Constrained Fairness Placement Scheme in Cooperative Dynamic Free Space Optical Network

Abdallah S. Ghazy[1], **Hossam A. I. Selmy**[2], **Ziad A. El-Sahn** [3] **and Hossam M. H. Shalaby**[1]

[1]*Egypt-Japan University of Science and Technology (E-JUST), Alexandria 21934, Egypt*
[2]*Cairo University, Cairo, Egypt*
[3] *Photonics Group, Electrical Engineering Department, Alexandria University, Alexandria 21544, Egypt*

Abdallah.Ghazy@ejust.edu.eg, hossamselmy@yahoo.com, ziad.elsahn@ieee.org, shalaby@ieee.org

Abstract

In this paper, a new scheme is proposed to obtain the strategic locations of the cooperative transceivers on free space optical node in last-mile network. The scheme is formulated as bi-level multiple-objective linear integer programming (BL-MO-ILP) problem, and solved by exhaustive search method to obtain the optimal solutions. The scheme leads to an increasing in the immunity of network against severe weather conditions at the efficient cost in terms of number of optical transceivers. The numerical results reveal that improvements are obtained in the network performance, reliability and fairness, specially at low visibility conditions.

Keywords: Free space optics, Weather influence, Dynamic networks, transceiver placement.

1. Introduction

Free space optical (FSO) presents a promising solution for last mile connectivity problem, where remote network nodes have to be connected to central backbone node [1]. Figure 1 (A) shows one practical application which could be established by employing the FSO links. 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, air turbulence [1]. The weather conditions include fog that could absorb and scatter the transmitted optical signal. So, various suitable network topologies either static or dynamic FSO networks were investigated to mitigate the weather impairments and provide the required quality of service (QoS) for different nodes [2]. Currently, the significant innovation in pointing, acquisition and tracking system (PAT) makes the dynamic (reconfigurable) FSO network more feasible than before. Generally, performance enhancement of FSO networks requires installation a sufficient number of optical relay/redundant transceivers in order to support multiple/redundant path communication, and this rises the network cost. Thus, the determination of effective locations for optical relay/redundant transceivers is effective technique by which we could employ FSO transceivers in maximum performance at lower cost. In the previous work, two fair cooperative resource allocation schemes were proposed, lex-max-min constrained fairness and lex-max-min fairness schemes (LMMCF and LMMF), to enhance the performance of dynamic cooperative FSO networks against different atmospheric variations [3], [2]. Obviously, LMMCF and LMMF schemes exploit the fact that atmospheric degradations that frequently appear in last-mile network are distance dependent. And yields significant improvement in performance of FSO network by taking advantage of the resulting shorter hops, as shown in Fig. 1 (B). Clearly, At given number of optical transceivers, there are finite different placement vectors (number of FSO transceivers on each node) such as in Fig. 1 (C) and (D). Inner nodes are vital points for successful cooperation so they are worth to equipped by additional transceivers (cooperative transceivers), for example in Fig. 1 (C) outer nodes are equipped by one and inner nodes are equipped by two transceivers, however in Fig. 1 (D) outer nodes are equipped by one and inner nodes are equipped by three, two and one transceivers. Although the number of optical transceivers play important role in the dynamic network performance, however this role will not be completely achieved if the the locations of transceivers are not selected correctly (find the dominate placement vector) [4]. In this paper

978-1-5090-1467-5/16/$31.00 ©2016 IEEE

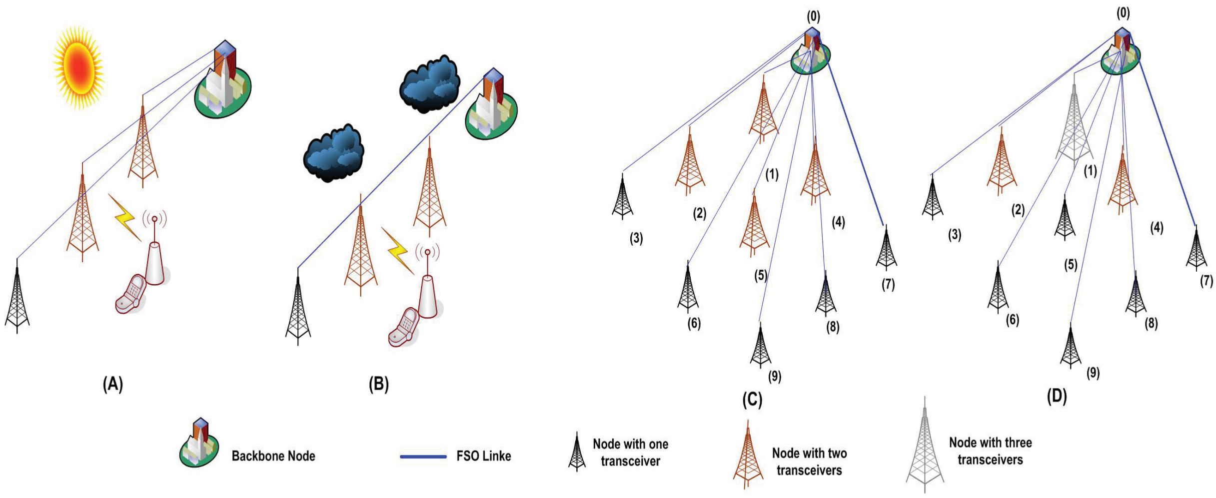


Fig. 1. Last-mile network (A) Direct links during clear weather. (B) Cooperative links during foggy weather. (C) One possible Placement vector . (D) Another Placement vector.

the optimal vector(s) is/are investigated in cooperative-reconfigurable last-mile network at given number of total transceivers during foggy weather conditions. New scheme is proposed to find the best vector(s) for given number of FSO transceivers, by which the FSO networks could achieve the best performance at the lowest cost during the highest density foggy conditions. Also, the impacts of transceiver misplacement (non-optimal placement vector) on the network performance will be illustrated by using numerical results. The scheme is formulated as bi-level multiple-objective linear integer programming (BL-MO-ILP) problem and solved by exhaustive search method.

2. FSO Link Model

Mainly there are two sources of loss in FSO; channel losses and system losses. The channel loss is caused by atmosphere conditions (fog, rain, snow and scintillation), and beam spreading (geometric loss) [5]. Both fog and geometric losses are considered and the rest of the losses are neglected. The fog loss is defined by several empirical models, the Kim model is used, which is the most accurate one for low visibility ($V \leq 6Km$) FSO link [1]. The geometric loss could be calculated using the model in [5]. Naturally the variation of weather is quasi-static in the spatial domain, so the homogeneous weather is assumed (equal visibility value over all the links). The eye safety regulation is considered, so the transmitted power of the FSO link is assumed to be constant during the atmosphere variation [5]. Essentially there are two kinds of noise sources; thermal noise and shot noise. When the background radiation (ambient noise) level is relatively high (out door FSO link), the thermal noise can be ignored and the receiver is modeled as shot noise limited system, also On Off Keying (OOK) technique is used to modulate the transmitted signal [6].

3. Transceivers Placement Parameters in Cooperative Dynamic FSO Network

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. Normally, each FSO node is equipped with one optical transceiver to transmit/receive it's own traffic to backbone node which is equipped with N optical transceivers. In order to take the advantages of cooperative reconfigurable FSO network, additional w optical transceivers are implemented. Given w, the total number of optical transceivers at k^{th} node is $z_k = \{1,2,\ldots,w+1\}$, where $k \in \{1,2,\ldots,N\}$. Specifically, the number of nodes equipped with s transceivers is given by n_s where $s \in \{1,2,\ldots,w+1\}$. Obviously, there is Λ placement vectors, $Z_a = (z_1,z_2,...,z_k,...,z_N)$ and $a \in \{1,2,...,\Lambda\}$. Also, all vectors can be summarized in matrix H with dimension $(N \times \Lambda)$, where Λ could be obtained by the upper bound:

$$\Lambda < \left[N + \sum_{b=2}^{w-1} \binom{N}{b} \times (w-1)^b + \binom{N}{w} \right], \quad w \leq N. \tag{1}$$

For each transceivers placement vector Z_a, there is a number of feasible configurations β_a that could be realized with this placement, where β_a is upper bounded by:

$$\beta_a < \left[\sum_{ii=1}^{ii=N} \binom{N}{ii}\right] \times \prod_{s=1}^{s=w+1} \left[\sum_{jj=0}^{jj=s} \binom{N}{jj}\right]^{n_s}. \tag{2}$$

The overall total number of feasible configurations for all placements vectors is

$$\alpha < \left[\sum_{a=1}^{a=\Lambda} \beta_a\right] \tag{3}$$

At a given visibility value, V, the losses of all FSO links are summarized in γ matrix, $\gamma = (\gamma_{00},\ldots,\gamma_{0N};\ldots,\gamma_{ij},\ldots;\gamma_{N0},\ldots,\gamma_{NN})$, where γ_{ij} is the loss coefficient of link between transmitter of i^{th} node and receiver of j^{th} node. Clearly, $0 \le \gamma_{ij} \le 1$, γ_{ii}= 0 and $\gamma_{ij} = \gamma_{ji}$ for any $i, j \in \{0,1,\ldots,N\}$. Each feasible d^{th} configuration, $d \in \{1,2,\ldots,\beta_a\}$, is identified by binary matrix G_d, and each placement vector Z_a has a set of β_a binary matrices, G_a, represents all configurations that could be implemented by it. The connection status between network nodes in d^{th} configuration are summarized in connections matrix $G_d = (g_{d00},\ldots,g_{I0N};\ldots,g_{dij},\ldots;g_{dN0},\ldots,g_{dNN})$, where g_{dij} is the connection status between i^{th} and j^{th} nodes in configuration d and $g_{dij} \in \{0,1\}$. The connection between nodes i and j is established in configuration d if $g_{dij} = 1$. Also, bidirectional links are assumed so that $g_{dij} = g_{dji}$ and $g_{dii} = 0$. 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 d is constant, $P_{dij} = P_0$. However, to increase link capacity and guarantee an error rate less than a specified maximum $BER_{dij} < BER_{max}$, the link between nodes i and j in configuration d adapts its transmission rate, T_{dij}, to be one of $q+1$ discrete values, where $T_{dij} \in \{0,x_1,x_2\ldots,x_q\}$ and $x_1 < x_2 < \ldots < x_q$. The transmission rate of node k in configuration d is denoted by T_{dk}, where $T_{dk} = \sum_{j=0}^{N} T_{dkj}$. The bit rate of node k (its own traffic) through connection to node j in configuration d is denoted by R_{dkj}. The overall bit rate of node k in configuration d is $R_{dk} = \sum_{j=0}^{N} R_{dkj}$. Obviously, $R_{dk} \le T_{dk}$ and for practical implementation both R_{dk} and $T_{dk} \in \{0,x_1,x_2,\ldots,x_q\}$. The end-to-end bit error rate of node k in configuration d, BER_{dk}, is bounded by $BER_{dk} \le BER_{max}$. The bit rates and bit-error rates associated with all nodes in the feasible configurations could be summarized in $(\beta_a \times N)$ matrices R_a and E_a, respectively. For the d^{th} configuration, the bit rates for all nodes are represented in vector $(1\times N)$ r_d, $r_d \in R_a$. Also, the bit-error rates in that configuration are summarized in vector $(1 \times N)$ e_d, $e_d \in E_a$. The network capacity associated with configuration d is $C_d = \sum_{k=1}^{N} R_{dk}$, and all capacities associated with all feasible configuration are summarized in vector $(\beta_a \times 1)$ C_a, $C_d \in C_a$.

4. Proposed Optimal FSO Transceivers Placement Scheme

In the proposed scheme, BL-MO-ILP problem formulated and solved. In both level of optimization, four objectives are considered; capacity, reliability (in terms of non-zero bit rate node), fairness ($F = \sum_{k=1}^{k=N} R_{lk}^2/(N \times \sum_{k=1}^{k=N} R_{lk}^2)\ : 0 \le F \le 1$, see [7]) then average error rate respectively. Where in first level and for each Z_a, the scheme obtains the optimal configuration, $\bar{G}_a(:,:,m)$, at each visibility interval $\Delta V_{a,m}$, $m \in \{1,2,..,M_a\}$. This could be achieved by maximizing $C_a(m)$, at the first, then optomizing $R_a(:,m)$ using sequential max-min that reduces the dropped nodes and rises the fairness, then optomizing for $E_a(:,m)$ using sequential min-max that reduces the error rates. From first level optimization, three matrices are obtained to each Z_a, $(M_a \times 1)$ $\bar{C}_a$, $(M_a \times N)$ $\bar{R}_a$ and $(M_a \times N)$ $\bar{E}_a$. And in second level the scheme determines the optimal placement vector Z_{a^*} among H and its associated configurations G_{a^*}. Here the area under curve, Ω_a, for the objective multiplied by the probability, $P(\Delta V_{a,m})$, are maximized (capaccity Ω_a^c, reliability Ω_a^R then fairness Ω_a^f) then minimized (error rate Ω_a^e) respectively, to obtain the dominant placement vector that achieves the best average performance along the visibility range. The proposed scheme could be formulated as shown in formula (4). Clearly, in this problem the improvement in the reliability and bit rate fairness between different users (sequential max-min optimization) is restricted by the maximization of network capacity. Several constraints are imposed in this problem, the bit error rate of each node must less than a predefined threshold, only specific discrete values for the bit rates are allowed, and the same average transmitted power is used for all nodes.

$$\begin{aligned}
&\underline{\textbf{Step One : Optimal configurations}}\\
&\underline{\textbf{Inputs:}}\, Z_a, \Delta V_{a,m}.\\
&\underset{d}{\textbf{Max}}: \left\{ C_d = \sum_{k=1}^{k=N} R_{dk} : C_d \in C_a \right\}\\
&\underset{d}{\textbf{Lex-Max-Min}}: \left\{ r_d = (R_{d1}, ..., R_{dN}) : r_d \in R_a \right\}\\
&\underset{d}{\textbf{Lex-Min-Max}}: \left\{ e_d = (BER_{d1}, ..., BER_{dN}) : e_d \in E_a \right\}\\
&\textbf{Subject to:}\\
&d \in \{1,2,3,...,\beta_a\}\,,\ z_k \in \{1,2,...,w+1\}, R_{dk} = \sum_{j=0}^{N} R_{dkj}\,,\ R_{dk} \le T_{dk}\,,\ T_{dk} = \sum_{j=0}^{N} T_{dkj},\\
&BER_{dk} \le BER_{max}\,,\ BER_{dij} < BER_{max}\,, P_{dij} = P_0\,,\ \{R_{dk}, R_{dkj}, T_{dk}, T_{dkj}\} \in \{0, x_1, x_2, \ldots, x_q\}\,,\\
&\ T_{djj} = R_{djj} = 0\,,\ \{i,j\} \in \{0,1,2,3,...,N\}\,,\ j \ne i.\\
&\underline{\textbf{Outputs:}}\, \bar{G}_a, \bar{C}_a, \bar{R}_a, \bar{E}_a.\\
&\underline{\textbf{Step Two: Optimal Placement}}\\
&\underline{\textbf{Inputs:}}\, \bar{G}_a, \bar{C}_a, \bar{R}_a, \bar{E}_a.\\
&\underset{a}{\textbf{Max:}} \left\{ \Omega_a^c = \sum_{m=1}^{m=M_a} P(\Delta V_{a,m})\ .\ \Delta V_{a,m}\ .\ \bar{C}_a(m) \right\},\\
&\underset{a}{\textbf{Max:}} \left\{ \Omega_a^R = \frac{1}{N} \sum_{m=1}^{m=M_a} P(\Delta V_{a,m})\,.\,\Delta V_{a,m}\,.\, \sum_{k=1}^{k=N} \delta_{mk} \right\}, \quad \delta_{mk} = \begin{cases} 1 & R_{mk} > 0 \\ 0 & R_{mk} = 0 \end{cases} \ : R_{mk} \in \bar{R}_a,\\
&\underset{a}{\textbf{Max:}} \left\{ \Omega_a^f = \sum_{m=1}^{m=M_a} P(\Delta V_{a,m})\ .\,\Delta V_{a,m}\,.\,F_m :\ R_{mk} \in \bar{R}_a \right\},\\
&\underset{a}{\textbf{Min:}} \left\{ \Omega_a^e = \sum_{m=1}^{m=M_a} P(\Delta V_{a,m})\,.\,\Delta V_{a,m}\,.\, \sum_{k=1}^{k=N} \frac{\bar{R}_a(m,k)\,.\,\bar{E}_a(m,k)}{\bar{C}_a(m)} \right\}\\
&\textbf{Subject to:}\\
&\quad a \in \{1,2,3,...,\Lambda\}\,.\\
&\underline{\textbf{Outputs:}}\, Za^*\ ,\ G_{a^*}.
\end{aligned} \tag{4}$$

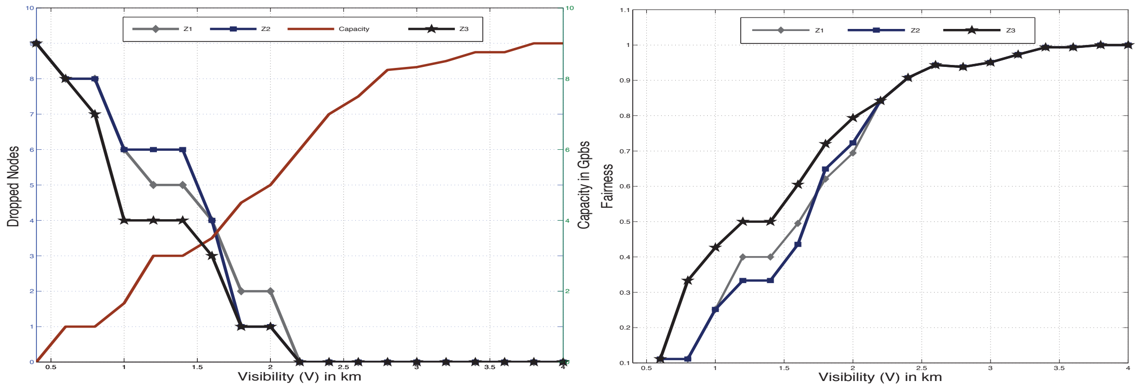
5. Simulation and Numerical Results

This section shows the numerical evaluation for the scheme in two network designs, first design has $w = 2$, the second one has $w = 4$ and $N = 9$. The simulation parameters and network dimensions are given in the table, where the maximum bit rate is 1 Gbps, maximum error-rate is 1e-4, the maximum distance between two nodes (backbone and node number 9) is 3.6km and the shortest link (backbone and node number 1) is 0.77 km as shown in Fig. 1 (C) and (D). To guarantee the optimality of the results, the scheme is solved by suing Exhaustive Research Method (ER) which leads to the best network performance. The objectives, $C(V)$, $\Re(V)$ and $F(V)$, are shown in two cases in the Fig. 2 (A) and (B). Obviously, the performance of $C(V)$ for all vectors and designs are identical, however, the values of both $\Re(V)$, $F(V)$ and $ABER(V)$ depend on both w and Z_a. In this results, the network performance degrades at misplacements and the best placements immune the network during the foggy weathers. Specifically, as shown in the Fig. 2 (A) for case $w = 2$, the best vector is $Z_3|_{[z_1,z_2=2]}$ and the worst ones are $Z_1|_{[z_2=3]}$ and $Z_2|_{[z_5=3]}$. Numerically, for $Z_2|_{[z_5=3]}$ the network behaviour is $\Re(1.4) = 3/9$ and $F(1.4) = 0.35$, for $Z_1|_{[z_2=3]}$ the network behaviour is $\Re(1.4) = 4/9$ and $F(1.4) = 0.4$, however, in case $Z_3|_{[z_1,z_2=2]}$, the network behaviour is $\Re(1.4) = 5/9$ and $F(1.4) = 0.5$. Also, from the Fig. 2 (B) for case $w = 4$, the best vectors are $Z_3|_{[z_1,z_2=2,z_5=3]}$ and $Z_2|_{[z_1=2,z_2=3,z_5=2]}$ but the worst one is $Z_1|_{[z_4=2,z_5=3]}$. In this network for $Z_3|_{[z_1,z_5=2,z_2=3]}$, the network behaves $\Re(1.4) = 7/9$

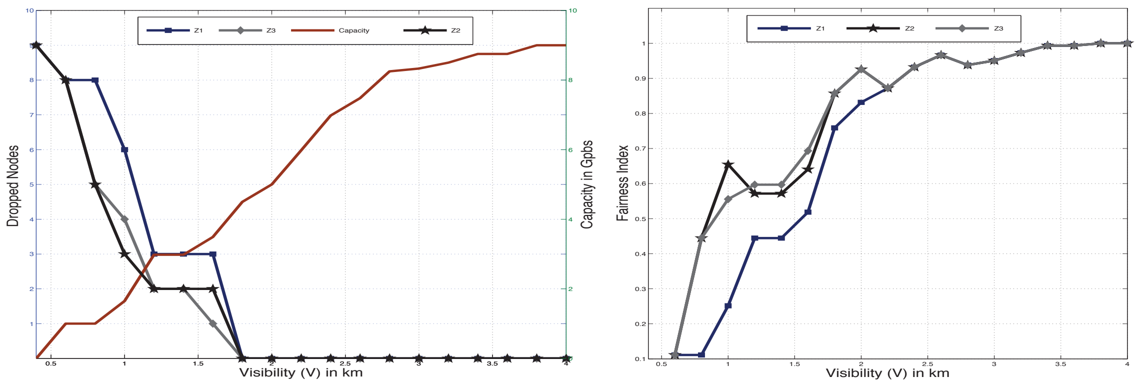
and $F(1.4) = 0.6$, for $Z_2|_{[z_1,z_2=2,z_5=3]}$, the network behaves $\Re(1.4) = 7/9$ and $F(1.4) = 0.57$, however, in case $Z_1|_{[z_4=2,z_5=4]}$, it behaves $\Re(1.4) = 5/9$ and $F(1.4) = 0.45$.

Table 1. Simulation Parameters

Link parameters	Values	Link parameters	Values
Signal wavelength	1550 nm	Divergence angle	2 mrad/m
Average Transmitted Power	-12 dBm	Bit Rates in Gbps	1, 3/4, 2/3, 1/2, 1/3, 1/4, 0.
Diameter of Transmitter	4 cm	Average ambient noise	-49.6 dBm
Diameter of Receiver	20 cm	BER threshold	$1e-4$
Network area	4x4 km	Cell length	1x1 km



(A) Two cooperative transceivers design



(B) Four cooperative transceivers design

Fig. 2. (A) and (B) Reliability, capacity and fairness performance.

References

1. I. I. Kim, B. McArthur, and E. J. Korevaar, “Comparison of laser beam propagation at 785 nm and 1550 nm in fog and haze for optical wireless communications,” in *Information Technologies 2000*. International Society for Optics and Photonics, 2001, pp. 26–37.
2. A. S. Ghazy, H. A. Selmy, and H. M. H. Shalaby, “Fair cooperative resource allocation schemes for foggy free space optical network,” *ICTON*, vol. 2, no. 6, pp. 178–200, 2015.
3. A. S. Ghazy, H. A. I. Selmy, and H. M. H. Shalaby, “Reliable-fair resource allocation schemes for snowy cooperative free space optical networks,” *ACP*, vol. 3, no. 6, pp. 278–300, 2015.
4. F. Ahdi and S. Subramaniam, “Optimal placement of fso relays for network disaster recovery,” in *Communications (ICC), 2013 IEEE International Conference on*. IEEE, 2013, pp. 3921–3926.
5. S. Bloom, E. Korevaar, J. Schuster, and H. Willebrand, “Understanding the performance of free-space optics [invited],” *Journal of optical Networking*, vol. 2, no. 6, pp. 178–200, 2003.
6. R. M. Gagliardi and S. Karp, *Optical Communications*, 2nd ed. New York: Wiley, 1995.
7. R. Jain, D. Chiu, and W. Hawe, “A quantitative measure of fairness and discrimination for resource allocation in shared computer systems,” *arXiv preprint cs/9809099*, 1998.