Routing in Degree-constrained FSO Mesh Networks

Ziping Hu, Pramode Verma, and James Sluss Jr.
School of Electrical & Computer Engineering
The University of Oklahoma, Schusterman Center
4502 E. 41st Street, Tulsa, OK 74135-2512, USA
{ziping.hu, pverma, sluss}@ou.edu

Abstract

This paper addresses the routing problem in packet switching free-space optical (FSO) mesh networks. FSO mesh networks are emerging as broadband communication networks because of their high bandwidth (up to Gbps), low cost, and easy installation. Physical layer topology design of degree-constrained FSO mesh networks has been studied in a recent communication [1]. In this paper, we propose four different routing algorithms, and evaluate their performances through simulations for a number of FSO mesh networks with different topologies and nodal degrees. The performance parameter against which we evaluate these algorithms is the mean end-to-end delay. Our proposed least cost path (LCP) routing algorithm, which is based on minimizing the end-to-end delay, is considered as the bench mark. The performance of each of other three proposed algorithms is evaluated against the bench mark. Our proposed minimum hop count with load-balancing (MHLB) routing algorithm is based on the number of hops between the source and the destination node to route the traffic. Simulations show that the MHLB routing algorithm performs best in most cases compared with the other two. It results in minimum average delay and least blocked traffic.

1. Introduction

FSO networks are emerging as broadband communication networks because of their high bandwidth (up to Gbps), low cost, and easy installation. An FSO network consists of a set of geographically distributed FSO nodes and FSO links interconnecting the nodes. Each FSO node can carry a router and several transceivers. An FSO node can carry only limited number of transceivers due to size, weight and power issues. Each transceiver operates both in transmitting and receiving modes. FSO links that form the communication channels of FSO networks are point-to-point directional light beams.

To improve the performance of FSO networks through network design, the two major issues are topology design and routing. Traditionally, for wired communication networks such as fiber-optic networks, a fixed physical layer topology is formed based on external traffic flow requirements and/or other requirements. Routing is then a task of finding optimal logical connections that can be mapped on the physical layer topology in order to achieve low delay, high throughput, or reduced congestion. Research in [2] presents a delay-constrained minimum hop (DCMH) distributed routing algorithm for real time communication applications. An optimal diverse routing algorithm is proposed in [3] to find the shortest pair of physically-disjoint paths in order to improve the reliability of fiber optical networks. Reference [4] presents an algorithm that computes the shortest path from a given source to a destination for any number of hops for QoS routing. Research in [5] extends the work in [4], and proposes an All Hops Shortest Paths (AHSP) algorithm to compute the shortest path with hop count limitation in order to find a feasible path. A load-balanced routing scheme is proposed in [6] to randomly distribute the traffic load over all available paths to the destination for real time applications. A survey is presented in [7] that introduce several approaches to solve multi-constrained paths problem for QoS routing. All the above mentioned routing approaches assume a given physical layer topology. However, for FSO networks, current approaches [8-11] have combined both topology design and routing problems into one making use of the auto-tracking function of FSO nodes. In these approaches, logical topologies are first calculated at upper layer. Physical layer topologies are then gradually formed based on the calculated logical topologies. Since the mapping of physical layer topology to logical topology involves a number of rounds of mechanical movements of transceivers in FSO nodes, and each movement of a transceiver takes about 500ms for alignment purpose only [8]; these approaches are not, in general, practical for FSO communication networks.

Our work approaches the problem in a way that is similar to wired networks. In our previous work [1], we constructed a highly reliable physical layer topology for an FSO mesh network through topology design. Now, based on given physical layer topology, and external traffic demands, our objective in this paper is finding optimal logical topology that can be mapped onto the physical layer topology in order to achieve low average packet delay. Four different routing algorithms are proposed in this paper. Through extensive simulations, we show that the proposed minimum hop count with load balancing (MHLB) routing algorithm leads to the best overall performance.

In this paper, Section 2 defines all the notations used in our work. Section 3 presents the problem that needs to be solved. A queuing system model is introduced in Section 4. Section 5 presents the mathematical background. The four proposed routing algorithms are presented in Section 6. Section 7 shows the simulation results. Section 8 concludes our work.

2. Notations

We treat a degree-constrained FSO mesh network as a graph G(N,L) with N representing the set of nodes and L representing the set of links. The following notations are used in our work.

$A=[\gamma_{jk}]$ denotes the N x N traffic matrix, where

γ_{jk} : external traffic flow entering node *j,* and destined to node *k*

$B=[\rho_{st}]$ denotes the N x N link utilization matrix, where

ρ_{st} : utilization of link between node *s* and node *t*.

μ : departure rate

λ_i : traffic load on link *i*

λ: total internal traffic load

γ: total external traffic demand

T: average delay for a packet traveling through the network

3. Problem Statement

Three factors can affect the delay performance of FSO networks: physical layer topology, external traffic demands, and routing strategy. In our work, we assume that the physical layer topology and external traffic demands are given. To simplify the problem, we also assume that all link capacities are the same. The problem becomes finding an optimal routing strategy that minimizes the average delay T; therefore it's a flow assignment (FA) problem [12]. The FA problem can be stated as follows.

Given: network topology and external traffic flows
Minimize: T
With respect to: $\{\lambda_i\}$, i =1, 2, …, L

4. System Model

To solve the FA problem, a packet switching FSO network is modeled as a network of queues. Each FSO node (or link) is modeled as a queue and a server, and treated as an independent M/M/1 model [12-13]. For example, given the physical layer topology of a five node network shown in Figure 1, external traffic flow, and the routing strategy of the traffic, the network can be modeled as a network of queues shown in Figure 2.

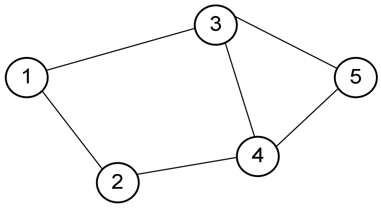

Figure 1. Physical layer topology of a L fine node

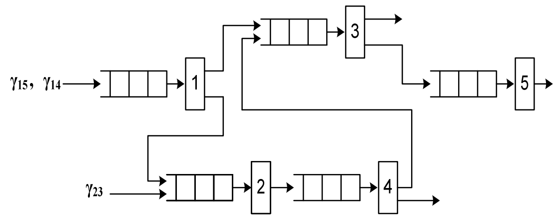

Figure 2. Network of queues

5. Mathematical Background

Assume for an FSO network with N nodes and L links, the external traffic flow requirement from a source node j to a destination node k is γ_{jk}, then the total external traffic flow γ (in packets per second) that is offered to the network can be expressed as

$$\gamma = \sum_{j=1}^{N} \sum_{k=1}^{N} \gamma_{jk} \qquad (1)$$

Since a packet may travel multiple hops from source to destination, the total internal traffic flow λ in the network will be higher than the external offered traffic. The total internal traffic load in the network is therefore given as

$$\lambda = \sum_{i=1}^{L} \lambda_i \qquad (2)$$

We can see that the total internal traffic flow depends on not only the external offered traffic, but also the actual paths taken by packets through the network. The total traffic load on each individual link is determined by both the offered traffic flows, and the routing algorithm.

Since each FSO link is actually a directional light beam, an FSO light signal propagates at light speed. With limited FSO link length (up to 4 km), the propagation delay can be neglected; therefore when a packet travels along its multi-hop path, it is served at a node, and then goes directly to the next node on its path. Let T_{ri} denote the residence time of a packet at link *i*. The average delay T can be defined as

$$\mathrm{T} = \frac{1}{\gamma}\sum_{i=1}^{L}\lambda_i \; T_{ri} \qquad (3)$$

By applying the M/M/1 model,

$$\mathrm{T} = \frac{1}{\gamma}\sum_{i=1}^{L}\frac{\lambda_i}{\mu-\lambda_i} = \frac{1}{\gamma}\sum_{i=1}^{L}\frac{\lambda_i/\mu}{1-(\lambda_i/\mu)} = \frac{1}{\gamma}\sum_{i=1}^{L}\frac{\rho_i}{1-\rho_i} \qquad (4)$$

Because of the separatibility [12] of each component at the right hand side of equation (4), the sensitivity of the average delay T to the utilization of link *i* can be expressed as

$$\frac{\partial T}{\partial \rho_i} = \frac{1}{\gamma(1-\rho_i)^2}\,, \quad i = 1, 2, \ldots, L \qquad (5)$$

Further,

$$\frac{\partial^2 T}{\partial \rho_i^{\,2}} = \frac{2}{\gamma(1-\rho_i)^3}\,, \quad i = 1, 2, \ldots, L \qquad (6)$$

Since the utilization of link *i*, $\rho_i = \lambda_i/\mu$, always satisfies that $0 \le \rho_i < 1$ to keep the network in a stable state; therefore, we have $\frac{\partial^2 T}{\partial \rho_i^{\,2}} > 0$ for all *i* under link utilization constraint. We conclude that T is a convex function of link utilization. It shows that with the increase of link utilization ρ_i, the growth of T becomes faster. Therefore, an optimal routing strategy should keep link utilization of each link minimal in order to minimize the average delay T. The total internal traffic flow in the network also affects the average delay T; therefore, given external traffic flow requirements and physical layer topology of a network, an optimal routing algorithm should be able to minimize the total internal traffic flow of the network in order to minimize the average delay T.

Based on above analysis, we specify the properties of an optimal routing algorithm:

- For all links in the network, the link utilization constraint has to be satisfied, i.e., $0 \le \rho_i < 1$, $i = 1, 2, \ldots, L$.
- The link utilization of each link has to be kept as low as possible, which means that links with low utilization should have higher priority of being chosen to route given traffic demand.
- Given physical layer topology and external traffic flow requirements, the total internal traffic should be kept as low as possible through routing in order to decrease the average delay.

6. Proposed Routing Algorithms

We first initialize traffic matrix *A*, and link utilization matrix *B*. Each entry of the traffic matrix consists of source node j, destination node k, and required traffic flow γ_{jk}, where j = 1, 2, … , N, k = 1, 2, … , N. If j = k, then γ_{jk}=0. Each entry of the link utilization matrix consists of node s, node t, and link utilization ρ_{st}, where s = 1, 2, … , N, t = 1, 2, … , N. If there is no direct link between node s and node t, or $s = t$, then ρ_{st} = 1. Otherwise, it sets to 0. For practical reasons and for simplification, we set the maximum link utilization $\rho_{\max}$ of each link as 0.8. Because of this link utilization constraint, all traffic that can't be routed is regarded as blocked traffic. We propose four different routing algorithms as follows.

6.1 Least Cost Path routing algorithm (LCP)

Assume the existing traffic load on link i is λ_i^*, or the existing link utilization of link i is $\rho_i^* = \frac{\lambda_i^*}{\mu}$. Using equation (5), we compute the cost (the increase of average delay) of routing traffic flow γ_{jk} through link i as

$$Cost(i) = \left.\frac{\partial T}{\partial \rho_i}\right|_{\rho_i=\rho_i^*} \times \frac{\gamma_{jk}}{\mu} = \frac{1}{\gamma(1-\rho_i^*)^2} \times \frac{\gamma_{jk}}{\mu} \quad (7)$$

Therefore, the total cost of routing traffic γ_{jk} through a path of m links is $\sum_{i=1}^{m} Cost(i)$.

In order to minimize the average delay T, each traffic demand has to be routed through the least cost path. Our proposed least cost path routing algorithm is as follows.

1. Set $\rho_{\max}$=0.8. Route all one hop count traffics under the constraint that $\rho_i \le \rho_{\max}$. Update traffic matrix and link utilization matrix.
2. Arrange all traffic demands in the decreasing order. If the maximum traffic demand is 0, then stop.
3. Starting from the heaviest traffic demand, find the least cost path to route the traffic under the constraint that $\rho_i < \rho_{\max}$ for any link i on the path. Because of the upper bound of link utilization, the part of traffic that can't be routed through the path remains unrouted. Update traffic matrix and link utilization matrix. If no such path exists, consider next traffic demand. Repeat Step 3 until all traffic demands are considered. Go to Step 2.

Variations of Dijkstra's or Bellman-Ford algorithm are the most widely used algorithms in least cost routing in packet-switching networks. In our LCP routing algorithm, because of link utilization constraint, we use a modified Dijkastra algorithm to find the least cost path at step 3 in order to route a given external traffic demand. Link cost is computed according to equation (7).

6.2 Minimum Hop Count Path Routing Algorithm (MHP)

Proposed minimum hop count path routing algorithm is used to route each traffic demand through the minimum hop count path in order to minimize the total internal traffic load on the network. In this way, it's expected to achieve low average packet delay. The proposed minimum hop count path routing algorithm is presented as:

1. Set $\rho_{\max}$=0.8. Route all one hop count traffics under the constraint that $\rho_i \le \rho_{\max}$. Update traffic matrix and link utilization matrix.
2. Arrange all traffic demands in the decreasing order. If the maximum traffic demand is 0, then stop.
3. Starting from the heaviest traffic demand, find the minimum hop count path to route the traffic under the constraint that $\rho_i < \rho_{\max}$ for any link *i* on the path. If more than one minimum hop count path exists, choose the one with the minimum maximum link utilization. Because of the upper bound of link utilization, the part of traffic that can't be routed through the path remains unrouted. Update traffic matrix and link utilization matrix. If no such path exists, consider next traffic demand. Repeat Step 3 until all traffic demands are considered. Go to Step 2.

At step 3, by setting the cost of each link to be the same, a modified Dijkastra's algorithm is used to find the minimum hop count path for a given traffic demand under link utilization constraint. For a path with *m* links, the maximum link utilization of the path is defined as: max $\{\rho_i, i=1, 2, \dots, m\}$. This concept is also used in the following routing algorithms.

6.3 Minimum Hop Count with Load Balancing Routing Algorithm (MHLB)

The MHLB routing algorithm is used to route all traffic demands based on the hop count of the paths. All one hop count traffic are routed first, then two hop count traffic, next three hop count traffic, and so on. The maximum link utilization of a link is set at 0.6 first, which is increased up to 0.8 in the subsequent rounds. The steps are as follows.

1. Set $\rho_{\max}$=0.6. Route all one hop count traffics under the constraint that $\rho_i \le \rho_{\max}$. Update traffic matrix and link utilization matrix. Set counter = 1.
2. Arrange all traffic demands in the decreasing order. If the maximum traffic demand is 0, then stop. Otherwise increase counter by 1 (or counter++), let $\rho_{\max} = \rho_{\max} + \alpha$, $0 < \alpha \le 0.2$ (the actual value of α selected is determined by searching the optimal value from a small set). If $\rho_{\max}$ > 0.8, then set $\rho_{\max}$=0.8.
3. Starting from the heaviest traffic demand, find the path with total hop count less or equal to counter to route the traffic under the constraint that $\rho_i < \rho_{\max}$ for any link *i* on the path. If more than one such path exists, choose the one with the minimum maximum link utilization. Update traffic matrix and link utilization matrix. If no such path exists, consider next traffic demand. Repeat Step 3 until all traffic demands are considered. Go to Step 2.

At step 3, a modified Bellman-Ford algorithm is used to find the path with total hop count less or equal to counter to route a given traffic demand. Traffic load balancing is achieved through increasing the upper bound of link utilization from 0.6 to 0.8 step by step. The MHLB is expected to achieve low average delay, low total internal traffic, and least blocked traffic.

6.4 Minimum Hop Count Routing Algorithm (MH)

Proposed MH routing algorithm is used to route all traffic demands based on the hop count of the paths similar to MHLB. All one hop count traffic are routed first, then two hop count traffic, next three hop count traffic, and so on. However for MH algorithm, the upper bound of link utilization always remains as 0.8 during the whole process.

1. Set $\rho_{\max}$=0.8. Route all one hop count traffic under the constraint that $\rho_i \le \rho_{\max}$. Update traffic matrix and link utilization matrix. Set counter = 1.
2. Arrange all traffic demands in the decreasing order. If the maximum traffic demand is 0, then stop. Otherwise increase counter by 1 (or counter++).
3. Starting from the heaviest traffic demand, find the minimum hop count path with total hop count less or equal to counter to route the traffic under the constraint that $\rho_i < \rho_{\max}$ for any link i on the path. If more than one such path exists, choose the one with the minimum maximum link utilization. Update traffic matrix and link utilization matrix. If no such path exists, consider next traffic demand. Repeat Step 3 until all traffic demands are considered. Go to Step 2.

At step 3, a modified Bellman-Ford algorithm is used to find the path with total hop countless or equal to counter to route a given traffic demand. Through MH routing the total internal traffic is expected to be the least.

7. Simulations and analysis

Case1:
Given a physical layer network topology of degree 3 with 10 nodes and 15 links, we set the departure rate μ as 130 units.
(a) Light external traffic demands:
For a 10 nodes network, there are 10×9 distinct source-destination node pairs. Therefore 90 external traffic demands are generated randomly from 0 to 9 units corresponding to the 90 different source-destination node pairs. Simulations are done over 10 different topologies with proposed four different routing algorithms to route the traffic. Under light external traffic demands, the total blocked traffic is 0. The average delay is shown in Table 1.

Table 1. Average delay (ms)

Topol.	LCP	MHP	MHLB	MH
1	18.64	18.62	18.62	18.62
2	21.73	21.87	21.69	21.69
3	18.66	18.64	18.61	18.61
4	19.13	19.14	19.17	19.17
5	22.76	22.79	22.8	22.8
6	22.29	22.48	22.66	22.66
7	18.6	18.58	18.61	18.61
8	18.28	18.28	18.45	18.45
9	23.19	23.19	23.19	23.19
10	21.24	21.11	21.06	21.06

(b) Heavy traffic demands:
90 external traffic demands are generated randomly from 0 to 19 units corresponding to the 90 different source-destination node pairs. Simulations are done over the same 10 different topologies with proposed four different routing algorithms to route the traffic. The average delay under heavy traffic load is shown in Table 2.1. The total blocked traffic in different scenarios is shown in Table 2.2.

Table 2.1. Average delay (ms)

Topol.	LCP	MHP	MHLB	MH
1	28.17	28.24	27.55	27.59
2	40.85	42.26	39.95	39.95
3	27.42	27.65	27.1	27.21
4	30.39	30.81	29.89	30.28
5	42.88	43.23	40.88	40.88
6	39.44	38.45	37.86	37.92
7	27.69	27.83	27.87	28.02
8	27.16	27.28	27.39	27.42
9	51.87	49.45	47.65	48.03
10	42.48	40.77	39.22	39.24

Table 2.2 Total blocked traffic (units)

Topol.	LCP	MHP	MHLB	MH
1	0	0	0	0
2	25	25	25	25
3	0	0	0	0
4	0	0	0	0
5	35	35	35	35
6	32	32	32	32
7	0	0	0	0
8	0	0	0	0
9	35	35	35	35
10	14	14	14	14

Case 2:

Given a physical layer network topology of degree 4 with 30 nodes and 60 links, we set the departure rate μ as 280 units.

(a) Light external traffic demands:

For a 30 nodes network, there are 30×29 distinct source-destination node pairs. Therefore 870 external traffic demands are generated randomly from 0 to 9 units corresponding to the 870 different source-destination node pairs. Simulations are done over 10 different topologies with proposed four different routing algorithms to route the traffic. In all different scenarios, the total blocked traffic is 0. The average delay is shown in Table 3.

(b) Heavy external traffic demands:

870 external traffic demands are generated randomly from 0 to 10 units corresponding to the 870 different source-destination node pairs. Simulations are done over the 10 different topologies with proposed four different routing algorithms to route the traffic. The average delay is shown in Table 4.1. The total blocked traffic in different scenarios is shown in Table 4.2.

The proposed three new routing algorithms are compared against the LCP algorithm, which is based on routing that mathematically minimizes the end-to-end delay. The LCP algorithm routes as much as possible traffic through the least cost path until the maximum link utilization 0.8 is reached. Because of this reason, LCP does not, under heavy traffic load, distribute traffic evenly over all available paths.

Table 3. Average delay (ms)

Topol.	LCP	MHP	MHLB	MH
1	16.0	16.20	16.07	16.07
2	23.91	25.13	24.53	24.59
3	20.01	20.84	20.98	20.99
4	22.78	24.46	23.94	24.35
5	20.46	21.37	21.44	21.49
6	23.51	26.66	24.81	25.85
7	22.48	24.11	23.71	23.99
8	19.02	19.40	19.62	19.63
9	22.12	24.0	23.0	23.35
10	18.32	18.92	18.58	18.84

Table 4.1. Average delay (ms)

Topol.	LCP	MHP	MHLB	MH
1	17.35	17.61	17.37	17.37
2	24.40	25.67	24.21	24.21
3	22.86	24.10	24.08	24.31
4	26.88	29.9	28.37	28.99
5	23.44	25.05	24.86	25.12
6	27.04	33.40	29.56	31.15
7	25.48	26.87	27.50	27.02
8	21.44	22.17	22.19	22.32
9	25.88	28.08	27.06	27.65
10	20.19	21.04	20.58	21.02

Table 4.2. Total blocked traffic (units)

Topol.	LCP	MHP	MHLB	MH
1	0	0	0	0
2	154	154	154	154
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	44	83	14	49
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0

Since the proposed MHLB algorithm does distribute the traffic more evenly by setting at first a link utilization limit of 0.6, and then increasing it up to 0.8 if necessary, MHLB is expected to result in better performance than LCP in most cases. Note also that while LCP determines the route after a computationally intensive process, MHLB doesn't require the computation of link cost prior to determining the route. It simply routes the traffic based on the hop count of the path, subject to, the limits on link utilization. Further, for the LCP algorithm, the link cost depends on the traffic, and the traffic in turn depends on the routes chosen. Because of the existence of this feedback condition, instabilities may result [13]. The other three routing algorithms, including the MHLB, are not subject to such instability.

Simulation results show that for small sized FSO networks, under light traffic demands, performance of the three proposed algorithms are similar to each other; under heavy traffic load, the proposed MHLB routing algorithm results in minimum average delay. For large sized FSO networks, simulation results show that, under light traffic demands, MHLB results in minimum average delay in most cases; under heavy traffic load, it results in minimum average delay and least blocked traffic in most cases. Compared with LCP, MHLB performs better for small sized FSO networks. For large sized FSO networks, even though LCP results in less average delay than MHLB, MHLB is expected to outperform LCP with the increase of the nodal degree because of its traffic load balancing feature.

8. Conclusions

This paper has proposed and analyzed three routing algorithms for degree-constrained FSO mesh networks of different sizes under varying traffic demands. In each case, the cost is characterized by average delay. The maximum link utilization is set as 0.8. Traffic that exceeds this constraint is regarded as blocked traffic. Simulation results show that for small sized FSO networks, under light traffic demands, the performance of the three proposed algorithms are similar to each other; under heavy traffic load, the proposed MHLB routing algorithm outperforms the others in most cases. For large sized FSO networks, simulation results show that MHLB performs best in most case.

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