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Research Article

Enhancing Communication Reliability: Designing Microwave Links for Bahir Dar-Woretta Connectivity

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This paper explores the need for establishing a microwave link between Bahir Dar and Woretta as an alternative communication solution to the existing optical fiber infrastructure. Microwave links offer an effective way to overcome challenges posed by rugged terrains and unfavorable environmental conditions that hinder the deployment of fiber optics. As Woretta emerges as a key economic and investment hub within the Amhara Region, demand for reliable and efficient communication is expected to grow significantly. The study encompasses various aspects of planning and designing the microwave link, including site surveys, consideration of fade margins, frequency planning, link budget calculations, and assessing the feasibility and reliability of the proposed link. The paper employs LINKPlanner 5.4.1 software to simulate and validate the results. Due to terrain constraints, a direct link between Bahir Dar and Woretta is not feasible. Instead, a two-hop link is proposed, involving transmission from Bahir Dar to Zege, and then from Zege to Woretta. This alternative configuration ensures optimal connectivity while addressing the terrain limitations. By presenting a comprehensive analysis and simulation of the microwave link, this paper provides valuable insights into the planning and implementation of a robust communication infrastructure. The proposed microwave link will offer a reliable and efficient alternative to the existing optical fiber network, ensuring uninterrupted connectivity to support the region's growth and development.

1. Introduction

Microwave links are of significant importance in the Amhara Region of Ethiopia due to the unsuitability of wired communication systems in most geographical areas [1]. These links are commonly utilized for short-range indoor communications, telecommunications, and connecting remote and regional telephone exchanges to larger (main) exchanges, eliminating the need for copper or optical fiber lines [2, 3]. Microwave frequencies are valuable for both terrestrial and satellite communication systems, including fixed and mobile setups. In the case of point-to-point radio links, antennas are installed on towers or other tall structures at adequate heights to establish a direct, unobstructed line-of-sight (LOS) path between the transmitter and receiver sites.

Designing a microwave link involves a methodical and systematic process, which can sometimes be time-consuming. It encompasses various activities such as site surveys, calculations for loss/attenuation and fading, determination of fade margins, frequency planning, interference calculations, and assessments of quality and availability, as depicted in Figure 1. The entire process is iterative and may undergo multiple redesign phases until the desired levels of quality and availability are achieved [3].

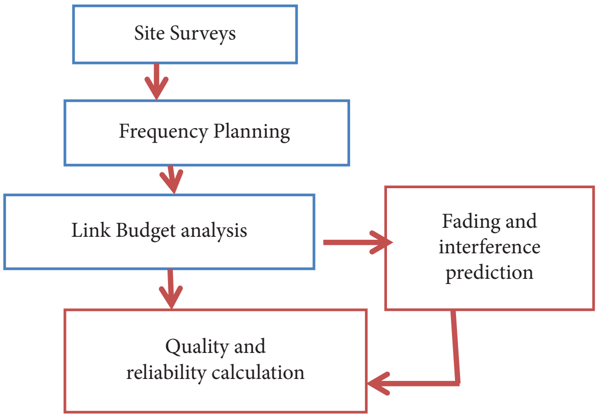

Figure 1: System design process flowchart [1].

2. Microwave Link from Bahir Dar to Woretta

The proposed terminal sites for the microwave link are Bahir Dar and Woretta, as indicated on the map shown in Figure 2. Both terminal points already have existing towers; however, there is currently no microwave link established between these two sites.

To establish a link, we measured the coordinates of the two sites using Global Positioning System (GPS) receivers. We then determined the possible hop distance using LINKPlanner 5.4.1 and Google software, which takes into account the coordinates [4, 5]. Table 1 shows the coordinates and possible hop distance of the proposed link.

Note that the specific values for latitude, longitude, and hop distances should be filled in according to the measurements and the simulation results.

2.1. Path Profile from Bahir Dar to Woretta. The path profile of the proposed microwave link depicts the visual representation of the route taken by radio waves between Bahir Dar and Woretta. The path profile is generated using LINKPlanner 5.4.1 software with the integration of Google Earth, which utilizes the data collected from Table 1 [4, 5]. This profile illustrates the maximum distance between hops, as well as the elevation of both sites. Furthermore, it displays the elevation and distance of any obstacles encountered along the path. Refer to Figure 3 for a visual representation of the path profile.

Based on the path profile depicted in Figure 3, it is evident that there is an obstacle situated between Bahir Dar and Woretta. The obstacle has an elevation of 1952 m and is located at a distance of 27.074 km from Bahir Dar, while its elevation is measured at 1950 m and it is situated 28.933 km away from Bahir Dar.

The obstacle's significant elevation creates a hindrance as there is no clear LOS between the two radio terminals. Consequently, the obstacle obstructs the transmission of radio waves between Bahir Dar and Woretta. Moreover, the elevation difference between the first site (Bahir Dar) and the obstacle amounts to 149.6 m. This indicates that in order to establish a clear line of sight, a tower height of approximately

Figure 2: Map of area of interest.

150 m would be required, in addition to the height of the trees. However, such a solution is impractical and not recommended.

Therefore, the most suitable resolution for this issue would be to seek an alternative path that incorporates a repeater station. Two potential alternative links are Bahir Dar to Zege and Zege to Woretta, which would enable the successful transmission of radio waves without being obstructed by the existing obstacle.

3. Link: Bahir Dar to Zege and Zege to Woretta

The alternative path considered for analysis consists of two hops: one from Bahir Dar to Zege and another from Zege to Woretta, with a repeater located at Zege. Additionally, by implementing an Add and Drop Multiplexer (ADM) equipment at Zege, we can add/drop data, voice, and video services, thereby establishing an alternate link to Zege as well. Figure 4 illustrates the map displaying the alternative links comprising the two hops.

The coordinates of the two hops, including latitude, longitude, and elevation, were determined by utilizing Global Positioning System (GPS) receivers at the existing towers. The specific measurements are provided in Table 2.

3.1. Path Profile from Bahir Dar to Zege. The maximum distance between the two terminals in the hop is 12.7 km. Although there are no obstacles due to Lake Tana between these terminals, there is no clear LOS due to the height of the trees at both locations. To achieve a clear LOS, antennas are needed for the wireless connection. To ensure that they are above tree level, they need to be installed on tall towers.

The path profile of the link between the two sites was analyzed using LINKPlanner 5.4.1 and Google Earth software [4, 5], based on the data provided in Table 2. The analysis results are displayed in Figure 5. In Figure 5, the red line represents the clear line of sight, while the blue line indicates the FFZ. To ensure a clear line of sight, the red line must be within the blue lines (FFZ).

3.2. Path Profile from Zege to Woretta. The maximum distance between the two terminals in the hop is 46.375 km. There are obstacles located at distances of 17.908 km and

Table 1: Proposed link coordinates and possible hop distance.

Path profile	Radio terminal sites	
	Bahir Dar	Woretta
Latitude	11°35′44.78″N	11°55′31.51″N
Longitude	37°23′10.33″E	37°41′40.32″E
Elevation	1802.4 m	1825.7 m
Maximum hop distance	49.59 km from Woretta	49.59 km from Bahir Dar

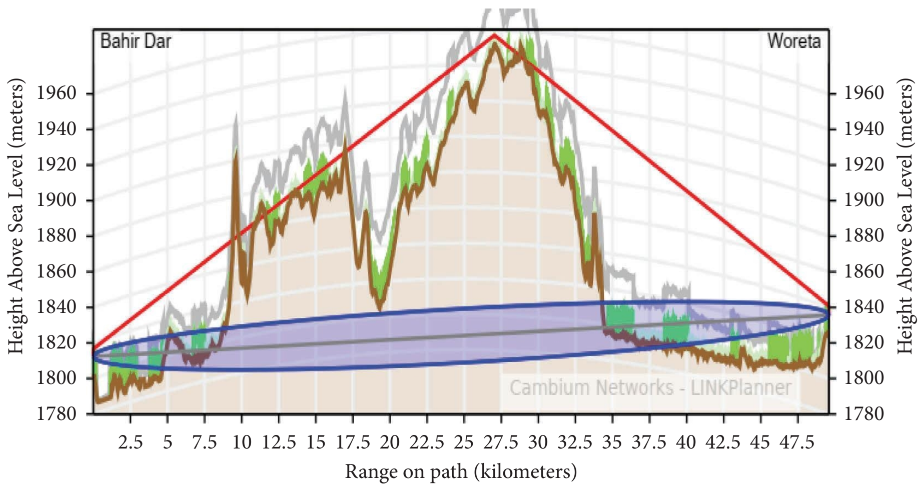

Figure 3: Path profiles from Bahir Dar to Woretta.

Figure 4: The hops from Bahir Dar to Zege and from Zege to Woretta.

Table 2: Coordinates of hop between Bahir Dar to Zege and Zege to Woretta.

Path profile	Radio terminal sites		
	Bahir Dar	Woretta	Zege
Latitude	11°35′44.78″N	11°55′31.51″N	11°41′58.68″N
Longitude	37°23′10.33″E	37°41′40.32″E	37°20′9.53″E
Elevation	1802.4 m	1825.7 m	1981.4 m
Maximum hop distance	12.7 km from Zege	46.4 km from Zege	46.4 km to Woretta and 12.7 km from Bahir Dar

19.498 km from Zege, with maximum elevations (heights) of 1847.9 m and 1884.6 m, respectively. The path profile of this link was generated using the data provided in Table 2 and analyzed using LINKPlanner 5.4.1 and Google Earth software [4, 5].

In Figure 6, it can be observed that the Zege terminal has a higher elevation than the obstacle height, while the Woretta site has a lower elevation than the obstacle. Due to the presence of the obstacle, the link does not have a clear LOS. However, this issue can be resolved by utilizing antennas with sufficient height at both terminals.

In Figure 6, the red line represents the clear LOS, while the blue line indicates the FFZ. For a clear LOS, the red line must be within the blue lines (FFZ).

Note. From the two figures, it is evident that both links do not have a clear LOS. Therefore, in order to establish a reliable microwave link communication, it is necessary to

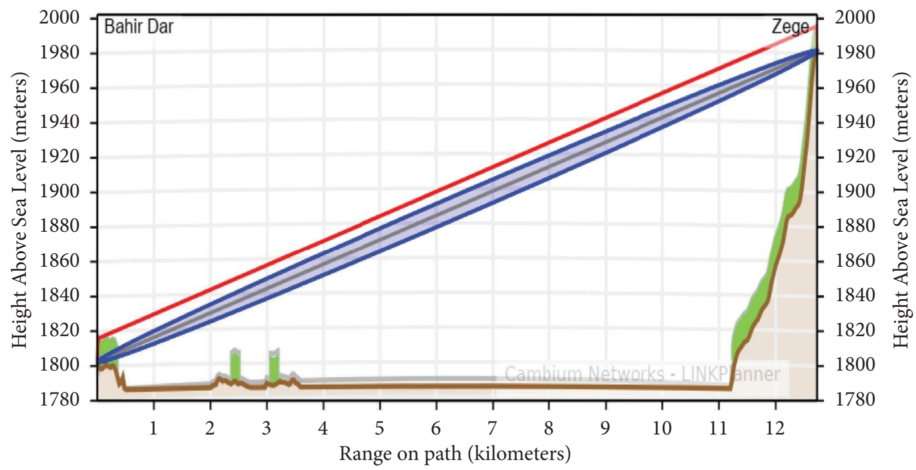

FIGURE 5: Path profile from Bahir Dar to Zege and their elevation.

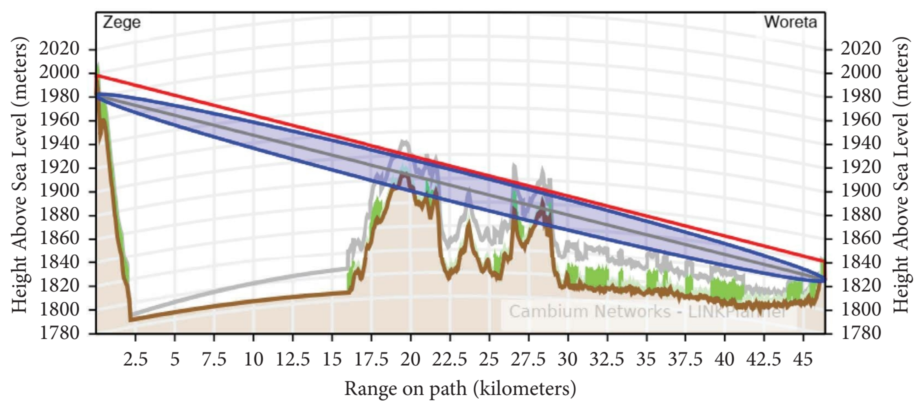

FIGURE 6: Path profile between Zege and Woretta and their elevation.

install antennas at each site terminal with sufficient height. These antennas will help overcome the obstacles and ensure a reliable and uninterrupted communication link.

4. Frequency Planning

The operating frequency of the microwave link is chosen based on the operating frequency of the existing link in the direction of the proposed link and the hop distance. This is done to prevent interference and minimize path loss. In this case, the existing link at Bahir Dar station operates at a frequency band of 4 GHz. Therefore, the frequency selected for the new link should be different from this band.

For our design, we have opted to use the 7 GHz frequency band. The frequency bands of the first and second hop are arranged and presented in Table 3. These frequencies have been carefully selected to ensure efficient and interference-free communication along the proposed microwave link based on ITU-R [6].

Considering the frequency bands mentioned above for the proposed link, the frequencies for both hops in the upper and lower bands are arranged as follows: the duplex frequency is set at 154MHz, a guard band of 3MHz is allocated, and the center band spans 14MHz.

The upper and lower frequency bands for the first hop are 7722 MHz to 7582 MHz which is used for the link from Zege to Bahir Dar and 7428 MHz to 7568 MHz which is used for the link from Bahir Dar to Zege, respectively.

For the second hop, the upper and lower frequency bands are 7282 MHz to 7422 MHz which is used for the link from Woretta to Zege and 7268 MHz to 7128 MHz which is used for the link from Zege to Woretta, respectively. By arranging the frequencies in this manner the higher frequencies are transmitted from Zege, which helps avoid conflicts in terms of high/low frequencies at Zege site.

5. First Fresnel Zone (FFZ) Calculation

In a feasible link, it is desirable to have at least 60% of the FFZ free from any type of obstruction along the communication path. The size of the FFZ depends on the distance between the transmitter and the receiver (known as the hop distance) as well as the operating frequency. The maximum radius of the FFZ can be calculated using the following formula:

$$F = 8.657\sqrt{\frac{d}{f}}, \quad (1)$$

Table 3: Frequency bands for each hop.

Station	Units	Frequency band	Center frequency	Duplex frequency (MHz)
Bahir Dar to Zege	MHz	7425–7725	7575	154
Zege to Woretta	MHz	7125–7425	7 275	154

where F = first Fresnel zone in meters, d = the maximum hop length in km, and f = operating frequency of the link in GHz.

When obstruction occurs between the two terminals, the first Fresnel zone is calculated by [7–9]

$$F_1 = 17.3\sqrt{\frac{d_1 * d_2}{f * d}}, \tag{2}$$

where F_1 = first Fresnel zone radius in meters, d_1 = distance of P from one end in km, d_2 = distance of P from the other end in km, and $d = d_1 + d_2$ in km.

It is important to note that this formula assumes a clear LOS between the transmitter and the receiver. If there are any obstacles or obstructions along the path, the size of the FFZ may be reduced, leading to potential signal degradation or interference.

5.1. FFZ: Bahir Dar to Zege. The maximum 60% FFZ radius of this path is calculated using equation (1)

$$F = 8.657\sqrt{\frac{d}{f}} = 8.657\sqrt{\frac{12.7}{7.425}} = 11\ \text{m}, \tag{3}$$

where d = distance from Bahir Dar to Zege in km = 12.7 km and f = operating frequency of the link = 7.425 GHz.

Based on the given information, the FFZ radius of the hop from Bahir Dar to Zege is 11 m, which represents 60% of the FFZ radius. The FFZ radius, as shown in Figure 7, is free from any obstructions and meets the criteria for microwave link design.

5.2. FFZ: Zege to Woretta. Using equation (2) and considering the following parameters: the operating frequency of the link (f = 7.125 GHz), the distance from Zege to the obstacle (d_1 = 19.5 km), and the distance from the obstacle to Woretta (d_2 = 26.9 km), the 60% radius of the FFZ for the given link can be determined.

$$F_1 = 17.3\sqrt{\frac{19.5 * 26.9}{7.125\,(19.5 + 26.9)}} = 21.6\ \text{m}. \tag{4}$$

Based on the given information, it is stated that there is a clear LOS between the two sites, and 60% of the FFZ is free from any obstructions. The FFZ radius from Zege to Woretta is shown in Figure 8.

6. Antenna Height Calculation

The antenna height of the microwave link is calculated based on Rec. ITU-R P.530-14. For the first hop, the antenna height (A_h) is calculated as 1.0 times the FFZ radius (F1), which results in 1 ∗ 11 m = 11 m. We must consider the height of trees (15 m) and the growth of vegetables (3 m). Therefore, the minimum antenna height for the first hop is A_h = 11 m + 15 m = 26 m.

For the second hop, the antenna height (A_h) is calculated as 1.0 times the FFZ radius (F1) plus 15 m, resulting in 1 ∗ 21.6 m + 15 m = 36.6 m. This is the minimum antenna height for the second hop. In both hops, the antenna should not be mounted at a height less than the calculated values.

In our design, the antennas can be mounted at 35 m and 40 m for the first hop and the second hop, respectively, on the existing tower heights to provide more clearance. The first and second hop path profiles with the recommended antenna heights (35 m and 40 m) are shown in Figures 7 and 8, respectively. These figures indicate that the link is feasible and there is a clear LOS for both links (Bahir Dar to Zege and Zege to Woretta).

7. Microwave Link Path Analysis

The path analysis (or link budget) is carried out to measure the link. It is a calculation involving the gain and loss factors associated with the antennas, transmitters, transmission lines, and propagation environment, to determine the maximum distance at which a transmitter and receiver can successfully operate.

7.1. Free-Space Loss. Free-space loss (FSL) is always present, and it is dependent on distance and frequency. The FSL between two isotropic antennas is derived from the relationship between the total output power from a transmitter and the received power at the receiver. After converting to units of frequency and expressing it in the logarithmic (decibel) form, it can be calculated using the following equation: [7, 10, 11]

$$L_{\text{FSL}} = 92.45 + 20\log(f) + 20\log(\text{d})\,[\text{dB}], \tag{5}$$

where f = frequency (GHz) and d = LOS range between antennas (km).

7.2. Received Signal Level. The received signal level (RSL) is the power level entering at the first active stage of the receiver. In most cases since the same duplex radio setup is applied to both stations, the calculation of the received signal level is independent of direction.

RSL can be calculated by the following formula:

$$\text{RSL} = P_t - L_{\text{ctx}} + \text{G}_{\text{atx}} - L_{\text{crx}} + G_{\text{atx}} - \text{FSL}\ [\text{dBm}], \tag{6}$$

where RSL ≥ Rx (receiver sensitivity threshold), P_t = output power of the transmitter (dBm), L_{ctx} = loss (cable, connectors, and branching unit) between transmitter and antenna (dB), L_{crx} = loss (cable, connectors, and branching unit) between receiver and antenna (dB), G_{atx} = gain of transmitter/receiver antenna (dBi), and FSL = free-space loss (dB).

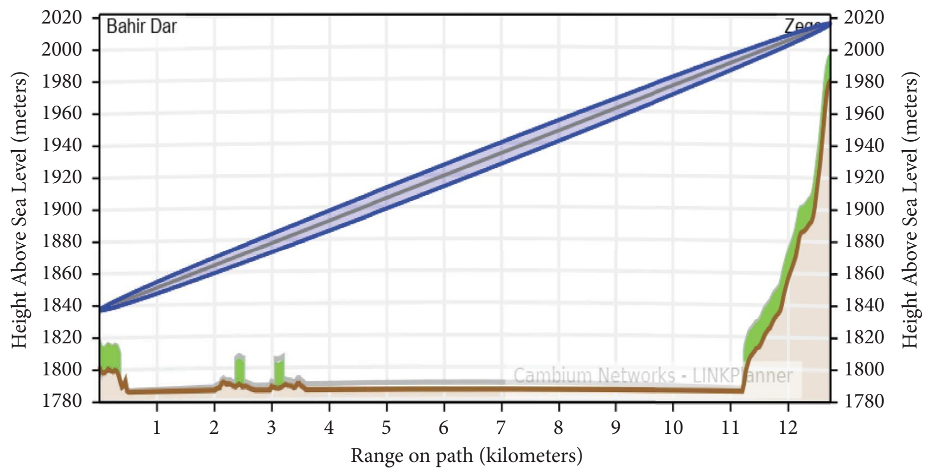

FIGURE 7: Path profile between Bahir Dar and Zege with antenna height of 35 m at both sides.

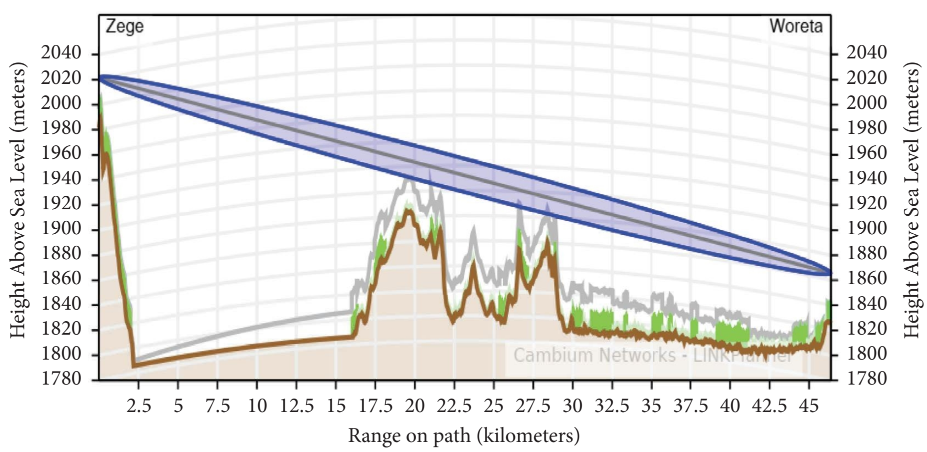

FIGURE 8: Path profile between Zege and Woretta with antenna height of 40 m at both sides.

8. Rain Attenuation Calculation

Rain attenuations are considered one of the factors that decrease the magnitude of the received power in microwave link, so it must be considered in link budget analysis by collecting the rain rates at the selected site of the link. For our design, rainfall rate data for a 23-year period in Bahir Dar, as well as 30-year data for Zege and Woretta, were gathered from the National Meteorology Agency of Ethiopia.

8.1. Rain Attenuation Calculation for the First Hop (Bahir Dar to Zege). The rain attenuation calculations are calculated based on ITU-R Model of Rain Attenuation because the rain attenuation is minimum in this model when compared to other methods. It is calculated by using the following steps [12].

Step 1: Obtain the rain rate $R_{0.01}$ exceeded for 0.01% of the time (with an integration of 1 min). In Bahir Dar, the monthly rain in mm is 1840 and based on ITU-R P.837-6, the rain rate is 57 mm/h [13, 14].

Therefore, $R_{0.01} = 57$ mm/h.

Step 2: Compute the specific attenuation, γ (dB/km) for 7 GHz frequency band, vertical polarization, and the above rain rate. It can be described as follows:

$$\Upsilon = \mathrm{k}\mathrm{R}^{\alpha}, \quad (7)$$

where Υ = rain rate at p% probability and k, α = functions of frequency, f (GHz), in the range 1 to 1000 GHz.

The specific attenuation is computed based on ITU-R P.838-3 for 7 GHz frequency using $k = 0.00265$ and $\alpha = 1.312$ [7, 15]. The calculation is done by using equation (7) as follows:

$$\Upsilon = 0.00265 * 57^{1.312} = \frac{0.53\,\mathrm{dB}}{\mathrm{km}}. \quad (8)$$

Step 3: Compute the effective path length d_{eff}, of the link by multiplying the actual path length (d) by a distance factor r. Before computing effective path length we must calculate distance factor r given by [8]

$$r = \frac{1}{0.477d^{0.633}R_{0.01}^{0.073\alpha}f^{0.123} - 10.579(1 - \exp(-0.024d))}, \quad (9)$$

where d is path length in km and f is frequency in GHz.

Based on the above equation, by using $d = 12.7$ km and $f = 7$ GHz, the distance factor can be determined by using equation (9).

$$r = 0.594. \quad (10)$$

Step 4: An estimate of the path attenuation exceeded for 0.01% of the time is given by [8]

$$A_{0.01} = \gamma d_{\text{eff}} = \Upsilon d.r \text{ dB}. \quad (11)$$

By using the values of distance factor and specific attenuation from the above analysis, the estimated path attenuation exceeded for 0.01% is calculated by using equation (11).

$$A_{0.01} = \frac{0.53 \text{ dB}}{\text{km}} * 12.7\text{km} * 0.594 = 4 \text{ dB}. \quad (12)$$

8.2. Rain Attenuation Calculation for the Second Hop (Zege to Woretta). The rain attenuation calculations are calculated based on ITU-R Model because the rain attenuation is minimum when compared to other methods [12]. It is calculated by using the following steps.

Step 1: Obtain the rain rate $R_{0.01}$ exceeded for 0.01% of the time (with an integration of 1 min). Based on ITU-R P.837-6, the rain rate at Zege is 60 mm/h [13, 14].

Therefore, $R_{0.01} = 60$ mm/h.

Step 2: Compute the specific attenuation, γ (dB/km) for 7 GHz frequency, vertical polarization, and the above rain rate. The specific attenuation is computed based on ITU-R P.838-3 for 7 GHz frequency using $k = 0.00265$ and $\alpha = 1.312$ [7, 15]. The calculation is done by using equation (7) as follows:

$$\Upsilon = 0.00265 * 60^{1.312} = \frac{0.6 \text{ dB}}{\text{km}}. \quad (13)$$

Step 3: Compute the effective path length, deff, of the link by multiplying the actual path length (d) by a distance factor r. Before computing effective path length, we must calculate distance factor r by using equation (9) [8]. Based on equation (9), by using $d = 46.4$ km and $f = 7$ GHz, the distance factor becomes

$$r = 0.323. \quad (14)$$

Step 4: An estimate of the path attenuation exceeded for 0.01% of the time is calculated by using equation (11).

$$A_{0.01} = \frac{0.6 \text{ dB}}{\text{km}} * 46.7 \text{ km} * 0.323 = 9 \text{ dB}. \quad (15)$$

The rain attenuation of the second hop is greater than the first hop because the hop distance and rain rate are greater. Rain attenuation is directly proportional to the rain rate and path length.

9. Fade Margin

Fade margin is the difference between the receiver's signal level at full strength and a receiving antenna's sensitivity. In the propagation path, determining sufficient fade margin is the most important step in microwave link design. If the margin is too small, the link will be unstable; as a result, sufficient availability of the link or quality of the provided services cannot be guaranteed.

A wide fade margin helps to assure link availability in case the signal is weak. Fade margin is calculated as follows [16, 17]:

$$\text{FM} = \text{RSL} - \text{RS [dB]}, \quad (16)$$

where FM = Fade Margin (dB), RSL = Received Signal Level (dBm), and RS = Receiver Sensitivity (dBm).

10. Link Budget Calculation of the Recommended Link

The recommended link has two hops. The link budget is calculated to know the reliability of the link to be designed by selecting different equipment with the appropriate rating [16]. The specification of the equipment used at the transmitter and receiver site is shown in Table 4 [18, 19].

10.1. Link Budget Calculation from Bahir Dar to Zege. In order to calculate the link budget, we use the specifications of the equipment given in Table 4.

10.1.1. FSL. It is the first and most important step in link budget analysis, and it depends on the operating frequency and the hop distance. It can be calculated using equation (5), with frequency (GHz) = 7.425 and d = link distance (km) = 12.7.

$$\begin{aligned} L_{\text{FSL}} &= 92.45 + 20\log(7.425) + 20\log(12.7)\,[\text{dB}], \\ L_{\text{FSL}} &= 92.45 + 17.41 + 22.1, \\ L_{\text{FSL}} &= 132 \text{ dB}. \end{aligned} \quad (17)$$

10.1.2. RSL. It is the amount of power reached at the receiver unit and can be evaluated by using link budget parameter values specified in Table 4 and the free-space loss. It can be calculated by using equation (6), based on the following parameter ratings.

Table 4: Specifications of equipment used at transmitter and receiver site.

Freq. bands (GHZ)		7
Full-duplex		FDD
Operating frequency		7125 MHz to 7900 MHz
Max uncompressed capacity		490–750 Mbps full duplex—varies by modulation, bandwidth, and packet mix
Modulation		QPSK
Power supply (V)		−45 to −72 Vdc direct or using PoE
Power consumption		48 to 72 watts dependent on sub-band
RF output power (dBm)		30
Receiver threshold		−94.4
Antenna gain (dBi) medium (0.9 m diameter)		35.5
Type of cable	Operating frequency	Loss in dB per 100 feet
LMR-900	7 GHz	2.9

$P_t = 30$ dBm.

$L_{ctx} = 6.467$ dB + 0.025 dB = 6.49 dB; because the cable length at the transmitter side is 68 m, it has 6.467 dB loss and 0.025 dB is connector loss.

$L_{crx} = 5.7$ dB + 0.025 dB = 5.725 dB; because the cable length at the transmitter side is 60 m, it has 5.7 dB loss and 0.025 dB is connector loss between transmitter/receiver and antenna (dB).

$$
\begin{aligned}
\text{Gatx} &= 35.5\ \text{dBi},\\
\text{Garx} &= 35.5\ \text{dBi},\\
\text{FSL} &= 132\ \text{dB},\\
R_t &= \text{rain attenuation (dB)} = 4,\\
\text{RSL} &= 30\ \text{dBm} + 35.5\ \text{dBi} - 6.49\ \text{dB} + 35.5\ \text{dBi} - 5.725\ \text{dB} - 132\ \text{dB} - 4\ \text{dB} = -47.3\ \text{dBm}.
\end{aligned}
\tag{18}
$$

10.1.3. FM. The presence of a fade margin ensures the reliability of the link. When the fade margin of the link is less than 10 dB, there is no reliable communication; therefore, the link margin of any link must be greater than 10 dB. It is calculated as follows by using equation (16):

$$
\begin{aligned}
\text{RSL} &= -47.3\ \text{dBm},\\
\text{RS} &= -94.4\ \text{dBm},\\
\text{FM} &= \text{RSL} - \text{RS} = -47.3\ \text{dBm} - (-94.4\ \text{dBm}) = 47\ \text{dB}.
\end{aligned}
\tag{19}
$$

The link margin of the link designed from Bahir Dar to Zege is greater than 10 dB, and hence the communication established in this link is reliable and guaranteed.

10.2. Link Budget Calculation from Zege to Woretta

10.2.1. FSL. The free space of the above link is calculated by using the hop distance between Zege and Woretta and the selected operating frequency. And equation (5) is used to calculate FSL.

$$
\begin{aligned}
f &= \text{frequency (GHz)} = 7.125,\\
d &= \text{LOS range between Zege and Woretta (km)} = 6.375,\\
L_{FSL} &= 92.45 + 20\log(7.125) + 20\log(46.4)\,[\text{dB}],\\
L_{FSL} &= 92.45 + 17.0556 + 33.326,\\
L_{FSL} &= 142.8\ \text{dB}.
\end{aligned}
\tag{20}
$$

10.2.2. RSL. It is the amount of power reached at the receiver unit, and it can be calculated by equation (6) using the following data.

$L_{ctx} = 5.7\,dB + 0.025\,dB = 5.725\,dB$; because the cable length at the transmitter side is 60 m, it has 5.7 dB loss and 0.025 is connector loss between transmitter/receiver and antenna (dB).

$L_{crx} = 5.7\,dB + 0.025\,dB = 5.725\,dB$; because the cable length at the transmitter side is 60 m, it has 5.7 dB loss and 0.025 is connector loss between transmitter/receiver and antenna (dB).

$$\begin{aligned} \text{FSL} &= 142.8\,\text{dB},\\ R_t &= \text{rain attenuation (dB)} = 9,\\ \text{RSL} &= 30\,\text{dBm} + 35.5\,\text{dBi} - 5.725\,\text{dB} + 35.5\,\text{dBi} - 5.725\,\text{dB} - 142.8\,\text{dB} - 9\,\text{dB} = -62.3\,\text{dBm}. \end{aligned} \tag{21}$$

10.2.3. FM. It assures the reliability of the link and is calculated as follows by equation (16):

$$\begin{aligned} \text{RSL} &= -62.3\,\text{dBm},\\ \text{RS} &= -94.4\,\text{dBm},\\ \text{FM} &= \text{RSL} - \text{RS}\\ &= -62.3\,\text{dBm} - (-94.4\,\text{dBm})\\ &= 32\,\text{dB}. \end{aligned} \tag{22}$$

The FM of the second hop is also greater than the recommended FM values (10 dB), so it indicates that the link is reliable but degree of reliability is less than the first hop.

11. Interference Prediction

When an unwanted signal is picked up by a radio receiver, it is known as interference. These interfering signals can originate from various sources. One of the most common types of interference sources is related to frequency planning, which can lead to issues such as insufficient bandwidth adherence, improper installation, outdated equipment, and the unwanted (interfering) signal from the interfering links.

The ratio of the desired signal to the unwanted (interfering) signal can be determined by considering the power received from the desired link and the interfering signal from the interfering transmitter that may enter the receiver.

The wanted signal S at the connector point of the receiver antenna is calculated as [20]

$$S\,[\text{dBm}] = P_{RX,S} = P_{TX,S} + G_{TX,S} + G_{RX,S} - \text{FSL}_S - L_S, \tag{23}$$

where $P_{TX,S}$ is the transmitted power of the wanted signal, $G_{TX,S}$ is transmitter antenna gain compared to the isotropic one, given in dBi units, $G_{RX,S}$ is the receiver antenna gain compared to the isotropic one, given in dBi units, FSL_S in dB is the free-space loss of the victim path, and L_S in dB units reflects other propagation losses such as obstacles in the victim path, e.g., buildings, power pylons, or trees. Due to interference, the victim path may experience degradation in the bit error rate (BER), and it becomes challenging to maintain long-term availability targets. The power level of the interfering signal, $P_{RX,I}$, received at the antenna connector point of the victim receiver can be calculated as follows [20]:

$$I\,[\text{dBm}] = P_{RX,I} = P_{TX,I} + G_{TX,I} + G_{RX,S} - \text{Discr}\left(\theta_S, \theta_I, \frac{V}{H}\right) - \text{FSL}_I - L_I, \tag{24}$$

where $P_{TX,I}$ is the power emitted by the interfering transmitter, $G_{TX,I}$ is interferor transmitter antenna gain compared to the isotropic antenna gain, given in dBi units, $G_{RX,S}$ is the antenna gain of the victim receiver compared to the isotropic one, given in dBi units, Discr is the total antenna (spatial) discrimination, in dB, FSL_I is the free-space loss in the interference path, and L_I reflects other losses in the interfering path, e.g., obstacles, buildings, power pylons, or trees. Spatial discrimination is depending on the following three main factors: θ_S gives discrimination due to the angle between the main lobe of the victim path and the interference path, θ_I gives the discrimination due to the angle between the main lobe of the interfering signal and the victim path, and V/H corresponds to polarization discrimination [20]. These three factors collectively contribute to spatial discrimination systems.

The signal to interference ratio is calculated then from the equations (22) and (23) as follows:

$$\frac{S}{I}\,[\text{dB}] = 10\log_{10}\left(\frac{P_{RX,S}}{P_{RX,i}}\right) = S\,[\text{dBm}] - I\,[\text{dBm}]. \tag{25}$$

In our design, both links interfere with each other and potentially affect other links in the vicinity of each site. However, the level of interference in the proposed link is minimal due to several factors. Firstly, the link has been equipped with sufficient bandwidth to accommodate the desired signal without significant degradation. Additionally, careful frequency planning has been implemented to minimize the chances of interference from other sources. Lastly, the use of new radio equipment ensures optimal performance and reduces the likelihood of interference.

12. Link Reliability (Performance) Evaluation

The path availability (also called link reliability) is the percentage of time that the received signal is above the required threshold, P_{req}. It is sometimes expressed as the expected minutes of outage per year. The path availability is a function of the radio frequency, diversity (if any), fade margin, path length, and local climate.

The International Telecommunication Union publishes reports with empirical models of required fade margin for different parts of the world. The percentage of time represents the outage time for a given link budget [17].

The calculation of the percentage of time (p_w) in which the fade depth (A) (in dB) is exceeded during the average worst month is performed using the following equation [7].

$$p_w = k * d^{3.6} * f^{0.89}\left(1 + |\varepsilon_p|\right)^{-1.4} * 10^{-A/10} \quad \%, \tag{26}$$

where k = geoclimatic factor, d = path distance in km, f = frequency in GHz, and A = fade margin in dB.

The path inclination $|\varepsilon_p|$ (mrad) of the link is calculated from the antenna heights of the transmitter and receiver (m above sea level or some other reference height), and it is calculated as follows [5, 7, 17]:

$$\varepsilon_p = \frac{(h_A - h_B)}{d}, \tag{27}$$

where h_A = antenna height + ground elevation at transmitter, m, and h_B = antenna height + ground elevation at receiver, m.

Geoclimatic (k) factors are an additional parameter that determines the percentage of time for the average worst month. It can be calculated using

$$k = 10^{-\left(5.9 - C_{\text{Lat}} - C_{\text{Log}}\right)} \text{PL}^{1.5}. \tag{28}$$

The aforementioned link equation is utilized due to the proposed link traversing medium-sized bodies of water, including a portion of Lake Tana. In accordance with ITU recommendations, the calculation of the geoclimatic factor (k) involves four categories, two for land links and two for over-water links. Estimation of k can be carried out by referring to contour maps provided in Figures of ITU-RPN.453-4, specifically Figures 7 and 8. This estimation is based on the percentage of time (PL) during which the average refractivity gradient in the lowest 100 m of the atmosphere is below 100 N-units per km [10].

The value of PL is determined using figures from ITU-R PN.453-4. According to these figures, the values of PL are determined to be 5, 20, 10, and 1 for the months of November, August, May, and February, respectively. To determine the final value of PL, we select the highest value among these, which is 20. Additionally, we take 0 dB as the value of C_{Lat} and 0.3 dB as the value of C_{Lon}. We can calculate the result by using equation (28).

$$k = 10^{-(5.9-0-0.3)} 20^{1.5} = 2.247 * 10^{-4}. \tag{29}$$

12.1. Link Reliability from Bahir Dar to Zege. After we determine geoclimatic factors, path inclination will be calculated by using equation (27) with $h_A = 1837.4$ m, $h_B = 2016.4$ m, and Path Length (d) = 12.7 km.

$$\varepsilon_p = \frac{(1837.4\,\text{m} - 2016.4\,\text{m})}{12.7\,\text{km}} = -14.09\,\text{mrad}. \tag{30}$$

And we use fade depth $(A) = 47$ dB and percentage of time (p_w) by using equation (26).

Finally,

$$p_w = 2.247 * 10^{-4} * 12.7^{3.6} * 7.425^{0.89} * (1 + |-14.09|)^{-1.4} * 10^{-47/10} = 5.63 * 10^{-6} = 0.0000000563\%. \tag{31}$$

We can consider that the above outage (unavailability) is due to propagation outage.

The outage is expressed in terms of hour, minute, and second. Let us consider that 1 year has 8760 hr, 525,600 min, or 31,536,000 sec. Then the annual expected outage of this link with unavailability of 0.0000000563% is

$$\begin{aligned} 8760\,\text{hr} * 0.000000000563 &= 0.00000493188\,\text{hr}, \\ 525,600\,\text{min} * 0.000000000563 &= 0.0002959128\,\text{min} \\ 31,536,000\,\text{sec} * 0.000000000563 &= 0.017754768\,\text{sec.}, \end{aligned} \tag{32}$$

Therefore, unavailability occurs in this hop 0.00000493188 hr, 0.0002959128 min, or 0.017754768 sec annually.

The availability of this link is determined based on the outage of the worth month or time percentage and it can be calculated as follows.

$$\text{Link availability}\,(p_A)\% = 100\% - p_w\% = 100\% - 0.0000000563\% = 99.9999999437\%. \tag{33}$$

From the above unavailability and availability values, we can say the link is reliable.

12.2. Link Reliability from Zege to Woretta. To calculate the reliability or availability of this link, we take the same procedures and k values of the first hop. Simply, we determine the inclination of path by equation (27), using $h_A = 2021.4$ m, $h_B = 1865.4$ m, and Path Length (d) = 46.4 km.

$$\varepsilon_p = \frac{(2021.4\,\text{m} - 1865.4\,\text{m})}{46.4\,\text{km}} = 3.362\,\text{mrad}. \quad (34)$$

The calculation of the percentage of time for the worst month is determined using equation (26), wherein the fade depth (A) is specified as 32 dB.

$$p_w = 2.247 * 10^{-4} * 46.4^{3.6} * 7.125^{0.89} * (1 + |3.362|)^{-1.4} * 10^{-32/10} = 10.3 * 10^{-3} = 0.0001\%. \quad (35)$$

The cause of this outage (unavailability) appears to be a propagation issue in the first hop. Upon analysis, it is evident that the outage in the second hop is more significant than that in the first hop.

The outage is expressed in terms of hour, minute, and second. Let us consider that 1 year has 8760 hr, 525,600 min, or 31,536,000 sec. Then the annual expected outage of this link with unavailability of 0.0001% is

$$\begin{aligned} 8760\,\text{hr} * 0.000001 &= 0.00876\,\text{hr}, \\ 525,600\,\text{min} * 0.000001 &= 0.5256\,\text{min}, \\ 31,536,000\,\text{sec} * 0.000001 &= 31.536\,\text{sec}. \end{aligned} \quad (36)$$

Therefore, unavailability occurs in this hop 0.00876 hr, 0.5256 min, or 31.536 sec annually.

The availability of this link is determined by calculating the outage percentage over a specific period, such as a month, and can be computed as follows.

$$\text{Link availability}\,(p_A)\% = 100\% - p_w\% = 100\,\% - 0.0001\% = 99.9999\%. \quad (37)$$

Based on the provided unavailability and availability values, we can conclude that the link is reliable. However, its reliability is lower compared to the first hop due to the high propagation loss.

13. Conclusion

Initially, a direct microwave link between Bahir Dar and Woretta was proposed due to the economic significance of Woretta as a growth center in the Amhara Region. However, Figure 3 reveals that there is a high-elevation obstacle along the path between the two sites, preventing the realization of this direct link due to non-line-of-sight (NLOS) propagation. Consequently, an alternative proposal involving a two-hop connection from Bahir Dar to Zege and from Zege to Woretta was considered. The link's path budget, free-space path loss, rain attenuation, fade margin, and reliability were calculated and simulated. The results align with practical expectations.

The path profiles and first Fresnel zone (FFZ) radii of the two-hop link, without antenna and with antenna heights of 35 m and 40 m, are depicted in Figures 5–8 for the first and second hops, respectively. These illustrations demonstrate that there are no obstructions impeding line-of-sight or affecting the FFZ radius. In other words, the feasibility of the two-hop links is confirmed.

The link availability of the two-hop connection was calculated based on ITU recommendations, resulting in a 99.9999999437% availability in the first hop and 99.9999% in the second hop, with a negligible outage or unavailability percentage of 0.0000000563% in the first hop and 0.0001% in the second hop. The fade margin exceeds the recommended values, with 47 dB in the first hop and 32 dB in the second hop. These values indicate that the designed link is highly reliable, ensuring the establishment of a quality service. The percentage availability and fade margin provide assurance of the link's quality and reliability, guaranteeing interference-free communication [21–37].

Acronyms

LOS: Line of sight
FFZ: First Fresnel zone
FSL: Free-space loss
FM: Fade margin
RSL: Received signal level
RS: Receiver sensitivity
P_t: Power of the transmitter
L_{ctx}: Loss (cable, connectors, and branching unit) between transmitter and antenna
L_{crx}: Loss (cable, connectors, and branching unit) between receiver and antenna

G_{atx}: Gain of transmitter antenna
G_{arx}: Gain of receiver antenna
km: Kilometer
m: Meter
GHz: Gigahertz
MHz: Megahertz
ITU: International Telecommunication Union
ITU-R: International Telecommunication Union Radio
NLOS: Non-line-of-sight
GPS: Global Positioning System.

Data Availability

No data were used to support this study.

Conflicts of Interest

The author declares that there are no conflicts of interest.

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