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On the design and optimization of a free space optical access network ☆

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A B S T R A C T

Although having high potential for broadband wireless access, wireless mesh networks are known to suffer from throughput and fairness problems, and are thus hard to scale to large size. To this end, hierarchical architectures provide a solution to this scalability problem. In this paper, we address the problem of design and optimization of a tiered wireless access network that exploits free space optical (FSO) communications. The lower tier consists of mesh routers that are clustered based on traffic demands and delay requirements. The cluster heads are equipped with wireless optical transceivers and form the upper tier FSO network. For topology design and optimization, we first present a *plane sweeping and clustering* (PSC) algorithm aiming to minimize the total number of clusters. PSC sweeps the network area and captures cluster members under delay and traffic load constraints. For the upper tier FSO network, we present an algebraic connectivity-based formulation for topology optimization. We then develop a *greedy edge-appending* (GEA) algorithm, as well as its distributed version, that iteratively inserts edges to maximize algebraic connectivity. The proposed algorithms are analyzed and evaluated via simulations, and are shown to be highly effective as compared to the performance bounds derived in this paper.

1. Introduction

The recent explosive increases in pervasive mobile devices and wireless data applications have greatly stressed the capacity of existing wireless access networks. The significant increase in wireless data volume will also have far-reaching impact on the design of future wireless access networks. To this end, wireless mesh networks (WMN) have emerged as a promising technology for providing ubiquitous broadband wireless access to mobile users [2]. Recent years have witnessed significant growth in WMN research and deployment. However, WMNs are also known to suffer from poor scalability. In [3], Jun and Sichitiu showed that the per node throughput decreases as $O(1/n)$, where n is the number of nodes. In [4], the authors demonstrated that starvation occurs even in the simple scenario where one-hop flows contend with two-hop flows for gateway access. This is largely due to the inefficiency and bi-stability of existing MAC protocols, as well as high penalty for multi-hop flows to re-capture system resources.

Historically, hierarchical network architectures have provided an effective solution to the scalability problem, as demonstrated in the Internet and wireless sensor networks [5]. In the case of WMNs, the authors in [6]

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investigated a hybrid network architecture consisting of an underlying n-node wireless ad hoc network and a sparse overlay network of m base stations, which are connected with high-bandwidth wired links. The authors showed that the asymptotic throughput capacity of the hybrid network increases linearly with m if m grows faster than $\sqrt{n}$.

In this paper, we investigate the design and optimization of a tiered wireless access network, as illustrated in Fig. 1. The lower tier consists of a WMN with a large number of mesh routers providing wireless access to mobile users. To mitigate the scalability problem, we group mesh routers into clusters with bounded diameter. Traffic from/to the cluster members is aggregated and routed through the cluster head, which is equipped with free space optical (FSO) transceivers with multi-gigabit data rates and multi-kilometer ranges. With this architecture, resource contention mainly occurs within the cluster and end-to-end hop counts are greatly reduced due to the use of FSO links. Compared to the architecture in [6], FSO links are easier to deploy than wired links, and can be easily rearranged when traffic requirements change, or when links or nodes fail. The challenging task of QoS provisioning (e.g., delay and throughput) can be greatly simplified.

FSO communications provide cost-effective, license-free, and high-bandwidth links for the upper tier [7]. FSO links require line-of-sight (LOS) and are point-to-point connections. They are immune to electromagnetic interference and are secure due to point-to-point connection with narrow beam divergence. However, FSO links are subject to impairments in the open-air transmission medium, such as attenuation, atmospheric turbulence, obstacles, and beam misalignment. It is important to design topologies with rich connectivity to cope with transmission impairments.

We address the challenging problem of network planning for the tiered wireless access network. The objective is to jointly determine the optimal partition for the lower tier WMN as well as the optimal topology for the upper tier FSO network. However, such a topology design problem is highly complex due to its combinatorial nature. To make the problem tractable, we take a divide-and-conquer approach to break it down into two sub-problems. The first sub-problem is cluster formation in the underlying WMN. In the two-tier architecture, each cluster head serves as an FSO node in the upper tier and is equipped with FSO transceivers. The more the clusters, the more the FSO transceivers that are required in the upper tier. Further, it would be desirable to include more mesh nodes in a cluster (as long as the aggregate traffic condition is satisfied, see Section 3.1) to fully utilize the high data rates an FSO link can offer. Therefore, the objective is to minimize the number of clusters (i.e., cost), while satisfying the delay and traffic load requirements. The second sub-problem is topology design and optimization for the upper tier FSO network to achieve maximum connectivity for a given number of edges. The two sub-problems are coupled with the common objectives of minimizing the cost and maximizing the reliability of the tiered system, while satisfying the QoS requirements.

The formulated sub-problems belong to the class of NP-hard problems [8].[1] To provide effective solutions, we take a graph theoretic approach to develop heuristic algorithms. First, we develop a *plane sweeping and clustering* (PSC) algorithm that sweeps the network area and captures cluster members one after another under delay and traffic load constraints. PSC chooses cluster members by manipulating the adjacency matrix and hop-count matrix of the underlying graph. We derive a lower bound on the number of clusters, which can be used as a benchmark for performance evaluation, and investigate effective schemes to reduce the computational complexity of PSC. Second, we present an algebraic connectivity-based formulation for FSO network topology optimization. We then develop a *greedy edge-appending* (GEA) algorithm, as well as its distributed version, that iteratively inserts edges to maximize algebraic connectivity. The proposed algorithms are analyzed with regard to complexity and performance bounds, and evaluated via simulations. They are shown highly effective for solving the network design and optimization problem as compared to the performance bounds developed in this paper.

The rest of this paper is organized as follows. We present the system model in Section 2. The design and optimization problems are formulated in Section 3. We present PSC and GEA, and analyze their performance in Sections 4 and 5, respectively. Simulation results are presented in Section 6, and related work is discussed in Section 7. Section 8 concludes the paper.

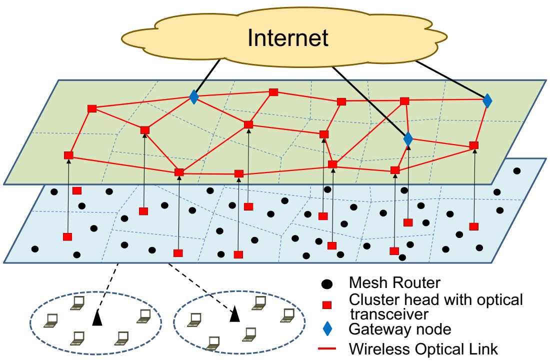

Fig. 1. Reference architecture for the tiered wireless access network.

2. System model

2.1. Tiered access network model

As shown in Fig. 1, the lower tier of the wireless access network is a WMN consisting of n mesh routers that provide access to mobile users [2]. The mesh routers use broadcast radio transceivers and each covers a small

[1] Aoun, et al. in [9] showed that their gateway placement problem is NP-hard in order to minimize the number of gateways, which is analogous to the number of clusters in the cluster formation subproblem. The FSO topology optimization problem is also NP-hard, since in [10] it was proven that maximizing algebraic connectivity with a given number of edges is NP-hard.