Proposed Resource Allocation Schemes for Rainy Free Space Optical Network

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Abstract: Free space optical (FSO) connections present promising solution for the limited access issue of the last mile networks. However, several factors contribute to significant FSO link performance degradation. One of Most serious conditions is the influence of the rain, that frequently appear, thus making the implementation of strongly connected FSO networks a demanding issue. Dynamic FSO networks is attractive ones over the robust static ones, i.e, partial and full relayed networks, for this demanding issue. In this paper two new resource allocation Schemes are proposed for cooperative-dynamic FSO networks, as attractive solution for both atmospheric variation and high cost of robust static network problems. Each Scheme is formulated as integer linear multi-objective optimization problem (ILP-MOP), where reliability-fairness, capacity and bit-error rate functions are targeted. And each scheme is composed of lexicographic, lex-max-min and lex-min-max criteria. Each ILP-MOP is solved using exhaustive search method to obtain the guaranteed optimal solution(s). The simulation results is used to reveal that two schemes are more reliable-fairness and cost efficient than the robust static topology, specially at sever weather conditions. Also, the results show the two schemes have different behavior, where one prioritize the reliability-fairness over capacity utilization and the another does the opposite.

1 INTRODUCTION

Free space optics (FSO) is line of site (LOS) wireless optical communication used as a promising and feasible solution for last mile connectivity problem where remote network nodes have to be connected to central backbone node. With the significant development in the optical technology in the last decade, more FSO links are deployed in a given service area to meet the user's huge demands on internet services and applications(Kim et al., 2001). Generally, FSO is used instead of optical fibers when short implementation time, flexible installation and low implementation cost are required (Refai et al., 2006). FSO link could be used to connect different nodes like mobile base station, telephone office or private networks to central backbone node as indicated in Fig. 1.

Even though the attractive features of FSO, it suffers from the free space channel impairments in infrared (IR) band spectrum, i.e., weather conditions, background radiations and air turbulence (Kim et al., 2001), (Bloom et al., 2003), (recommendation ITU-R P.1814, 2007). The weather conditions include fog, rain and snow that could absorb and scatter the transmitted optical signal (Vavoulas et al., 2012). In addition, eye safety regulation restricts the power of the transmitted light beam to certain threshold which consequently limits the communication range of FSO links (Bloom et al., 2003). Hence, suitable network topologies have to be investigated to mitigate the weather impairments and provide the required quality of service (QoS) for different nodes.

The conventional FSO network implements static direct links (D-L) between fiber backbone node and

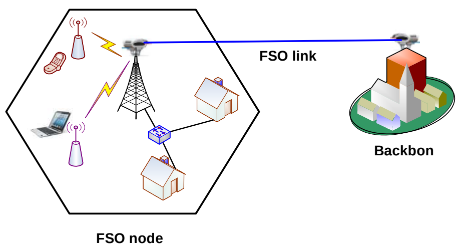

Figure 1: Last-mile FSO connection, the end users could use wire or wireless connections to FSO node.

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FSO nodes as indicated in Fig. 2(A). Although, this static topology has simple and low cost implementation, it has the worst communication performance against sever weather conditions. To overcome this degradation, serial-relayed topology is addressed (Vavoulas et al., 2012). In this topology, one or more relays are inserted between far nodes and backbone node. The relay has two optical transceivers and is located at equal distances from other nodes (optimal placement)(Kashani et al., 2013), as indicated in Fig. 2(B) for partial relayed links network (P-L). By increasing number of intermediate relays between remote nodes and backbone node, the best FSO link performance could be achieved. Obviously, this enhancement in the network performance comes at a significant increase in the network cost. The topology where each node is supported with one relay is called fully relayed links network (F-L) as indicated in Fig. 2(C).

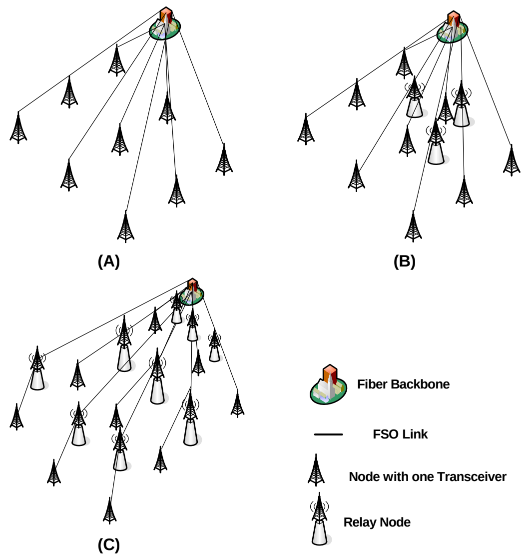

Figure 2: Different recent static topologies at last-mile, (A) Direct Link model (D-L), (B) Partial Relayed Link Model (P-L), (C) Full Relayed Link Model (F-L).

Better performance could be achieved at reasonable lower cost by implementing dynamic (reconfigurable) FSO network topologies (Milner et al., 2002). These dynamic topologies are classified according to network resources sharing into cooperative and non-cooperative topologies. In dynamic non-cooperative FSO network topologies no resources are shared among different users (Milner et al., 2002). Users with bad links switch their traffic to users with relatively better links and the transmission rate of each user is kept the same. This is achieved by increasing transmission rates of good links to be sum of switched transmission rates. Clearly, increasing transmission rate of optical link is not feasible and has practical limitations (Bloom et al., 2003).

To overcome these limitations, dynamic cooperative topologies are introduced. In these topologies, users with bad optical links switch their transmissions to users with better links and share their links capacities. Clearly, transmission rate of a good optical link is divided between node's traffic and switched transmissions in order to keep quality of service for switched ones. In other words, the networks' users cooperate and share their resources (optical bandwidths) to keep connectivities between backbone node and far users which in turn increases FSO network's reliability (decrease number of dropped nodes) during rainy weather conditions. Moreover, at given weather conditions, the network resources could be fairly allocated (achieves near the same transmission rate to backbone node) among different users by implementing proper resource allocation scheme. Although, the number of optical transceivers available at each node plays an important role in the network performance, it is still much lower than that required in static topologies to achieve the same performance.

In this paper, two fair and cooperative resource allocation schemes are proposed to enhance the performance of dynamic cooperative FSO networks against atmospheric variation which is caused by rain droplets. The reset of this paper is organized as the following. Section 2 presents FSO link model. Section 3 illustrates reconfigurable cooperative FSO network parameters. Section 4 introduces the proposed resource allocation schemes. Section 5 shows the numerical evaluations for proposed resource allocation schemes. Lastly, section 6 concludes the final network evaluations and the remarkable notes.

2 FSO LINK MODEL

Three main factors affect the FSO link performance namely, link losses, turbulence (scintillation) and noises. The link losses include both atmospheric and geometric losses. These losses cause signal scattering, absorbing and spreading(Gagliardi and Karp, 1995). The atmospheric loss includes fog, rain, snow (recommendation ITU-R P.1814, 2007). Naturally, these weather phenomena fog. rain, and snow rarely occur concurrently, and this allows in studying rainy influence separately (Vavoulas et al., 2012). At sever rainy weather conditions, the scintillation has relatively small impact and could be neglected (Vavoulas et al., 2012), (Khalighi and Uysal, 2014). Therefore, the total FSO link loss in this case is given by

$$\gamma = \gamma_{rain} + \gamma_{geo}.\ dB \quad (1)$$

Where γ presents the total link loss. Also γ_{rain} and γ_{geo} are rain and geometric losses, respectively.
The rain loss is calculated using Jaban's empirical model, as (recommendation ITU-R P.1814, 2007).

$$\gamma_{rain} = 1.58 \times D^{0.63} \times L.\ dB \quad (2)$$

Or by using France's empirical model, as (recommendation ITU-R P.1814, 2007).

$$\gamma_{rain} = 1.076 \times D^{0.67} \times L.\ dB \quad (3)$$

Where D is the rain fall rate in mm/h and L is the distance in km.
Even in clear weather conditions, the geometric loss is presented due to the spreading of the beam when propagating through the medium of free space. This loss is calculated by (Bloom et al., 2003):

$$\gamma_{geo} = 10 \times \log\left(\frac{d_t + L \times \Theta}{d_r}\right)^2.\ dB \quad (4)$$

Where d_r is the receiver diameter, d_t is the transmitter diameter, both in mm, Θ is divergence angle in $mm.rad/km$.

The system noise include both external noise (ambient or background noise) and internal noise (dark current and thermal noises). When the background radiation level is relatively high, for example in outdoor FSO links, the receiver thermal noise is ignored and the system noise is modeled using Poisson's model (shot-noise limited receiver). Also, the selected modulation formate plays important role in the FSO link performance (Gagliardi and Karp, 1995). The prime intensity modulation/direct detection techniques, namely, none return-zero on-off keying (NR-OOK) are considered in this paper. Hence, at given transmitted q_t photons/slot and channel loss, γ, $q_s = (\gamma \times q_t)$ is the average number of received signal photons per slot and q_b is the average number of received ambient photons per slot. The bit-error-rate of OOK, P_e, when model the photo detector as shot-noise limited receiver is given by (Gagliardi and Karp, 1995).

$$P_e = \frac{1}{2} \times \sum_{q=0}^{m_t} (q_b + q_s)^q \times \frac{\exp\left[-(q_b + q_s)\right]}{q!} + \frac{1}{2} \times \sum_{q=mt}^{\infty} (q_b)^q \times \frac{\exp\left[q_b\right]}{q!}. \quad (5)$$

And

$$m_t = \frac{q_s}{log\left(1 + \frac{q_s}{q_b}\right)}. \quad (6)$$

Where, m_t is the threshold of bit detection.

In the considered network, the homogeneous weather is assumed over all the network regions. In other words, all FSO links are affected by the same specific atmospheric losses (dB/km) and the same background radiation level impacts all FSO receivers.

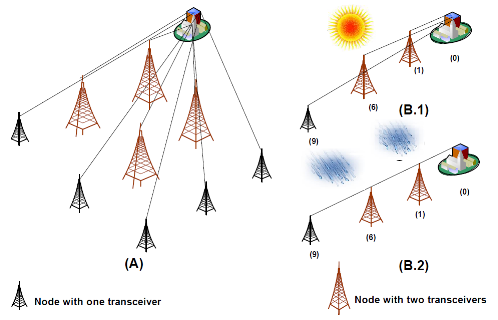

Figure 3: Reconfigurable-Cooperative network, (A) Network topology . (B) Reconfiguration of the links versus the atmospheric variation using the proposed schemes, where in (B.1) at clear weather and in (B.2) at rainy weather conditions.

3 RECONFIGURABLE COOPERATIVE FSO NETWORK PARAMETERS

Currently, the significant innovation in pointing, acquisition and tracking system (PAT) makes the dynamic FSO network more feasible than before (Dat et al., 2010). In reconfigurable topologies, the number of FSO transceivers could be significantly reduced by replacing actual FSO relay nodes by transceivers on other working nodes (virtual FSO relay nodes) (Milner et al., 2002).
Generally, the cooperative FSO network consists of N nodes $(v_1, ..., v_N)$ with arbitrary geographical distribution in addition to the backbone node v_0. The number of optical transceivers at k^{th} node is denoted by Z_k where $\{k\} \in \{1, \ldots, N\}$. The backbone node is assumed to be equipped with N optical transceivers. In the considered FSO network, the inner n_2 nodes near to the backbone node are assumed to have two transceivers while the far $n_1 = N - n_2$ nodes have only one transceiver, i.e. $Z_k \in \{1, 2\}$. An example of reconfigurable cooperative FSO network with one central node and nine remote nodes is indicated in Fig. 3(A). In this network $N = 9$, each node of the inner four nodes has two transceivers (n_2=4) and each node of the outer five nodes has one transceiver (n_1=5), total additional transceivers is $w = \sum_{k=1}^{N}(Z_k - 1) = 4$. At clear weather conditions, all nine nodes are direct connected to the central node as indicated in Fig. 3(B.1). At high density fall rate of rain, each

node could switch to its neighbor node to maintain its connectivity to the central node as indicated in Fig. 3(B.2).

The losses of all FSO links (rain and geometric attenuations) are summarized in γ matrix, $\gamma = (\gamma_{00},\dots,\gamma_{0N};\dots,\gamma_{ij},\dots;\gamma_{N0},\dots,\gamma_{NN})$, where γ_{ij} is the loss coefficient of link between transmitter of i^{th} node and receiver of j^{th} node. Clearly, $0 \leq \gamma_{ij} \leq 1$, $\gamma_{ii}= 0$ and $\gamma_{ij} = \gamma_{ji}$ for any $\{i, j\} \in \{0,1,\dots,N\}$. At a given weather state, the cooperative FSO network could be connected with different feasible configurations that satisfy the required QoS parameters, i.e. grantee minimum bit rates at bit error rates less than certain threshold. The number of these configurations is Λ. For l^{th} configuration, $l \in \{1,2,\dots,\Lambda\}$, the connection status between network nodes are summarized in connections matrix $G_l = (g_{l00},\dots,g_{l0N};\dots,g_{lij},\dots;g_{lN0},\dots,g_{lNN})$, where g_{lij} is the connection status between i^{th} and j^{th} nodes in configuration l and $g_{lij} \in \{0,1\}$. The connection between nodes i and j is established in configuration l if $g_{lij} = 1$. Also, bidirectional links are assumed so that $g_{lij} = g_{lji}$ and $g_{lii} = 0$.

Moreover, all FSO links are assumed to have the same average transmitted power, i.e., the power of optical link between nodes i and j in configuration l is constant, $P_{lij} = P$. However, to increase link capacity and guarantee an error rate less than a specified maximum $BER_{lij} < BER_{max}$, the link between nodes i and j in configuration l adapts its transmission rate, T_{lij}, to be one of $m+1$ discrete values, where $T_{lij} \in \{0,x_1,x_2\dots,x_m\}$ and $x_1 < x_2 < \dots < x_m$.

The transmission rate of node k in configuration l is denoted by T_{lk}, where $T_{lk} = \sum_{j=0}^{N} T_{lkj}$. The bit rate of node k (its own traffic) through connection to node j in configuration l is denoted by R_{lkj}. The overall bit rate of node k in configuration l is $R_{lk} = \sum_{j=0}^{N} R_{lkj}$. Obviously, $R_{lk} \leq T_{lk}$ and $\{R_{lk}, T_{lk}\} \in \{0,x_1,x_2,\dots,x_m\}$. The end-to-end bit error rate of node k in configuration l, BER_{lk}, is bounded by $BER_{lk} \leq BER_{max}$.

The bit rates and bit error rates associated with all nodes in the feasible configurations could be summarized in $(\Lambda \times N)$ matrices R and E, respectively. For a given configuration l, the bit rates for all nodes are represented in vector $(1\times N)$ r_l, $r_l \in R$. Also, the bit error rates in that configuration are summarized in vector $(1\times N)$ e_l, $e_l \in E$. The network capacity associated with configuration l is $C_l = \sum_{k=1}^{N} R_{lk}$, and all capacities associated with all feasible configuration are summarized in vector $(\Lambda \times 1)$ $C, C_l \in C$. Also, the maximum network capacity that could be achieved by any configuration is that obtained from direct links configuration l^* and is defined by $C_{max} = \sum_{k=1}^{N} T_{l^*k0}$, i.e. $C_l \leq C_{max}$.

Network Parameters:

v :	Nodes vector $(1\times(N+1))$
γ:	Loss coefficient Matrix $((N+1)\times(N+1))$
G :	Connections matrix $((N+1)\times(N+1))$
R_k :	Bit rate of k^{th} node
r :	Bit rate vector $(1\times N)$
R :	Bit rate matrix $(\Lambda\times N)$
BER_k :	Bit error rate of k^{th} node
e :	Bit error rate vector $(1\times N)$
E :	Bit error rate matrix $(\Lambda\times N)$
BER_{max} :	Bit error rate threshold
C_l :	Capacity of the Network for l^{th} configuration
C :	Capacity vector $(\Lambda\times 1)$
C_{max} :	Maximum Capacity
U_l :	Capacity utilization for l^{th} configuration
T_k :	Transmission rate of k^{th} node
Z_k :	Number of transceivers of k^{th} node
w :	additional number of transceivers in the network
P_{ij} :	Power of i, j link

The size of the feasible space, Λ, is upper bounded by the following inequation:

$$\Lambda < \left[\sum_{ii=1}^{N+1}\binom{N+1}{ii}\right] \times \left[\sum_{jj=0}^{jj=Z_k=2}\binom{N+1}{jj}\right]^{(n_2)} \times \left[\sum_{kk=0}^{kk=Z_k=1}\binom{N+1}{kk}\right]^{(n_1)}. \tag{7}$$

Clearly, the size of feasible space is defined by number of FSO nodes, number of nodes equipped by one transceiver, and number of nodes equipped by two transceivers.

4 PROPOSED FAIR COOPERATIVE RESOURCE ALLOCATION SCHEME

Dynamic cooperative FSO networks deploy resource allocation schemes in order to increase capacity, reliability and fairness as well as to decrease the bit error rate under rainy weather conditions. Increasing network capacity is achieved by maintaining the largest number of direct links to central node. Also, increasing network's reliability implies decreasing number of dropped users, while enhancing fairness means near the same bit rates are assigned to different supported users. Obviously, at clear weather conditions, all nodes are direct connected to the central node to get highest bit rates (maximum network capacity) at bit error rates less than a predefined threshold as indicated in Fig. 3(B.1). On contrary, at bad weather conditions, direct links of far nodes are dropped and switched to other nodes according to the resource allocation scheme in order to keep to connectivities to the central node. Resource allocation in dynamic cooperative FSO network could be optimized for several performance metrics. Given number of optical transceivers in each node (one or two transceivers in our case), loss coefficient matrix of FSO links γ and transmitted power for FSO link; many feasible configurations could enable k^{th} node ($k \in \{1,...,N\}$) to have bit rate $R_k \in \{0, x_1, x_2, ..., x_m\}$ at bit error rate less than the threshold $BER_k \leq BER_{max}$. Among these feasible configurations, one or more could achieve highest network's reliability, fairness, capacity and/or lowest bit error rate.

In this section, two resource allocation schemes are proposed to enhance the performance of dynamic cooperative FSO networks. However, these schemes are proposed for FSO networks that use two optical transceivers for inner nodes and one transceiver for outer nodes as indicated in Fig.1 (A) as current case study. The schemes use concept of lex-max-min fairness which is widely used in computer and wireless networks to overcome the congestion and limited reliability of the network (Ogryczak and Sliwinski, 2007). lex-max-min fairness is a criteria for achieving near equal resource sharing between N nodes at a relatively high network capacity, i.e avoiding inefficient fairness (allocate the lowest bit rate, x_1, for all nodes to achieve the maximum fairness). lex-max-min fairness is the generalization of ordinary max-min fairness as it searches sequentially for next maximals in case two or more solutions have the same maximal at one level in space of feasible solutions (Ogryczak and Sliwinski, 2007), (Ogryczak and Śliwiński, 2006).

The first proposed scheme is called lex-max-min constrained fairness (LMMCF) which aims to enhance network's capacity while keeping the fairness between different nodes. The second proposed scheme is called lex-max-min fairness (LMMF) that aims to enhance both reliability and fairness of the network regardless the capacity. The LMMCF scheme targets three objective functions; maximizing network capacity then maximizing bit rate fairness and then minimizing bit-error rate. However, the LMMF scheme targets two objective functions; maximizing bit rate fairness then minimizing bit-error rate.

Clearly, the optimized objective functions are conflicted, so each scheme is presented by multiple objective optimization problem (MOP). There are several methods to treat MOPs such as lexicographic (hierarchical), weighted summation, product and bounded objective-functions (Marler and Arora, 2004). Lexicographic is a criteria to optimize the conflicted objectives hierarchically and it has the ability to achieve the schemes goals (Isermann, 1982), (Marler and Arora, 2004). Lexicographic presents LMMCF problem in three optimization levels and LMMF in two levels based on the priorities between the objectives.

4.1 LEX-MAX-MIN Constrained Fairness Scheme

This scheme aims to increase network capacity then proceed to improve both network reliability and fairness. The network capacity is the summation of all nodes' bit rates. Also, the improvement in both reliability and fairness raised by maximizing bit rates of far nodes. Specifically, at the first optimization level, LMMCF scheme selects from the feasible Λ configurations the ones that maximize network capacity. After that in the second optimization level, the scheme searches the previously selected configurations for the ones that maximize the minimum bit rate for all nodes. If there are more than one configuration that have the same max-minimum bit rate, the LMMCF scheme proceeds to select from them the configurations that have next max-minimum bit rate (sequential max-min optimization) (Ogryczak and Sliwinski, 2007). However, if there are more than one configuration with the same sequential max-minimum values, the LMMCF selects from them in a third optimization level the configuration that has sequential minimum of maximum bit error rate values (sequential min-max optimization) (Ogryczak and Śliwiński, 2006).

Lexicographic represents the problem in three levels of optimization based on the priorities between the objectives as:

$$\textbf{Max}\left\{C_l = \sum_{k=1}^{k=N} R_{lk} : C_l \in C\right\}$$

$$\textbf{Lex-Max-Min}\{r_l = (R_{l1}, R_{l2}, ..., R_{lN}) : r_l \in R\}$$

$$\textbf{Lex-Min-Max}\{e_l = (BER_{l1}, ..., BER_{lN}) : e_l \in E\}$$

$$\begin{aligned}&\textbf{Subject to}:\\ &BER_{lk} \leq BER_{max},\ R_{lk} \in \{0, x_1, ..., x_m\},\\ &P_{lij} = P,\ Z_k \in \{1,2\},\ k \in \{1,...,N\},\\ &l \in \{1,...,\Lambda\}, \{i,j\} \in \{0,1,...,N\}, j \neq i.\end{aligned} \tag{8}$$

Several constraints are imposed in the stated multi-objective optimization problem. The bit error rate of each node must less than a predefined threshold. Also, only specific discrete values for the bit rates are allowed. Moreover, the same average transmitted power is used for all nodes. Clearly, in this optimization problem, the improvement in the bit rate fairness between different users is restricted by the network capacity.

4.2 LEX-MAX-MIN Fairness Scheme

Toward more increasing in the network reliability and fairness, the capacity could not be considered and select among the feasible configuration ones that maximize the reliable and fair configuration(s), then proceeding to minimize the bit error rates (maximize QoS). Lexicographic represents the problem in two levels of optimization based on the priorities between the objectives as in:

$$\textbf{Lex-Max-Min}\,\{r_l = (R_{l1}, R_{l2}, ..., R_{lN}) : r_l \in R\}$$

$$\textbf{Lex-Min-Max}\ \{e_l = (BER_{l1}, ..., BER_{lN}) : e_l \in E\}$$

$$\begin{aligned} &\textbf{Subject to}\ :\\ &BER_{lk} \leq BER_{max},\ R_{lk} \in \{0, x_1, ..., x_m\},\\ &P_{lij} = P,\ Z_k \in \{1,2\},\ k \in \{1, ..., N\},\\ &l \in \{1, ..., \Lambda\}, \{i, j\} \in \{0, 1, ..., N\}, j \neq i. \end{aligned} \tag{9}$$

This MOP is solved at the same previous constraints. Both equations (9) and (8) are classified as integer linear programming (ILP) optimization problems (discrete linear MOP). Each equation could be solved using exhaustive search (ES) method to obtain the optimal solution(s). ES method generates all possibles network forms (Λ) then evaluates the objective-functions and lastly compares between feasible solution to select the optimal one(s) (global max and min values) (Paar and Pelzl, 2009). However, the schemes could be solved by ES method in open time like off-line schemes (precomputed optimal values) to overcome the time computing complexity of ES method. Clearly, two schemes provide different service levels and the SLA (Service Level Agreement) between the nodes (end users) and backbone (optical service provider) determines the appropriate resource allocation technique.

According to the proposed schemes, it is suitable to add an index to measure the fairness between the N nodes. Jains index, F, is the most common and appropriate one (Jain et al., 1998).

$$F = \frac{\left(\sum_{k=1}^{k=N} R_k\right)^2}{N \times \left(\sum_{k=1}^{k=N} R_k^2\right)}, \quad 0 \leq F \leq 1. \tag{10}$$

5 SIMULATION AND NUMERICAL RESULTS

In this section LMMCF and LMMF resource allocation schemes are evaluated and compared to traditional robust static ones to indicate the superior performance of the proposed schemes. The evaluations consider four performance parameters which are reliability, capacity, fairness and bit-error rate. Four topologies which are considered in the evaluations are direct link (D-L) (Fig. 2(A)), partial relayed (P-L) (Fig. 2(B)), full relayed (F-L) (Fig. 2(C)) and reconfigurable cooperative (Fig. 3(A)) models. The number of the transceivers for these networks are 18, 24, 36, and 22 respectively. As shown in Fig. 4, the assumed service area of the considered FSO networks is $3*3$ km and nine FSO nodes are assumed to be located uniformly in this area. Moreover, same homogeneous weather is assumed through out the service area. All FSO links operate with predefined six bit rates, $m = 6$, at constant average optical power. Table.1 shows the assigned values of the simulated FSO network parameters which are selected to be in the practical range, also we use Japan's rain loss model.

Table 1: Simulation Parameters.

Link parameters	Values
Signal wavelength (λ)	1550nm
Divergence angle (Θ)	2 mm.rad/m
Diameter of Transmitter (d_t)	4 cm
Diameter of Receiver (d_r)	20 cm
average transmitted signal counts/slot ($q_t = q_s/\gamma$)	250,000
average background counts/slot (q_b)	50
Average transmitted Power (P)	-15 dBm
Average background noise power	-52 dBm
Discrete bit-rates ($\{x_m, ..., x_2, x_1\}$) in Gbps	1, 3/4, 1/3, 1/2, 1/3, 1/4
Modulation formate	NR-OOK
BER threshold (BER_{max})	10^{-4}
Area of FSO Network	$3 \times 3\ km^2$
Area of FSO-node Cell	$1 \times 1\ km^2$

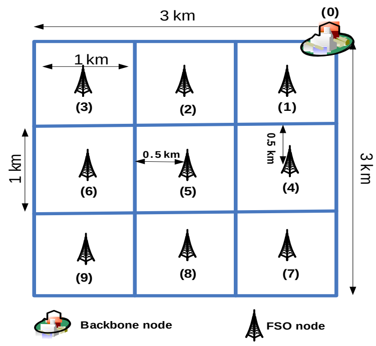

Figure 4: Dimensions of simulated FSO networks.

Figure 5 indicates the reliability of the topologies versus rain fall rates. Clearly, at $D \leq 3mm/h$ the 9 nodes for all topologies work properly using their direct FSO links. On contrary, at $D \geq 180mm/h$ all nodes for all topologies are dropped i.e. can't achieve minimum bit rate, $0.25Gbps$, at bit error rate less than threshold $1e-4$. Between these two rain fall rate levels, different network topologies have different performances. At D=$20mm/h$ the dropped nodes in the D-L, P-L, and LMMCF/LMMF are 6, 3 and 2 nodes respectively. Although, LMMCF and LMMF have identical performance curves, but in general the reliability of LMMF is better than the LMMCF due to its flexibility in link reconfiguration (no capacity constraint).

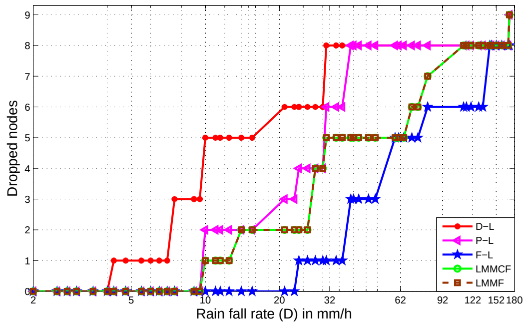

Figure 5: Reliability versus the rain fall rate (D) for five networks; D-L, F-L, P-L, LMMCF and LMMF.

Figure 6 shows the capacity of the networks where the capacity is $9Gbps$ for all topologies at $D \leq 3mm/h$, and zero at $D \geq 180mm/h$. And the performance of three topologies D-L, LMMCF and LMMF are almost the same, however the D-L and LMMCF topologies are better than the LMMF at certain D values as expected. Numerically, at $D = 7mm/h$ the capacity of D-L and LMMCF are $6Gbps$ while in LMMF it is $5.5Gbps$, this is due to the maximization capacity in LMMCF scheme.

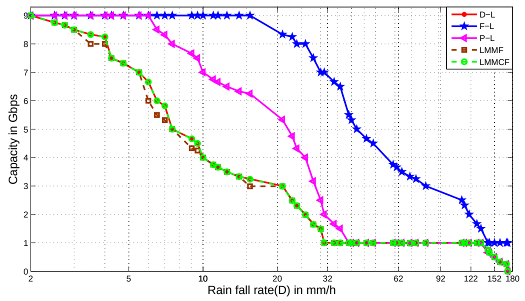

Figure 6: Capacity (C) versus the rain fall rate (D) for five networks; D-L, F-L, P-L, LMMCF and LMMF.

Figure 7 explains the fairness between the nodes in the capacity of the backbone node. The maximum fairness is 1 at $D \leq 3mm/h$ for all topologies. The proposed approaches improve the fairness and outperform P-L, specially at channel degradation. At $D = 10mm/h$ the fairness is 0.9 for both LMMCF and LMMF, 0.8 for P-L and 0.45 for D-L as shown. Note that, the fairness performance in LMMF case is better than that in LMMCF case as indicated from the MOPs formulations and numerical results. LMMF is better than LMMFC in fairness performance curve, specifically, at $D = 9mm/h$ the fairness is 1 and 0.9 for both LMMF and LMMCF respectively.

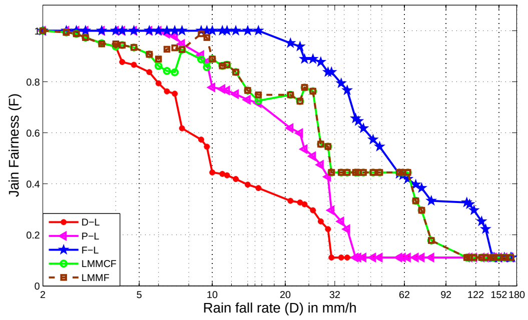

Figure 7: Fairness (F) versus the rain fall rate (D) for five networks; D-L, F-L, P-L, LMMCF and LMMF.

Figure 8 indicates to the bit-error rate of the networks, and both LMMF and LMMFC have the same performance around 10^{-5} bit error rate and dos not exceed 10^{-4}. However the F-L and P-L outperform the two other topologies, because the proposed schemes prioritize the reliability-fairness over the bit-error rate. We show the result for $D \leq 25mm/h$, because the networks at $D \geq 25mm/h$ have little number of survived nodes.

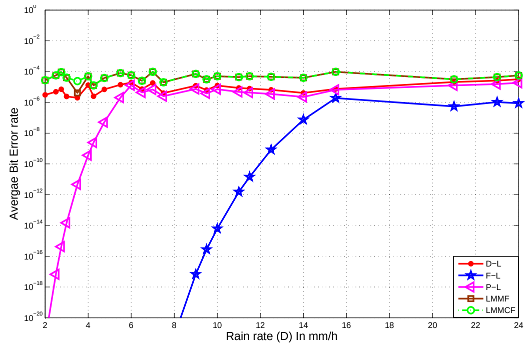

Figure 8: Average error rate (BER) versus the rain fall rate (D) for five networks; D-L, F-L, P-L, LMMCF and LMMF.

6 CONCLUSION

Two new resource allocation schemes, namely, LMMCF and LMMF have been proposed to increase both reliability and fairness of cooperative reconfigurable FSO networks at last-mile during sever rainy weather conditions. The proposed schemes outperform both D-L and P-L traditional schemes. Furthermore, this enhancement comes at much lower implementation cost as the number of installed transceivers for P-L and LMMCF/LMMF are 24 and 22 respectively. In addition, LMMCF and LMMF have different optimization criteria, where LMMF gives the priority for fairness and reliability over the capacity, while LMMCF does the opposite. The exhaustive search method has been used to solve the two ILP-MOPs. In order to overcome the solution complexity for LMMCF/LMMF the optimal solution(s) could be computed off line, then it could be registered as lookup table in FSO tracking controller, which reconfigures the topology to optimal configuration versus the rain fall rate in real time environment.

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