Joint Relay Selection and Power Allocation in Cooperative FSO Networks

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***Abstract*—Cooperative diversity is considered as an effective means for combating weather turbulence in FSO networks. We investigate the problem of maximizing the FSO network-wide throughput under constraint of a given power budget and a number of FSO transceivers. The problem is formulated as a Mixed Integer Nonlinear Programming (MINLP) problem. We propose both centralized and distributed algorithms using bipartite matching and convex optimization to obtain highly competitive solutions. The proposed algorithms are shown to outperform the non-cooperative scheme and an existing relay selection protocol with considerable gains through simulations.**

I. Introduction

Drawing increasing attention, free space optics (FSO) is a cost effective technology with applications ranging from high capacity military communications to "last-mile" broadband access solutions. Although FSO links are able to support data intensive communications, a line-of-sight (LOS) path is required and there are many factors leading to significant link performance degradation. Most common is the adverse atmospheric conditions (e.g., due to the temperature and pressure changes or flying objects), which can greatly degrade the link performance [1]. Fading-mitigation techniques have to be employed to maintain FSO system performance.

To this end, topology control in FSO networks has been studied and proved to be effective in maintaining system performance [2]. On the other hand, spatial diversity techniques, extensively studied in RF communication systems [3], have recently been introduced to FSO systems. Multiple-input multiple-output (MIMO) FSO system can achieve significant diversity gain in the presence of atmospheric fading by deploying multiple transmit or receiver apertures [4]. Under the circumstance of limited transceivers or antennas, another cost-effective (compared to MIMO-FSO) alternative is the cooperative diversity technique, which is studied in this paper.

Cooperative diversity is considered as an effective means for combating weather turbulence in FSO networks. Usually FSO networks are usually well planned with perfect LOS paths. However, under the situations of severe weather or flying objects, an FSO base station may still experience degraded communication performance. However, if the FSO BS transmits cooperatively through an FSO BS relay whose surrounding weather is better, the degradation can be greatly mitigated. In [5], one-relay cooperative diversity is demonstrated to achieve significant gains over non-cooperative FSO links that suffer from correlated fading while multi-hop relaying can also be employed in FSO networks [6].

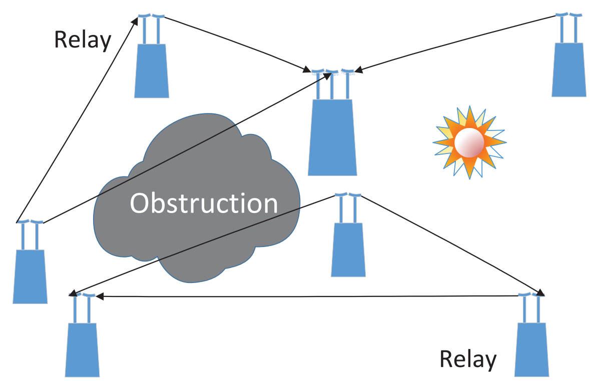

Fig. 1. Illustration of a cooperative FSO network.

In this paper, we consider the decode-and-forward (DF) cooperation strategy with one relay for FSO links [7]. The cooperative FSO network framework is illustrated in Fig. 1, within which each FSO BS is equipped with two or three transceivers. During operation, the LOS path might be influenced by severe weather conditions but a cooperative FSO transmission strategy can mitigate the weather influence and enhance the system performance. We consider one-relay cooperative FSO communication with intensity modulation and direct detection (IM/DD). In the proposed cooperative FSO network, a BS can transmit directly to the destination BS, or use another BS as relay. In the latter case, the source BS first transmits symbols to the relay BS in one time slot. Then, the source and relay BS's will simultaneously transmit the symbols to destination BS in the next time slot.

Unlike the prior work on cooperative FSO networks that focused on physical layer aspects, we investigate the problem of maximizing the network-wide throughput with consideration of power budget and cost (i.e., the number of available FSO transceivers) constraints. Specifically, we formulate the problem of joint relay selection and power allocation as a Mixed Integer Nonlinear Programming (MINLP) problem. We develop both centralized and distributed algorithms to solve the formulated problem. First, we design a centralized algorithm for relay selection based on *maximum weight matching* on a bipartite graph. We then show that the remaining power allocation problem is convex and then solve it using the *gradient method* in convex optimization. In the case when centralized coordination is not available, we develop a distributed

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algorithm that uses only local channel state information (CSI). The distributed algorithm is based on the the *Distributed Extended Gale-Shapley* (DiEGS) algorithm originally designed for solving the stable marriage problem [8]. The performance of the proposed algorithms are evaluated with simulations and are shown to outperform a non-cooperative scheme and an existing relay selecting protocol with considerable gains.

The remainder of this paper is organized as follows. The related work is discussed in Section II. We introduce the system model in Section III. We present the problem formulation and solution algorithms in Section IV and our simulation studies in Section V. Section VI concludes this paper.

II. Related Work

FSO has attracted significant interest both in academia and industry as a promising solution for high capacity, long distance communications [9]. Relay-assisted FSO communication has been studied in [10]–[12]. Both serial and parallel relaying coupled with amplify-and-forward and decode-and-forward cooperation modes are considered in [10]. The authors adopted multiple-relay communication to shorten the distance between FSO BS's and reduce the hop counts, resulting in considerable performance improvements. The work in [10] was extended in [11] and the authors further provided an interesting diversity gain analysis. In [12], the authors propose to select only a single relay in each transmission slot, to avoid the need for synchronizing multiple relays' transmissions.

In a recent work [5], a one-relay cooperative diversity scheme was proposed for combating turbulence-induced fading and cooperative diversity was analyzed for non-coherent FSO communications. Numerical results demonstrated considerable performance gains over non-cooperative FSO networks. Abou-Rjeily and Haddad in [13] studied cooperative FSO systems with multiple relays. An optimal power allocation strategy was proposed to enhance diversity order and minimize error probability. It turned out that the solution was to transmit with the entire power along the strongest link between the source and destination.

The prior work on optimal relay selection or relay placement in FSO networks focus on maximizing the diversity gain, reducing the outage probability, or maximizing the capacity for an individual BS. In this paper, we consider the challenging problem of relay selection and power allocation under power and cost constraints. We aim at maximizing the overall FSO network capacity. We develop effective algorithms that are based on bipartite matching and convex optimization to compute highly competitive solutions to maximize the throughput of the cooperative FSO network.

III. System Model

Cooperative communication is investigated in this paper as a fading mitigation method for FSO networks. When the direct link between source and destination suffers from atmospheric turbulence, FSO BS's can use relays to enhance link quality.

A. Channel Model

FSO links are highly directional and are prone to degradation caused by weather turbulence. In this paper, we consider both effects of path loss and turbulence-induced fading over FSO links [6]. The optical channel state h is a product of two factors, as

$$h = h_l \cdot h_f, \tag{1}$$

where h_l denotes the propagation loss and h_f represents the impact of atmospheric turbulence. h_l is a function of optical wavelength λ and link length d, as [1]

$$h_l = \frac{A_{TX} \cdot A_{RX} \cdot e^{-\alpha d}}{(\lambda \cdot d)^2}, \tag{2}$$

where A_{TX} and A_{RX} are aperture areas of the transmitter and receiver, respectively. The coefficient α is a parameter related to wavelength and environment. For h_f, we assume the impact of atmospheric turbulence can be modeled as a log-normal distribution, which is a widely used in FSO network literature, especially under weak-to-moderate turbulence conditions.

The FSO channel model can be written as

$$y = h \cdot x + n, \tag{3}$$

where x and y are the transmitted and received signals, respectively; n is the additive Gaussian noise. With the non-cooperative strategy, the maximum achievable data rate for a communication pair is given by the Shannon formula as

$$w_{s,d} = B \log_2 \left(1 + \frac{|h_{s,d}|^2 P_s}{\sigma^2} \right), \tag{4}$$

in which $h_{s,d}$ denotes the channel state of the direct link between source and destination. Let $W_{s,r}$ denote the maximum achievable capacity between source and destination when one relay is used, which can be expressed as

$$\begin{aligned} w_{s,r} \quad = \quad & \frac{B}{2} \min \left\{ \log_2 \left(1 + \frac{|h_{s,r}|^2 P_s}{\sigma^2} \right), \right. \\ & \left. \log_2 \left(1 + \frac{|h_{s,d}|^2 P_s}{\sigma^2} + \frac{|h_{r,d}|^2 P_r}{\sigma^2} \right) \right\}, \end{aligned} \tag{5}$$

where P_s and P_r represent the source and relay's transmit power, and $h_{s,r}$ and $h_{r,d}$ are the channel states of the source-relay link and and the relay-destination link, respectively.

B. Cooperation Model

We consider a relay-assisted IM/DD FSO communication system with the DF strategy [14]. The transmission takes two time slots. In the first time slot, the source station first transmits symbols to one relay station, which will detect the information symbols; in the second time slot, the source and relay will simultaneously transmit the symbols to the destination.

The cooperation model consists of K base stations. Each base station may transmit directly, or use one relay to assist its transmission. We assume the base stations will not decline a cooperation request under any circumstance. We have $M (M \leq K)$ BS's generating traffic among these base stations.

The set of source base stations is denoted by $\mathcal{S}$ and the set of destination base stations is denoted by $\mathcal{D}$. The cardinalities of $\mathcal{S}$ and $\mathcal{D}$ are both M. The destination of source S_i is denoted as D_i. Usually an FSO BS has a limited number of transceivers, which limits the number of communication links that a BS can have simultaneously.

For every source-destination pair, we assume at most one relay is assigned. Assuming CSI is known, every source would like to greedily choose its best relay to maximize its data rate. However, every BS has a limited number of transceivers and a limited power budget. In this paper, we thus focus on the problem of relay selection and transmit power allocation to maximize the overall capacity of the cooperative FSO network.

IV. Problem Formulation and Solution Algorithms

In this section, we present the problem formulation. We also develop centralized and distributed relay selection and power control algorithms to solve the formulated problem.

First, define the following variables for relay selection.

$$I_{i,j} = \begin{cases} 1, & \text{if BS } i \text{ selects BS } j \text{ as relay} \\ 0, & \text{otherwise,} \end{cases} \quad \text{for all } i,j \in \{1,\cdots,M\}. \quad (6)$$

Note that $I_{i,i}=1$ indicates that BS i transmit directly to its destination without using any relay.

The limited number of transceivers at the BS's is translated into constraint $\sum_{i=1}^{M} I_{i,j} \leq T_j$, for all j, where T_j is the number of transceivers at BS j. The base stations will use their transceivers to cooperate with each other and allocate power to each transceiver. The power budget constraint for each base station is represented as $\sum_{j=1}^{M} P_{i,j} \leq P_i$, for all i, where $P_{i,j}$ is the power that BS i allocates to assist source j and P_i is the power budget of BS i. For eye safety considerations, we enforce a peak power bound for the transmit powers, as $P_{i,j} \leq P_{max}$, for all $i,j \in \mathcal{S}$.

Given the transceivers and power constraints, the objective is to develop a relay selection and power allocation scheme for each BS, while the overall network capacity is maximized. The problem is formulated as follows.

$$\max \quad \sum_{i=1}^{M} (I_{i,i} w_{s,d}^{i,i} + \sum_{j=1, j\neq i, j \neq D_i}^{K} I_{i,j} w_{s,r}^{i,j}) \quad (7)$$

$$s.t. \quad \sum\nolimits_{i=1}^{M} I_{i,j} \leq T_j, \forall\, j \in \mathcal{B} \quad (8)$$

$$\sum\nolimits_{j=1}^{K} I_{i,j} \leq 1, \forall\, i \in \mathcal{S} \quad (9)$$

$$\sum\nolimits_{j=1}^{M} P_{i,j} \leq P_i, \forall\, i \in \mathcal{B} \quad (10)$$

$$0 \leq P_{i,j} \leq P_{max}, \forall\, i \in \mathcal{B}, j \in \mathcal{S} \quad (11)$$

$$I_{i,j} \in \{0,1\}, \forall\, i \in \mathcal{B}, j \in \mathcal{S}, \quad (12)$$

where the capacity achieved by direct communication (i.e., $w_{s,d}^{i}$) and the capacity achieved by using BS j as relay (i.e., $w_{s,r}^{i,j}$) can be calculated using (4) and (5), respectively. Each source can choose to either transmit directly or use one relay, which is specified in constraint (9).

A. Centralized Algorithm

The formulated problem is an MINLP problem with binary variables $I_{i,j}$'s and real variables $P_{i,j}$'s, which is NP-hard [15]. We develop a centralized algorithm that first determines the relay selections and then allocates transmit powers to selected relays. The main idea is to fix I-variables first and then consider optimized power allocation at each relay.

The first phase of the centralized algorithm is to solve the relay selection problem. The relay selection problem here can be interpreted as a weighted bipartite matching problem, which can be solved with polynomial-time algorithms such as Hungarian algorithm. First we construct a bipartite graph as follows: one disjoint set consists of the source BS's, and the other disjoint set contains the destination BS's and the BS's that have available transceivers to relay traffic for the sources. We call such a BS a *relay BS*. The weight of each matching edge is the corresponding link capacity.

The heuristic relay selection algorithm is presented in Algorithm 1, which incorporates maximum weight matching. Let N_j be the number of sources that relay j serves. Initially, N_j is set to be as large as possible to accommodate more sources; however, the power that each source is allocated may be too small to achieve the desired capacity gain in this case. As the algorithm evolves over time, N_j will be decreased finally to one. If a source i cannot achieve the desired capacity gain even with one relay that is allocated with all the power budget P_i, it has to transmit directly to its destination. Actually, for every source i and relay j, we can calculate the minimum relay power $P_{min}^{i,j}$ required to achieve more capacity than by the direct transmission, according to (4) and (5).

In Line 16 of Algorithm 1, maximum weight matching is executed on the constructed bipartite graph. The bipartite graph is constructed as a undirected complete bipartite graph $G(\mathcal{A} \cup \mathcal{B}, E)$. As discussed, the disjoint set $\mathcal{A}$ consists of all the source nodes, while the other disjoint set $\mathcal{B}$ is the union of the relay nodes and destination nodes. In this graph, there are actually N_j nodes for one relay, as given in Line 6 in Algorithm 1. The weight of each edge is the capacity achieved by transmitting using the link, which can be calculated and assigned before the matching computation. During every iteration, we check if a relay has been assigned to any source or not. If a relay BS j has not been matched to any source BS's, we will decrease its service capacity N_j, which is the number of source BS's that this relay serves. By decreasing service capacity, more power is available for candidate source BS's.

After the I-variables are determined as in Algorithm 1, the second phase of our centralized algorithm is to solve the power allocation problem, which can be shown to be a convex problem. The power allocation problem in the second phase, which is presented as

$$\max \quad \sum\nolimits_{i \in \mathcal{S}_1} w_{s,d}^{i,i} + \sum\nolimits_{i \in \mathcal{S}_2} w_{s,r}^{i,r_i} \quad (13)$$

$$s.t. \quad \sum\nolimits_{j=1}^{M} P_{i,j} \leq P_i, \forall\, i \in \mathcal{S} \quad (14)$$

$$0 \leq P_{i,j} \leq P_{max}, \forall\, i,j \in \mathcal{S}. \quad (15)$$

Algorithm 1: Centralized Relay Selection Algorithm

Initialize source $\mathcal{S}$, relay $\mathcal{R}$ and destination $\mathcal{D}$;
Remove source $\{i|h_{i,j} < h_i, \forall j\}$ from $\mathcal{S}$ and set $I_i = 1$;
while *$\mathcal{S}$ is not empty && $\mathcal{R}$ is not empty* **do**
  for $j \in \mathcal{R}$ **do**
    Find the minimum power to achieve capacity gain: $P^j_{min} = \min_{i \in S} P^{j,i}_{min}$;
    Get N_j: $N_j = \min\{N_j, T_j, P_{max}/P^j_{min} - \sum_i I_{i,j}\}$;
    if $N_j \leq 0 \parallel P_{max} \leq P^j_{min}$ **then**
      Remove j from $\mathcal{R}$;
    end
  end
  if $|\mathcal{R}| \leq 0$ **then**
    break ;
  end
  Calculate $w^{i,j}_{s,r}$ by setting $P_{j,i} = P_{max}/(N_j + \sum_i I_{i,j})$;
  Calculate $w^i_{s,d}$ by setting $P_{i,i} = P_{max}/(N_i + \sum_j I_{j,i})$;
  Initial bipartite graph $\mathcal{G}$ with set $\mathcal{S}$ and set $\mathcal{R} \cup \mathcal{D}$ and capacity assigned as weights;
  Compute the maximum weight matching ;
  for $i \in \mathcal{S}$ **do**
    if *source i is matched to relay j* **then**
      Remove source i from $\mathcal{S}$ and Set $I_{i,j} = 1$ and $T_j = T_j - 1$;
    end
  end
  for $j \in \mathcal{R}$ **do**
    if *j is not matching saturated* **then**
      Set $N_j = N_j - 1$;
    end
  end
end
if $|\mathcal{S}| \geq 0$ **then**
  Set $I_i = 1, \forall i \in \mathcal{S}$;
end

The sources are divided into two sets: one set is transmitting directly without using any relays, denoted by $\mathcal{S}_1$; the other set is transmitting using one relay, denoted by $\mathcal{S}_2$. For each BS i in $\mathcal{S}_2$, its relay is denoted by r_i. This power allocation problem can be solved by many convex optimization methods, such as gradient, Interior point, or Newton method.

B. Distributed Algorithm

The centralized algorithm requires a central controller to gather all channel information and execute the algorithm. It may not be applicable when there is no such centralized entity. In this section, we propose a distributed greedy algorithm, where each base station only use its own channel gains.

With knowledge of the channel gains, a source will always prefer to transmit through the channel with the best channel gain. Hence, for source BS i, we create a preference list according to channel gains $h_{i,j}$; for relay j BS, we also get a preference list according to channel gains $h_{j,i}$. Then we have two sets: one set is the source nodes; the other set is the relay or destination nodes. Each source node will select one node from the other set given the preference lists.

The problem of determining the I-variables can be solved with the DiEGS algorithm [8]. In our case, the size of two parts are not equal; but, it is known that, an instance of stable marriage with sets of unequal size has exactly the same set of stable matchings as the same instance with the unmatched nodes deleted. Hence, with some modification of the DiEGS algorithm, we can distributedly solve the relay selection problem in polynomial time.

Now we have to solve the power allocation problem in a distributed manner, which is given in (13)–(15). For each BS, we have local variables P_i and $P_{i,j}$. For BS i in $\mathcal{S}_2$, variable $P_{j,i}$ is the power that relay BS allocates to assist its transmission, which is not local. We will introduce auxiliary variables $t^\star_i$ to localize capacity $w^{i,r_i}_{s,r}$ and $P^\star_i$ to localize power allocation at the relay. Now the problem becomes

$$\begin{aligned} \max \ & \sum\nolimits_{i \in \mathcal{S}_1} w^{i,i}_{s,d} + \sum\nolimits_{i \in \mathcal{S}_2} t^\star_i \qquad (16) \\ s.t. & \sum\nolimits_{j=1}^{M} P_{i,j} \leq P_i, \forall\, i \in \mathcal{B} \\ & 0 \leq P_{i,j} \leq P_{max}, \forall\, i \in \mathcal{B}, j \in \mathcal{S} \\ & \frac{B}{2}\log_2\left(1 + \frac{|h_{i,r_i}|^2 P_{i,i}}{\sigma^2}\right) \geq t^\star_i, \forall\, i \in \mathcal{S}_2 \\ & \frac{B}{2}\log_2\left(1 + \frac{|h_{i,i}|^2 P_{i,i}}{\sigma^2} + \frac{|h_{r_i,i}|^2 P^\star_i}{\sigma^2}\right) \geq t^\star_i, \forall\, i \in \mathcal{S}_2 \\ & t_{r_i,i} = t_i, t_{j,i} = 0, \forall\, i \in \mathcal{S}_2, j \neq i, j \neq r_i \\ & P_{r_i,i} = P^\star_i, P_{j,i} = 0, \forall\, i \in \mathcal{S}_2, j \neq i, j \neq r_i, \end{aligned}$$

where the subscription of $t_{r_i,i}$ indicates that the power allocation is determined by relay r_i.

We next take a dual decomposition approach to obtain a distributed algorithm for power allocation [16]. Applying the Lagrangian method, we show the original problem can be decomposed into subproblems with only local variables. For a BS in set $\mathcal{S}_1$, we have the local maximization problem as

$$\begin{aligned} \max \quad & w^{i,i}_{s,d} + \lambda_{1,i}(P_i - \sum_j P_{i,j}) + \qquad (17) \\ & \boldsymbol{\gamma_{1,i}}^T \boldsymbol{t_i} + \boldsymbol{\gamma_{2,i}}^T \boldsymbol{P_i}, \forall\, i \in \mathcal{S}_1. \end{aligned}$$

where $\lambda_{1,i}, \boldsymbol{\gamma_{1,i}}, \boldsymbol{\gamma_{2,i}}$ are all Lagrange multipliers and $\boldsymbol{P_i} = [P_{i,1}, P_{i,2}, \cdots, P_{i,m}]^T$ is the power allocation vector. In this paper, we use bold letters to denote vectors and $(\cdot)^T$ denotes the transpose operation of a matrix. The local dual problem is to minimize $g_1(\lambda_{1,i})$, which is obtained as the maximum value of the Lagrangian solved in (17) for given $\lambda_{1,i}$.

For a BS in set $\mathcal{S}_2$, we have the local maximization problem, which is more complicated since its relay power is decided by the relay BS.

$$\begin{aligned} \max \ & t^\star_i + \lambda_{1,i}(P_i - \sum_j P_{i,j}) + \qquad (18) \\ & \lambda_{2,i}\left(\frac{B}{2}\log_2\left(1 + \frac{|h_{i,r_i}|^2 P_{i,i}}{\sigma^2}\right) - t^\star_i\right) + \\ & \lambda_{3,i}\left(\frac{B}{2}\log_2(1 + \frac{|h_{i,i}|^2 P_{i,i}}{\sigma^2} + \frac{|h_{r_i,i}|^2 P^\star_i}{\sigma^2}) - t^\star_i\right) - \\ & \gamma_{1,i,i} t^\star_i - \gamma_{2,i,i} P^\star_i + \boldsymbol{\gamma_{1,i}}^T \boldsymbol{t_i} + \boldsymbol{\gamma_{2,i}}^T \boldsymbol{P_i}, \forall\, i \in \mathcal{S}_2, \end{aligned}$$

Algorithm 2: Distributed Relay selection and Power allocation Algorithm

```
Initialize the channel gains and obtain the preference list of source BS's ;
Run the Men- or Women-procedure of DiEGS and determine the I-variables ;
Set t = 0, initialize γ_{1,i,j}(0), γ_{2,i,j}(0) to some value ;
while termination criterion not met do
    Each BS solves (17) or (18) locally and sends solution to related BS's ;
    Update prices with the iterate in (20) and announce new prices to related BS's ;
    Set t ← t + 1 ;
end
```

where $\lambda_{1,i}, \lambda_{2,i}, \lambda_{3,i}, \gamma_{1,i}, \gamma_{2,i}$ are all Lagrange multipliers. The local dual problem is to minimize $g_2(\lambda_{2,i}, \lambda_{3,i})$ and the dual objective is defined as the maximum value of the Lagrangian over $\boldsymbol{P_i}$ and $\boldsymbol{t_i}$.

The master problem is given by

$$\min \quad g(\boldsymbol{\gamma_1}, \boldsymbol{\gamma_2}). \tag{19}$$

The optimal value of (17) and (18) for given sets of $\boldsymbol{\gamma_1}$ and $\boldsymbol{\gamma_2}$ defines the dual function $g(\boldsymbol{\gamma_1}, \boldsymbol{\gamma_2})$ and this master problem can be solved with the following iterative updates:

$$\gamma_{1,i,j}(t+1) = \gamma_{1,i,j}(t) - \alpha(t_{j,i}(t) - t_i(t)^\star) \tag{20}$$

$$\gamma_{2,i,j}(t+1) = \gamma_{2,i,j}(t) - \alpha(P_{j,i}(t) - P_i(t)^\star). \tag{21}$$

Finally, the distributed algorithm for power allocation is as follows. First, initialize $\gamma_{2,i,j}(0), \gamma_{2,i,j}(0)$ to some value; then each BS solves its local maximization problem and sends its solution to the related BS's (determined in the step of relay selection); each BS updates its prices γ-value iteratively, then sends the new prices to other coupled BS's. The algorithm terminates when convergence is achieved or when a maximum number of iterations is reached. The distributed relay selection and power allocation algorithm is presented in Algorithm 2.

V. Performance Evaluation

We evaluate the performance of the proposed algorithms using MATLAB simulations. In the simulations, the FSO BS's are randomly placed in an area of radius R. We assume enough transceivers are equipped and FSO BS's are allowed to communicate with any other BS's. In one half of this area, there is clear weather; the other half of this area suffers from fog. We calculate channel gains as in Section III-A. The simulation parameters are listed in Table I [17]. The atmospheric attenuation coefficients are related to weather and the values are listed in Table II [17].

First, we examine the impact of the power budget P_i available at each BS. We also simulated a simple non-cooperative scheme where no relays are used. To fully examine the impact of the power budget, we set the number of transceivers to five. In Fig. 2, we increase P_i from 0.5 to 3 and plot the total network throughput. It can be seen from the figure that P_i has no impact on the non-cooperative scheme; but as P_i is increased from 0.5 W to 2.5 W, the throughput of the FSO network increases when both the centralized and distributed algorithms are used. Due to the limited number of transceivers, the network throughput stops increasing when the power budget is larger than 2.5 W.

We then examine the impact of the number of FSO transceivers at each BS on the total system capacity. The number of BS's is set to be 20. In Fig. 3, we find that when the number of transceivers is greater than six, the average throughput of the three schemes all decrease. This is because when the number of BS's that a relay BS serves is too large, the power that the relay BS can allocate to each BS becomes too small. However, before this critical point, the average throughput increases with the number of transceivers for the centralized algorithm. It is interesting to see that the number of transceivers has little impact on the distributed algorithm and the non-cooperative scheme, indicating that the system have not been fully utilized by these two algorithms.

Finally, we compare the proposed algorithms with an existing scheme in Fig. 4. The relaying protocol in [12], which was called *Select Max*, selects a relay with the maximum minimum

TABLE I
Simulation Parameters

Symbol	*Definition*
$\lambda = 1550$ nm	Wavelength
$D_r = D_t = 0.1$ m	Rx. and Tx. Aperture Diameter
$K = M = 20$	Number of FSO BS's in the area
$B = 10$ MHz	Bandwidth
$R = 5$ Km	Radius of area
$P_{max} = 2$ W	Peak power constraint
$P_i = 0.5$ W , $\forall\, i$	Power budget for FSO BS i
$T_i = 3$, $\forall\, i$	Number of transceivers on FSO BS i

TABLE II
Atmospheric Attenuation Coefficient α

Weather Condition	α	*Weather Condition*	α
Very Clear	0.48 dB/km	Light Fog	13 dB/km
Clear	0.96 dB/km	Dense Fog	73 dB/km
Haze	2.8 dB/km	Deep Fog	309 dB/km

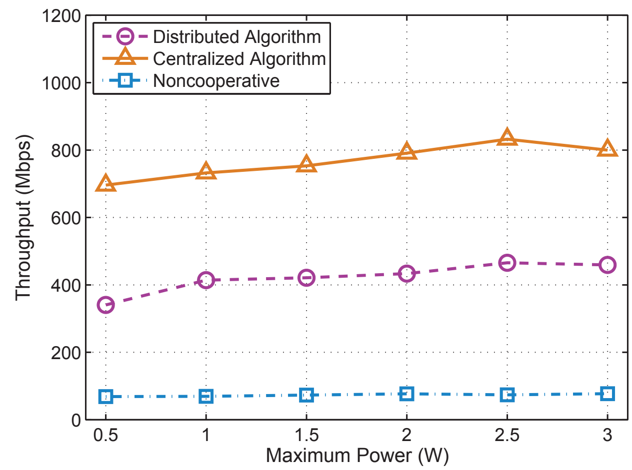

Fig. 2. Throughput vs. power budget.

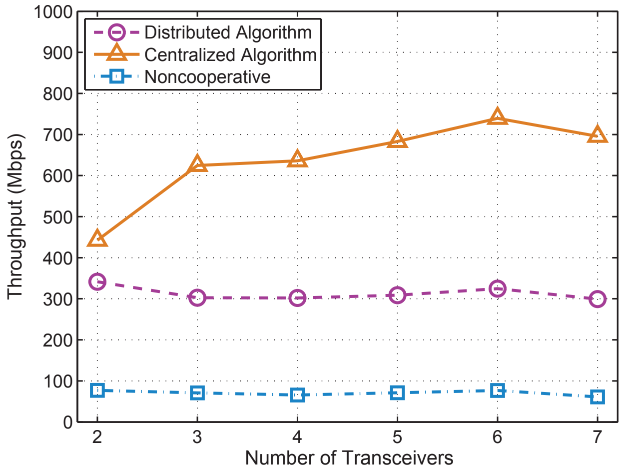

Fig. 3. Throughput vs. number of FSO transceivers.

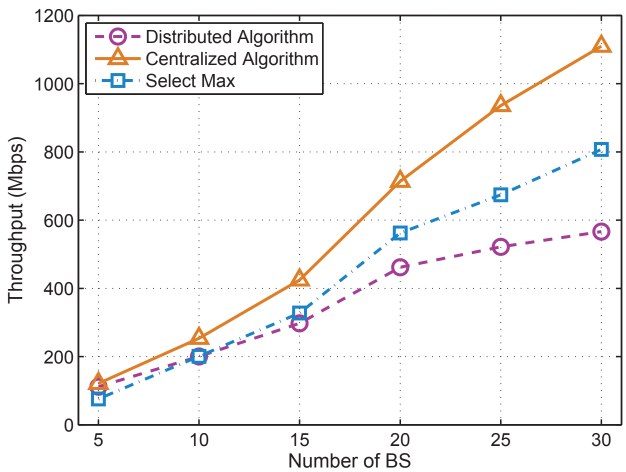

Fig. 4. Throughput vs. number of FSO BS's.

SNR of the path's intermediate links, i.e.,

$$\arg\min_{r}\{SNR_{s,r}, SNR_{r,d}\}. \quad (22)$$

In this scheme, every source BS uses one relay, and the same power is used for both source BS and relay BS transmissions. This scheme is a centralized one and thus achieves better performance than the proposed distributed algorithm, when the network size becomes large. In the case of small network sizes, this scheme has almost the same performance as the proposed distributed algorithm. Under the same scenario when there is centralized control, our proposed centralized algorithm outperforms Select-Max in all the scenarios studied with considerable gains.

VI. Conclusion

In this paper, we investigated the problem of maximizing the FSO system throughput under the constraints of limited power budget and number of FSO transceivers. Two algorithms are proposed and compared with non-cooperative scheme. Our simulation study showed that the centralized algorithm achieved the greatest capacity but it required a central controller, while the proposed distributed algorithm can be adopted to achieve better performance than non-cooperative scheme if centralized coordination is not available.

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