Quality Aware Design and Analysis of FSO Link in Wireless Optical System

Kappala Vinod Kiran, Vikram Kumar, Ashok Kumar Turuk#, Santos Kumar Das*
Department of Electronics and Communication
#Department of Computer Science and Engineering
National Institute of Technology Rourkela, India
*Email: dassk@nitrkl.ac.in

***Abstract*—Wireless optical system has an astounding potential to support the next generation massive data transfer requirements. Free space optics (FSO) is one of such technology used for long distance communication. Its a compelling alternative or complementary solution to commonly deployed fiber optics and wireless radio-frequency links. It provides a viable solution to the first/last mile problem to the broadband communication. Despite advantages, it remains sensitive to environmental conditions, like fog, rain, snow, etc. This paper focuses on the performance analysis of the FSO link held down to various atmospheric conditions. Also, a novel quality based network routing on various quality parameters are used for the evaluation of connection availability. Link margin (L_M) is used as one of the collective quality parameters for the design and analysis of FSO link. L_M based routing is used for finding the network route which provides a high reliability to the FSO link even for the adverse weather phenomenon.**

***Index Terms*—FSO, Link margin (L_M), Atmospheric attenuation, Routing.**

I. Introduction

FSO is capable of providing high bandwidth communication links between remote sites. The range of frequencies over which it operates makes FSO free from licensing [1]. It solves the last-mile problem in broadband internet access. Next generation optical network with high speed connectivity can deploy FSO links for point-to-point or point-to-multipoint [2], [3]. Apart from many advantages, FSO link is limited to different attenuation created by atmospheric conditions such as rain, fog, snow, and haze. Establishing a connection under adverse weather conditions with reliability is the more challenging issue in the case of FSO network. A brief review of the available literature on FSO, Maged [4] evaluated the performance of FSO communication under fog environment and proposed a unified empirical fog model. Nadeem [5] analyzed the weather effects on an FSO link under fog, rain, and snow. Wakamori [6] has compared the cumulative distribution of meteorological data and experimental data to validate rain attenuation. It employed a cascade connection of FSO links consisting of links spanning for a long distance. The condition of the links cannot be determined when there is a link failure. Vavoulas [7] proposed the use of relay communication between two transceivers to mitigate the weather effects. In this case, a multi-hop FSO network with nodes distributed at fixed position on a given path/connection was analyzed. It determined the service length of the known FSO transceivers. It considered the one-dimensional network architecture and doesn't support network scalability. We propose a novel routing strategy based on collective quality parameters of the FSO link is used to establish a connection.

Following to the introduction, the paper is organized as follows: section II represents the system model, section III elaborates the design of FSO link and network characterization on atmospheric conditions, section IV explains the proposed L_M based routing and blocking probability computation, section V explains the simulation results and finally, section VI concludes our work.

II. System Model

The system model is shown in Fig. 1 consists of FSO transceiver connected through different routers. Each router forms an FSO transceiver with IoT interface node. These nodes are connected to form an IoT cloud and are controlled by a central management service with complete database. This has the information about the link status and routing strategy. A typical FSO transceiver module is shown in Fig. 2 with transmitter, T_{xi} and receiver, R_{xj}. It consists of transmitter power, receiver sensitivity, beam divergence angle and attenuation due to different environmental conditions. In an FSO link, several effects are considered such as the losses due to atmospheric absorption, scattering, and turbulence, microclimate environment, localized effects, link distance and link misalignment, etc. Based on these parameters a collective parameter L_M which form the basis for routing in the network.

III. FSO Link and Network Characterization

Based on the proposed system model of Fig. 1, initially a FSO link has to be characterized with various effective quality parameters. Individual link analysis is used for the FSO network characterization are explained in the subsequent sections.

A. FSO Link Characterization

FSO link is primarily characterized on the atmospheric attenuation and geometrical attenuation, a brief discussion of the individual parameters is as explained below:

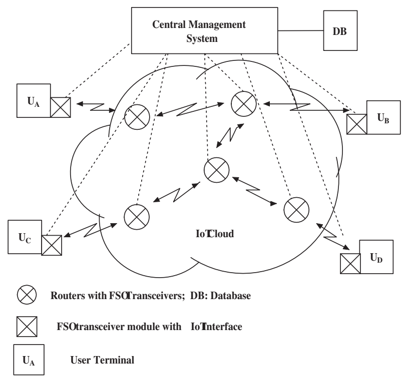


Fig. 1: System Model

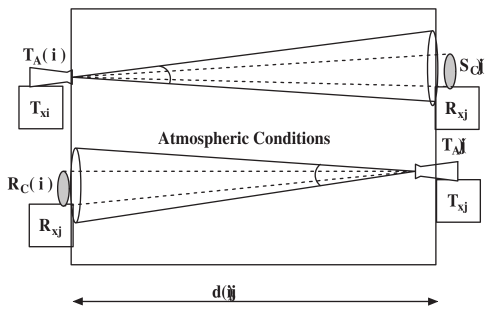


Fig. 2: A Typical FSO Transceiver Link Model

1) Geometrical Attenuation (α_{GA}): As the light beam travels in free space for a long distance, the beam diverges, and a very less amount of power is received due to small receiver capture area as shown in Fig. 2. This leads to geometrical attenuation (GA), $\alpha_{GA}(i,j)$, which is expressed as [8],

$$\alpha_{GA}(i,j) = \frac{T_A(i)}{R_C(j)} \tag{1}$$

where, $T_A(i) = \frac{\pi}{4}(d(i,j)\theta)^2$ is the transmitter illumination area; θ light beam divergence angle; $d(i, j)$ corresponds to the distance between transmitter T_{xi} to receiver R_{xj}; $R_C(j)$ is the capture area.

2) Atmospheric Attenuation (α_{AA}): There are different types of attenuation occurred due to variation in weather conditions such as rain, fog, snow, scintillation etc. To quantify the attenuation, empirical models were taken into consideration, since the theoretical approach has an increased mathematical complexity.

- Rain Attenuation (α_{RA})
  Atmospheric attenuation, $\alpha_{RA}(i,j)$ due to rain is expressed as per unit distance. Using the Carbonneau model [9], it can be expressed as,

$$\alpha_{RA}(i,j) = 1.076 \times R^{0.67} \tag{2}$$

  where, R is the precipitation intensity in mm/hr.
- Fog Attenuation (α_{FA})
  Attenuation due to fog is mainly caused by Mie-scattering [10], this predicts the droplets of fog and attenuation coefficient [11]. Here, it depends on the meteorological visibility, V wavelength, (λ) and size distribution of diffusing particles, q, attenuation due to fog is expressed as [8],

$$\alpha_{FA}(i,j) = \frac{3.91}{V}\left(\frac{\lambda}{550 \times 10^{-9}}\right)^{-q} \tag{3}$$

  where,

$$q = \begin{cases} 1.6, & \text{if } V > 50\text{km}. \\ 1.3, & \text{if } 6\text{km} < V < 50\text{km}. \\ 0.16, & \text{if } 1\text{km} < V < 6\text{km}. \\ V - 0.5, & \text{if } 0.5\text{km} < V < 1\text{km}. \\ 0, & \text{if } 0.5\text{km} < V. \end{cases}$$

- Snow Attenuation (α_{SA})
  The attenuation caused due to snow can be classified as dry and wet snow. Attenuation due to low humidity snow fall (dry snow) is higher than the wet snowfall. Specific attenuation due to snow is expressed as [8],

$$\alpha_{SA}(i,j) = a \times S^b \tag{4}$$

  where, a and b are constants with values for dry snow : $a = 5.42 \times 10^{-5}\lambda + 5.4958776; b = 1.3$ and for wet snow: $a = 1.023 \times 10^{-4}\lambda + 3.7855466; b = .72$, λ is the operating wavelength and S is the precipitation intensity in mm/hr.
  Apart from the above, there is scintillation effect, mis-alignment losses, etc., also important but not taken into consideration as we focused on the attenuation created by the adverse weather effect. Now, based on (1), (2), (3) and (4) an important collective quality parameter of FSO link is the link margin, $L_M(i,j)$, which is expressed as follows [8],

$$L_M(i,j) = P_t(i) + |R_s(j)| - [10log_{10}\alpha_{GA}(i,j) \times d(i,j)] - [10log_{10}\alpha_{AA}(i,j) \times d(i,j)] - \alpha_{SL}(i,j) \tag{5}$$

  where, $P_t(i)$ is i^{th} transmitter power; $R_s(j)$ is j^{th} receiver sensitivity; $\alpha_{GA}(i,j)$ represents the geometrical attenuation between link (i,j); $\alpha_{SL}(i,j)$ is the system losses and $\alpha_{AA}(i,j)$ is the attenuation due to atmospheric conditions expressed as,

$$\alpha_{AA}(i,j) = \begin{cases} \alpha_{RA}(i,j) \\ \alpha_{FA}(i,j) \\ \alpha_{SA}(i,j) \end{cases}$$

B. FSO Network Characterization

Network characterization is based on the routing strategy and network traffic. Typically three types of routing techniques are mostly used, they are fixed routing, fixed-alternative routing and adaptive routing [12]–[15]. Once the route is selected, a particular wavelength is assigned to it. If no route or wavelength is available for a (s, d) pair, then the connection request is termed as blocked [16]. Blocking probability (BP) is a key parameter for the evaluation of optical network performance. This can be investigated at each node and link [17] in a given network.

All available paths in the given FSO network is represented with a *n* x *n* matrix [18]- [19], **A**, for a network load, μ_{net}. The corresponding network load, N_L, between each link can be expressed as [20],

$$N_L(i,j) = \frac{\mu_{net}}{\sum_{i=1}^{n}\sum_{j=1}^{n} A(i,j)}\mathbf{A} \quad (6)$$

where, *n* is the number of nodes in the network; $A(i, j)$ is the number of supported paths for link (i, j) belongs to **A**.

The BP for links, $B_L(i,j)$, with $A(i, j)$ can be expressed by using the Erlang−B formula given as [21],

$$B_L(i,j) = \frac{\frac{N(i,j)^{W(i,j)}}{W(i,j)!}}{\sum_{c=0}^{W(i,j)} N_L(i,j)^c} \quad (7)$$

where, $W(i, j)$ is the number of wavelengths available on link (i,j). BP of the overall network, B_{NetB}, can be expressed as,

$$B_{NetB} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} B_L(i,j) \times A(i,j)}{\sum_{i=1}^{n}\sum_{j=1}^{n} A(i,j)} \quad (8)$$

Node-wise BP, B_{NodeB}, can be expressed as follows [20],

$$B_{NodeB} = \frac{\sum_{j=1}^{n} B_L(i,j) \times A(i,j)}{\sum_{j=1}^{n} A(i,j)} \quad (9)$$

The above parameters are used to analyze the network performance under different scenario.

IV. Proposed L_M based Path and Blocking Probability Computation

Based on FSO link and network characterization in the given network, a novel path and BP computation algorithm has been proposed. Algorithm 1 provides the steps for computation of available paths (routes) based on L_M i.e., for each (*s*, *d*) pair, all possible paths are computed based on [22] L_M within each link. The path with maximum L_M is selected for the establishment of connection, also an L_M based BP computation mechanism is evaluated by checking the availability of wavelengths and on the number of available paths based on threshold L_M.

Algorithm 1 Available Path and BP computation based on L_M

```
Compute all possible paths 'A' based on [22]
for i = 1 → n do
    for j = 1 → n do
        Estimate the LM for each link (i, j)
    end for
    Calculate the Minimum LM for each path
end for
L_M = Minimum Link Margin of all paths
A = Sort the no of paths based on threshold of Link Margin
Compute N_L(i,j), B_L(i,j), B_NetB(i,j), B_NodeB
```

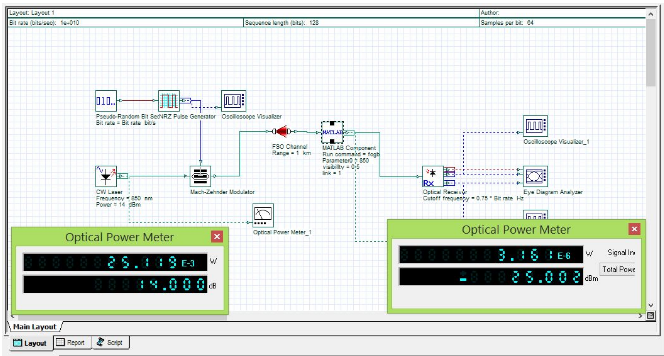


Fig. 3: Co-Simulation for the moderate fog (V = 500m) in OptiSystem 14.0

V. Simulation Results and Discussion

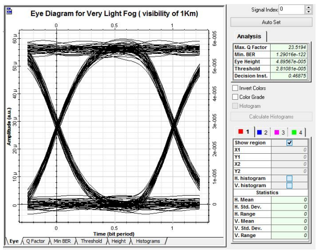
The FSO link characterization has been verified, using numerical as well as software simulation. The numerical simulation work is being done using MATLAB environment, and software simulation is performed using Optisystem [23]. Parameters considered for the simulation are as mentioned in Table 1. Following performance analysis have been evaluated based on link and network topology.

A. *Performance Analysis of FSO Link*

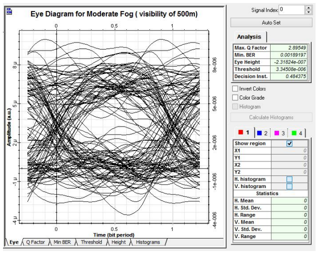
FSO link performance is evaluated based on geometrical attenuation (GA) and atmospheric attenuation. Appropriate channel condition is simulated using the specific attenuation due to (2), (3) and (4) in the MATLAB environment. Using the co-simulation of the Optisystem corresponding channel condition is interfaced, and individual link analysis under different channel conditions is explained below:

1) Evaluation of FSO Link Affected by Fog: Fig. 4 shows the performance of link under GA and for different fog events. Fig. 4b and Fig. 4c shows the effect due to moderate and thick fog events. The eye diagram is used to evaluate the quality of received data; it also evaluates the bit error rate (BER) and signal to noise ratio. Corresponding analysis of the parameters like BER and eye height from the eye diagram is shown in Table II, which represents that the link fails for the moderate and as well as thick fog events. L_M under different fog events is calculated using (5) and is shown in Table II. It can be observed that L_M for thick and dense fog is below the minimum threshold level (0 dB), i.e., thick fog with L_M of -17.392 and dense fog with L_M of -134.76 has a deep impact leading to catastrophic link failure.

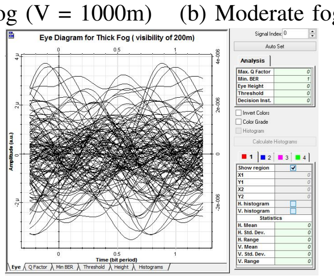
2) Evaluation of FSO Link Affected by Rain: The performance is evaluated for different precipitation intensity. Fig 5 shows the eye diagram for light, medium and heavy rainfall. Corresponding analysis of the parameters like BER and eye height is shown in Table II. Here, the rain precipitation increases the BER has increased, and corresponding height of the eye has also been decreased leading to link failure. It is observed that Fig. 5c, 5b with medium and heavy rain the eye completely closes degrading the performance. L_M with



(a) Very light fog (V = 1000m)



(b) Moderate fog (V = 500m)



(c) Thick fog (V = 200m)

Fig. 4: Eye Diagram for different Visibility of Fog Event

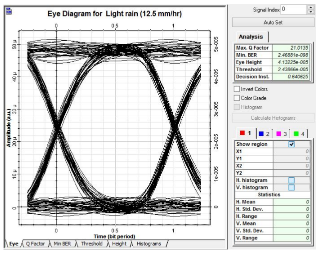
TABLE I: Parameters for Simulation

Parameters	FSO link
Range (d)	1 km
Transmission Speed	10 Gbps
Wavelength	850 nm
Transmitter power	14 dBm
Receiver sensitivity	-31 dBm
Transmitter Aperture	5 cm
Receiver Aperture	20 cm
System losses	3 dB

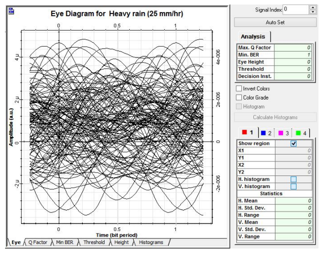
TABLE II: L_M for different atmospheric events

Type of Event	BER	Eye. Height	RP (dBm)	LM (dB)
Very light fog (V = 1000m)	1.29e-122	4.89e-05	-15.795	15.2
Moderate fog (V = 500m)	0.00189194	-2.32e-07	-25.002	5.99
Thick fog (V = 200m)	1	0	-48.393	-17.392
Dense fog (V = 50m)	1	0	-100	-134.76
Light rain (R = 2.5mm/hr)	2.47e-98	4.13e-05	-16.408	14.59
Medium rain (R = 12.5mm/hr)	0.000196411	1.24e-06	-24.051	6.94
Heavy rain (R = 25mm/hr)	1	0	-31.031	-0.03
Dry snow (S = 2mm/hr)	1	0	-35.789	-4.78
Wet snow (S = 2mm/hr)	5.85e-10	6.88e-06	-21.904	9.09

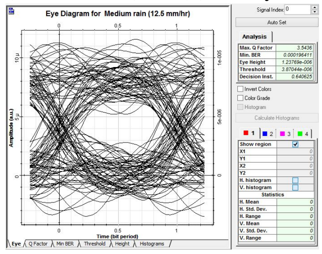
*RP: Received Power
*LM: Link Margin



(a) Light Rain (R=2.5mm/hr)



(b) Heavy Rain (R=25mm/hr)



(c) Medium Rain (R=12.5mm/hr)

Fig. 5: Eye Diagram for different Precipitation of Rain Event

GA under different scenario using (5) is evaluated and shown in Table II. Heavy rain with L_M of -0.03 dB predominantly leads to link failure.

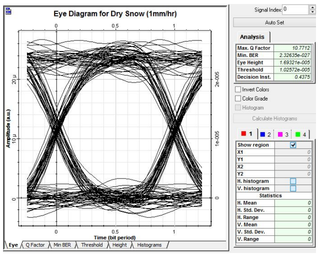
3) Evaluation of FSO Link Affected by Snow: The eye diagram for dry snow with different precipitation is shown in Fig. 6a and Fig. 6b. As the precipitation increases the eye completely closes. Fig. 6c and Fig. 6d represents the eye diagram for wet snow, it is observed that dry snow has a high impact than the wet snow. It is observed that for a dry snow BER is high and eye height is zero leading to link failure as shown in the Table II. Also, L_M under different snow events is calculated using (6) and is shown in Table II. The effect of dry snow with L_M of -4.78 dB degraded the FSO link.

Based on the performance analysis of FSO link, we propose a L_M based network routing under different channel conditions.

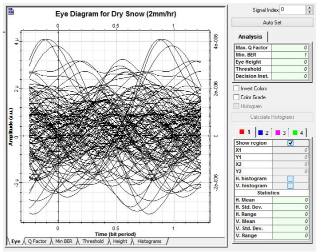
B. Performance Analysis Using Network Topology

Consider an FSO network similar to NSFNet topology for performance analysis is shown in Fig. 7 with 10 nodes and 16 links having FSO transceivers. Here, the link length with 1 span corresponds to a distance of 1 km or link margin of 5 dB. Network performance is evaluated on computing the reliable route preliminary and also based on the network traffic which is explained below:

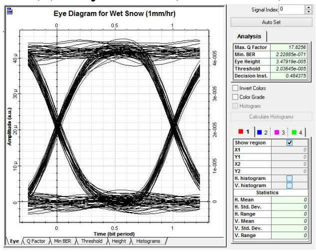
1) Computation of L_M Based Available Paths : Computation of all possible paths based on algorithm 1 is shown in Fig. 8. The vertical bar represents all available routes from each source to the other destination nodes based on distance (L_M > 0dB). For example, a source node 2 −destination node 3, (2, 3) pair has 21 routes, similarly a (4,10) has 31 routes. Here, routing algorithm based on shortest distance does not add any information on the status of the network which is dynamic in nature, since the link condition is purely



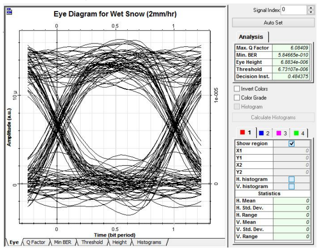
(a) Dry Snow (S=1mm/hr)



(b) Dry Snow (S = 2mm/hr)



(c) Wet Snow (S = 1mm/hr)



(d) Wet Snow (S = 2mm/hr)

Fig. 6: Performance of FSO Link under different conditions

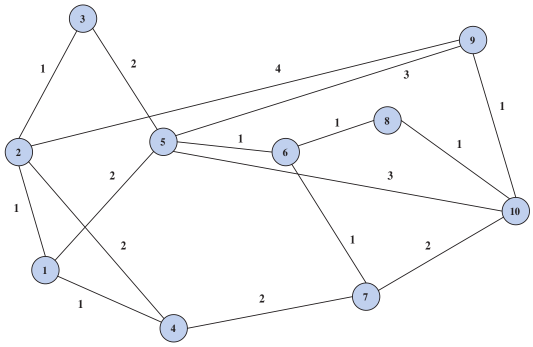


Fig. 7: An FSO network topology with 1 span = 1km, L_M = 5dB

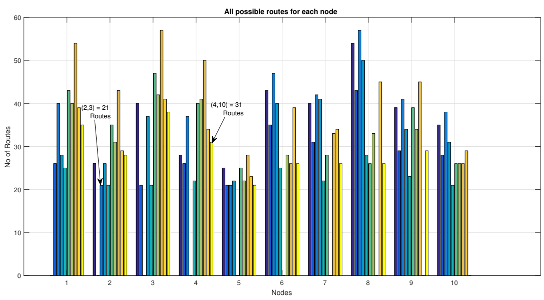


Fig. 8: All available paths from each node to other destination node based on distance or $L_M > 0$dB

Fig. 9: L_M plot for all possible routes of source−destination pair (2, 3) in sorted order

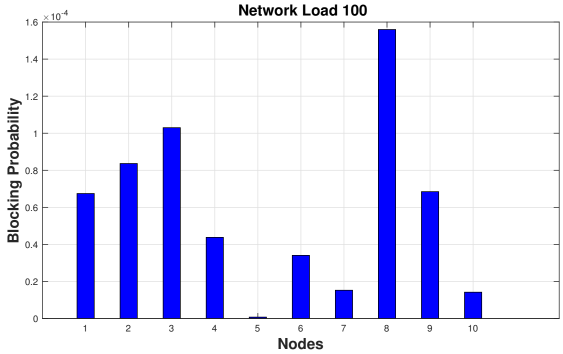


Fig. 10: Network Load of = 100E

dependent on L_M. There can be situations where the link may be unavailable due to different attenuation. Since the network is not cognizant which limits the reliability of communication system. The topology is to be controlled by selecting a path using the current scenario of the network. An adaptive routing algorithm based on the L_M was proposed to choose the path with maximum availability even on the adverse environmental affects. Consider a source-destination pair (2, 3) for ($L_M >$ 0dB), it has 21 all possible paths with different L_M. These paths are sorted in decreasing order of L_M is shown in Fig. 9. Unlike the path with the shortest distance, the best paths are selected based on the L_M threshold. As the L_M increases the number of supported paths decreases but the link reliability increases.

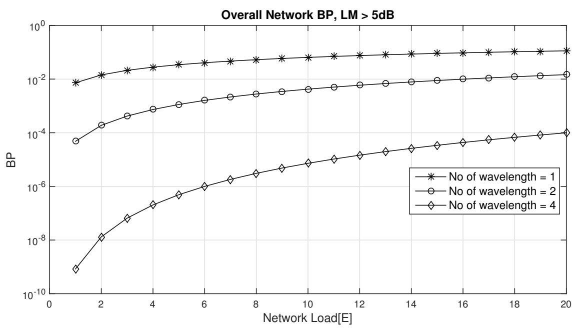


Fig. 11: Overall network BP for network load (1E to 20E)

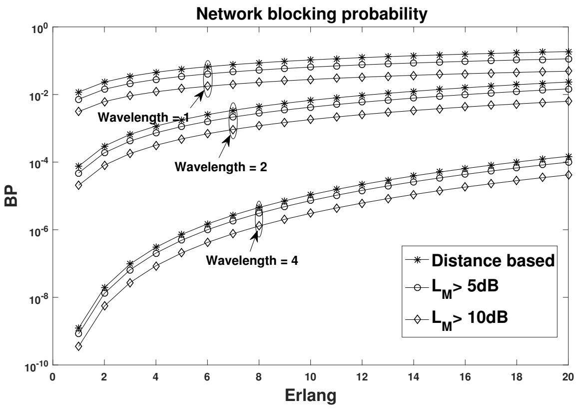


Fig. 12: Network BP for L_M based and shortest distance algorithms

2) Analysis of Network Traffic Load: The performance analysis of the network is based on (8) and (9). Fig. 10 represents the blocking probabilities at each node with $L_M >$ 5dB and number of wavelengths (λ = 8) as 8. It is observed that node 5 offers least BP among the other nodes. A path having node 5 is better chosen than the other paths. The overall network performance based on the network traffic and a number of available wavelengths per link is shown Fig. 11. It is observed, the paths with $L_M > 5$dB, as the number of available wavelengths is increased, there is a considerable decrease in BP. Also, the network blocking performance of the overall network based on shortest distance and L_M based routing is shown in Fig. 12. It is observed that the proposed routing outperforms the existing algorithms.

VI. Conclusion

The primary goal of this work is to analyze the performance of FSO link under various atmospheric conditions. It also evaluated an efficient routing technique for a reliable communication link under adverse weather condition providing a high reliability. An FSO network topology is used for the validation of link margin based path computation and analysis of network traffic load regarding BP. It may be beneficial to the future link design guidance and can be extended by considering different quality parameters.

Acknowledgment

This work has been supported by Department of Electronics and IT (Deity), Ministry of Communications and IT, Government of India under Visvesvaraya PhD Scheme for Electronics and IT (Grant no: PhD-MLA/4(13)/2015-16).

References

[1] V. W. Chan, "Free-space optical communications," *Journal of Lightwave Technology*, vol. 24, no. 12, pp. 4750–4762, 2006.

[2] C. C. Davis, I. I. Smolyaninov, and S. D. Milner, "Flexible optical wireless links and networks," *IEEE Communications Magazine*, vol. 41, no. 3, pp. 51–57, 2003.

[3] A. K. Majumdar and J. C. Ricklin, *Free-space laser communications: principles and advances*. Springer Science & Business Media, 2010, vol. 2.

[4] M. A. Esmail, H. Fathallah, and M.-S. Alouini, "Outdoor FSO communications under fog: Attenuation modeling and performance evaluation," *IEEE Photonics Journal*, vol. 8, no. 4, pp. 1–22, 2016.

[5] F. Nadeem, V. Kvicera, M. S. Awan, E. Leitgeb, S. S. Muhammad, and G. Kandus, "Weather effects on hybrid fso/rf communication link," *IEEE Journal on Selected Areas in Communications*, vol. 27, no. 9, 2009.

[6] K. Wakamori, K. Kazaura, and I. Oka, "Experiment on regional broadband network using free-space-optical communication systems," *Journal of Lightwave Technology*, vol. 25, no. 11, pp. 3265–3273, 2007.

[7] A. Vavoulas, H. G. Sandalidis, and D. Varoutas, "Weather effects on FSO network connectivity," *Journal of Optical Communications and Networking*, vol. 4, no. 10, pp. 734–740, 2012.

[8] O. Wilfert, V. Kvicera, Z. Kolka, M. Grabner, and O. Fiser, "Propagation study of 850 nm/58 GHz hybrid municipal system," *SPIE Optical Engineering Applications*, vol. 7814, pp. 781 414–781 422, 2010.

[9] S. A. Zabidi, W. Khateeb, M. R. Islam, and A. W. Naji, "The effect of weather on free space optics communication (FSO) under tropical weather conditions and a proposed setup for measurement," *International Conference on Computer and Communication Engineering , IEEE*, pp. 1–5, 2010.

[10] A. Prokes and V. Skorpil, "Estimation of free space optics systems availability based on meteorological visibility," *IEEE Latin-American Conference on Communications*, pp. 1–4, 2009.

[11] "Propagation data required for the design of terrestrial free-space optical links," *ITU-R Recommendation P.1817, Geneva*, 2012.

[12] J. Zheng and H. T. Mouftah, "Routing and wavelength assignment for advance reservation in wavelength-routed WDM optical networks," *IEEE International Conference on Communications*, vol. 5, pp. 2722–2726, 2002.

[13] R. Ramamurthy and B. Mukherjee, "Fixed-alternate routing and wavelength conversion in wavelength-routed optical networks," *IEEE/ACM Transactions on Networking*, vol. 10, no. 3, pp. 351–367, 2002.

[14] V. Saminadan and M. Meenakshi, "In-band crosstalk performance of WDM optical networks under different routing and wavelength assignment algorithms," *Lecture Notes in Computer Science, Springer Berlin Heidelberg*, vol. 3741, pp. 159–170, 2005.

[15] G.-S. Poo and A. Ding, "Blocking performance analysis on adaptive routing over WDM networks with finite wavelength conversion capability," *Photonic Network Communications*, vol. 12, no. 2, pp. 211–218, 2006.

[16] B. Mukherjee, *Optical WDM networks*. Springer Science & Business Media, 2006.

[17] R. Ramaswami and K. Sivarajan, *Optical Networks: A Practical Perspective*. Morgan Kaufmann, 2009.

[18] S. Das, A. Samantray, and S. Patra, "Hybrid crosstalk aware Q-factor analysis for selection of optical virtual private network connection," *International Journal of Electronics*, vol. 103, no. 1, pp. 113–129, 2016.

[19] S. K. Das and S. K. Patra, "Physical layer impairments aware OVPN connection selection mechanisms," *International Journal of Computer and Electrical Engineering*, vol. 4, no. 3, p. 331, 2012.

[20] L. H. Bonani and I. E. Fonseca, "Estimating the blocking probability in wavelength-routed optical networks," *Optical Switching and Networking*, vol. 10, no. 4, pp. 430–438, 2013.

[21] D. Mitra and J. Seery, "Comparative evaluations of randomized and dynamic routing strategies for circuit-switched networks," *IEEE Transactions on Communications*, vol. 39, no. 1, pp. 102–116, 1991.

[22] S. K. Das, C. P. Kalyan, and S. K. Patra, "Data-path selection mechanism based on physical layer impairments for WDM network," *International Journal of Signal and Imaging Systems Engineering*, vol. 5, no. 4, pp. 239–245, 2012.

[23] *Optiwave Design Software for Photonics*, http://www.optiwave.com.