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DEVELOPMENT AND PERFORMANCE ANALYSIS OF BISECTION METHOD-BASED OPTIMAL PATH LENGTH ALGORITHM FOR TERRESTRIAL MICROWAVE LINK

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ABSTRACT

In this paper, Bisection method-based algorithm for the computation of optimal path length of terrestrial microwave link is presented. Also, performance analysis of the algorithm is presented in terms of the convergence cycle of the algorithm. The impact of various link parameters on the convergence cycle of the algorithm is also presented. Mathlab program was used to carry out sample numerical computation for a microwave link having the following parameters: frequency (f) = 12 GHz, transmit power (P_T) = 10dBm, transmitter antenna gain (G_T) = 35 dBi, receiver antenna gain (G_R) = 35 dBi, fade margin (fm_s) =20dB, receiver sensitivity (P_S) = -80dBm, Rain Zone = N, point refractivity gradient (dN1) = -400, link percentage outage $(po) = 0.01\%$. The results showed that the Bisection algorithm converged at the 17th cycle. It was found from the analysis that the convergence cycle of the algorithm varied linearly with frequency, decreasing with frequency from a value of 17 at frequency of 12 GHz to 15 at a frequency of 45 GHz. On the other hand, the convergence cycle varied nonlinearly with percentage availability of the link. Also, for a given frequency and link percentage availability the convergence cycle increased with increase in rain rate. The result of the research is very essential for microwave link designers to determine the optimal path length for effective link performance under different link configurations and locations.

Contribution/Originality: This study applies Bisection algorithm to determine the optimal path length of line of site wireless communication link. The Bisection method presented in this paper is simpler and easier to be applied in more situations than the Newton Raphson method. Used in Emenyi, et al. [1].

1. INTRODUCTION

As the adoption of wireless communication across the globe increases, wireless communication link designers seek to adopt measures to ensure optimal performance of the system. One factor that significantly impacts on system performance is the communication link path length [2-5]. Generally, the maximum link path is determined from the knowledge of the link parameters applied in the link budget equation [6-12]. With link budget, the expected received signal power can be determined and the percentage availability of the link under different weather conditions can also be ascertained.

In most cases, the focus has been on the maximum path length. However, research has found that such approach should be reconsidered given that it gives rise to more signal outages than what is expected by the design specifications [1]. In view of this , the concept of optimal path length is has been proposed in Emenyi, et al. [1]. Optimal path length is the transmitter to receiver distance at which the available fade margin is equal to the maximum fade depth expected from the fade mechanisms to which the signal will be subjected to as it propagates from the transmitter to the receiver. Previous studies have tried to determine the optimal path length using Newton Raphson iterative algorithm [1]. However, such approach requires differentiation of the operating mathematical expression before it can be applied. In this paper, the Bisection method is used. It is simple to apply to diverse situations without the complex mathematical exercises required in Newton Raphson's method.

2. METHODOLOGY

2.1. Analytical Model for Determination of the Optimal Path Length of Terrestrial Microwave Link

In wireless link design, the Free Space Path Loss (LFSP) is given as Aba [13]; Shamanna [14]; Tsai [15]; Mämmelä, et al. [16]; De Bruyne, et al. [17];

$$LFSP = 32.4 + 20\log(f*1000) + 20\log(d) \quad (1)$$

where f is frequency of the emitted signal in GHz and d is the length of the link in km. Also, in wireless link design, for any given fade margin (fms) and receiver sensitivity (Ps), the received signal (P_R) is given as:

$$P_R = fm_s + P_S \quad (2)$$

Also, based on link budget equation for wireless link, P_R can also be determined as follows [13-19]:

$$P_R = P_T + (G_T + G_R) - (LFSP + L_T + L_M + L_R) \quad (3)$$

where;

P_R = Received Signal Power (dBm)

P_T = Transmitter Power Output (dBm)

G_T = Transmitter Antenna Gain (dBi)

G_R = Receiver Antenna Gain (dBi)

LFSP = Free Space Path Loss (dB).

L_T = Losses from Transmitter (cable, connectors etc.) (dB)

L_R = Losses from Receiver (cable, connectors etc.) (dB)

L_M = Misc. Losses (fade margin, polarization misalignment etc.) (dB)

Based on Eq 1 to Eq 3 the path length (d) can be obtained as follows:

$$d = 10^{\left(\frac{(P_T + G_T + G_R - fm_S - P_S) - 32.4 - 20\log(f*1000)}{20}\right)} \quad (4)$$

The rain fade depth can be determined using ITU-R PN.838 recommendations, whereby the specific attenuation originating from rainfall is defined as $\gamma_{R_{po}}$ in dB/km and modelled using the power-law relationship as follows [13-19]:

$$\gamma_{R_{po}} = k\left(R_{po}\right)^{\alpha} \quad (5)$$

where R_{po} is the rainfall rate in mm/h exceeded for Po % of an average year . k and α are frequency dependent constants. The rain fade depth, A_{Rain} for a path length, d (in Km) is given as;

$$A_{Rain} = \left(\gamma_{R_{po}}\right)d = \left(k\left(R_{po}\right)^{\alpha}\right)d \quad (6)$$

In reality, k and α are given for the vertical polarization and horizontal polarization and hence, A_{Rain} is computed for vertical polarization and horizontal polarization and the larger of the two is the effective rain fade depth.

As regards multipath fading , the ITU quick planning applications model can be used , whereby for the percentage of time Po that fade depth, $A_{multipath}$ (dB) is exceeded in the average worst month and it is given as follows [1, 20, 21];

$$po = Kd^{3.1}(1+|\varepsilon_P|)^{-1.29} \left(f^{0.8}\right) 10^{\left(-0.00089h_L - \frac{(A_{multipath})}{10}\right)} \quad (7)$$

where:

d is the propagation path length or distance (in km) between the transmitter and the receiver

f is frequency (GHz)

h_L is altitude of lower antenna (m)

$A_{multipath}$ is multipath fade depth (dB)

$dN1$ is point refractivity gradient

K is geoclimatic factor and can be obtained from:

$$K = 10^{(-4.6-0.0027dN1)} \quad (8)$$

ε_P is the path inclination, (in mrad). ε_P is calculated using the following expression

$$|\varepsilon_p| = \frac{(|h_t - h_r|)}{d} \quad (9)$$

where:

d is the propagation path length or distance (in km) between the transmitter and the receiver

h_t is the antenna height of the transmitter

h_r is the antenna height of the receiver (where h_t and h_r are in meters about sea level),

$$h_L = minimum(h_t, h_r) \quad (10)$$

Hence, the multipath fade depth, $A_{multipath}$ (in dB) is obtained from the expression for Po as follows;

$$A_{multipath} = 10(-0.00089h_L) - (10)\log\left(\frac{po}{\{K(d^{3.1})(1+|\varepsilon_p|)^{-1.29}(f^{0.8})\}}\right) \quad (11)$$

In all, the larger of the rain fade depth and multipath fade depth is taken as the link maximum fade depth (fd_m) and it is expressed as;

$$fd_m = maximum(A_{multipath}, A_{Rain}) \quad (12)$$

The optimal path length (d_{mop}) is obtained when the following condition is fulfilled;

$$fd_m = P_R - P_S \quad (13)$$

2.2. Bisection Method of Solving a Nonlinear Equation

2.2.1. The Theorem behind the Bisection Method:

The bisection method is a numerical method used for finding the root of a nonlinear equation , such as $f(x)=0$ where $f(x)$ has at least a root between x_ℓ and x_u (as shown is Figure 1) [22-24]. If $f(x_\ell)f(x_u)<0$, there may be more than one root between x_ℓ and x_u otherwise when $f(x_\ell)f(x_u)>0$, there may or may not be any root between x_ℓ and x_u. Essentially, the bisection method guarantees at least one root between x_ℓ and x_u.

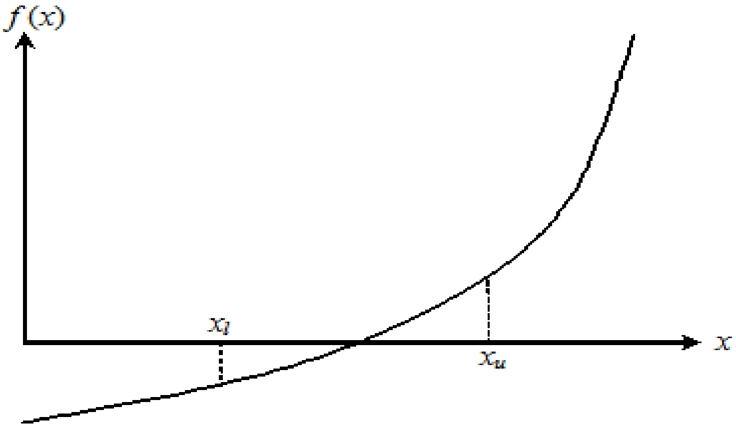

Figure-1. The root of a nonlinear equation by the bisection method.
Source: Kaw [25]

2.2.2. Application of Bisection Algorithm for Calculating the Optimal Path Length

In other to arrive at the optimal path length based on the condition in Eq 13, the value of d is adjusted by an adjustment value (d_{adj}) and the values of LFSP, fd_m and P_R are re-computed. The process is repeated until the optimal path length condition in Eq13 is satisfied. In the bisection method, the adjustment value for the i^{th} iteration is defined as $d_{adj}(i)$ and can be obtained as follows;

The upper limit of d is defined from Eq 3 as d_{up} where;

$$d_{up} = d = 10^{\left(\frac{(P_T + G_T + G_R - fm_S - P_S) - 32.4 - 20\log(f*1000)}{20}\right)} \qquad (14)$$

Now, replacing d with d_{up} in Eq 6 for the vertical polarization and horizontal polarization gives;

$$A_{Rain} = \text{maximum}\left(\left(K_v\left(R_{po}\right)^{\alpha_v}\right) * d_{up}, \left(K_h\left(R_{po}\right)^{\alpha_h}\right) * d_{up}\right) \qquad (15)$$

Also, replacing d with d_{up} in Eq 11 for multipath fading gives

$$\boldsymbol{A}_{multipath} = 10(-0.00089h_L) - (10)\log\left(\frac{po}{\left\{K\left((d_{up})^{3.1}\right)(1+|\varepsilon_p|)^{-1.29}(f^{0.8})\right\}}\right) \qquad (16)$$

Then Eq 12 gives

$$fd_{m(up)} = maximum\left(\boldsymbol{A}_{multipath}, A_{Rain}\right) \text{ where } d = d_{up} \qquad (17)$$

Using Eq 1 compute LFSP as follows LFSP = 32.4 + 20 log(f*1000) + 20 log(d_{up})

Use Eq 4 compute P_R as follows $P_R = P_T + (G_T + G_R) - (LFSP + L_T + L_M + L_R)$

Using Eq 2 to compute fm_e as follows

$$fm_e = P_R - P_S \qquad (18)$$

Then, the lower limit of d is defined as d_{Lw} where;

$$d_{Lw} = \frac{fm_e}{fd_{m(up)}} \qquad (19)$$

In this given cycle i, the adjustment value for the path length is defined as $d_{adj}(i)$ where;

$$d_{adj}(i) = \frac{(d_{up} + d_{Lw})}{2} \qquad (20)$$

Compute the percentage error, ϵ_a

$$|\epsilon_a| = \left(\frac{(d_{adj}(i) - d_{adj}(i-1))}{d_{adj}(i)}\right) * 100 \qquad (21)$$

In this research, what is used is $\left|\left(d_{adj}(i) - d_{adj}(i-1)\right)\right| < 0.001$; the iteration stops if the condition $\left|\left(d_{adj}(i) - d_{adj}(i-1)\right)\right| < 0.001$ is satisfied , otherwise the next $d_{adj}(i+1)$ is computed. Then, compute the following

$$Kfm = (P_T + G_T + G_R) - 32.4 - 20\log(f*1000) - P_S \qquad (22)$$

$$f(d_{up}) = \left(\gamma_{po}\right) d_{up} + 20\log\left(d_{up}\right) - Kfm \qquad (23)$$

$$f(d_{Lw}) = \left(\gamma_{po}\right) d_{Lw} + 20\log\left(d_{Lw}\right) - Kfm \qquad (24)$$

$$f(d_{adj}(i)) = \left(\gamma_{po}\right)\left(d_{adj}\right) + 20\log\left(d_{adj}\right) - Kfm \qquad (25)$$

If, $f(d_{Lw}) * f(d_{adj}(i) < 0$, then the root lies between d_{Lw} and $d_{adj}(i)$; then $d_{Lw} = d_{Lw}$ and $d_{up} = d_{adj}(i)$.

a) If $f(x_\ell)f(x_m) > 0$, $f(d_{up}) * f(d_{adj}) > 0$ then the root lies between $d_{adj}(i)$ and d_{up}; then $d_{Lw} = d_{adj}(i)$ and $d_{up} = d_{up}$

b) If $f(d_{up}) * f(d_{adj}(i) = 0$; then the root is $d_{adj}(i)$. Stop the algorithm if this is true.

If none of the two conditions

(i) $\left|\left(d_{adj}(i) - d_{adj}(i-1)\right)\right| < 0.001$ and

(ii) $f(d_{up}) * f(d_{adj}(i) = 0$ are satisfied then the iteration continues from Eq 19 given as $d_{adj}(i) = \frac{\left(d_{up} + d_{Lw}\right)}{2}$

If any of the two stated conditions is satisfied, the iteration stops and the $d_{adj}(i)$ at that point is the optimal path length. Then, the optimal fade margin (fm_{op}) and the Optimal Free Space Path Loss $(FSPL_{op})$ are given as follows;

$$fm_{op} = fd_m = maximum\left(\boldsymbol{A}_{multipath}, A_{Rain}\right) = P_R - P_S \qquad (26)$$

$$FSPL_{op} = 32.4 + 20\log(f*1000) + 20\log(d_{mop}) \qquad (27)$$

3. NUMERICAL COMPUTATION OF THE OPTIMAL PATH LENGTH USING THE BISECTION METHOD ALGORITHM

The bisection method optimal path length algorithm is computed using Mathlab program. the program was used to compute the optimal path length for a sample fixed point terrestrial LOS microwave link with the following link transmit power , equipment and geo-climatic parameters: Frequency (f) = 12 GHz, Transmit power (P_T) = 10dBm, Transmitter Antenna Gain (G_T) = 35 dBi, Receiver Antenna Gain (G_R) = 35 dBi, Fade Margin (fm_s) =20dB, Receiver Sensitivity (P_S) = -80dBm, Rain Zone = N, Point Refractivity Gradient (dN1) = -400, Link Percentage Outage $(po) = 0.01\%$. Also, Rain Fade Constants; $k_h = 0.01217$, $\alpha_h = 1.2571$, $k_v = 0.01129$, $\alpha_v = 1.2156$; Rain rate $(R_{po}) = 95$mm/h, transmitter antenna height $(h_t) = 295m$ and receiver antenna height (h_r)= 320m. For each simulation run, the convergence cycle (n) at which the optimal path length is obtained is noted along with other relevant parameters. The simulation was also carried out for different frequencies, namely 15 GHz, 18 GHz , 21GHz, …, 45 GHz. The simulation was also carried out for different network percentage availability namely; 99%, 99.7%, 99.9 %, 99.97%, 99.99%, 99.997% and 99.999%. Finally, the simulation was also carried out for different, namely; Rain Zone A, C,E,…,Q

4. RESULTS AND DISCUSSION

The numerical computation results for the optimal path length, the convergence cycle of the algorithm and the effect of various parameters on the convergence cycle are given in this section. In Table 1 to Table 3, as well as Figure 2 to Figure 3, frequency is 12 GHz and the rain zone is N, with percentage availability of 99.99%. The convergence cycle for the bisection algorithm is 17. That means, as shown in Table 1, Table 2, and Table 3, (as well as, Figure 2, Figure 3, and Figure 4), the bisection algorithm is iterated for 17 times before the optimal path length is obtained. Also, the optimal path length is 5.8905 km, the optimal free space path loss is 129.43 dB, the optimal fade margin the system can accommodate is 30.57 dB while the optimal fade depth is 30.65 dB. In essence, at the optimal path length, a maximum fade depth of 30.57 dB can be accommodated by the link. However, the maximum fade depth the rain and multipath fading can present at the optimal path length of 5.8905 km is 30.65dB which is 0.08 dB above the optimal fade margin.

Table-1. Bisection Method: Rain Fading, Multipath Fading , Free Space Path Loss , Effective Fade Margin , Effective Maximum Depth and Effective Path Length vs Number of Iterations

Number of Iterations (n)	Effective Rain Fading	Multipath Fading	Free Space Path Loss	Effective Fade Margin	Effective Fade Depth	Effective Path Length
0	104.03	26.59	140.04	19.96	104.03	19.99
1	19.98	0.00	125.71	34.29	19.98	3.84
2	19.98	0.00	125.71	34.29	19.98	3.84
3	30.49	5.30	129.38	30.62	30.49	5.86
4	30.49	5.30	129.38	30.62	30.49	5.86
5	30.49	5.30	129.38	30.62	30.49	5.86
6	30.49	5.30	129.38	30.62	30.49	5.86
7	30.49	5.30	129.38	30.62	30.49	5.86
8	30.49	5.30	129.38	30.62	30.49	5.86
9	30.65	5.40	129.43	30.57	30.65	5.89
10	30.65	5.40	129.43	30.57	30.65	5.89
11	30.65	5.40	129.43	30.57	30.65	5.89
12	30.65	5.40	129.43	30.57	30.65	5.89
13	30.65	5.40	129.43	30.57	30.65	5.89
14	30.65	5.40	129.43	30.57	30.65	5.89
15	30.65	5.40	129.43	30.57	30.65	5.89
16	30.65	5.40	129.43	30.57	30.65	5.89
17	30.65	5.40	129.43	30.57	30.65	5.89
18	30.65	5.40	129.43	30.57	30.65	5.89
19	30.65	5.40	129.43	30.57	30.65	5.89
20	30.65	5.40	129.43	30.57	30.65	5.89

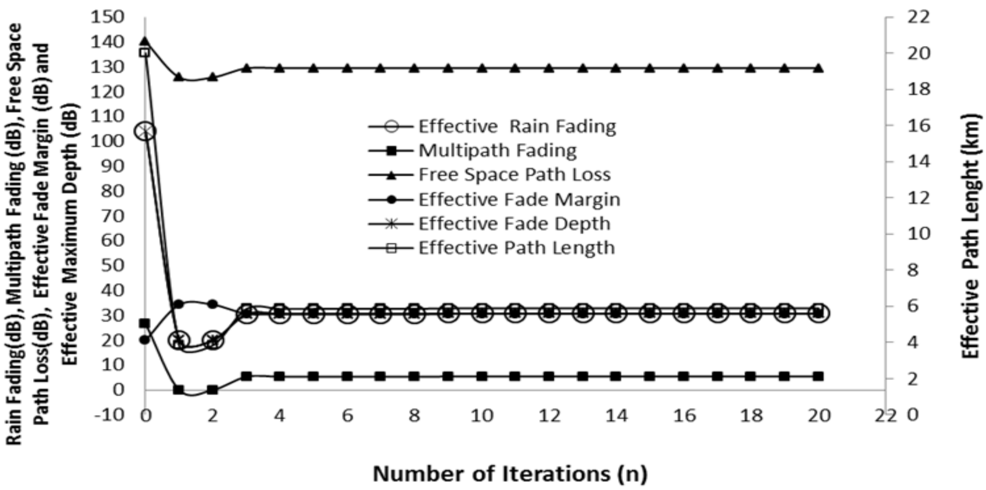

Figure-2. Bisection Method: Rain Fading, Multipath Fading , Free Space Path Loss , Effective Fade Margin , Effective Maximum Depth and Effective Path Length vs Number of Iterations (n)

Table-2. Bisection Method:Differential Fade Depth and Effective Path Length vs Number of Iterations

Number of Iterations (n)	Differential Fade Depth	Effective Path Length (de)
0	84.067	19.99
1	-14.307	3.84
2	-14.307	3.84
3	-0.132	5.86
4	-0.132	5.86
5	-0.132	5.86
6	-0.132	5.86
7	-0.132	5.86
8	-0.132	5.86
9	0.079	5.89
10	0.079	5.89
11	0.079	5.89
12	0.079	5.89
13	0.079	5.89
14	0.079	5.89
15	0.079	5.89
16	0.079	5.89
17	0.080	5.89
18	0.080	5.89
19	0.080	5.89
20	0.080	5.89

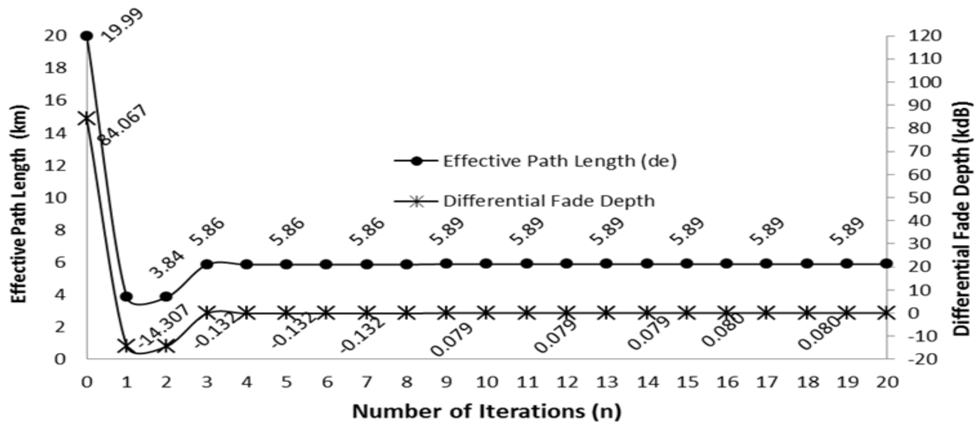

Figure-3. Bisection Method: Differential Fade Depth and Effective Path Length vs Number of Iterations (n)

Table-3. Bisection Method: Initial and Optimal Values For Free Space Path Loss, Fade Depth , Fade Margin, Received Power , Differential Fade Depth , Differential Path Length , Path Length and Convergence Cycle

	n	Free Space Path Loss (in dB)	Fade Depth (in dB)	Fade Margin (in dB)	Received Power (in dBm)	Path Length (in km)
Initial Value	**0**	140.04	104.03	19.96	-60.04	19.9903
Optimal Value	**17**	129.43	30.65	30.57	-49.43	5.8905

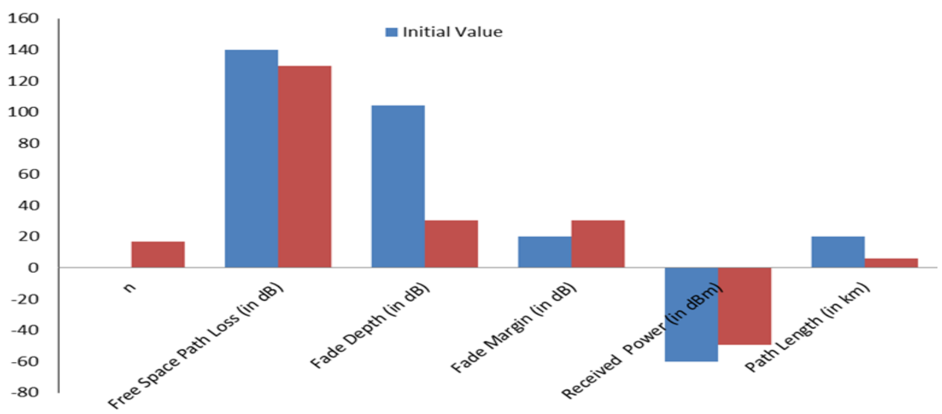

Figure-4. Bisection Method: Initial and Optimal Values For Free Space Path Loss, Fade Depth , Fade Margin, Received Power , Path Length and Convergence Cycle

Effect of Frequency on the convergence cycle the Bisection algorithm: With respect to the Bisection method, Table 4 and Figure 5 show how the various link parameters vary with frequency, from 3 GHz to 45 GHz. The convergence cycle for the Bisection algorithm varies from 17 at 12 GHz to 15 at 45 GHZ. Essentially, the bisection method converges faster as frequency increases. It can also be inferred from table 4 that the initial path length decreases as the frequency increases. As such, it can be said that the bisection algorithm converses faster as the initial path length decreases.

Table-4. Bisection Method: Initial Path Length, Optimal Path Length and Convergence Cycle vs frequency

f (GHz)	Convergence Cycle	Initial Path Length (km)	Optimal Path Length (km)
12	17	19.99	5.88
15	17	15.99	4.22
18	16	13.33	3.29
21	16	11.42	2.70
24	16	10.00	2.31
27	16	8.88	2.03
30	16	8.00	1.82
33	15	7.27	1.66
36	15	6.66	1.54
39	15	6.15	1.44
42	15	5.71	1.36
45	15	5.33	1.30

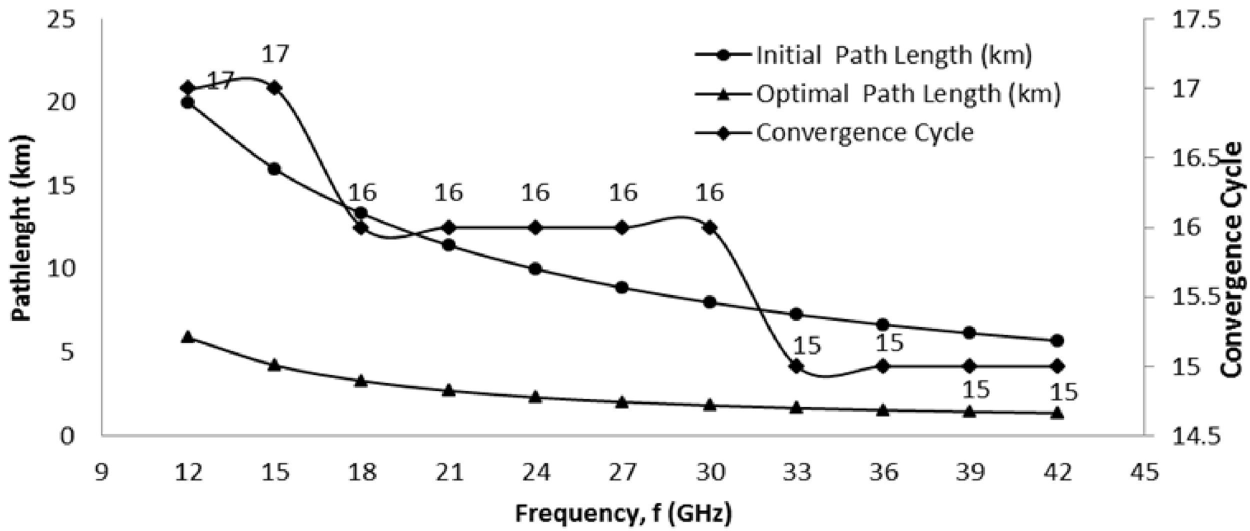

Figure-5. Bisection Method: Initial Path Length, Optimal Path Length and Convergence Cycle vs frequency

Effect of Percentage Availability on the convergence cycle the Bisection algorithm: With respect to the Bisection method, Table 5 and Figure 6 show how the various link parameters vary with seven different values of percentage availability of the link, from 99.0% to 99.999%. In Table 5 and Figure 6 , the convergence cycle for the Bisection algorithm varies from 18 at 99.0% link availability to 15 at 99.9% , and eventually to 17 to 15 at 99.999% link availability.

It is observed that as the percentage availability increases the rain fade depth increases and the optimal path length decreases. The convergence cycle is affected by both the rate at which the rain rate varies with link percentage availability and the value of the optimal path length. As such, the variation of the convergence cycle with link percentage availability is not linear.

Table-5. Bisection Method: Initial Path Length, Optimal Path Length and Convergence Cycle vs Percentage Availability

Percentage Availability, Pa (%)	Convergence Cycle	Initial Path Length (km)	Optimal Path Length (km)
99	18	15.99	30.63
99.7	15	15.99	19.45
99.9	16	15.99	9.92
99.97	16	15.99	5.88
99.99	17	15.99	4.22
99.997	17	15.99	2.99
99.999	17	15.99	2.38

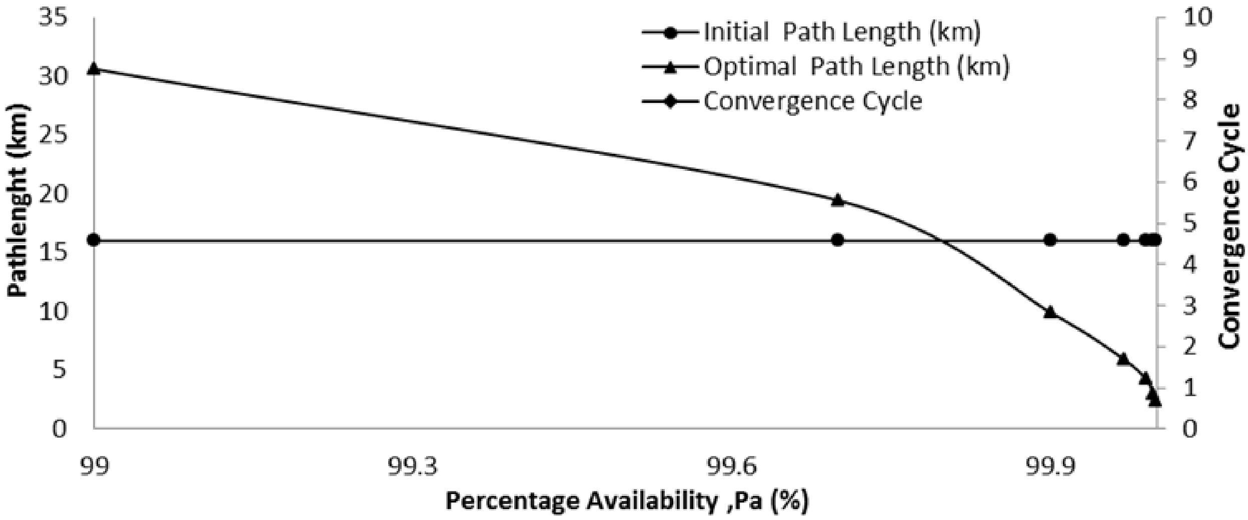

Figure-6. Bisection Method: Initial Path Length, Optimal Path Length and Convergence Cycle vs Percentage Availability ,Pa (%)

Effect of Rain Zone on the convergence cycle the Bisection algorithm: With respect to the Bisection method, Table 6 and Figure 7 show how the various link parameters vary with fifteen different values of rain zone , from rain zone A, C,E,…,Q. The convergence cycle for the Bisection algorithm is constant at 15 for rain zone A to G; 16 for rain zone J to L and then 17 for rain zone N to Q. Further examination shows that for a given link percentage availability the rain rate varies with the various rain zones; it has the lowest value in rain zone A and the highest value with rain zone Q. Again, smaller rain rate amounts to smaller rain fade depth and smaller optimal path length. It can be inferred from Table 6 that for the given link percentage availability , the initial path length is constant but the convergence cycle increases with increasing rain rate; from rain zone A with the lowest rain rate to rain zone Q with the highest rain rate.

Table-6. Bisection Method: Initial Path Length, Optimal Path Length and Convergence Cycle vs Rain Zone

Rain Zone	Rain Zone(#)	Convergence Cycle	Initial Path Length (km)	Optimal Path Length (km)
A	1	15	15.99	13.86
C	3	15	15.99	13.86
E	5	15	15.99	13.86
G	7	15	15.99	11.25
J	9	16	15.99	9.92
L	11	16	15.99	6.30
N	13	17	15.99	4.22
Q	15	17	15.99	3.57

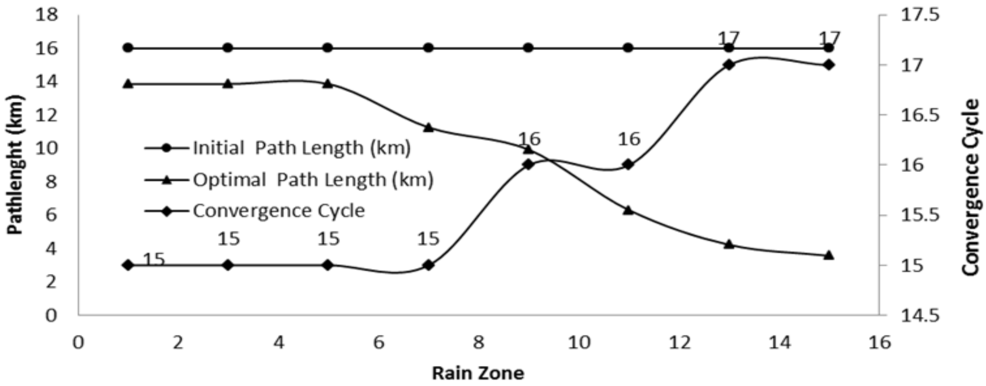

Figure-7. Bisection Method: Initial Path Length, Optimal Path Length and Convergence Cycle vs Rain Zone

In all, the bisection method can be used to determine the optimal path length of terrestrial microwave link. However, the convergence cycle of the algorithm is affected by various link parameters.

5. CONCLUSION

Development of bisection method for determination of optimal path length of terrestrial microwave link is presented along with performance analysis of the algorithm in terms of the convergence cycle of the algorithm. It was found from the analysis that the convergence cycle of the algorithm varies linearly with frequency and it varies non linearly with percentage availability of the link. Also, for a given frequency and link percentage availability, the convergence cycle increases with increase in rain rate.

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