SSRG International Journal of Electrical and Electronics Engineering
ISSN: 2348-8379/ https://doi.org/10.14445/23488379/IJEEE-V12I4P104

Volume 12 Issue 4, 63-71, April 2025

Original Article

Line-of-Sight and Fresnel Zone Clearance Link Budget Analysis for Planning Outdoor TV White Space Wireless LAN

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Received: 03 February 2025 Revised: 05 March 2025 Accepted: 06 April 2025 Published: 29 April 2025

Abstract - *A comprehensive link budget analysis for outdoor IEEE 802.11af-based networks has not been available to date. This analysis is essential for planning and developing highly reliable wireless links. This paper determines path loss measurements - based on the link budget for the IEEE 802.11af - compliant devices at 593 MHz for three different sites in a suburban environment. Google Earth Pro visualizes an unobstructed line-of-sight between the AP - STA pair. Additionally, the 1st Fresnel zone and its 60% clearance around the line-of-sight are carefully considered and analyzed to ensure effective transmission in uneven terrain. According to the study's findings, the calculated link budget aligns reasonably well with the actual measurements taken when the Log-regression path loss model is used. The calculated fade margin differences between the measured and computed values in dB are 2 for Site 1, 2 for Site 2, and 7 for Site 3, resulting in an average difference of 4 dB. However, based on a 20 - dB minimum fade margin, none of the computed values for the three sites can provide a reliable RF propagation link, while only the measured value of 23 dB at Site 3 can provide a reliable link. Nevertheless, a link budget improvement can be achieved if the radiated power is increased to an FCC-permitted 30 dBm. Applying the Log-regression path loss model increases the margin to 29 dB for Site 1, 24 dB for Site 2, and 26 dB for Site 3.*

Keywords - *Fade margin, 1st Fresnel zone, Link budget, TV white space, Path loss model.*

1. Introduction

In a one-page brief, the Office of the UN Secretary General's Envoy on Technology reported that approximately 3.7 billion people, or almost half of the world's population, currently lack internet access. The least developed countries are the most disconnected, with only 19% of their populations online. By 2030, it is envisioned that everyone will have safe and affordable internet access [1]. The critical importance of this goal was highlighted during the COVID-19 pandemic, when schools transitioned to online learning and many jobs shifted to remote operations, underscoring the internet's role as an essential tool for daily life. In recent years, TV white space technology has emerged as a key broadband wireless communication solution that provides connectivity to unserved and underserved regions. The Institute of Electrical and Electronics Engineers (IEEE) developed the IEEE 802.11af standard, also known as the TV white space Wireless LAN standard that permits unauthorized users to utilize available TV bands opportunistically [2]. Research detailed in [3] demonstrated that devices compliant with IEEE 802.11af can interface with the IEEE 802.22 backhaul to extend internet coverage. Additionally, a study in [4] successfully implemented a multi-hop IEEE 802.11af network using both devices as Access Points (APs) and Stations (STAs), highlighting its potential as an easily deployable, robust Information and Communications Technology (ICT) infrastructure during disasters. In designing any RF communication system, performing an analysis of the link budget is crucial for estimating the various losses that occur as the RF wave propagates from the transmitter on one side to the receiver on the other. An accurate and detailed model that forecasts all attenuations within the propagation link is essential for determining the necessary transmitter power and receiver sensitivity. Link budget estimations have been thoroughly researched. It is a method used to determine the link margin in underwater acoustic communication [5]. In [6], a link budget analysis tool was proposed to make an efficient, effective, and user-friendly approach to calculating link budgets for satellite communications. A link budget was calculated for a typical suburban residential scenario using measurements of path loss from the WiMAX actual signal operating at 3.5 GHz [7]. The study in [8] evaluates the assumed parameters of a proposed 5G communication link budget in tropical regions against practical values derived from experimental data, aiming to enhance the receiver's Signal-to-Noise Ratio (SNR). Meanwhile, [9] introduces the initial framework for performing link budget analysis for nanodevices operating within the human body. In [10], a comprehensive link budget evaluation for Millimeter-Wave and Terahertz fixed wireless links is presented, aimed at designing highly reliable systems capable of functioning under various weather conditions. Furthermore, [11] analyzes a Line-Of-Sight (LOS) link budget for wireless communication channels that encounter knife-edge diffraction obstacles. However, to date, a comprehensive link budget analysis for outdoor IEEE 802.11af-based networks has not been available. This analysis is essential for developing highly reliable wireless links. In this research, we present a practical evaluation of the link budget model for the requirement analysis of IEEE 802.11af communication systems at 593 MHz. Free space path loss and Log - regression models were used to compute the fade margin and compare it with the measured values for the three test sites. Additionally, the 1st Fresnel zone and its 60% clearance around the line-of-sight were carefully considered and analyzed to ensure effective transmission in uneven terrain. Results show that the use of the Log - regression model gave a better correlation between the computed and measured fade margin. The calculated fade margin differences between the measured and computed values in dB are 2 for Site 1, 2 for Site 2, and 7 for Site 3, resulting in an average difference of 4 dB. This again makes the Log - regression path loss model a best-fit prediction model for IEEE 802.11af-based network devices operating outdoors, suggesting further that the Link Budget for these LOS RF links was better estimated by the Log - regression model.

2. IEEE 802.11af Device Configuration, Field Tests and Measurement Setup

2.1. IEEE802.11af Prototype Specifications

Before conducting field tests, IEEE 802.11af prototypes manufactured by Japan's National Institute of Information and Communications Technology (NICT) were evaluated in a laboratory setting. This testing used a variable attenuator to assess the device's performance centered on the Received Signal Strength Indicator (RSSI) and measured throughputs in the downlink and uplink channels across various attenuation levels. Figure 1 illustrates the laboratory setup of the experimental devices, with one performing as a transmitter (Access Point, AP) and the other as a receiver (Station, STA). A computer monitor, mouse, and keyboard were connected to the AP, and STA was set up for monitoring and control. A Keysight attenuator, adjustable from 0 to 100 dB, was placed between the AP (transmitter) and STA (receiver) to characterize throughput, RSSI, and Modulation and Coding Scheme (MCS). Data was transmitted from the AP to the STA on Channel 34, centered at 593 MHz. A splitter at the attenuator's receiving end directed the signal to both the STA for throughput, RSSI, and MCS readings and to the HAMEG 3 GHz Spectrum Analyzer for signal spectral analysis.

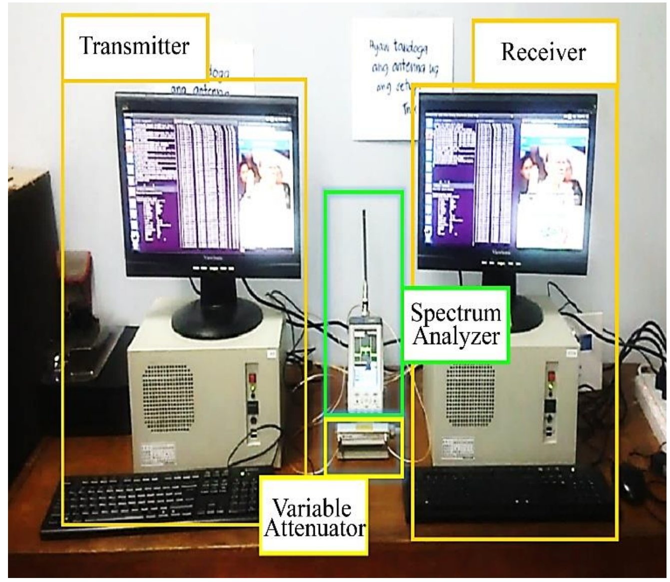

Fig. 1 IEEE 802.11af prototype developed by NICT used as AP and STA

The device specifications and the Physical (PHY) and Medium Access Control (MAC) parameters of the prototype are detailed in [2]. This prototype delivers a 20 dBm maximum power output and features a compact measurement of 30 x 23 x 20 cubic centimeters. It supports modulation and coding schemes ranging from index 0 to index 7, with the data rates for a single spatial stream detailed in [12]. For this study, however, only MCS0 is used, which employs BPSK modulation with a coding rate of ½.

2.2. Field Tests and Measurement Setup

All field tests and measurements were carried out on the premises of the University of San Carlos Campus in Cebu City, the oldest school in the Philippines. The University is a private Catholic University comprising about 78 hectares of land area. It is situated in a hilly environment consisting of several major buildings and a vegetation environment in some areas. The buildings, ranging in height from approximately 15 to 20 meters, are constructed with concrete walls. Also, several cars are parked at the side of the buildings and roads.

Figure 2 shows the measurement setup used in this study. A 1.7 m-high Access Point (AP) served as the transmitter, operating at 20 dBm transmit power. The Station (STA), positioned at a height of 1.2 m, was configured similarly to the AP. Both devices were equipped with an omnidirectional whip antenna with an approximate isotropic gain of 2.1 dB, connected to the NICT device via an SMA-SMA RF cable, assumed to have a 1.0 dB cable loss. The channel bandwidth was set to 6 MHz, centered at 593 MHz, corresponding to the Philippines' UHF Channel 34. At each test location, the AP's position was fixed while the STA was moved every 5 meters from the AP. At each position, received signal power and throughput were recorded in dBm and Mbps, respectively, averaged over a 120-second period.

Fig. 2 Field tests and measurement setup

Shown in Figure 3 are the three internal roads chosen as experimental sites color-coded as blue, yellow, and red for Site 1, Site 2, and Site 3 in that particular order for easy identification of its topographical profile when performing link budget and path loss modeling and analysis.

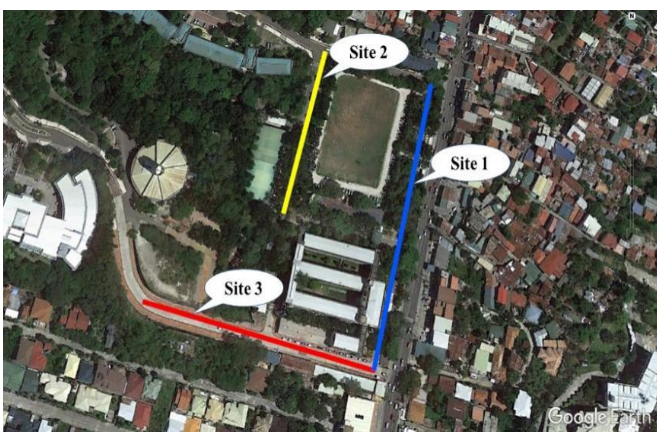

Fig. 3 Aerial view of the three experimental sites at the university campus

Site 1 extends approximately 250 meters from the campus's main gate to the first gate; however, there were distances in the study that had weak or intermittent signals in the initial 20 meters. This site features a two-lane road 15 meters wide. On the right side, a pedestrian path is flanked by lines of single-story and two-story low-rise structures and residential houses, whereas the left side features a stretch of trees extending roughly 100 meters and a five-story edifice. Location 2 covers a distance of 156 meters along a 10-meter-wide road lined with trees on both sides, experiencing minimal vehicle and pedestrian traffic. Additionally, Figure 3 depicts the location of Site 3, which spans approximately 229 meters along a 20-meter-wide pavement, bordered on both sides by low-rise buildings taller than the antenna heights of both the AP and the STA.

3. Link Budget, Fresnel Zone, and Path Loss Models

In this study, a link budget based on FSPL and log regression path loss models were conducted and validated by field tests at three different locations for an actual prototype of the IEEE 802.11af standard. In all three environments, the AP - STA pair is positioned to ensure that the line of sight is unobstructed. Corresponding RSSI and throughputs were also measured in each test site. Additionally, the Fresnel zone around the line-of-sight is also examined to be clear of obstacles using Google Earth to ensure effective transmission.

3.1. Link Budget

One of the key concepts in RF wireless communications is the link budget, which refers to accounting for all gains and losses in a communication link. This involves measuring power levels at different points in the communication system, from the transmitter through the transmission medium to the receiver. The primary goal of a link budget is to ensure that the received signal strength is sufficient for effective communication. Figure 4 illustrates a practical and simplified link budget design based on path loss models.

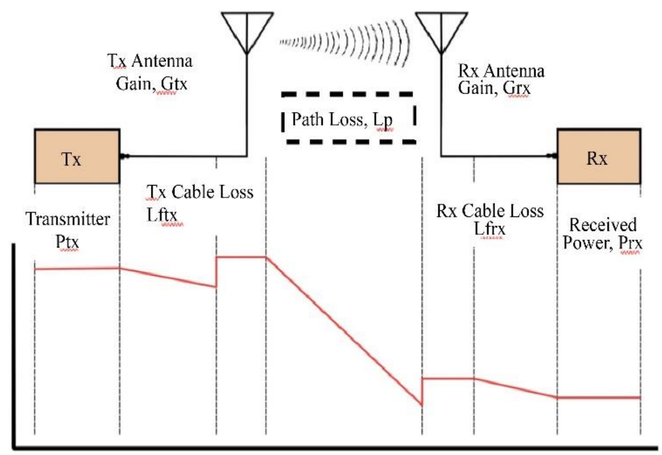

Fig. 4 A practical and simplified link budget design based on models for path loss

Mathematically, a practical link budget and the factors that affect it can be expressed as:

$$P_{rx}(dBm) = P_{tx}(dBm) - Lf_{tx}(dB) + G_{tx}(dB) - Lp(dB) + G_{rx}(dB) - Lf_{rx}(dB) \quad (1)$$

Where $P_{rx}(dBm)$ is the received signal strength; $P_{tx}(dBm)$ is the initial power produced by the transmitter; $G_{tx}(dB)$ is the antenna gain of the transmitter; $G_{rx}(dB)$ is the receiver antenna gain; Lp(dB) the path loss; $Lf_{tx}(dB)$ and $Lf_{rx}(dB)$ are the feeder and losses at the cable of the transmitter and receiver.

The other equally important factors that affect a link budget are the Receiver sensitivity and Fade Margin. Receiver sensitivity is the lowest signal strength that the receiver needs to detect and process a signal. Simply put, it indicates the RF input minimum power necessary to generate a usable signal at the output. Usual values range from -90 to -120 dBm. However, based on the indoor experiment conducted in [13] for IEEE 802.11af using Modulation and Coding Scheme 0 (MCS 0, BPSK, ½ coding rate), the receiver minimum input level sensitivity for 6 or 7 MHz is - 88 dBm. This value was used in all computations requiring its value.

On the other hand, fade margin is the amount of received power beyond what is needed for a minimum acceptable system performance. Extra power is included to compensate for uncertainties and variations in the propagation environment. It is termed such because it offers a safety buffer to accommodate temporary reductions or fading in the received signal power. This value is computed as

$$Fade\ Margin, FM\ (dB) = P_{rx} - Rx\ Sensitivity \quad (2)$$

3.2. Models for Path Loss and RMSE Computations

The path loss models considered in this study were the Free Space Path Loss (FSPL) and the Logarithmic Regression models. Both models were utilized by the authors in their recently published journal paper. The FSPL model is widely used for estimating the signal power received when a clear, unobstructed line of sight exists between the Transmitter (Tx) and Receiver (Rx). According to FSPL, the received signal strength decreases based on the Tx - Rx distance, raised to a certain power [14]. Path loss refers to the decrease in signal strength as it propagates from the transmitter to the receiver, measured as the difference between transmitted and received signal in decibels (dB). The FSPL model is defined as:

$$FSPL = 32.45 + 20log f_{MHz} + 20log d_{Km} \quad dB \quad (3)$$

Logarithmic regression, on the other hand, is often used to model real-world situations that show a rapid initial increase or decrease followed by a slower rate over time [15]. This type of regression is practical across various applications. The commonly used logarithmic function, also applied in the previous study, is defined as follows:

$$\hat{y}_i = b_0 + b_1 ln x_i \quad (4)$$

Where $\hat{y}_i$ represents the estimated loss in dB; b_1 is the coefficient determining the rate of growth ($b_1 > 0$) or decay ($b_1 < 0$); x_i is the distance in meters and b_0 is the constant or y-intercept.

The performance of both path loss models was assessed using Root Mean Square Error (RMSE) as the evaluation metric. A lower RMSE value indicates a better-fitting model. To compute RMSE, each error is squared and averaged, and then the square root of the result is taken. Mathematically, it is expressed as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n}} \quad (5)$$

Where y_i is the loss observed at each measurement path location *i and* $\hat{y}_i$ is the predicted loss by the model at the same location.

3.3. Line-Of-Sight and the 1st Fresnel Zone [16]

The path loss models considered in this study were the Free Space Path Loss (FSPL) and the Logarithmic Regression models. Both models were utilized by the authors in their recently published journal paper. In point-to-point wireless communications, maintaining an unobstructed Line of Sight (LOS) between two systems is essential, as obstacles like terrain, vegetation, buildings, or wind farms can cause signal loss. For optimal system performance, it's important to keep the elliptical region between transmitting and receiving antennas-known as the Fresnel Zone-clear of obstructions. The size of this 3D elliptical area is determined by the operational frequency and the distance between the two locations.

To define Fresnel zones, determine the RF line of sight (RF LoS), which is the direct path between the transmitting and receiving antennas. The Fresnel zone surrounds this RF LoS, with the radius of each zone being widest at the midpoint and tapering to a point behind each antenna.

While there are theoretically infinite Fresnel zones, the first or innermost Fresnel zone is the critical clearance area for LOS. If obstacles partially intrude into this zone without fully blocking the LOS, they may cause constructive or destructive interference due to wavefront reflections. Remembering that a Fresnel zone is three-dimensional, obstructions can enter from above, below, or the sides of the LOS path. The clear line of sight between the Tx - Rx link is illustrated in Figure 5, encircled by the ellipsoid-shaped first Fresnel zone.

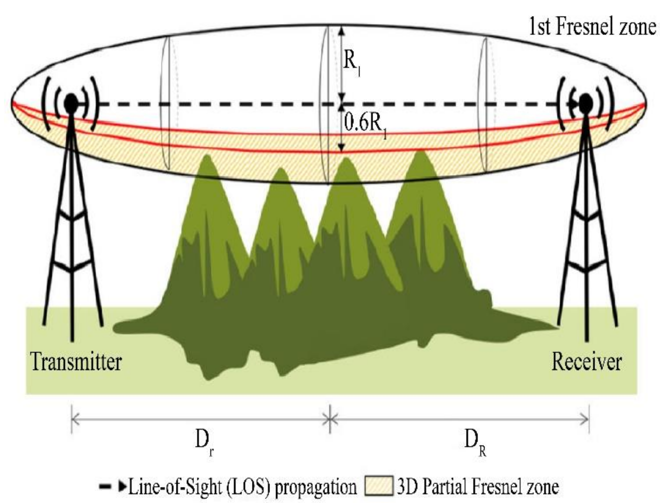

Fig. 5 Tx-Rx Line-Of-Sight with the 1st Fresnel zone

The first Fresnel Zone radius at a specific point between the transmitter and the receiver can be computed using the formula:

$$R_1 = \sqrt{\frac{D_T D_R \lambda}{D_T + D_R}} \quad (6)$$

Where R_1 is the 1st Fresnel zone radius in meters, D_T and D_R are spaces from the obstacle to the link endpoints in kilometers, and wavelength λ relates the frequency f to the speed of light c by $\lambda = \frac{c}{f}$ where c is approximately equal to $3x10^8$ m/s.

LOS_{CLR} is the line-of-sight clearance with reference to the obstruction that can be computed as

$$LOS_{CLR} = H_R + \frac{H_T - H_R}{D_T + D_R} D_R - H_{\varepsilon r} - H_O \quad (7)$$

Where H_R is the Rx antenna or STA height in meters; H_T is the Tx antenna height or AP in meters; H_O is the obstruction height in meters and $H_{\varepsilon r}$ is the effective earth radius, which, for a distance of less than 1 km between the Tx and Rx, is considered insignificant. A positive value for LOS_{CLR} indicates that the obstruction is below the LOS, while a negative value indicates above the LOS obstruction.

If an object intrudes into the innermost part of the first Fresnel zone, the received signal level will diminish or fade. When the obstruction reaches the point of being tangent to the Line-Of-Sight (LOS) path, signal loss can reach 6 dB or higher. To prevent signal fading, keeping at least 60% of the first Fresnel zone radius free of any obstacles is recommended. From Equation (8), the relative clearance between 60% of the radius of the 1st Fresnel zone and the obstacle can be computed as:

$$C_{LOS} = LOS_{CLR} - 0.6 \quad (8)$$

4. Results and Discussion

4.1. Models for Path Loss

As outlined in Section 3, the path loss models employed by the authors in their recent journal publication were applied in this study to aid in link margin computation. The Path Loss model for Free Space was applied, as it represents a fundamental wireless communications' path loss derived from Friis' equation [14].

The Log-regression model was included, as it demonstrated the lowest RMSE among the models evaluated in the prior study, indicating higher accuracy in outcome prediction (see Table 1). For each site, the derived Log - regression models were as follows:

$$\text{Site 1: } \hat{y}_i = 34.727 + 10.315\ln(x_i) \quad (9)$$

$$\text{Site 2: } \hat{y}_i = 33.881 + 12.375\ln(x_i) \quad (10)$$

$$\text{Site 3: } \hat{y}_i = 41.949 + 9.6116\ln(x_i) \quad (11)$$

Table 1 summarizes the RMSE values in dB for each site for each path loss model, highlighting, in particular, the FSPL and the Log - regression models. Building on previous analyses, the findings reveal that for outdoor IEEE 802.11af network devices, the logarithmic regression model attains the lowest Root-Mean-Square Error (RMSE), with an average estimation error of 5 dB across all test locations. Furthermore, the study indicates that the free space path loss model can serve as a reliable conservative path loss approximation across all sites, generally overestimating by 18 dB. This overestimation provides an added level of protection for primary users against potential interference from secondary users.

4.2. Link Budget and the 1st Fresnel Zone Clearance

The topographical profile of the transmission path is essential for understanding signal propagation. For this analysis, Google Earth Pro was employed to determine the elevation and length profiles of the transmission paths, identifying hills, buildings, and other obstacles that could obstruct or diffract the signal, resulting in attenuation and distortion.

This profile visualizes the existence of a Line-Of-Sight (LOS) path between each AP-STA pair at each test site. Following this, a link budget analysis was conducted to calculate the link margin for the three paths, incorporating factors like effective radiated power, received power, antenna gain, distance, and path loss. Although all sites examined in this study demonstrated an LOS, it is essential to note that a clear line of sight does not guarantee an unobstructed Fresnel zone. Given the significance of the 1st Fresnel zone in determining critical clearance for LOS, it is also analyzed and calculated in this study. As seen in Figures 6, 7, and 8, all sites have an uneven terrain.

Table 1. Summary of RMSE values (dB) for each path loss model at different sites

Experimental Sites	Path Loss Model RMSE (dB)						
	FSPL	**Section 4.1.2 LoS lower**	**Section 4.1.2 LoS upper**	**Section 4.3.1 p(90%)**	**Section 4.3.1 p(99%)**	**Linear Regression**	**Logarithmic Regression**
Site 1	**14.22**	10.26	13.70	6.19	9.23	5.8 (R^2=0.8451)	**5.26 (R^2=0.8723)**
Site 2	**20.72**	15.81	6.39	11.05	6.15	8.93 (R^2=0.7228)	**3.65 (R^2=0.9534)**
Site 3	**18.73**	8.30	19.61	10.18	7.13	8.41 (R^2=0.3803)	**6.33 (R^2=0.7772)**

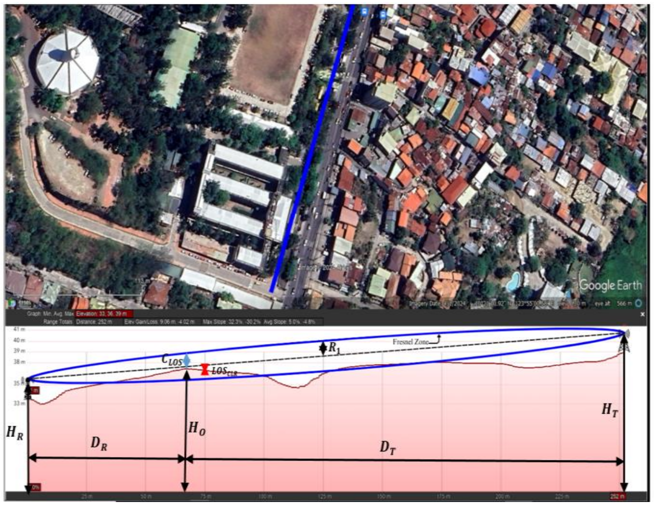

Fig. 6 Site 1 path profile traversing uneven terrain with obstruction at 1st Fresnel zone

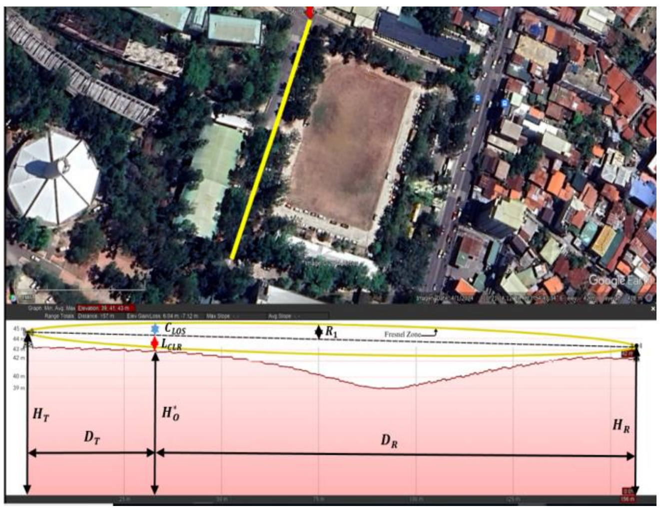

Fig. 7 Site 2 path profile traversing uneven terrain without obstruction at 1st Fresnel zone

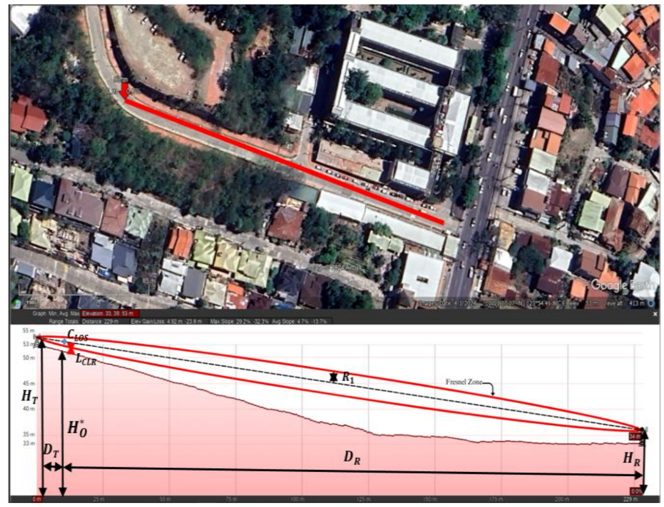

Fig. 8 Site 3 path profile traversing uneven terrain without obstruction at 1st Fresnel zone

The measured and computed parameters for the 1st Fresnel zone and the 60% clear Fresnel Zone radius were tabulated and presented in Table 2. This 60% clearance is a practical rule of thumb when planning wireless links.

For Site 1 that covers about 250 meters, the distances D_T and D_R from the obstruction height H_O, were measured to be 59 and 191 meters, respectively. Using Equation (6), the maximum radius of the 1st Fresnel Zone of this link operating at 593 MHz is 4.79 m. With the receiver antenna height H_R of 35 m as a reference point, the 1st Fresnel Zone would pass 39.79 m above ground (35+4.79).

The 60% clear Fresnel Zone radius is computed as $0.6 * R_1$ or equal to 2.88 m. Adding this value to H_R would indicate that the maximum obstruction height between the AP - STA devices within the 60% clear Fresnel Zone is 37.88 m.

Table 2. Summary of 1st Fresnel zone clearance for each site

Location	Distance, D (m) ($D_T + D_R$)	Tx/AP Antenna Height, H_T(m) above mean sea level	Rx/STA Antenna Height, H_R(m) above mean sea level	1st Fresnel Zone Clearance, R_1(m)	60% 1st Fresnel Zone Clearance, $0.6R_1$(m)	LOS_{CLR} (m)	C_{LOS}(m)
Site 1	250	40	35	4.79	2.88	-2.82	-5.70
Site 2	156	45	44	3.72	2.23	2.78	0.55
Site 3	229	54	40	2.00	1.20	1.45	0.25

Based on Equation (7), the computed value of the line-of-sight clearance with reference to the obstruction (LOS_{CLR}) is -2.82 m while according to Equation (8), the relative clearance between 60% of the 1st Fresnel zone and the obstacle (C_{LOS}) is -5.70 m. The negative values for both LOS_{CLR} and C_{LOS} indicate that the obstruction H_O is above the LOS path, thereby intruding into the 1st Fresnel zone, which causes signal attenuation on the receiving device. In sum, for Site 1, over 93% of the 1st zone is obstructed, and the obstacle protrudes 5.70 m into the critical $0.6R_1$ region.

In Site 2, there's no obstruction along the LOS path and the 1st Fresnel zone surrounding the 156-m link connecting the AP and the STA devices. Based on the parameters given in Table 3 for Site 2, and with the aid of Equations (6), (7), and (8), the maximum radius of the 1st Fresnel zone is 3.72 m while the 60% clearance is computed as 2.23 m. A positive value for LOS_{CLR} of 2.78m indicates that the obstruction H_O^* is below the LOS. On the other hand, the positive C_{LOS} value of 0.55m shows no intrusion into the first Fresnel zone. In other words, while the radius of the 1st zone is narrower at the location of the possible obstruction H_O^* , there is still a LOS clearance of about 2.78 m relative to the obstruction point; hence, there was no signal attenuation at this point. The maximum obstruction height for an H_O^* of 42 m is 44.78 m. This is the height within the Fresnel zone where an obstruction can exist without significantly degrading the signal strength. Among the three experimental locations considered, the 229 - m Site 3 has the smallest value of the maximum 1st Fresnel zone radius at 2 meters with a 60% clear Fresnel Zone radius of 1.20 meters. Just like Site 2, the RF LOS link is unobstructed. H_O^* represents the height of the obstacle nearest to the ellipsoid representing the 3D 1st Fresnel area. Referring to Table 2 and using the same equations used for Site 1 and Site 2, the computed line-of-sight clearance LOS_{CLR} of 1.45 meters means that the 1st Fresnel zone would pass up to 53.45 m of obstruction when H_O^* measures 52 m. A 0.250 - m C_{LOS}value represents the first Fresnel zone radius at the obstruction point. Based on the measured and computed parameters at Site 3, no signal attenuation can be attributed to the non-clearance of the zone.

4.3. Link Budget Using Free Space Path Loss and Logarithmic - Regression Models

The link budget was calculated for a 593 MHz LOS for an IEEE 802.11af wireless communication link at three different locations inside the University campus. Table 3 lists the network and link parameters. Two path loss models were considered. Equation (1) was used for all sites to compute the received power and then compare it with the actual received power. Equation (2) was utilized to calculate both the received and computed Fade Margin with the Receiver Sensitivity of -88 dBm [13].

For the FSPL model, the calculated fade margin values are 34 dB for Site 1, 38 dB for Site 2, and 35 dB for Site 3. For a highly critical RF communications link, the goal should be to achieve a minimum fade margin between 20 and 30 dB [16]. While the computed values seemed to provide a reliable link, when compared with the measured FM of 17, 12, and 23 dB, the computed FM overestimated the measured FM by 17, 26, and 12 dB, respectively, or an average of 18 dB. Such wide disparity is crucial as it indicates using the FSPL as a poor path loss model for estimating the required Link margin between a pair of outdoor AP - STA Line-of-Sight Wireless LAN in television White Space. Conversely, using the log regression model gave a better correlation between the computed and measured fade margins. The calculated fade margin differences between the measured and computed values in dB are 2 for Site 1, 2 for Site 2, and 7 for Site 3, resulting in an average difference of 4 dB. This again makes the log-regression path loss model a best-fit prediction model for IEEE 802.11af-based network devices operating outdoors, suggesting further that the Link Budget for these LOS RF links was better estimated by the Log - regression model. To improve on the link budget using the log-regression model as the path loss model, the transmitter power, $P_{tx}(dBm)$, can be increased from 20 to 30 dBm as [16] listed 36 dBm as radiated power for IEEE 802.11af. It is safe to assume this much power is permissible under FCC regulations. This improves the link margin of Site 1 to 29, Site 2 to 24, and Site 3 to 26 dB. This can be further improved by choosing an antenna with a gain greater than 2 dB at one or both ends of the propagation channel. Table 3 summarizes the parameters used and the link budget analysis results for each experimental site considered in this study.

Table 3. The link budget analysis results for each LOS experimental site (MCS 0)

Parameters	Site 1	Site 2	Site 3
Distance, d(meters)	250	156	229
Transmitter power, P_{tx}(dBm)	20		
Operating frequency, f_o(MHz)	593		
Bandwidth, B(MHz)	6		
Tx antenna gain, G_{tx}(dB) Whip antenna	2.1		
Tx feeder and cable losses, L_{ftx}(dB)	1		
Path loss, L_p(dB) (Free Space Path Loss)	72.26	71.72	77.16
Path loss, L_p(dB) (Logarithmic Regression Model)	87.37	96.29	96.44
Rx antenna gain, G_{rx}(dB) Whip antenna	2.1		
Rx feeder and cable losses, L_{frx}(dB)	0.04		
Rx sensitivity, $SenR_{rx}$(dBm) MCS0, BPSK, ½	88		
Actual Received power, P_{rx}(dBm)	71	76	65
Computed Received power, P_{rx}(dBm) [FSPL]	53.56	49.57	52.91
Computed Received power, P_{rx}(dBm) [Log Reg Model]	69.48	74.17	71.78

Fade margin, FM(dB) [FSPL and Log Reg Models] (Measured)	17	12	23
Fade Margin, FM(dB) [FSPL] (Computed)	34	38	35
Fade margin, FM(dB) [Log Reg Model] (Computed)	19	14	16
Link Status (based on Measured FM)	fairly reliable	poor reliability	reliable

5. Conclusion

The link budget was calculated for a 593 MHz LOS for an IEEE 802.11af wireless communication link at different locations inside the University campus. Free space path loss and Log - regression models were used to compute the fade margin and compare it with the measured values for the three test sites. Additionally, the 1st Fresnel zone and its 60% clearance around the line-of-sight were carefully considered and analyzed to ensure effective transmission in uneven terrain. Results show that using the Log - regression model gave a better correlation between the computed and measured fade margin. The calculated fade margin differences between the measured and computed values in dB are 2 for Site 1, 2 for Site 2, and 7 for Site 3, resulting in an average difference of 4 dB. This again makes the Log - regression path loss model a best-fit prediction model for IEEE 802.11af-based network devices operating outdoors, suggesting further that the Link Budget for these LOS RF links was better estimated by the Log - regression model. To ensure a reliable path between the AP - STA pair, at least a 20 - dB fade margin is necessary. Using the Log - regression model as a path loss model, the transmitter power, $P_{tx}(dBm)$, can be increased from 20 to 30 dBm.

This improves the link margin of Site 1 to 29, Site 2 to 24, and Site 3 to 26 dB. This can be further enhanced by choosing an antenna gain greater than 2 dB at one or both ends of the Tx and Rx of the propagation channel.

Funding Statement

This research was funded by the National Institute of Information and Communications Technology (NICT), Japan, under the auspices of the project on “TV White Space (TVWS) Experimental for Application in Remote Area.” The authors would also like to express their gratitude to the Department of Science and Technology (DOST) and the Commission on Higher Education (CHED) of the Philippines through its scholarship grants.

Acknowledgments

The authors would like to thank the Administration of the University of San Carlos for allowing us to conduct the field tests and measurements at the University campus, the students of the Department of Electrical and Electronics Engineering, and the Research, Development, Extension, and Publication Office (RDEPO) of the University of San Carlos, in Cebu City, Philippines for providing the technical support.

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