal_PL

dist_z = 0.835771
Using Normal_PL

dist_z = 0.852486
Using Normal_PL

dist_z = 0.869202
Using Normal_PL

dist_z = 0.885917
Using Normal_PL

dist_z = 0.902633
Using Normal_PL

dist_z = 0.919348
Using Normal_PL

dist_z = 0.936063
Using Normal_PL

dist_z = 0.952779
Using Normal_PL

dist_z = 0.969494
Using Normal_PL

dist_z = 0.986210
Using Normal_PL

dist_z = 1.002925
Hata/COST_PL = 131.065493

dist_z = 1.019641
Hata/COST_PL = 131.315802

dist_z = 1.036356
Hata/COST_PL = 131.562040

dist_z = 1.053071
Hata/COST_PL = 131.804339

dist_z = 1.069787
Hata/COST_PL = 132.042821

dist_z = 1.086502
Hata/COST_PL = 132.277606

dist_z = 1.103218
Hata/COST_PL = 132.508807

dist_z = 1.119933
Hata/COST_PL = 132.736530

dist_z = 1.136649
Hata/COST_PL = 132.960880

dist_z = 1.153364
Hata/COST_PL = 133.181955
```

Suburban output using the Hata and COST-231 model respectively:





Rural output using the Hata model respectively:

```
C:\PROGRA~1\OPNET\...
dist_z = 0.752370
Using normal path_loss =

dist_z = 0.769089
Using normal path_loss =

dist_z = 0.785808
Using normal path_loss =

dist_z = 0.802528
Using normal path_loss =

dist_z = 0.819247
Using normal path_loss =

dist_z = 0.835966
Using normal path_loss =

dist_z = 0.852686
Using normal path_loss =

dist_z = 0.869405
Using normal path_loss =

dist_z = 0.886124
Using normal path_loss =

dist_z = 0.902844
Using normal path_loss =

dist_z = 0.919563
Using normal path_loss =

dist_z = 0.936282
Using normal path_loss =

dist_z = 0.953002
Using normal path_loss =

dist_z = 0.969721
Using normal path_loss =

dist_z = 0.986440
Using normal path_loss =

dist_z = 1.003160
Hata/COST PL = 91.830444

dist_z = 1.019879
Hata/COST PL = 92.079026

dist_z = 1.036598
Hata/COST PL = 92.323566

dist_z = 1.053318
Hata/COST PL = 92.564193

dist_z = 1.070037
Hata/COST PL = 92.801030

dist_z = 1.086756
Hata/COST PL = 93.034196

dist_z = 1.103476
Hata/COST PL = 93.263801

dist_z = 1.120195
Hata/COST PL = 93.489954

dist_z = 1.136914
Hata/COST PL = 93.712756

dist_z = 1.153634
Hata/COST PL = 93.932306
```

Appendix C: Suburban Simulation Results

Suburban simulation results obtained from OPNET at 880 MHz using the parameters found in Table 4. The data is an average of all values collected from a two second bucket.

time (sec)						Distance (Km)
60	-46.717	-46.717	-46.717	-46.717	-46.717	1.000
62	-46.718	-46.718	-46.718	-46.718	-46.718	1.033
64	-47.193	-47.193	-47.193	-47.193	-47.193	1.067
66	-47.654	-47.654	-47.654	-47.654	-47.654	1.100
68	-48.100	-48.100	-48.100	-48.100	-48.100	1.133
70	-48.533	-48.533	-48.533	-48.533	-48.533	1.167
72	-48.954	-48.954	-48.954	-48.954	-48.954	1.200
74	-49.362	-49.362	-49.362	-49.362	-49.362	1.233
76	-49.760	-49.760	-49.760	-49.760	-49.760	1.267
78	-50.147	-50.147	-50.147	-50.147	-50.147	1.300
80	-50.523	-50.523	-50.523	-50.523	-50.523	1.333
82	-50.891	-50.891	-50.891	-50.891	-50.891	1.367
84	-51.249	-51.249	-51.249	-51.249	-51.249	1.400
86	-51.598	-51.598	-51.598	-51.598	-51.598	1.433
88	-51.940	-51.940	-51.940	-51.940	-51.940	1.467
90	-52.273	-52.273	-52.273	-52.273	-52.273	1.500
92	-52.599	-52.599	-52.599	-52.599	-52.599	1.533
94	-52.918	-52.918	-52.918	-52.918	-52.918	1.567
96	-53.230	-53.230	-53.230	-53.230	-53.230	1.600
98	-53.535	-53.535	-53.535	-53.535	-53.535	1.633
100	-53.834	-53.834	-53.834	-53.834	-53.834	1.667
102	-54.127	-54.127	-54.127	-54.127	-54.127	1.700
104	-54.415	-54.415	-54.415	-54.415	-54.415	1.733
106	-54.696	-54.696	-54.696	-54.696	-54.696	1.767
108	-54.972	-54.972	-54.972	-54.972	-54.972	1.800
110	-55.244	-55.244	-55.244	-55.244	-55.244	1.833
112	-55.510	-55.510	-55.510	-55.510	-55.510	1.867
114	-55.771	-55.771	-55.771	-55.771	-55.771	1.900
116	-56.028	-56.028	-56.028	-56.028	-56.028	1.933
118	-56.280	-56.280	-56.280	-56.280	-56.280	1.967
120	-56.528	-56.528	-56.528	-56.528	-56.528	2.000
122	-56.772	-56.772	-56.772	-56.772	-56.772	2.033
124	-57.012	-57.012	-57.012	-57.012	-57.012	2.067
126	-57.247	-57.247	-57.247	-57.247	-57.247	2.100
128	-57.480	-57.480	-57.480	-57.480	-57.480	2.133
130	-57.708	-57.708	-57.708	-57.708	-57.708	2.167

132	-57.933	-57.933	-57.933	-57.933	-57.933	2.200
134	-58.154	-58.154	-58.154	-58.154	-58.154	2.233
136	-58.372	-58.372	-58.372	-58.372	-58.372	2.267
138	-58.587	-58.587	-58.587	-58.587	-58.587	2.300
140	-58.799	-58.799	-58.799	-58.799	-58.799	2.333
142	-59.008	-59.008	-59.008	-59.008	-59.008	2.367
144	-59.214	-59.214	-59.214	-59.214	-59.214	2.400
146	-59.416	-59.416	-59.416	-59.416	-59.416	2.433
148	-59.617	-59.617	-59.617	-59.617	-59.617	2.467
150	-59.814	-59.814	-59.814	-59.814	-59.814	2.500
152	-60.009	-60.009	-60.009	-60.009	-60.009	2.533
154	-60.201	-60.201	-60.201	-60.201	-60.201	2.567
156	-60.390	-60.390	-60.390	-60.390	-60.390	2.600
158	-60.577	-60.577	-60.577	-60.577	-60.577	2.633
160	-60.762	-60.762	-60.762	-60.762	-60.762	2.667
162	-60.945	-60.945	-60.945	-60.945	-60.945	2.700
164	-61.125	-61.125	-61.125	-61.125	-61.125	2.733
166	-61.303	-61.303	-61.303	-61.303	-61.303	2.767
168	-61.479	-61.479	-61.479	-61.479	-61.479	2.800
170	-61.652	-61.652	-61.652	-61.652	-61.652	2.833
172	-61.824	-61.824	-61.824	-61.824	-61.824	2.867
174	-61.994	-61.994	-61.994	-61.994	-61.994	2.900
176	-62.161	-62.161	-62.161	-62.161	-62.161	2.933
178	-62.327	-62.327	-62.327	-62.327	-62.327	2.967
180	-62.491	-62.491	-62.491	-62.491	-62.491	3.000
182	-62.653	-62.653	-62.653	-62.653	-62.653	3.033
184	-62.813	-62.813	-62.813	-62.813	-62.813	3.067
186	-62.972	-62.972	-62.972	-62.972	-62.972	3.100
188	-63.129	-63.129	-63.129	-63.129	-63.129	3.133
190	-63.284	-63.284	-63.284	-63.284	-63.284	3.167
192	-63.437	-63.437	-63.437	-63.437	-63.437	3.200
194	-63.589	-63.589	-63.589	-63.589	-63.589	3.233
196	-63.740	-63.740	-63.740	-63.740	-63.740	3.267
198	-63.888	-63.888	-63.888	-63.888	-63.888	3.300
200	-64.036	-64.036	-64.036	-64.036	-64.036	3.333
202	-64.181	-64.181	-64.181	-64.181	-64.181	3.367
204	-64.326	-64.326	-64.326	-64.326	-64.326	3.400
206	-64.469	-64.469	-64.469	-64.469	-64.469	3.433
208	-64.610	-64.610	-64.610	-64.610	-64.610	3.467
210	-64.750	-64.750	-64.750	-64.750	-64.750	3.500
212	-64.889	-64.889	-64.889	-64.889	-64.889	3.533
214	-65.027	-65.027	-65.027	-65.027	-65.027	3.567
216	-65.163	-65.163	-65.163	-65.163	-65.163	3.600
218	-65.298	-65.298	-65.298	-65.298	-65.298	3.633
220	-65.431	-65.431	-65.431	-65.431	-65.431	3.667
222	-65.564	-65.564	-65.564	-65.564	-65.564	3.700
224	-65.695	-65.695	-65.695	-65.695	-65.695	3.733
226	-65.825	-65.825	-65.825	-65.825	-65.825	3.767
228	-65.954	-65.954	-65.954	-65.954	-65.954	3.800
230	-66.082	-66.082	-66.082	-66.082	-66.082	3.833

232	-66.209	-66.209	-66.209	-66.209	-66.209	3.867
234	-66.334	-66.334	-66.334	-66.334	-66.334	3.900
236	-66.459	-66.459	-66.459	-66.459	-66.459	3.933
238	-66.582	-66.582	-66.582	-66.582	-66.582	3.967
240	-66.705	-66.705	-66.705	-66.705	-66.705	4.000
242	-66.826	-66.826	-66.826	-66.826	-66.826	4.033
244	-66.946	-66.946	-66.946	-66.946	-66.946	4.067
246	-67.066	-67.066	-67.066	-67.066	-67.066	4.100
248	-67.184	-67.184	-67.184	-67.184	-67.184	4.133
250	-67.302	-67.302	-67.302	-67.302	-67.302	4.167
252	-67.418	-67.418	-67.418	-67.418	-67.418	4.200
254	-67.534	-67.534	-67.534	-67.534	-67.534	4.233
256	-67.648	-67.648	-67.648	-67.648	-67.648	4.267
258	-67.762	-67.762	-67.762	-67.762	-67.762	4.300
260	-67.875	-67.875	-67.875	-67.875	-67.875	4.333
262	-67.987	-67.987	-67.987	-67.987	-67.987	4.367
264	-68.098	-68.098	-68.098	-68.098	-68.098	4.400
266	-68.208	-68.208	-68.208	-68.208	-68.208	4.433
268	-68.318	-68.318	-68.318	-68.318	-68.318	4.467
270	-68.427	-68.427	-68.427	-68.427	-68.427	4.500
272	-68.534	-68.534	-68.534	-68.534	-68.534	4.533
274	-68.641	-68.641	-68.641	-68.641	-68.641	4.567
276	-68.748	-68.748	-68.748	-68.748	-68.748	4.600
278	-68.853	-68.853	-68.853	-68.853	-68.853	4.633
280	-68.958	-68.958	-68.958	-68.958	-68.958	4.667
282	-69.062	-69.062	-69.062	-69.062	-69.062	4.700
284	-69.165	-69.165	-69.165	-69.165	-69.165	4.733
286	-69.268	-69.268	-69.268	-69.268	-69.268	4.767
288	-69.369	-69.369	-69.369	-69.369	-69.369	4.800
290	-69.471	-69.471	-69.471	-69.471	-69.471	4.833
292	-69.571	-69.571	-69.571	-69.571	-69.571	4.867
294	-69.671	-69.671	-69.671	-69.671	-69.671	4.900
296	-69.770	-69.770	-69.770	-69.770	-69.770	4.933
298	-69.868	-69.868	-69.868	-69.868	-69.868	4.967
300	-69.966	-69.966	-69.966	-69.966	-69.966	5.000
302	-70.063	-70.063	-70.063	-70.063	-70.063	5.033
304	-70.159	-70.159	-70.159	-70.159	-70.159	5.067
306	-70.255	-70.255	-70.255	-70.255	-70.255	5.100
308	-70.350	-70.350	-70.350	-70.350	-70.350	5.133
310	-70.444	-70.444	-70.444	-70.444	-70.444	5.167
312	-70.538	-70.538	-70.538	-70.538	-70.538	5.200
314	-70.632	-70.632	-70.632	-70.632	-70.632	5.233
316	-70.724	-70.724	-70.724	-70.724	-70.724	5.267
318	-70.816	-70.816	-70.816	-70.816	-70.816	5.300
320	-70.908	-70.908	-70.908	-70.908	-70.908	5.333
322	-70.999	-70.999	-70.999	-70.999	-70.999	5.367
324	-71.089	-71.089	-71.089	-71.089	-71.089	5.400
326	-71.179	-71.179	-71.179	-71.179	-71.179	5.433
328	-71.268	-71.268	-71.268	-71.268	-71.268	5.467
330	-71.357	-71.357	-71.357	-71.357	-71.357	5.500

332	-71.445	-71.445	-71.445	-71.445	-71.445	5.533
334	-71.533	-71.533	-71.533	-71.533	-71.533	5.567
336	-71.620	-71.620	-71.620	-71.620	-71.620	5.600
338	-71.707	-71.707	-71.707	-71.707	-71.707	5.633
340	-71.793	-71.793	-71.793	-71.793	-71.793	5.667
342	-71.878	-71.878	-71.878	-71.878	-71.878	5.700
344	-71.963	-71.963	-71.963	-71.963	-71.963	5.733
346	-72.048	-72.048	-72.048	-72.048	-72.048	5.767
348	-72.132	-72.132	-72.132	-72.132	-72.132	5.800
350	-72.216	-72.216	-72.216	-72.216	-72.216	5.833
352	-72.299	-72.299	-72.299	-72.299	-72.299	5.867
354	-72.381	-72.381	-72.381	-72.381	-72.381	5.900
356	-72.463	-72.463	-72.463	-72.463	-72.463	5.933
358	-72.545	-72.545	-72.545	-72.545	-72.545	5.967
360	-72.626	-72.626	-72.626	-72.626	-72.626	6.000
362	-72.707	-72.707	-72.707	-72.707	-72.707	6.033
364	-72.788	-72.788	-72.788	-72.788	-72.788	6.067
366	-72.868	-72.868	-72.868	-72.868	-72.868	6.100
368	-72.947	-72.947	-72.947	-72.947	-72.947	6.133
370	-73.026	-73.026	-73.026	-73.026	-73.026	6.167
372	-73.105	-73.105	-73.105	-73.105	-73.105	6.200
374	-73.183	-73.183	-73.183	-73.183	-73.183	6.233
376	-73.261	-73.261	-73.261	-73.261	-73.261	6.267
378	-73.338	-73.338	-73.338	-73.338	-73.338	6.300
380	-73.415	-73.415	-73.415	-73.415	-73.415	6.333
382	-73.492	-73.492	-73.492	-73.492	-73.492	6.367
384	-73.568	-73.568	-73.568	-73.568	-73.568	6.400
386	-73.643	-73.643	-73.643	-73.643	-73.643	6.433
388	-73.719	-73.719	-73.719	-73.719	-73.719	6.467
390	-73.794	-73.794	-73.794	-73.794	-73.794	6.500
392	-73.868	-73.868	-73.868	-73.868	-73.868	6.533
394	-73.942	-73.942	-73.942	-73.942	-73.942	6.567
396	-74.016	-74.016	-74.016	-74.016	-74.016	6.600
398	-74.090	-74.090	-74.090	-74.090	-74.090	6.633
400	-74.163	-74.163	-74.163	-74.163	-74.163	6.667
402	-74.236	-74.236	-74.236	-74.236	-74.236	6.700
404	-74.308	-74.308	-74.308	-74.308	-74.308	6.733
406	-74.380	-74.380	-74.380	-74.380	-74.380	6.767
408	-74.451	-74.451	-74.451	-74.451	-74.451	6.800
410	-74.523	-74.523	-74.523	-74.523	-74.523	6.833
412	-74.594	-74.594	-74.594	-74.594	-74.594	6.867
414	-74.664	-74.664	-74.664	-74.664	-74.664	6.900
416	-74.735	-74.735	-74.735	-74.735	-74.735	6.933
418	-74.804	-74.804	-74.804	-74.804	-74.804	6.967
420	-74.874	-74.874	-74.874	-74.874	-74.874	7.000
422	-74.943	-74.943	-74.943	-74.943	-74.943	7.033
424	-75.012	-75.012	-75.012	-75.012	-75.012	7.067
426	-75.081	-75.081	-75.081	-75.081	-75.081	7.100
428	-75.149	-75.149	-75.149	-75.149	-75.149	7.133
430	-75.217	-75.217	-75.217	-75.217	-75.217	7.167

432	-75.285	-75.285	-75.285	-75.285	-75.285	7.200
434	-75.352	-75.352	-75.352	-75.352	-75.352	7.233
436	-75.419	-75.419	-75.419	-75.419	-75.419	7.267
438	-75.486	-75.486	-75.486	-75.486	-75.486	7.300
440	-75.552	-75.552	-75.552	-75.552	-75.552	7.333
442	-75.618	-75.618	-75.618	-75.618	-75.618	7.367
444	-75.684	-75.684	-75.684	-75.684	-75.684	7.400
446	-75.749	-75.749	-75.749	-75.749	-75.749	7.433
448	-75.814	-75.814	-75.814	-75.814	-75.814	7.467
450	-75.879	-75.879	-75.879	-75.879	-75.879	7.500
452	-75.944	-75.944	-75.944	-75.944	-75.944	7.533
454	-76.008	-76.008	-76.008	-76.008	-76.008	7.567
456	-76.072	-76.072	-76.072	-76.072	-76.072	7.600
458	-76.136	-76.136	-76.136	-76.136	-76.136	7.633
460	-76.200	-76.200	-76.200	-76.200	-76.200	7.667
462	-76.263	-76.263	-76.263	-76.263	-76.263	7.700
464	-76.326	-76.326	-76.326	-76.326	-76.326	7.733
466	-76.388	-76.388	-76.388	-76.388	-76.388	7.767
468	-76.451	-76.451	-76.451	-76.451	-76.451	7.800
470	-76.513	-76.513	-76.513	-76.513	-76.513	7.833
472	-76.575	-76.575	-76.575	-76.575	-76.575	7.867
474	-76.636	-76.636	-76.636	-76.636	-76.636	7.900
476	-76.698	-76.698	-76.698	-76.698	-76.698	7.933
478	-76.759	-76.759	-76.759	-76.759	-76.759	7.967
480	-76.820	-76.820	-76.820	-76.820	-76.820	8.000
482	-76.880	-76.880	-76.880	-76.880	-76.880	8.033
484	-76.940	-76.940	-76.940	-76.940	-76.940	8.067
486	-77.000	-77.000	-77.000	-77.000	-77.000	8.100
488	-77.060	-77.060	-77.060	-77.060	-77.060	8.133
490	-77.120	-77.120	-77.120	-77.120	-77.120	8.167
492	-77.179	-77.179	-77.179	-77.179	-77.179	8.200
494	-77.238	-77.238	-77.238	-77.238	-77.238	8.233
496	-77.297	-77.297	-77.297	-77.297	-77.297	8.267
498	-77.356	-77.356	-77.356	-77.356	-77.356	8.300
500	-77.414	-77.414	-77.414	-77.414	-77.414	8.333
502	-77.472	-77.472	-77.472	-77.472	-77.472	8.367
504	-77.530	-77.530	-77.530	-77.530	-77.530	8.400
506	-77.588	-77.588	-77.588	-77.588	-77.588	8.433
508	-77.645	-77.645	-77.645	-77.645	-77.645	8.467
510	-77.702	-77.702	-77.702	-77.702	-77.702	8.500
512	-77.759	-77.759	-77.759	-77.759	-77.759	8.533
514	-77.816	-77.816	-77.816	-77.816	-77.816	8.567
516	-77.873	-77.873	-77.873	-77.873	-77.873	8.600
518	-77.929	-77.929	-77.929	-77.929	-77.929	8.633
520	-77.985	-77.985	-77.985	-77.985	-77.985	8.667
522	-78.041	-78.041	-78.041	-78.041	-78.041	8.700
524	-78.097	-78.097	-78.097	-78.097	-78.097	8.733
526	-78.152	-78.152	-78.152	-78.152	-78.152	8.767
528	-78.208	-78.208	-78.208	-78.208	-78.208	8.800
530	-78.263	-78.263	-78.263	-78.263	-78.263	8.833

532	-78.317	-78.317	-78.317	-78.317	-78.317	8.867
534	-78.372	-78.372	-78.372	-78.372	-78.372	8.900
536	-78.426	-78.426	-78.426	-78.426	-78.426	8.933
538	-78.481	-78.481	-78.481	-78.481	-78.481	8.967
540	-78.535	-78.535	-78.535	-78.535	-78.535	9.000
542	-78.589	-78.589	-78.589	-78.589	-78.589	9.033
544	-78.642	-78.642	-78.642	-78.642	-78.642	9.067
546	-78.696	-78.696	-78.696	-78.696	-78.696	9.100
548	-78.749	-78.749	-78.749	-78.749	-78.749	9.133
550	-78.802	-78.802	-78.802	-78.802	-78.802	9.167
552	-78.855	-78.855	-78.855	-78.855	-78.855	9.200
554	-78.907	-78.907	-78.907	-78.907	-78.907	9.233
556	-78.960	-78.960	-78.960	-78.960	-78.960	9.267
558	-79.012	-79.012	-79.012	-79.012	-79.012	9.300
560	-79.064	-79.064	-79.064	-79.064	-79.064	9.333
562	-79.116	-79.116	-79.116	-79.116	-79.116	9.367
564	-79.168	-79.168	-79.168	-79.168	-79.168	9.400
566	-79.219	-79.219	-79.219	-79.219	-79.219	9.433
568	-79.271	-79.271	-79.271	-79.271	-79.271	9.467
570	-79.322	-79.322	-79.322	-79.322	-79.322	9.500
572	-79.373	-79.373	-79.373	-79.373	-79.373	9.533
574	-79.424	-79.424	-79.424	-79.424	-79.424	9.567
576	-79.474	-79.474	-79.474	-79.474	-79.474	9.600
578	-79.525	-79.525	-79.525	-79.525	-79.525	9.633
580	-79.575	-79.575	-79.575	-79.575	-79.575	9.667
582	-79.625	-79.625	-79.625	-79.625	-79.625	9.700
584	-79.675	-79.675	-79.675	-79.675	-79.675	9.733
586	-79.725	-79.725	-79.725	-79.725	-79.725	9.767
588	-79.774	-79.774	-79.774	-79.774	-79.774	9.800
590	-79.824	-79.824	-79.824	-79.824	-79.824	9.833
592	-79.873	-79.873	-79.873	-79.873	-79.873	9.867
594	-79.922	-79.922	-79.922	-79.922	-79.922	9.900
596	-79.971	-79.971	-79.971	-79.971	-79.971	9.933
598	-80.020	-80.020	-80.020	-80.020	-80.020	9.967
600	-80.068	-80.068	-80.068	-80.068	-80.068	10.000

Suburban simulation results obtained from OPNET at 1922 MHz using the parameters found in Table 4. The data is an average of all values collected from a two second bucket.

time (sec)						Distance (Km)
60	-66.798	-66.798	-66.798	-66.798	-66.798	1.00
62	-66.799	-66.799	-66.799	-66.799	-66.799	1.03
64	-67.274	-67.274	-67.274	-67.274	-67.274	1.07
66	-67.735	-67.735	-67.735	-67.735	-67.735	1.10
68	-68.181	-68.181	-68.181	-68.181	-68.181	1.13
70	-68.614	-68.614	-68.614	-68.614	-68.614	1.17
72	-69.035	-69.035	-69.035	-69.035	-69.035	1.20
74	-69.443	-69.443	-69.443	-69.443	-69.443	1.23
76	-69.841	-69.841	-69.841	-69.841	-69.841	1.27
78	-70.228	-70.228	-70.228	-70.228	-70.228	1.30
80	-70.604	-70.604	-70.604	-70.604	-70.604	1.33
82	-70.972	-70.972	-70.972	-70.972	-70.972	1.37
84	-71.330	-71.330	-71.330	-71.330	-71.330	1.40
86	-71.679	-71.679	-71.679	-71.679	-71.679	1.43
88	-72.021	-72.021	-72.021	-72.021	-72.021	1.47
90	-72.354	-72.354	-72.354	-72.354	-72.354	1.50
92	-72.680	-72.680	-72.680	-72.680	-72.680	1.53
94	-72.999	-72.999	-72.999	-72.999	-72.999	1.57
96	-73.311	-73.311	-73.311	-73.311	-73.311	1.60
98	-73.616	-73.616	-73.616	-73.616	-73.616	1.63
100	-73.915	-73.915	-73.915	-73.915	-73.915	1.67
102	-74.208	-74.208	-74.208	-74.208	-74.208	1.70
104	-74.496	-74.496	-74.496	-74.496	-74.496	1.73
106	-74.777	-74.777	-74.777	-74.777	-74.777	1.77
108	-75.053	-75.053	-75.053	-75.053	-75.053	1.80
110	-75.325	-75.325	-75.325	-75.325	-75.325	1.83
112	-75.591	-75.591	-75.591	-75.591	-75.591	1.87
114	-75.852	-75.852	-75.852	-75.852	-75.852	1.90
116	-76.109	-76.109	-76.109	-76.109	-76.109	1.93
118	-76.361	-76.361	-76.361	-76.361	-76.361	1.97
120	-76.609	-76.609	-76.609	-76.609	-76.609	2.00
122	-76.853	-76.853	-76.853	-76.853	-76.853	2.03
124	-77.093	-77.093	-77.093	-77.093	-77.093	2.07
126	-77.328	-77.328	-77.328	-77.328	-77.328	2.10
128	-77.561	-77.561	-77.561	-77.561	-77.561	2.13
130	-77.789	-77.789	-77.789	-77.789	-77.789	2.17

132	-78.014	-78.014	-78.014	-78.014	-78.014	2.20
134	-78.235	-78.235	-78.235	-78.235	-78.235	2.23
136	-78.453	-78.453	-78.453	-78.453	-78.453	2.27
138	-78.668	-78.668	-78.668	-78.668	-78.668	2.30
140	-78.880	-78.880	-78.880	-78.880	-78.880	2.33
142	-79.089	-79.089	-79.089	-79.089	-79.089	2.37
144	-79.295	-79.295	-79.295	-79.295	-79.295	2.40
146	-79.497	-79.497	-79.497	-79.497	-79.497	2.43
148	-79.697	-79.697	-79.697	-79.697	-79.697	2.47
150	-79.895	-79.895	-79.895	-79.895	-79.895	2.50
152	-80.090	-80.090	-80.090	-80.090	-80.090	2.53
154	-80.282	-80.282	-80.282	-80.282	-80.282	2.57
156	-80.471	-80.471	-80.471	-80.471	-80.471	2.60
158	-80.658	-80.658	-80.658	-80.658	-80.658	2.63
160	-80.843	-80.843	-80.843	-80.843	-80.843	2.67
162	-81.026	-81.026	-81.026	-81.026	-81.026	2.70
164	-81.206	-81.206	-81.206	-81.206	-81.206	2.73
166	-81.384	-81.384	-81.384	-81.384	-81.384	2.77
168	-81.560	-81.560	-81.560	-81.560	-81.560	2.80
170	-81.733	-81.733	-81.733	-81.733	-81.733	2.83
172	-81.905	-81.905	-81.905	-81.905	-81.905	2.87
174	-82.075	-82.075	-82.075	-82.075	-82.075	2.90
176	-82.242	-82.242	-82.242	-82.242	-82.242	2.93
178	-82.408	-82.408	-82.408	-82.408	-82.408	2.97
180	-82.572	-82.572	-82.572	-82.572	-82.572	3.00
182	-82.734	-82.734	-82.734	-82.734	-82.734	3.03
184	-82.894	-82.894	-82.894	-82.894	-82.894	3.07
186	-83.053	-83.053	-83.053	-83.053	-83.053	3.10
188	-83.210	-83.210	-83.210	-83.210	-83.210	3.13
190	-83.365	-83.365	-83.365	-83.365	-83.365	3.17
192	-83.518	-83.518	-83.518	-83.518	-83.518	3.20
194	-83.670	-83.670	-83.670	-83.670	-83.670	3.23
196	-83.821	-83.821	-83.821	-83.821	-83.821	3.27
198	-83.969	-83.969	-83.969	-83.969	-83.969	3.30
200	-84.117	-84.117	-84.117	-84.117	-84.117	3.33
202	-84.262	-84.262	-84.262	-84.262	-84.262	3.37
204	-84.407	-84.407	-84.407	-84.407	-84.407	3.40
206	-84.550	-84.550	-84.550	-84.550	-84.550	3.43
208	-84.691	-84.691	-84.691	-84.691	-84.691	3.47
210	-84.831	-84.831	-84.831	-84.831	-84.831	3.50
212	-84.970	-84.970	-84.970	-84.970	-84.970	3.53
214	-85.108	-85.108	-85.108	-85.108	-85.108	3.57
216	-85.244	-85.244	-85.244	-85.244	-85.244	3.60
218	-85.379	-85.379	-85.379	-85.379	-85.379	3.63
220	-85.512	-85.512	-85.512	-85.512	-85.512	3.67

222	-85.645	-85.645	-85.645	-85.645	-85.645	3.70
224	-85.776	-85.776	-85.776	-85.776	-85.776	3.73
226	-85.906	-85.906	-85.906	-85.906	-85.906	3.77
228	-86.035	-86.035	-86.035	-86.035	-86.035	3.80
230	-86.163	-86.163	-86.163	-86.163	-86.163	3.83
232	-86.290	-86.290	-86.290	-86.290	-86.290	3.87
234	-86.415	-86.415	-86.415	-86.415	-86.415	3.90
236	-86.540	-86.540	-86.540	-86.540	-86.540	3.93
238	-86.663	-86.663	-86.663	-86.663	-86.663	3.97
240	-86.786	-86.786	-86.786	-86.786	-86.786	4.00
242	-86.907	-86.907	-86.907	-86.907	-86.907	4.03
244	-87.027	-87.027	-87.027	-87.027	-87.027	4.07
246	-87.147	-87.147	-87.147	-87.147	-87.147	4.10
248	-87.265	-87.265	-87.265	-87.265	-87.265	4.13
250	-87.383	-87.383	-87.383	-87.383	-87.383	4.17
252	-87.499	-87.499	-87.499	-87.499	-87.499	4.20
254	-87.615	-87.615	-87.615	-87.615	-87.615	4.23
256	-87.729	-87.729	-87.729	-87.729	-87.729	4.27
258	-87.843	-87.843	-87.843	-87.843	-87.843	4.30
260	-87.956	-87.956	-87.956	-87.956	-87.956	4.33
262	-88.068	-88.068	-88.068	-88.068	-88.068	4.37
264	-88.179	-88.179	-88.179	-88.179	-88.179	4.40
266	-88.289	-88.289	-88.289	-88.289	-88.289	4.43
268	-88.399	-88.399	-88.399	-88.399	-88.399	4.47
270	-88.508	-88.508	-88.508	-88.508	-88.508	4.50
272	-88.615	-88.615	-88.615	-88.615	-88.615	4.53
274	-88.722	-88.722	-88.722	-88.722	-88.722	4.57
276	-88.829	-88.829	-88.829	-88.829	-88.829	4.60
278	-88.934	-88.934	-88.934	-88.934	-88.934	4.63
280	-89.039	-89.039	-89.039	-89.039	-89.039	4.67
282	-89.143	-89.143	-89.143	-89.143	-89.143	4.70
284	-89.246	-89.246	-89.246	-89.246	-89.246	4.73
286	-89.349	-89.349	-89.349	-89.349	-89.349	4.77
288	-89.450	-89.450	-89.450	-89.450	-89.450	4.80
290	-89.552	-89.552	-89.552	-89.552	-89.552	4.83
292	-89.652	-89.652	-89.652	-89.652	-89.652	4.87
294	-89.752	-89.752	-89.752	-89.752	-89.752	4.90
296	-89.851	-89.851	-89.851	-89.851	-89.851	4.93
298	-89.949	-89.949	-89.949	-89.949	-89.949	4.97
300	-90.047	-90.047	-90.047	-90.047	-90.047	5.00
302	-90.144	-90.144	-90.144	-90.144	-90.144	5.03
304	-90.240	-90.240	-90.240	-90.240	-90.240	5.07
306	-90.336	-90.336	-90.336	-90.336	-90.336	5.10
308	-90.431	-90.431	-90.431	-90.431	-90.431	5.13
310	-90.525	-90.525	-90.525	-90.525	-90.525	5.17

312	-90.619	-90.619	-90.619	-90.619	-90.619	5.20
314	-90.713	-90.713	-90.713	-90.713	-90.713	5.23
316	-90.805	-90.805	-90.805	-90.805	-90.805	5.27
318	-90.897	-90.897	-90.897	-90.897	-90.897	5.30
320	-90.989	-90.989	-90.989	-90.989	-90.989	5.33
322	-91.080	-91.080	-91.080	-91.080	-91.080	5.37
324	-91.170	-91.170	-91.170	-91.170	-91.170	5.40
326	-91.260	-91.260	-91.260	-91.260	-91.260	5.43
328	-91.349	-91.349	-91.349	-91.349	-91.349	5.47
330	-91.438	-91.438	-91.438	-91.438	-91.438	5.50
332	-91.526	-91.526	-91.526	-91.526	-91.526	5.53
334	-91.614	-91.614	-91.614	-91.614	-91.614	5.57
336	-91.701	-91.701	-91.701	-91.701	-91.701	5.60
338	-91.787	-91.787	-91.787	-91.787	-91.787	5.63
340	-91.874	-91.874	-91.874	-91.874	-91.874	5.67
342	-91.959	-91.959	-91.959	-91.959	-91.959	5.70
344	-92.044	-92.044	-92.044	-92.044	-92.044	5.73
346	-92.129	-92.129	-92.129	-92.129	-92.129	5.77
348	-92.213	-92.213	-92.213	-92.213	-92.213	5.80
350	-92.296	-92.296	-92.296	-92.296	-92.296	5.83
352	-92.380	-92.380	-92.380	-92.380	-92.380	5.87
354	-92.462	-92.462	-92.462	-92.462	-92.462	5.90
356	-92.544	-92.544	-92.544	-92.544	-92.544	5.93
358	-92.626	-92.626	-92.626	-92.626	-92.626	5.97
360	-92.707	-92.707	-92.707	-92.707	-92.707	6.00
362	-92.788	-92.788	-92.788	-92.788	-92.788	6.03
364	-92.869	-92.869	-92.869	-92.869	-92.869	6.07
366	-92.949	-92.949	-92.949	-92.949	-92.949	6.10
368	-93.028	-93.028	-93.028	-93.028	-93.028	6.13
370	-93.107	-93.107	-93.107	-93.107	-93.107	6.17
372	-93.186	-93.186	-93.186	-93.186	-93.186	6.20
374	-93.264	-93.264	-93.264	-93.264	-93.264	6.23
376	-93.342	-93.342	-93.342	-93.342	-93.342	6.27
378	-93.419	-93.419	-93.419	-93.419	-93.419	6.30
380	-93.496	-93.496	-93.496	-93.496	-93.496	6.33
382	-93.572	-93.572	-93.572	-93.572	-93.572	6.37
384	-93.649	-93.649	-93.649	-93.649	-93.649	6.40
386	-93.724	-93.724	-93.724	-93.724	-93.724	6.43
388	-93.800	-93.800	-93.800	-93.800	-93.800	6.47
390	-93.875	-93.875	-93.875	-93.875	-93.875	6.50
392	-93.949	-93.949	-93.949	-93.949	-93.949	6.53
394	-94.023	-94.023	-94.023	-94.023	-94.023	6.57
396	-94.097	-94.097	-94.097	-94.097	-94.097	6.60
398	-94.171	-94.171	-94.171	-94.171	-94.171	6.63
400	-94.244	-94.244	-94.244	-94.244	-94.244	6.67

402	-94.316	-94.316	-94.316	-94.316	-94.316	6.70
404	-94.389	-94.389	-94.389	-94.389	-94.389	6.73
406	-94.461	-94.461	-94.461	-94.461	-94.461	6.77
408	-94.532	-94.532	-94.532	-94.532	-94.532	6.80
410	-94.604	-94.604	-94.604	-94.604	-94.604	6.83
412	-94.675	-94.675	-94.675	-94.675	-94.675	6.87
414	-94.745	-94.745	-94.745	-94.745	-94.745	6.90
416	-94.815	-94.815	-94.815	-94.815	-94.815	6.93
418	-94.885	-94.885	-94.885	-94.885	-94.885	6.97
420	-94.955	-94.955	-94.955	-94.955	-94.955	7.00
422	-95.024	-95.024	-95.024	-95.024	-95.024	7.03
424	-95.093	-95.093	-95.093	-95.093	-95.093	7.07
426	-95.162	-95.162	-95.162	-95.162	-95.162	7.10
428	-95.230	-95.230	-95.230	-95.230	-95.230	7.13
430	-95.298	-95.298	-95.298	-95.298	-95.298	7.17
432	-95.366	-95.366	-95.366	-95.366	-95.366	7.20
434	-95.433	-95.433	-95.433	-95.433	-95.433	7.23
436	-95.500	-95.500	-95.500	-95.500	-95.500	7.27
438	-95.566	-95.566	-95.566	-95.566	-95.566	7.30
440	-95.633	-95.633	-95.633	-95.633	-95.633	7.33
442	-95.699	-95.699	-95.699	-95.699	-95.699	7.37
444	-95.765	-95.765	-95.765	-95.765	-95.765	7.40
446	-95.830	-95.830	-95.830	-95.830	-95.830	7.43
448	-95.895	-95.895	-95.895	-95.895	-95.895	7.47
450	-95.960	-95.960	-95.960	-95.960	-95.960	7.50
452	-96.025	-96.025	-96.025	-96.025	-96.025	7.53
454	-96.089	-96.089	-96.089	-96.089	-96.089	7.57
456	-96.153	-96.153	-96.153	-96.153	-96.153	7.60
458	-96.217	-96.217	-96.217	-96.217	-96.217	7.63
460	-96.281	-96.281	-96.281	-96.281	-96.281	7.67
462	-96.344	-96.344	-96.344	-96.344	-96.344	7.70
464	-96.407	-96.407	-96.407	-96.407	-96.407	7.73
466	-96.469	-96.469	-96.469	-96.469	-96.469	7.77
468	-96.532	-96.532	-96.532	-96.532	-96.532	7.80
470	-96.594	-96.594	-96.594	-96.594	-96.594	7.83
472	-96.656	-96.656	-96.656	-96.656	-96.656	7.87
474	-96.717	-96.717	-96.717	-96.717	-96.717	7.90
476	-96.779	-96.779	-96.779	-96.779	-96.779	7.93
478	-96.840	-96.840	-96.840	-96.840	-96.840	7.97
480	-96.901	-96.901	-96.901	-96.901	-96.901	8.00
482	-96.961	-96.961	-96.961	-96.961	-96.961	8.03
484	-97.021	-97.021	-97.021	-97.021	-97.021	8.07
486	-97.081	-97.081	-97.081	-97.081	-97.081	8.10
488	-97.141	-97.141	-97.141	-97.141	-97.141	8.13
490	-97.201	-97.201	-97.201	-97.201	-97.201	8.17

492	-97.260	-97.260	-97.260	-97.260	-97.260	8.20
494	-97.319	-97.319	-97.319	-97.319	-97.319	8.23
496	-97.378	-97.378	-97.378	-97.378	-97.378	8.27
498	-97.437	-97.437	-97.437	-97.437	-97.437	8.30
500	-97.495	-97.495	-97.495	-97.495	-97.495	8.33
502	-97.553	-97.553	-97.553	-97.553	-97.553	8.37
504	-97.611	-97.611	-97.611	-97.611	-97.611	8.40
506	-97.669	-97.669	-97.669	-97.669	-97.669	8.43
508	-97.726	-97.726	-97.726	-97.726	-97.726	8.47
510	-97.783	-97.783	-97.783	-97.783	-97.783	8.50
512	-97.840	-97.840	-97.840	-97.840	-97.840	8.53
514	-97.897	-97.897	-97.897	-97.897	-97.897	8.57
516	-97.954	-97.954	-97.954	-97.954	-97.954	8.60
518	-98.010	-98.010	-98.010	-98.010	-98.010	8.63
520	-98.066	-98.066	-98.066	-98.066	-98.066	8.67
522	-98.122	-98.122	-98.122	-98.122	-98.122	8.70
524	-98.178	-98.178	-98.178	-98.178	-98.178	8.73
526	-98.233	-98.233	-98.233	-98.233	-98.233	8.77
528	-98.288	-98.288	-98.288	-98.288	-98.288	8.80
530	-98.344	-98.344	-98.344	-98.344	-98.344	8.83
532	-98.398	-98.398	-98.398	-98.398	-98.398	8.87
534	-98.453	-98.453	-98.453	-98.453	-98.453	8.90
536	-98.507	-98.507	-98.507	-98.507	-98.507	8.93
538	-98.562	-98.562	-98.562	-98.562	-98.562	8.97
540	-98.616	-98.616	-98.616	-98.616	-98.616	9.00
542	-98.670	-98.670	-98.670	-98.670	-98.670	9.03
544	-98.723	-98.723	-98.723	-98.723	-98.723	9.07
546	-98.777	-98.777	-98.777	-98.777	-98.777	9.10
548	-98.830	-98.830	-98.830	-98.830	-98.830	9.13
550	-98.883	-98.883	-98.883	-98.883	-98.883	9.17
552	-98.936	-98.936	-98.936	-98.936	-98.936	9.20
554	-98.988	-98.988	-98.988	-98.988	-98.988	9.23
556	-99.041	-99.041	-99.041	-99.041	-99.041	9.27
558	-99.093	-99.093	-99.093	-99.093	-99.093	9.30
560	-99.145	-99.145	-99.145	-99.145	-99.145	9.33
562	-99.197	-99.197	-99.197	-99.197	-99.197	9.37
564	-99.249	-99.249	-99.249	-99.249	-99.249	9.40
566	-99.300	-99.300	-99.300	-99.300	-99.300	9.43
568	-99.352	-99.352	-99.352	-99.352	-99.352	9.47
570	-99.403	-99.403	-99.403	-99.403	-99.403	9.50
572	-99.454	-99.454	-99.454	-99.454	-99.454	9.53
574	-99.505	-99.505	-99.505	-99.505	-99.505	9.57
576	-99.555	-99.555	-99.555	-99.555	-99.555	9.60
578	-99.606	-99.606	-99.606	-99.606	-99.606	9.63
580	-99.656	-99.656	-99.656	-99.656	-99.656	9.67

582	-99.706	-99.706	-99.706	-99.706	-99.706	9.70
584	-99.756	-99.756	-99.756	-99.756	-99.756	9.73
586	-99.806	-99.806	-99.806	-99.806	-99.806	9.77
588	-99.855	-99.855	-99.855	-99.855	-99.855	9.80
590	-99.905	-99.905	-99.905	-99.905	-99.905	9.83
592	-99.954	-99.954	-99.954	-99.954	-99.954	9.87
594	-100.003	-100.003	-100.003	-100.003	-100.003	9.90
596	-100.052	-100.052	-100.052	-100.052	-100.052	9.93
598	-100.101	-100.101	-100.101	-100.101	-100.101	9.97
600	-100.149	-100.149	-100.149	-100.149	-100.149	10.00

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14. ABSTRACT

The goal of this research is to develop a more realistic estimate of received signal strength level as calculated by OPNET. The goal is accomplished by replacing the existing free-space pathloss model used by OPNET with the Hata and COST-231 pathloss models.

An important aspect of a wireless communication system is the planning process. The planning phase of a wireless communication system will determine the number of necessary transmitting antennas, the frequency to be used for communications, and ultimately the cost of the entire project. Because of the possible expense of these factors it is important that the planning stage of any wireless communications project produce an accurate calculation of the coverage area.

15. SUBJECT TERMS

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