Reliable-Fair Resource Allocation Schemes for Snowy Cooperative Free Space Optical Networks

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Abstract: New resource allocation schemes are proposed to improve the performance of snowy cooperative FSO networks. Each scheme is formulated as multi-objective optimization problem. The simulation results indicate the superior performance over existing relayed ones.

OCIS codes: Free Space Optical, Snowy weather conditions, Relaibility, Fairness, Cooperative, Lex-Max-Min.

1. Introduction

FSO is a promising solution for the existing last mile connectivity problem. However, FSO channel is affected by various weather conditions. One of these conditions is the snowy weather which could absorb and scatter the transmitted optical signal. To overcome this performance degradation and increase the network reliability, FSO static relays can be used to construct robust static networks [1]. The major drawback of these solutions is increasing number of implemented optical transceivers. The dynamic (reconfigurable) FSO networks are proposed to reduce this number while maintaining acceptable network performance which presented in fairness and reliability (reduction of dropped FSO nodes number) [2]. The dynamic FSO networks are classified according to resource sharing into cooperative and non-cooperative. In the cooperative network, the links' bandwidths are fixed and nodes with relatively good links share their capacity with other nodes in order to guarantee the connectivity of far nodes to the central node (fiber backbone node) with acceptable bit rates.

In this paper, two resource allocation schemes are proposed to enhance the performance of reconfigurable cooperative FSO networks under wet and dry snowy weather conditions at extremely low implementation cost.

2. FSO Link Model

The FSO channel losses are accumulated from many sources, e.g., atmosphere variations (fog, rain, and snow), beam spreading (geometric), and scintillation. In the considered networks, both snow and geometrical losses are assumed the dominating ones. The snowy weather is either dry or wet with droplet fall rates of S_d, and S_w, respectively. The considered snow losses is defined by the empirical models in [3]. Moreover, a homogeneous snowy weather is assumed over the entire network with the same snow fall rate. The used geometric loss is described in [4]. Two sources contribute to the noise of FSO links, namely, shot and thermal noises. When the background radiation level is relatively high (out-door FSO link), the thermal noise could be ignored and the receiver can be modeled as shot noise limited (photo counter) [5]. In addition, intensity modulation direct detection (IM/DD) with non return to zero on-off keying (NR-OOK) formate is considered for all FSO links in network.

3. Reconfigurable Cooperative FSO Network Parameters

Generally, the cooperative FSO network consists of N nodes, $(v_1,...,v_N)$, with arbitrary geographical distribution that are connected to central backbone node, v_0. The number of optical transceivers at k^{th} node is denoted by Z_k where $k \in \{1,2,...,N\}$. Clearly, the inner nodes are assumed to have two transceivers (n_2 nodes) while the outer ones have one transceiver (n_1 nodes), where $Z_k \in \{1,2\}$. Also, the backbone node is equipped with N transceivers, as indicated in Fig. 1(b), where $N = 9$, $n_1 = 5$ and $n_2 = 4$. The losses of different FSO links are characterized in 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, $\gamma_{ij} = \gamma_{ji}$, and $\{i, j\} \in \{0,1,\ldots,N\}$. At a given snowy weather state, the cooperative FSO network could be connected with different feasible configurations (connection matrices) that achieve the minimum QoS parameters (minimum bit and bit-error rates). The number of these matrices is Λ. For a configuration $l \in \{1,2,\ldots,\Lambda\}$, the connection status between network nodes are summarized by connections matrix, $G_l = (g_{l00},\ldots,g_{l0N};\ldots,g_{lij},\ldots;g_{lN0},\ldots,g_{lNN})$, where g_{lij} is the connection status between i^{th} node and j^{th} node in configuration l and $g_{lij} \in \{0,1\}$. The connection between nodes i and j is established if $g_{lij} = 1$. Also, bidirectional links are assumed so that $g_{lij} = g_{lji}$ and $g_{lii} = 0$. Moreover, all FSO links have the same average power, i.e., the power of optical link between nodes i and j in configuration l is constant, $P_{lij} = P$. However, to increase the transmission rate of link g_{lij} and guarantee an transmission error rate less than a specified maximum one, $BER_{lij} < BER_{max}$, the connection between nodes i and j in configuration l adapts its transmission rate, T_{lij}, to be one of $m+1$ discrete values, where $T_{lij} \in \{x_1, x_2, \ldots, x_m, 0\}$ and $x_1 > x_2 \ldots > x_m$. The transmission rate of node k in configuration l is denoted by T_{lk}, where $T_{lk} = \sum_{j=0}^{j=N} T_{lkj}$. The data rate of node k (its own traffic) through connection to node j in configuration l is denoted by R_{lkj}. The overall data rate of node k in configuration l is $R_{lk} = \sum_{j=0}^{N} R_{lkj}$. Obviously, $R_{lk} \leq T_{lk}$ and $\{R_{lk}, T_{lk}\}$ $\in \{x_1, x_2, \ldots, x_m, 0\}$. 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 rate and bit error rate for all nodes associated with all feasible configurations could be summarized in $(\Lambda \times N)$ matrices R and E, respectively. For a given configuration l, the bit rate for all nodes is represented in $(1 \times N)$ vector r_l, $r_l \in R$. Also, the bit error rates in that configuration are summarized in $(1 \times N)$ vector e_l, $e_l \in E$. The network capacity associated with configuration l is $C_l = \sum_{k=1}^{k=N} R_{lk}$, and all capacities could be summarized in vector $(\Lambda \times 1)$ C, $C_l \in C$. Also, the maximum capacity is defined by $C_{max} = \sum_{k=1}^{k=N} T_{k0}$. Clearly, $C_l \leq C_{max}$ and capacity utilization is computed as $U_l = C_l / C_{max}$.The size of the feasible space, Λ, is upper bounded by the following inequality:

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

4. Proposed Lex-Max-Min Constrained Fairness and Lex-Max-Min Fairness Schemes

Toward increasing network reliability and decreasing number of dropped nodes, two resource allocation schemes are proposed. The first scheme, called Lex-Max-Min Constrained Fairness (LMMCF), selects from the feasible Λ configurations the ones that maximize the network capacity, $C_l = C_{max}$. If there are more than one solution that achieved the maximum capacity value, C_{max}, the algorithm selects among them the configurations that maximize minimum bit rate for all nodes. For configurations 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) [6]. If there are more than one vector solution with same sequential max-minimum values, the LMMCF selects the configuration that has best sequential min-max optimization in bit-error rate. This scheme is formulated as multiple objective optimization problem, lexicographic is a method to optimize the conflicted objectives and it has the ability to achieve the scheme goals [7]. Lexicographic represents the problem in three levels optimization based on the priorities between the objective-functions:

$$\begin{aligned}
&\textbf{MAX} \left\{ C_l = \sum_{k=1}^{k=N} R_{lk} : C_l \in C \right\} \\
&\textbf{LEX-MAX-MIN} \quad \{ r_l = (R_{l1}, R_{l2}, \ldots, R_{lN}) \ : r_l \in R \} \\
&\textbf{LEX-MIN-MAX} \quad \{ e_l = (BER_{l1}, BER_{l2}, \ldots, BER_{lN}) : e_l \in E \} \\
&\quad \textbf{subject-to}: \\
&\quad BER_{lk} \leq BER_{max}, R_{lk} \in \{x_1, \ldots, x_m, 0\}, P_{lij} = P, Z_k \in \{1,2\}, \{k,i,j\} \in \{0,1,\ldots,N\}, k \neq 0, i \neq j, l \in \{1,2,\ldots,\Lambda\}.
\end{aligned} \tag{2}$$

This scheme aims to increase network capacity then network reliability and fairness among different nodes then to decrease bit-error rates as final optimization level. However, further reliability-fairness improvement could be achieved by the second proposed scheme which is called Lex-Max-Min Fairness (LMMF). The goal of LMMF optimization is to increase both network reliability and fairness among different nodes then decrease bit-error rates without considering capacity optimization. LMMF is formulated as LMMCF but in two levels optimization problem.

5. Simulation and Numerical Results

Both of problems (LMMCF and LMMF) could be solved using exhaustive search method to guarantee the optimal solution(s). The physical dimension of considered network is indicated in Fig. 1(b), where the area of each cell is '$1km^2$'. The proposed schemes are compared to three static models; direct 'D-M', partial relayed 'P-M' (one relay for each one of three remotest nodes and the relay is placed at the half distance as optimal placement), and full relayed 'F-M' (one relay for each node) models. The simulation parameters are; transmitting wavelength '1550 nm' average transmitted power '-15 dBm', average background noise '-52 dBm', diameter of transmitter/receiver '4/20 cm', divergence angle '2 mm.rad/m', bit-rates in Gbps '1, 0.75, 0.66, 0.5, 0.33, 0.25' and error-rate threshold '1e-4'. Also, Jains index is used to measure the network fairness, $0 \leq F \leq 1$, [8]. As indicated in Fig. 1 (a), (b) and (d), both LMMCF and LMMF schemes achieve better reliability-fairness performance than D-L and P-L models at all S_d and S_w values. Clearly at $S_d = S_w$, the weather impact of dry snow on the network performance is higher than wet snow as shown in Fig. 1(a) and (d). As expected, fairness performance of LMMF is higher than that in LMMCF case as shown in Fig. 1 (b). However, capacity value of LMMCF is higher than that in LMMF case as shown in Fig. 1 (c). Furthermore, this enhancement comes at much lower implementation cost where the number of installed transceivers for D-M, P-M, F-M, and LMMCF/LMMF are 18, 24, 36 and 22 respectively.

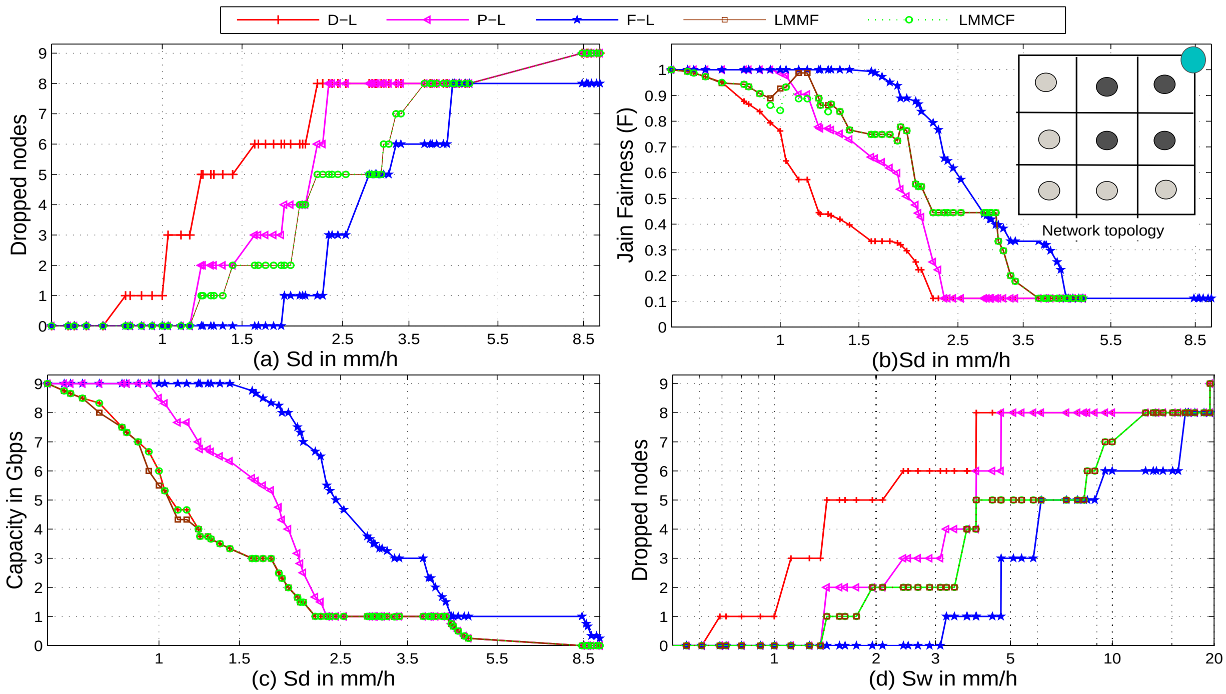

Fig. 1. Reliability, fairness and capacity values versus dry (S_d) and wet (S_w) snow fall rates.

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