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On joint topology design and load balancing in free-space optical networks ☆

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ABSTRACT

Free-space optical networks have emerged as a viable technology for broadband wireless backbone networks of the next generation. In this paper, we investigate the challenging problem of joint topology design and load balancing in FSO networks. We consider FSO link characteristics, cost constraints, traffic characteristics, traffic demand, and QoS requirements in the formulation, along with various objective functions including network-wide average load and delay. We apply the reformulation–linearization technique (RLT) to obtain linear programming (LP) relaxations of the original complex problem, and then incorporate the LP relaxations into a branch-and-bound framework. The proposed algorithm can produce highly competitive solutions with the performance guarantees in the form of bounded optimality gap. For reducing computation complexity, we also develop a fast heuristic algorithm to provide highly competitive solutions. The heuristic algorithm iteratively perturbs the current topology and computes network flows for the new topology, thus progressively improving the configuration and load balancing of the FSO network. The proposed algorithms are complementary to each other, since jointly applying the algorithms can make the FSO network dynamically adaptive to events occurring at both large and small timescales. The proposed algorithms are evaluated with extensive simulations. Our simulation results show that the heuristic algorithm can achieve an optimality gap close to that of the branch-and-bound algorithm, with significantly reduced computation time.

1. Introduction

Free-space optics (FSO) have emerged as a promising technology for broadband wireless networks of the next generation [3]. FSOs are wireless systems that use free space as transmission medium to transmit optical data signals at high bit rates. FSOs have many advantages such as cost effectiveness, long transmission range, free license, interference immunity, and high-bandwidth, among others. In recent years, considerable advances have been made in understanding the FSO channel, and both experimental data and commercial FSO transceivers are now available [3]. For the widespread deployment of FSO networks, several important network problems should be addressed, such as how to design an FSO network topology with rich connectivity (making it robust to link failures) and how to accommodate traffic demands and QoS requirements of the underlying wired or wireless access network.

The FSO network topology design problem has been addressed in several prior works. In [4], a distributed minimum spanning tree (MST) algorithm was proposed

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to build degree-bounded tree topologies. In [5,6], algorithms were developed to maximize network connectivity and make a mesh topology. The load balancing problem was addressed in [7,8], where several topology design heuristics were developed to minimize network-wide average load. To maximize the potential of FSO networks, the unique characteristics of FSO links should be considered in the formulation, and the problems of topology design and routing of the traffic flows should be jointly considered and optimized [7,8]. Usually such problems are highly complex. Consequently, an approximation algorithm with the performance guarantees (i.e., in the form of a bounded *optimality gap*) would be highly appealing.

An FSO link is "pseudo-wired" in the sense that it has high bandwidth, narrow beam, and long distance as an optical fiber link. However, it is also like a radio frequency (RF) link that is flexibly steerable, in contrast to buried optical fiber links. Thus the network topology can be adaptively reconfigured on-the-fly in response to network dynamics. In this paper, we investigate the problem of joint topology design and load balancing in FSO networks, considering important design issues such as link reliability, cost constraints, traffic characteristics and demand, QoS requirements, routing policies, and network topology. We assume that a traffic matrix is known and the total number of edges used for building a topology is given a priori (due to some cost constraint). We then formulate the joint topology design and load balancing problem with objectives to minimize network-wide average load or network-wide average delay. Since for the same offered load, different traffic models will yield very different delay performance, we consider both short-range dependent (SRD) and long-range dependent (LRD) traffic models when deriving network delays.

With the objective function of average load, the formulated problem is a mixed integer linear programming (MILP) problem. With the objective function of an average delay, the formulated problem is a mixed integer nonlinear programming (MINLP) problem. These problems are NP-hard in general [7,8]. In prior work [7,8], effective heuristic algorithms are presented to minimize the network-wide average load. However, there was no guarantee on the optimality performance of the heuristic algorithms, and they do not apply to the more complex problem of minimizing network-wide average delay.

In this paper, we first develop a branch-and-bound algorithm incorporating the reformulation–linearization technique (RLT) that can produce highly competitive solutions with bounded performance. RLT is a useful technique that can be applied to derive linear programming (LP) relaxations for an underlying nonlinear non-polynomial programming problem [9]. We first adopt RLT to obtain LP relaxations for the complex MILP and MINLP problems. We then incorporate the LP relaxations into the branch-and-bound framework to compute $(1-\epsilon)$-optimal solutions, where $0 \leq \epsilon \ll 1$ is a prescribed tolerance. When the algorithm terminates, it produces a feasible solution to the original MILP or MINLP problem, which is within the ϵ range of the global optimum.

Although highly appealing, the RLT-based branch-and-bound algorithm has a relatively high computation complexity. We next present a fast heuristic algorithm to the joint topology design and load balancing problem. The heuristic algorithm consists of three components: (i) initial topology design, (ii) multipath routing for load balancing, and (iii) topology perturbation. Starting from an initial topology that is designed to minimize the network-wide average load, the heuristic algorithm iteratively perturbs the current topology and computes network flows for the new topology, thus progressively improving the configuration and load balancing of the FSO network.

The proposed algorithms are evaluated with extensive simulations, and are shown to be highly suitable for joint topology and load balancing optimization in FSO networks. Our simulation results also show that the heuristic algorithm can achieve an optimality gap close to that of the branch-and-bound algorithm, but with significantly reduced computation time.

The proposed fast heuristic algorithm and the branch-and-bound algorithm are complementary to each other. The latter is suitable for optimizing the FSO network design and operation at large timescales with guaranteed optimality. The former is suitable for dynamic reconfiguration of the FSO network in response to small timescale events. We envision that the branch-and-bound algorithm will be executed at relatively large time intervals when significant changes occur in the FSO network, while the heuristic algorithm will be kept running to continuously optimize the operation and configuration of the FSO network in response to small timescale events such as bad weather conditions or fluctuations in traffic demand.

The remainder of this paper is organized as follows. In Section 2, we describe the system model and assumptions, and formulate the optimization problem. The RLT-based algorithm is presented in Section 3 and the fast heuristic algorithm is presented in Section 4. The algorithms are evaluated in Section 5. We discuss related work in Section 6, and Section 7 concludes this paper.

2. System model and problem statement

2.1. Network model

We consider an FSO network consisting of n base stations (BS), which provide mobile users with network access. Each BS could be the head of a cluster consisting of multiple access points. The aggregate traffic at the BS's will be relayed through wireless optical links. We assume that each BS has multiple sets of wireless optical devices in order to support the aggregate traffic load and provide a rich mesh connectivity. The FSO links are point-to-point connections with narrow beam divergence, and are immune to electromagnetic interference [3,6–8].

The FSO network can be modeled as a *simple* graph $G(V, E)$, where each vertex $v \in V$ represents a BS and each edge $e \in E$ is an FSO link. Let n and m denote the cardinality of V and E, respectively. We assume an $n \times n$ *traffic matrix* $\mathbf{F}$ that describes the traffic demand (measured, estimated, or projected) for the access network, where each element $f_{sd} = [\mathbf{F}]_{sd}$ represents the mean data rate between each source and destination BS pair s–d.