# Evaluation of Signal Attenuation for Bluetooth, ZigBee and Sound in Foliage

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*Abstract*—**Rural environments have been struggling to get connected due to various reasons, one of them being the fact that the signal attenuation is too high in foliage, drastically affecting range and power consumption. This study evaluates the effect of foliage in the attenuation of 2.4 GHz signals, namely Bluetooth and ZigBee. An alternate candidate signal, sound is also analyzed in a similar environment. In order to further the experiment, a simulation model using Omnet++ was created and the alpha value, which marks the environmental constant was noted. We have concluded from the study that the signal attenuation for the 2.4 GHz signals are very high in foliage. The high frequency sound signals also suffered drastic signal loss in foliage, but the low frequencies penetrated quite well. Therefore, high frequency signals are poor candidate carrier signals for such environments.**

*Index Terms*—**Signal Attenuation; Bluetooth; ZigBee; Sound.**

## I. Introduction

Rural areas, such as forests and villages, experience issues getting connected using wireless technologies. The random and very high attenuation of the communication signals is the main reason for this. In this research, we will study the attenuation of high frequency signals, namely ZigBee and Bluetooth, in various environments to formalize the effects of foliage on signal attenuation. We also extend the study to notice the effect of foliage on various frequencies of sound in order to evaluate sound as a potential carrier signal. A simulation experiment using OMNET++ allows us to bring more clarity to the effect of foliage on RF signals and also forms a platform for further simulation studies in this direction.

IEEE 802.15 is a standard for Personal Area Networks and low power devices [1]. IEEE 802.15.1 for Bluetooth, was initially conceived as a short range cable replacement has evolved. The latest version at the time of this study, Bluetooth 4.1 with its Low Energy (LE) and high data rates of up to 24 Mbps [2]. IEEE 802.15.4 is a standard is for wireless personal area networks (WPAN). It is catered for low-power, low-cost, low-speed communication between devices. The basic framework conceives a 10-meter range with 250 Kilobits per second transfer rate [3]. The latest offering is in the form of the IEEE 802.11af, also called White-Fi [4]. It reutilizes use of unused spectrum in the TV white space (TVWS) and is found to be exceptionally efficient in remote terrains offering acceptable speeds and connectivity in otherwise challenging environments. This scheme allows making use of the licensed frequency bands which may be under-utilized and secondary users may be allowed to take advantage of it. The 2.4 GHz band is called the "unlicensed band". Because of this, Wi-Fi, cordless phones, wireless peripherals, microwave ovens, Bluetooth, ZigBee etc. all operate in this band and this leads to unwanted interference. This spectrum is also affected by ambient weather and environmental conditions as well as obstacles like buildings, trees, shrubs, etc.

K. Mathew, et. al. did analysis of ZigBee and Bluetooth penetration in foliage. The experiment showed that there is an increase in attenuation of these signals in the presence of vegetative growth [5]. N. L. Muda, et. al. presented interference effects on ZigBee and S. Ahmed, et. al. presented interference effects on Bluetooth, both with similar conclusions [6], [7]. The IEEE standards specifications define the specifics of networking layers. 802.11 define Wireless LANs, 802.15 for Wireless PANs etc. 802.11af is a new standard that allows sharing of the Television White Spaces (TVWS) so that unused spectrums could be better utilized. 802.15.1 defines Bluetooth, 802.15.4 ZigBee, and 802.15.6 Body Area Networks (BAN) [1],[3],[4],[8],[9]. Analysis of ZigBee with other technologies in the 2.4GHz band was discussed by Atmel [10]. This whitepaper concludes that ZigBee can co-exist with other technologies of the same band.

The objective of this paper is to examine the effect of foliage on the 2.4 GHz (Bluetooth and ZigBee) signals and the interference of one protocol signal on another in those conditions and on Sound signals. A simulation model based on Onmet++ MiXim framework was carried out to notice how powerful the impact of the environment is on signal attenuation [11].

## II. Methodology

### *A. Initial Considerations*

This experiment evaluates the attenuation of the Bluetooth and ZigBee (2.4 GHz) signals in the presence and absence of foliage and the effect of interference on each other. We also analyze how sound, an alternative ubiquitous signal, performs in the same environments. However, since the sound signal is of a different nature, we will only be concerned with the signal penetration distances, and record the distance at which the transmitted sound signal is noticeable over noise. The experiment is run in three environments, as mentioned in the following sub-section.

Two Lumina smartphones were used to measure Bluetooth (version 4.0). A free Android app called "Bluetooth Signal" was used to measure signal strength. The distance was considered reachable if we are able to successfully transfer data text. USB ZigBee devices were connected to 2 laptops to test the ZigBee signals. The signal strength was measured using Fluke Networks AirMagent Spectrum XT application. The devices were considered reachable if we are able to transfer data between the devices. Sound was generated using a smartphone and played out using a speaker capable of generating signals from very low (25 Hz) to high frequency (20 KHz) signals. The sound of various frequencies was played and was recorded using the Zoom H4n recorder. This recording was later analyzed and considered reachable if the transmission frequency was noticeable over ambient noise at the specific distance it was recorded. The experiment was conducted at increasing distances from the source. The transmission signal strength is different for each device, but this difference is not very relevant for this study as we are mainly interested in the degradation pattern of the signals. For each data, a few readings were taken and the average of the readings is presented as the data for this study.

### *B. Environments of Study*

Three environments were selected for this study, namely the Stadium parking lot, the village and the forest. The Stadium Parking Lot is a Zero Interference and Zero Obstacle environment because it did not have any radio signals in the 2.4 GHz band and had clear line of sight. Figure 1. shows the picture of this location.

Figure 1: The Stadium Parking Lot

The Village is an environment with Zero Interference and Mild Foliage as obstacles because it did not have any radio signals in the 2.4 GHz band. Mild obstacles were present in the form of knee height foliage and some banana trees. The experiment was conducted in normal weather conditions with clear sky and no rain. Figure 2 shows the picture of this location.

Figure 2: The Village

The Forest offers Zero Interference and Thick Foliage as obstacles. The thickness of the foliage did not permit us to walk beyond 30m to take the measurements and the line or sight was obscured by the dense foliage. It was clear weather during the time of experiment. Figure 3. shows the picture of this location.

Figure 3: The Forest

### *C. Simulation Study*

We used the data collected from the study in various environments to draw a simulation model for based on the MiXiM framework using the OMNET++ tool for network simulation. The OMNET++ allows for rapid development and testing of various simulation models to facilitate rapid testing of the network parameters. The ini based configuration optios allows us to make changes to the various parameters of the simulation very quickly and study the results. OMNET++ is free of cost and comes with a good number of frameworks that can be used with almost little modifications for most cases. The result of the simulation study allows us to formalize the effect of the environment on foliage, as observed from the empirical study using a simple path-loss model available in the MiXiM framework. We used OMNET++ version 4.6 with MiXiM 2.3 for this simulation experiment.

## III. Results and Discussion

We studied five cases, (a) Bluetooth alone, (b) Bluetooth with ZigBee interference, (c) ZigBee alone, (d) ZigBee with Bluetooth as interference and (e) Sound to evaluate their propagation. We chose environments with zero interference. We introduced ZigBee to test the effect of interference for Bluetooth and Bluetooth for ZigBee since both signals operate in the same 2.4 GHz band. The results are grouped according to their environment of study and discussed, as follows.

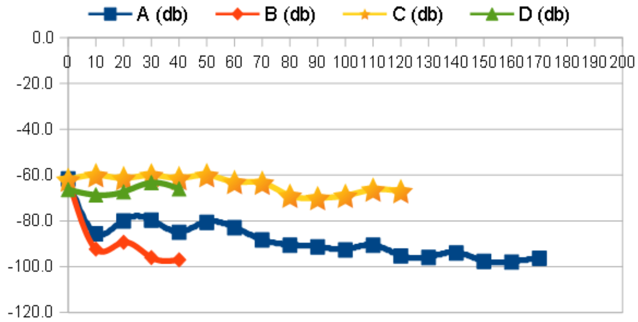
### *A. The Stadium Parking Lot*

The stadium parking lot offers zero obstacles with clear line of sight. No radio signal in the 2.4 GHz band was present, causing zero interference as well.

Bluetooth signal operating alone showed exceptional results, with the signal penetration reaching up to 170 meters. ZigBee, in the same conditions could penetrate only up to 120 meters. Both these distances are exceptional when we consider the fact that these technologies were designed for short range communications.

However, with the introduction of interference, both Bluetooth and ZigBee ranges dropped to just 40 meters.

Interference in the same bandwidth causes crowding of the spectrum, leading to signal loss, which is as evidenced in Figure 1 and Table 1.




A: Bluetooth with zero interference
B: Bluetooth with ZigBee interference
C: ZigBee with zero interference
D: ZigBee with Bluetooth interference

Figure 4: Bluetooth and ZigBee attenuation at zero obstacles

Table 1
Bluetooth And Zigbee Attenuation at Zero Obstacles

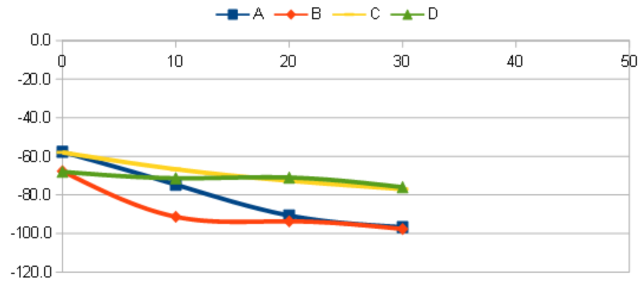
| Stadium parking lot | | | | |
|---|---|---|---|---|
| **Distance(m)** | **A (db)** | **B (db)** | **C (db)** | **D (db)** |
| **0** | -61.7 | -61.7 | -62.0 | -66.3 |
| **10** | -85.7 | -92.3 | -60.0 | -68.7 |
| **20** | -80.0 | -89.3 | -61.3 | -67.3 |
| **30** | -79.7 | -96.0 | -60.0 | -63.3 |
| **40** | -85.0 | -97.0 | -61.3 | -66.0 |
| **50** | -80.7 | | -60.0 | |
| **60** | -83.0 | | -63.0 | |
| **70** | -88.3 | | -63.3 | |
| **80** | -90.7 | | -69.0 | |
| **90** | -91.3 | | -70.0 | |
| **100** | -92.7 | | -69.0 | |
| **110** | -90.7 | | -66.3 | |
| **120** | -95.3 | | -67.0 | |
| **130** | -96.0 | | | |
| **140** | -94.0 | | | |
| **150** | -97.7 | | | |
| **160** | -98.0 | | | |
| **170** | -96.3 | | | |

A: Bluetooth with zero interference
B: Bluetooth with ZigBee interference
C: ZigBee with zero interference
D: ZigBee with Bluetooth interference

Table 2
Bluetooth And Zigbee Attenuation with Mild Obstacles

| Village | | | | |
|---|---|---|---|---|
| **Distance(m)** | **A** | **B** | **C** | **D** |
| **0** | -57.7 | -67.7 | -58.0 | -68.0 |
| **10** | -74.7 | -91.3 | -66.7 | -71.3 |
| **20** | -90.7 | -93.7 | -72.7 | -71.0 |
| **30** | -96.7 | -97.7 | -77.0 | -76.0 |

A: Bluetooth with zero interference
B: Bluetooth with ZigBee interference
C: ZigBee with zero interference
D: ZigBee with Bluetooth interference




A: Bluetooth with zero interference
B: Bluetooth with ZigBee interference
C: ZigBee with zero interference
D: ZigBee with Bluetooth interference

Figure 5: Bluetooth and ZigBee attenuation with mild obstacles

With zero obstacles, sound can propagate a long distance. The sound of a drum beat can be heard very far, though higher frequency signals attenuate faster. We noticed this expected pattern during the experiment. The low frequency sound at 250 Hz was recorded beyond 150 meters whereas sound at 15 KHz could not be noticed beyond 60 meters (Table 4 and Figure 7). It is also to be noted that the sound, unlike RF, is also affected by other unseen factors such as wind, humidity, temperature, etc., which are not considered for this study.

Table 3
Bluetooth and ZigBee attenuation at thick foliage

| Forest | | | | |
|---|---|---|---|---|
| **Distance(m)** | **A** | **B** | **C** | **D** |
| **0** | -62.3 | -62.7 | -67.7 | -68.7 |
| **5** | -72.3 | -84.0 | -70.0 | -74.3 |
| **10** | -81.0 | -94.0 | -69.3 | -71.0 |
| **15** | -92.7 | -95.7 | -71.7 | -72.0 |
| **20** | -95.0 | -97.7 | -61.3 | -58.3 |
| **25** | | | | |

A: Bluetooth with zero interference
B: Bluetooth with ZigBee interference
C: ZigBee with zero interference
D: ZigBee with Bluetooth interference

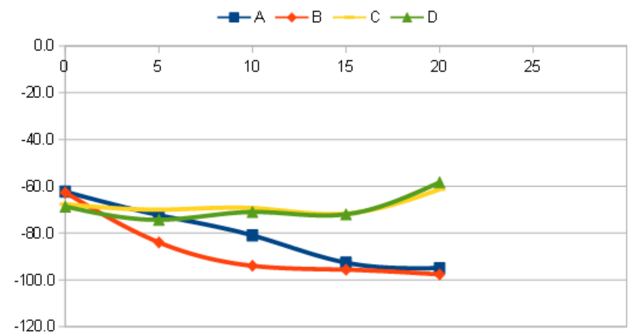
### *B. The Village*

The village scenario selected for our experiment presents mild foliage as obstacles, in the form of knee high grass and some banana tree clusters. This area was also devoid of radio signals in the bandwidth region of our study.

The signals did not penetrate far under this condition, and is attributed to the mild foliage in the area. We could see that the attenuation was sharper than the first scenario with zero obstacles. We were unable to measure beyond 30 meters due to constraints in the environment.

The received signal strength was lower when interference was introduced, which is consistent with the first scenario, and due to the same reason identified. This result asserts the fact that foliage plays a role in signal attenuation. The data is presented in Table 2 and Figure 5.

Foliage had its impact on sound signals as well. It was interesting to note that when the speaker was kept at ground level, the attenuation was too sharp to take any reading. This could be due to the grass that was growing along the ground. We conducted the experiment with the speaker on a pedestal of about 1 meter height. We were able to record the high frequency sound only up to 20 meters, but the low frequency was audible even at the full distance of the study at 30 meters (Table 4 and Figure 7).




A: Bluetooth with zero interference
B: Bluetooth with ZigBee interference
C: ZigBee with zero interference
D: ZigBee with Bluetooth interference

Figure. 6: Bluetooth and ZigBee attenuation at thick foliage

Table 4
Attenuation study – Sound

| Scenario | Distance (m) | |
|---|---|---|
| | Low Freq (250Hz) | High Freq (15 KHz) |
| A | 150 | 60 |
| B | 30 | 20 |
| C | 25 | 10 |

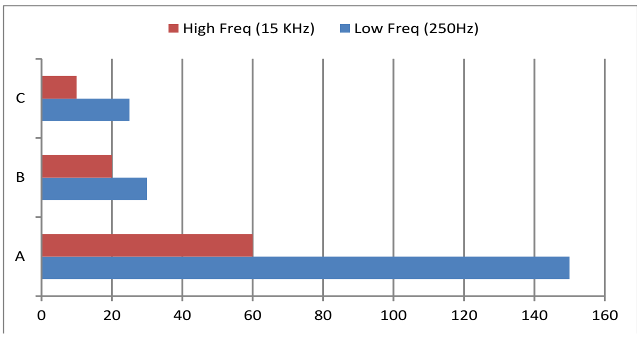
A: The Stadium Carpark
B: The Village
C: The Forest

### *C. The Forest*

The forest contains thick foliage as obstacles. The foliage was thick and almost impenetrable, with no line of sight beyond a few meters. The area does not have any ambient radio signals in the bandwidth region of our study.

The foliage had a very prominent effect on signal propagation. Even without any interference, we can see that the Bluetooth signal, that covered 170 meters without any obstacles, dies after 20 meters. ZigBee signal was slightly better, but the terrain was impenetrable and therefore we could not measure beyond 20 meters for ZigBee. The result, however, sufficiently proves the strong impact of foliage on these signals.

The interference only served to worsen the received signal strength, both for Bluetooth as well as ZigBee. This is consistent with the previous experiments and for the same reasons. This experiment proves that foliage serves as a serious damper for high frequency signal penetration.




A: The Stadium Carpark
B: The Village
C: The Forest

Figure 7: Sound attenuation in various scenarios

The thick foliage had its impact on the high frequency sound signals, but the low frequency sound penetrated through easily. The high frequency sound was barely noticeable above ambient noise even at 10 meters (Table IV and Figure 7). One of the possible contributors for this would be the fact that the ambient noise in a live forest environment is also relatively higher. The low frequency sound at 250 Hz could be easily heard even to the full distance of this study, at 25 meters.

## IV. SIMULATION

The terrain of some of the environment did not allow us to progress to do a complete study on the actual range of the signals in such conditions. Hence, we will also do a simulation study based on the values derived from the experiment in order to estimate the actual distance range for the signals.

### *A. The Simulation Software*

We have done the simulation using the OMNET++ open source object oriented simulation software. OMNeT++ is an extensible, modular, component-based C++ simulation library and framework, primarily for building network simulators. The tool is powerful, flexible and allows rapid development of scenarios once a basic model is established. Any further analysis required was done on Excel spreadsheets.

### *B. MIXIM Framework Model*

The Omnet++ is a simulation engine and it comes with a host of models. Each of the models provides implementations of the common protocols, channel models etc. required for rapid development and testing of scenarios. MiXiM is an OMNeT++ modeling framework created for mobile and fixed wireless networks. It offers models of radio wave propagation, interference estimation, radio transceiver power consumption and wireless MAC protocols. We will use this framework model for our simulation and testing. We use the "BaseNetwork" MiXiM sample for running our experiments.

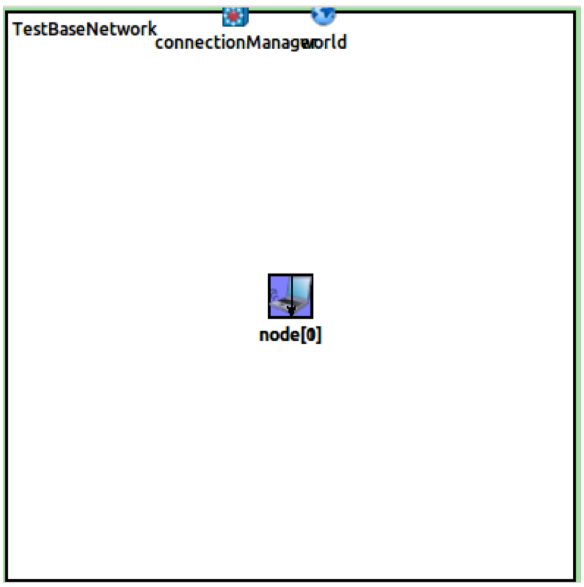



Figure 8: Omnetpp Experiment Simulation (a)

### *C. Simulation Parameters*

We are interested in analyzing the attenuation at the 2.4GHz signal in various environmental considerations. This will help us to evaluate the maximum range of signal propagation under the conditions. We will make use of the built in channel models such as "SimplePathLossModel" to factor the propagation attenuation factors. This model uses a constant "Alpha" to factor the environmental characteristics. The value for alpha usually ranges from 2, for clear line of sight to 3.5 for heavy obstacles. Since we have some empirical results, we will try and find the alpha value that closely matches the results for each of the scenarios.

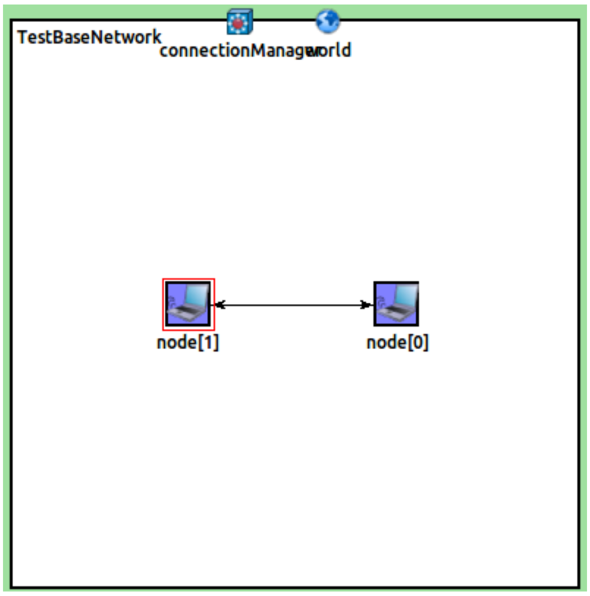



Figure 9: Omnetpp Experiment Running (b)

omnetpp.ini: This ini file allows creation of new simulations using configurable parameters. The parameters allow us to configure the simulation options. Each of the components are created as modules, which can be extended to create more complex modules. The following are some of the options used.

```
Playground Size
BaseNetwork.playgroundSizeX = 500m
BaseNetwork.playgroundSizeY = 500m
BaseNetwork.playgroundSizeZ = 5m

Connnection
BaseNetwork.connectionManager.pMax = 100mW
BaseNetwork.connectionManager.alpha = 2.0
BaseNetwork.connectionManager.carrierFrequency =
2.412e+9Hz

Mobility
BaseNetwork.node[*].mobilityType = "LinearMobility"
BaseNetwork.node[*].mobility.angle = 180

Analog Model
AnalogueModel type="SimplePathlossModel"
```

Therefore, we have a playground size that is of 500x500x5 meters (though we are not concerned about the height for this experiment). We will be working with a 2.412e9Hz carrier frequency (2.4GHz) and 100mW transmission power. We have chosen the linear mobility model with 180-degree angle, so that the nodes are travelling in opposite directions. We are interested in calculating the attenuation based on the path loss model and notice the resultant signal in dBm. We will assume that any signal strength of -90dBm or less in not good for efficient and effective communication since they either consume a lot of power, or experience more failure or both.

The value of alpha is varied in an attempt to match closely with our environments of study, namely the stadium parking lot, the village and the forest. We expect the alpha for the stadium to be closer to 2, and the alpha for the Forest to be beyond normal ranges. When we run the simulation, the nodes begin to travel away from each other till at some point, they cannot connect anymore. The simulation is as seen in Figure 8. Shows both nodes starting from the center of the 500x500 playground and moving in opposite directions. Figure 9. shows the screen capture from the Omnet++ simulation during the middle of the run, when the nodes are still within range and connected.

Table 5
Attenuation of 2.4 GHz Simulation

| Distance | Alpha | | | |
|---|---|---|---|---|
| | 2 | 2.2 | 2.5 | 3.5 |
| 5 | -54.07 | -55.47 | -57.57 | -64.56 |
| 10 | -60.1 | -62.1 | -65.1 | -75.1 |
| 15 | -63.62 | -65.97 | -69.5 | -81.26 |
| 20 | -66.12 | -68.72 | -72.62 | -85.63 |
| 25 | -68.05 | -70.85 | -75.04 | -89.02 |
| 30 | -69.64 | -72.59 | -77.02 | -91.79 |
| 40 | -72.14 | -75.34 | -80.15 | -96.17 |
| 50 | -74.07 | -77.47 | -82.57 | -99.56 |
| 60 | -75.66 | -79.21 | -84.55 | -102.33 |
| 70 | -77 | -80.69 | -86.22 | -104.67 |
| 80 | -78.16 | -81.96 | -87.67 | -106.7 |
| 90 | -79.18 | -83.09 | -88.95 | -108.49 |
| 100 | -80.1 | -84.1 | -90.1 | -110.1 |
| 110 | -80.92 | -85.01 | -91.13 | -111.54 |
| 120 | -81.68 | -85.84 | -92.07 | -112.87 |
| 130 | -82.37 | -86.6 | -92.94 | -114.08 |
| 140 | -83.02 | -87.31 | -93.75 | -115.21 |
| 150 | -83.62 | -87.97 | -94.5 | -116.26 |
| 160 | -84.18 | -88.59 | -95.2 | -117.24 |
| 170 | -84.7 | -89.17 | -95.86 | -118.16 |
| 180 | -85.2 | -89.71 | -96.48 | -119.03 |
| 190 | -85.67 | -90.23 | -97.06 | -119.85 |
| 200 | -86.12 | -90.72 | -97.62 | -120.63 |

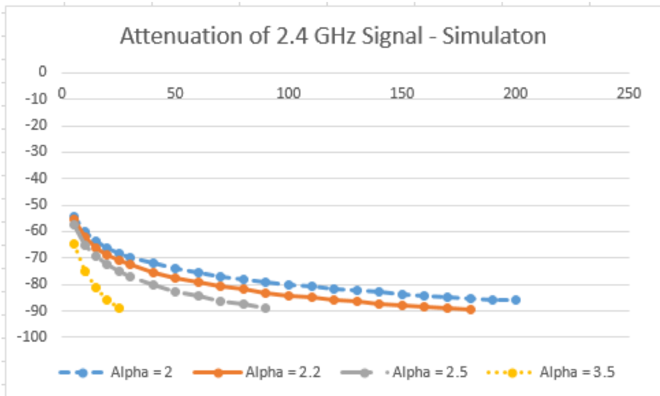



Figure. 10: Omnet++ Experiment Running (b)

The simulation data at various distance intervals are as shown in Table V. This result is plotted in the chart shown in Figure 10. Since we consider signals below -90 dBm as unusable, the same is reflected in the chart. We can observe that the stadium, with clear line of sight is close to the ideal condition at alpha=2.2. The village is a possible normal scenario with alpha=2.5. However, the forest with very thick foliage would push the alpha value up to 3.5. This further clarifies that the attenuation of the 2.4GHz band is very high in thick foliage.

## V. Conclusion and Future Works

The results of the study allow us to conclude that foliage causes too much attenuation for high frequency RF signals, particularly of the 2.4 GHz band. We can see the value of alpha is close to ideal in open environment, but way over normal observed ranges in the forest environments, in the simulation environments. The attenuation peaks when RF interference of the same bandwidth is introduced in the same environment with obstacles. The scenario therefore can cause random loss of signals within the coverage areas (aka blind spots), reduction of coverage area, etc. The interference issue, which worsens the situation, can be addressed by using wider band for multiple non-interfering channels. The foliage issue for high frequency signals can be technically countered by using lower frequency signals. Though these are currently under the ambit of frequency licensing, if adequate policies can be framed to allow secondary users to access unutilized frequencies, it can effectively address the issue.

In future, the study may be extended to include more terrains and frequency bands to notice the effect of each of the terrains on each of the frequency channel bands and draw up a closer estimate of the actual effect of foliage of various kinds on various RF frequencies. Then the effect of foliage on alternate candidate signals, such as sound, light, etc. can also be studied to identify the best carrier signals in various environments.

## Acknowledgment

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