# Free-Space Optical Gateway Placement in Hybrid Wireless Mesh Networks

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***Abstract*—The capacity of wireless mesh networks (WMN) must usually be upgraded as usage demands evolve over time. This is normally done by adding gateways which serve to increase the backhaul capacity of the network. In this paper we consider adding capacity in this manner using free-space optical (FSO) backhaul links. To accomplish this, we formulate a joint clustering and gateway placement problem which includes the strong rate-distance dependence of practical FSO links. The formulation incorporates the positions of existing wireline gateways and minimizes the number of additional hybrid-FSO/RF gateways which are needed to satisfy the target capacity requirements. After showing the complexity of the problem, a solution that is motivated by genetic algorithms is proposed. The performance of our algorithm is then compared to an optimal solution generated via an integer linear program (ILP) for small WMNs. The proposed algorithm is then modified to allow for balancing the traffic load that is carried by each gateway in the WMN. Many scenarios are considered which demonstrate the value of using FSO backhaul links to obtain post-deployment capacity upgrades in response to changes in user traffic.**

***Index Terms*—Free-space optical communication systems, gateway placement problem, genetic algorithms, optical wireless backhaul, wireless mesh networks.**

## I. Introduction

WIRELESS mesh networks (WMNs) are becoming increasingly common in modern cities. Many commercial and open source WMN implementations now exist using both proprietary and off-the-shelf IEEE 802.11 hardware [1]–[3]. The main function of metro-area WMNs is to aggregate user traffic and to provide access to wired gateways using multi-hop backhaul radio relaying. These types of networks are currently being standardized under the IEEE 802.11s activities.

The capacity of a WMN must often be increased as end user demands evolve with time. In [4], for example, it was shown that the factors affecting the frequency with which gateways must occur are related by

$$\bar{H} < \frac{\frac{C}{N}}{\frac{w}{r}}, \tag{1}$$

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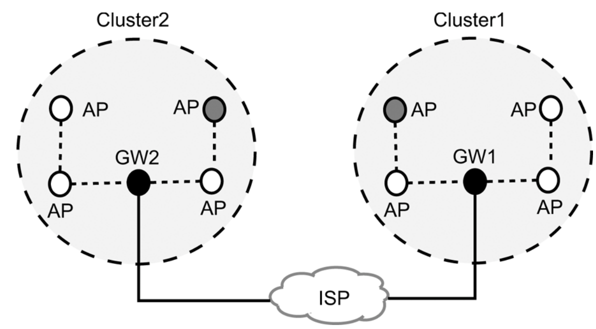


Fig. 1. A clustered mesh network with wireline gateways.

where $\bar{H}$ is the expected number of hop-counts, $C$ is the one-hop capacity, $N$ is the number of nodes in the network, $w$ is the per node demand, and $r$ is the radio transmission range and where shortest-path routing is assumed. From this result it is clear that maintaining effective throughput of a traffic source with higher demands requires shorter hop-counts before reaching a gateway. One way to achieve this is to increase the number of gateways to accommodate evolving traffic load.

In Fig. 1 an example is shown of a mesh network with two gateways, GW1 and GW2, that are serving the access points residing in Cluster1 and Cluster2 respectively. The gateways have wireline backhaul links, represented by solid lines, connecting them to an ISP. Within a cluster, traffic is aggregated and forwarded to the gateway over RF links, represented by dashed lines. It was shown in [5] that segmenting WMNs is necessary to prevent the per node throughput from diminishing to zero.

In many situations, post-deployment changes such as other-network interference and increased end-user demand result in significant performance degradation. External interference results in a decrease in $C$. Combating this decrease in the one-hop capacity by changing the frequency plan may not be possible in WMN implementations operating using unlicensed RF spectrum due to the limited number of available frequencies. In addition, there are often strict hardware limitations to improving single node capacity by increasing the number of radios per node. These types of degradations are exacerbated by the increases in end-user demand, $w$, due to demanding applications such as VoIP, video and other multimedia applications. To improve the performance of the WMN, additional gateways often need to be installed. Even though this is a simple and ideal solution, it may not be practical in deployments where conventional wireline backhauling is expensive or unavailable [3].

In this paper, we consider existing WMN deployments with a need for added gateway capacity. We consider the use of free-space optical (FSO) links in building a hybrid RF/FSO gateway

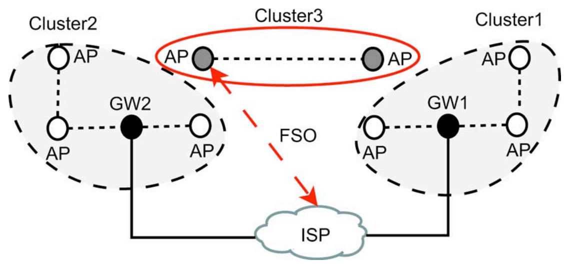


Fig. 2. A clustered mesh network with wireline and hybrid RF/FSO gateways.

architecture to supplement the performance of existing wireline gateways. Continuing the previous example, consider the case where the two APs represented by grey-shaded circles in Fig. 1 experience degraded post-deployment performance due to increased end-user demand. The WMN can be repartitioned, such as in Fig. 2, to maintain the original design constraints. The association of the two overloaded APs to their original gateways is terminated, and a new cluster is formed, Cluster 3, where the two APs are connected via an RF link. In the new cluster, one of the APs is equipped with an FSO link, which backhauls the traffic of Cluster 3 directly to the ISP.

FSO links have a number of attractive properties. They can provide high data rates in the 1–4 Gbps range in terrestrial networks over distances of about 4 km. In addition, for short range links less than 200 m, their reliability is comparable to that of RF links [6]. For this reason, FSO links are now being considered for practical short-range backhaul applications [7]. However, over backhaul distances considered in this paper, the reliability of the FSO links is limited by atmospheric conditions. In this work, we explicitly consider the reliability of the FSO links in our designs.

A key novelty of this problem stems from the strong rate-distance dependence that FSO links exhibit at a given reliability. This link capacity dependence must be incorporated into the placement of additional gateways. In addition to the proposed gateway architecture, we develop a genetic algorithm (GA) to solve the joint clustering and gateway placement problem. The objective of the algorithm is to find and locate the minimum number of *additional* hybrid gateways which are required such that the network satisfies the added traffic profile demands. The algorithm takes into consideration the location of the existing wireline gateways.

The balance of the paper is organized as follows. Section II provides background material and in Section III the contributions of this paper are summarized. Then Section IV presents the design parameters of the FSO backhaul links. In Section V the problem is formulated as an integer linear program (ILP) and a genetic algorithm (GA) approach is used. In Section VI experiments and discussion are provided showing the performance of the proposed architecture and the placement algorithm. Finally, Section VII presents conclusions and directions for future work.

## II. Background

The gateway placement problem is well known in the literature [8]–[10]. Typically it requires finding the minimum number of gateways while satisfying design constraints for a given end-user demand, represented by the vector $W$. The most common design constraints are delay, backhauling capacity and relay load constraints. The delay constraint arises from quality of service (QoS) requirements which restrict the maximum number of hops and thus the *cluster radius*, $R$. The backhauling capacity constraint, $S$, arises from the physical limitations on the rate offered by the backhaul link. Since traffic is aggregated and forwarded, every wireless node should not exceed its RF relay capacity, $L$, which is dictated by the number of radios and the transmission rate.

In [8], the optimal placement of $k$ gateways is considered such that the total throughput of the WMN is maximized while satisfying a fairness constraint among the network nodes. In [9], the network is modelled as a network flow problem while allowing for multi-path routing. A greedy algorithm is proposed with the objective of minimizing the number of Internet Transit Access Points (ITAPs) required while satisfying the users' demand requirements. In [11], a large number of orthogonal frequencies is assumed such that interference across adjacent links is negligible. An algorithm to solve a joint routing and clustering optimization problem is proposed such that the network is divided into the minimum number of clusters with each cluster having a spanning-tree rooted at the gateway. Delay, backhaul capacity and relay load constraints are all considered. In [10] the WMN is clustered while ensuring that the total demand within a cluster is bounded. The problem is modelled as a capacitated facility location problem (CFLP). However, instead of evolving the routing and clustering problems in parallel, two disjoint problems are considered. First, the minimum number of clusters satisfying the maximum radius constraint is found. Then, a spanning-tree is constructed within each cluster. If either of the RF relay load or backhaul capacity bounds is violated, the cluster is further subdivided and the procedure is repeated.

In this work we propose a more generic framework for gateway placement that is inherited from the constrained CFLP. First, our framework allows for restricting the positions of some of the gateways (e.g., wireline gateways), allowing for post-deployment modifications of the WMNs. Second, since FSO is used as a backhauling technology for the additional gateways, the backhaul capacity constraint becomes a function of the distance between the gateway and a central entity such as an ISP. Third, to minimize the sensitivity of individual gateways to future increases in end-user demand, our framework load balances the traffic over the selected gateways. Additional constraints such as the cluster radius and RF relay capacity are maintained. After modelling the problem as an ILP, we use a GA to solve it.

Free-space optical links have gained attention in recent years as an effective means for transmitting at high data rates. FSO inter-satellite [12] links have been shown to provide inherent benefits over conventional RF links since they offer higher data rates, lower cost, and lower power consumption. FSO links have also been considered for use in point-to-point terrestrial networks [13]–[16]. For example, in [17] an FSO mesh network architecture is proposed for broadband access which extends home and SOHO xDSL connections. FSO links have also been used in [7] for traffic backhaul in regional broadband networks. Reference [18] describes a broadband network consisting of densely spaced packet-switching nodes interconnected by FSO links in a multihop mesh arrangement. This work considers the capacity of the network by looking at the maximum number of virtual connections which can be supported such that all quality of service guarantees are maintained. The same framework is extended in [19] to include routing and load balancing. Unlike previous work, our paper considers the design of hybrid RF/FSO WMNs taking into account the rate-distance tradeoff of the FSO links while minimizing the number of additional gateways added.

## III. Contributions

In this paper, existing WMN deployments are considered which have a need for added gateway capacity. To accomplish this, free-space optical links are used to build hybrid RF/FSO gateways, which are then used to supplement the performance of existing wireline gateways. A key novelty of our problem formulation stems from the strong rate-distance dependence that FSO links exhibit at a given link reliability. A framework is proposed to mitigate post-deployment performance degradation by restricting the positions of certain gateways (e.g., wireline gateways), and then by locating the minimum number of additional hybrid-FSO/RF gateways which are needed so that the network satisfies the new target end-user demands.

The proposed model formulation includes the impact of the strong rate versus distance dependence of FSO links, and this dependence could be incorporated into design problems using other link technologies. However, the match for the gateway placement problem formulation is much more appropriate for FSO links. For example, buried cable links could be another option. However, in metropolitan deployments these types of cables would rarely be available at all possible gateway locations, and to incorporate this into the model would have to either include the costs associated with deploying the links or the problem would have to be constrained to known locations where these links are available. This solution is not consistent with the freedom that we have assumed in our gateway placement algorithm formulation, which requires free-space links. In addition, buried links typically do not exhibit such a strong rate/distance dependence that would require the new type of formulation that we have made. When considering issues such as the data rates required for backhauling, and cost per unit bandwidth, not all focused millimeter wave links are ideal for the application considered either. This option also typically requires that the service provider have the appropriate licensing to operate such links, which is often not the case. For these reasons, FSO links are the ideal candidate technology for the application considered.

The problem of finding and positioning the minimum number of FSO-enabled additional gateways is modelled as an integer linear program with constraints restricting certain gateway positions and backhauling capacity. After establishing the complexity of the problem using a reduction to the well-known NP-complete minimum dominating set problem, a genetic algorithm is proposed and used over mesh networks of reasonable sizes. The proposed algorithm also allows for load balancing the backhaul traffic which can help to reduce the sensitivity of the solutions to future changes in end-user demands.

## IV. Free-Space Optical Links

Optical signal propagation in free-space suffers from two primary impairments: atmospheric turbulence and misalignment errors. Each fades the signal at the receiver and deteriorates the link performance. In this work, we assume an active tracking mechanism is established to combat misalignment errors. The trade-off between link distance, rate and reliability in FSO links with atmospheric turbulence is quantified for a given bit-error rate (BER).

### A. System Model and Definitions

In FSO systems, transmit electronics supply an electrical current which modulates the instantaneous intensity of a laser diode. At the receiver, the optical intensity is detected by a photodiode and converted to a proportional electrical current. The received photocurrent, which is related to the incident optical power by the detector responsivity $r_d$ and optics efficiency $\eta$, is demodulated and the original transmitted data is extracted. This intensity modulated direct detection (IM/DD) system is popular in commercial links. The system is well represented by the following discrete time model [13]:

$$y = h\, r_d\, \eta\, x + n \tag{2}$$

where $x$ is the transmitted optical intensity, $h$ is the channel state, $n$ is signal-independent additive white Gaussian noise with variance $\sigma_n^2$ and $y$ is the received electrical signal. The transmitted symbols are drawn equiprobably from an on-off keying (OOK) constellation such that $x \in \{0, 2P_t\}$ where $P_t$ is the average transmitted optical power. The channel state $h$ models the random attenuation of the propagation channel which arises due to path loss, geometric spread loss and atmospheric turbulence fading.

### B. Optical Channel Fading Model

Atmospheric turbulence causes variations in the refractive index along the propagation path. This results in both optical signal intensity and phase fluctuations at the receiver [14]. A recent approach to FSO channel modelling [20], [21], is to employ a Gamma-Gamma distribution to model the atmospheric fading. It was shown that this distribution provides close agreement with the measurements under a variety of turbulence conditions [20], [21]. The statistical distribution of $h$ is given as

$$f(h) = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\tilde{h}\Gamma(\alpha)\Gamma(\beta)} \left(\frac{h}{\tilde{h}}\right)^{(\alpha+\beta)/2-1} K_{\alpha-\beta}\left(2\sqrt{\alpha\beta\frac{h}{\tilde{h}}}\right)$$

where $K_{\alpha-\beta}(\cdot)$ is the modified Bessel function of the second kind, $\Gamma(\cdot)$ is the Gamma function, and $1/\beta$ and $1/\alpha$ are parameters related to the Rytov variance defined as

$$\sigma^2_{\mathrm{Rytov}} = 1.23\, C_n^2\, k^{7/6}\, d^{11/6}$$

where $C_n^2$ is the index of refraction structure parameter, $k = 2\pi/\lambda$ is the optical wave number, $d$ is the propagation distance

[13]. In this model $\tilde{h}$ represents both the geometric spread loss and path attenuation and can be written as

$$\tilde{h}(d) = \left[\frac{D_R^2}{(D_T + \theta_T d)^2}\right] e^{-\nu d}$$

where $D_R$ is the receiver diameter, $D_T$ is the transmitter diameter, $\theta_T$ is the beam divergence angle at the transmitter and $\nu$ is the attenuation coefficient [22]. The presented statistical model $f(h)$ will be utilized to obtain the maximum achievable rate for a given distance, BER and reliability.

### C. BER and Link Reliability

Consider a free-space optical link where the channel statistical model is governed by the distribution $f(h)$. The link reliability is defined as the percentage of time that the channel state exceeds a threshold $h_o$ as follows:

$$\mathcal{L}_{\mathrm{r}}(d) = 100 \times \int_{h_o}^{\infty} f(h) dh\% \tag{3}$$

and the instantaneous BER associated with a channel state $h$ with the Gaussian noise model discussed is given by

$$\mathrm{BER}(h) = \frac{1}{2}\,\mathrm{erfc}\left(\frac{P_t\, h\, r_d\, \eta}{\sqrt{2\rho}\,\sigma}\right) \tag{4}$$

where $\rho$ is the rate in bits per seconds (bps). Let $\mathrm{BER}_o$ be the design target BER for the link. The design procedure can be summarized as follows. A statistical model $f(h)$ is utilized to describe the optical channel with distance dependence through $\tilde{h}$ and $\sigma^2_{\mathrm{Rytov}}$. Next, for a required link reliability $\mathcal{L}_{\mathrm{r}}$, the channel state threshold $h_o$ is obtained from (3). Finally, the maximum rate $\rho$ which satisfies

$$\mathrm{BER}_o \geq \frac{1}{2}\,\mathrm{erfc}\left(\frac{P_t\, h_o\, r_d\, \eta}{\sqrt{2\rho}\,\sigma}\right)$$

is obtained as the maximum rate which can be achieved with reliability $\mathcal{L}_{\mathrm{r}}$. From the design procedure, it is clear that the rate $\rho$ depends on the distance, the target BER and the link reliability which can be written as $\rho(d, \mathcal{L}_{\mathrm{r}})$.

The physical parameters of an FSO link corrupted by moderate scintillation are listed in Table I [15], [16], [23]. These values are substituted into the fading model and used in the balance of the simulations. Fig. 3 presents the achievable rates, $\rho$ versus distance, $d$, for different weather conditions under a fixed reliability of 99.99% for a $\mathrm{BER}_o = 10^{-6}$. The values of the index of refraction structure parameter and the attenuation coefficient for the different weather conditions are summarized in Table II. From the figure, it can be seen that for a given distance the rate is a strong function of the weather condition. Under thin and light fog conditions the rates offered by the FSO link are not suitable for backhauling purposes. In fog conditions the design rate cannot be maintained and the network would have to revert to its non-FSO backhaul configuration. In a recent survey of 10 major US cities, fog occurred on average 2% of the time while the clear weather appeared 80% of the time on average [16, Fig. 6]. However, this is averaged over a wide range of geographic locations. Clearly fog will not be an issue in some geographic regions and yet will prohibit the practical use of FSO links in other areas where thin and light fog (as in Fig. 3) leads to unacceptable link performance. In regions between these two extremes, network designers would have to assess whether the fog-related outage statistics associated with that deployment location are consistent with the satisfaction of the temporal peak bandwidth requirements for which the FSO links are being installed. In the balance of this work, the FSO links are assumed to operate under clear weather conditions. Also, notice the strong dependence between the rate and distance for a given weather condition under a fixed $\mathcal{L}_{\mathrm{r}}$. That is, as the distance increases, in order to guarantee a given reliability the rate must be greatly reduced. This dependence is incorporated into the problem formulation in the next section.

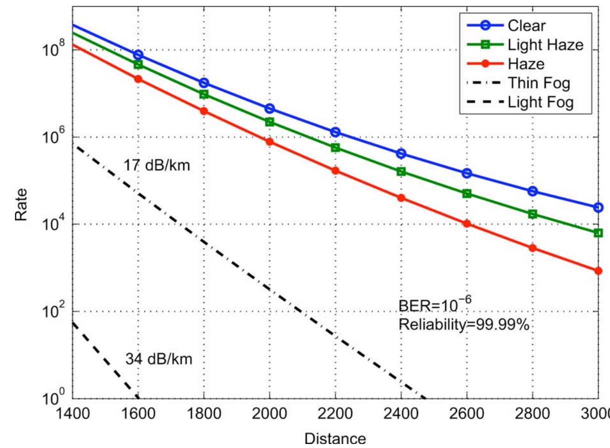


Fig. 3. Rate, $\rho$, [bits/sec] versus distance, $d$, [m] for reliability $\mathcal{L}_{\mathrm{r}} = 99.99\%$.

TABLE I
FSO CHANNEL PARAMETERS

| Parameter | Symbol | Value |
|---|---|---|
| Optical transmitted power | $P_t$ | 40 mW |
| Optics efficiency | $\eta$ | 0.64 |
| Responsivity | $r_d$ | 0.5 A/W |
| Noise standard deviation | $\sigma$ | $3.2 \times 10^{-12}$ A/$\sqrt{\mathrm{Hz}}$ |
| Receiver/Transmitter diameter | $D_R = D_T$ | 20 cm |
| Transmit divergence | $\theta_T$ | 2.5 mrad |

TABLE II
REFRACTION INDEX AND ATTENUATION COEFFICIENT

| | Clear | Light Haze | Haze | Thin Fog | Light Fog |
|---|---|---|---|---|---|
| $C_n^2$ [$\times 10^{-14}\mathrm{m}^{-2/3}$] | 2 | 1.8 | 1.5 | 0.5 | 0.2 |
| $\nu$ [km$^{-1}$] | 0.196 | 0.491 | 0.954 | 3.91 | 7.82 |

## V. PROBLEM FORMULATION

In the initial deployment of a WMN, the APs are often assumed to have uniform demands. The gateway placement problem is then to find and locate the minimum number of wired gateways satisfying the cluster radius, backhaul capacity and RF relay capacity constraints. This is a standard procedure and is followed in classical WMN deployment problems.

However, as the post-deployment demand increases these constraints will eventually be violated. A second gateway placement is considered in these cases to resolve this increase in end-user demand. The WMN is repartitioned and the location and minimum number of additional hybrid RF/FSO gateways are defined such that all the new clusters satisfy the previous performance constraints. It is important to note, however, that all of the original wired gateways will continue to be used without perturbing their location. The new gateway locations will include both RF relaying and a bidirectional FSO link.

A WMN can be represented by an undirected graph $G = (V, E)$, where each AP represents a node and each edge represents a link between two nodes if they are within reliable communication range. Define $V' \subseteq V$ as the set of wired gateways determined in the initial deployment. Additionally, define the current demand vector $W = \{w_i\}$, where $w_i$ represents the demand of AP $i$, $1 \leq i \leq N$. Floyd's algorithm is used to pre-compute shortest paths between every pair of nodes in $G$, where $p_{ij}$ denotes the length of this path between nodes $i$ and $j$, and $z_{ij}^k = 1$ if the path passes through node $k$, and 0, otherwise.

A newly formed cluster which is serviced by a hybrid gateway $i$ has a maximum backhauling capacity of $\rho(d_i, \mathcal{L}_{\mathrm{r}})$, where $\mathcal{L}_{\mathrm{r}}$ is the desired FSO link reliability, and $d_i$ is the propagation distance between gateway $i$ and the ISP, as shown in Fig. 3. Since the maximum total traffic carried by any hybrid gateway, $T_i$, is constrained by the gateway's RF relay capacity and its backhauling ability, then $T_i \leq \min(L, \rho(d_i, \mathcal{L}_{\mathrm{r}}))$. This is referred to as the *hybrid capacity constraint* and is included in the problem formulation. Similarly, the maximum total traffic carried by any wired gateway is the minimum of the wired backhauling capacity, $S$, and RF relay capacity, $L$. Note that single link capacity constraints are not needed since a multi-radio AP can be treated as a single-radio AP with an aggregate capacity that is temporally and spatially multiplexed.

Given $G$, the objective is to choose a minimum cardinality subset of nodes as hybrid gateways and their association with other APs subject to satisfying the radius and capacity constraints. Let $\Delta(G)$ denote the maximum degree in $G$. For the special case when $V' = \emptyset$, $R = 1$, $T_i = L = \Delta(G)$ and $w_i = 1\ \forall i$, the problem is equivalent to finding the minimum dominating set of $G$ which is a well known NP-Complete problem [24]. Thus, it is unlikely that a direct search will be feasible to find the locations and number of hybrid gateways required.

To formulate the above optimization problem as an ILP, the assignment variable

$$y_i = \begin{cases} 1, & \text{if node } i \text{ has been chosen as a gateway} \\ 0, & \text{otherwise} \end{cases}$$

and the association variable

$$x_{ij} = \begin{cases} 1, & \text{if node } j \text{ has been assigned to gateway } i \\ 0, & \text{otherwise} \end{cases}$$

are defined for $1 \leq i,\ j \leq N$.

The formal definition of the objective is thus,

$$\text{minimize} \sum_{i \in V} y_i$$

subject to the following constraints:

$$\forall j \in V : \sum_{i \in V} x_{ij} = 1 \tag{5}$$

$$\forall i,\ j \in V : y_i \geq x_{ij} \tag{6}$$

$$\forall j \in V : \sum_{i \in V} p_{ij} x_{ij} \leq R \tag{7}$$

$$\forall i \in V' : y_i = 1 \tag{8}$$

$$\forall i \in V' : \sum_{j \in V} x_{ij} w_j \leq \min(S, L) \tag{9}$$

$$\forall i \in V \setminus V' : \sum_{j \in V} x_{ij} w_j \leq T_i \tag{10}$$

$$\forall i, k \in V : \sum_{j \in V} z_{ij}^k x_{ij} w_j \leq L. \tag{11}$$

Constraint (5) ensures that each AP will be assigned to one and only one gateway. Constraint (6) ensures that a node can only be assigned to already chosen gateways. Constraint (7) ensures that an AP will be assigned to a gateway only if the gateway is at most $R$ hops away from the AP. Constraint (8) ensures that the wireline gateways remain unchanged. Constraint (9) ensures that the total demand of all APs which will be served by a wired gateway will not violate its RF relay capacity and backhauling constraints. Constraint (10) ensures that the total demand of all APs which will be served by a hybrid gateway, will not be exceeding $T_i$. Constraint (11) ensures that the RF relay load of each AP is below the maximum RF relay capacity, $L$.

The number of binary variables in this model is $N + N^2$ and the number of constraints is equal to $3N + 2N^2 + |V'|$. The solutions of the above ILP will give us the minimum number of required gateways and their assignment to APs.

In practice, an ILP solver, such as CPLEX [25], is able to handle small sized networks due to the rapid increase in the number of variables and constraints. Instead, for larger sized networks, we use the genetic algorithm (GA) approach to find a near-optimal solution.

### A. Genetic Algorithm for WMN Gateway Placement

*1) GA Without Load Balancing:* A classical genetic algorithm [26] is used to determine the number and location of additional hybrid gateways required subject to constraints (5)–(11). Consider the graph $G = (V, E)$ representing the WMN where $V = (v_1, \ldots, v_n)$. A permutation of the nodes in $V$ is considered as a string, i.e., *chromosome*, $X$, which is generated using the standard selection, crossover and mutation operations.

The fitness, $F(X)$, of a string is found by the following procedure. Initially the set $V''$ of hybrid gateways is empty. For each $v_i \in V$, search in $X$ from left to right until $v_j \in V' \cup V''$ is found which satisfies constraints (5)–(11), i.e., until the AP $v_i$ is assigned to a possible gateway $v_j$. If such $v_j$ exists, associate $v_i$ to $v_j$ and update the association variable. Otherwise, $v_i$

TABLE III
NUMBER OF HYBRID GATEWAYS ASSIGNED BY GA AND ILP

| $R$ | ILP $W = 8$Mbps | GA $W = 8$Mbps | ILP $W = 12$Mbps | GA $W = 12$Mbps |
|---|---|---|---|---|
| 1 | 0 | 0 | 3 | 3 |
| 2 | 4 | 4 | 8 | 8 |
| 3 | 5 | 5 | 9 | 9 |
| 4 | 5 | 5 | 9 | 9 |
| 5 | 5 | 5 | 9 | 9 |

is designated as a hybrid gateway and $v_i$ is added to $V''$, i.e., $V'' \leftarrow V'' \cup v_i$. Finally, $F(X)$ returns $|V''|$, the number of hybrid gateways which arises due to the ordering $X$.

*2) GA With Load Balancing:* To reduce the sensitivity of a proposed gateway placement to changes in end-user demand, the GA is modified to incorporate load balancing. The procedure to find $F(X)$ is changed so that an AP $v_i$ is assigned to the gateway $v_j$ that has the minimum $load_j/Capacity_j$ from all candidate gateways, where $load_j$ is the current load on gateway $v_j$ and $Capacity_j$ is $L$ if $v_j \in V'$ and $T_j$, if $v_j \in V''$. If the list of candidate gateways for AP $v_i$ is empty (i.e., no existing node $v_j$ satisfies constraints (5)–(11)), then $v_i$ is chosen as a hybrid gateway.

## VI. RESULTS AND SIMULATIONS

In this section, hybrid FSO/RF gateway assignment results are presented using the proposed problem formulation and algorithms. A small network is first used to compare the performance of the genetic algorithm to an optimal solution generated using an ILP. Following this, larger networks are considered which compare the performance of the genetic algorithm incorporating load balancing to previous work.

### A. GA Versus ILP

As mentioned in Section V, solving the ILP for a large WMN is computationally infeasible. However, in Table III the performance of the GA without load balancing is compared to that of the ILP for a WMN containing 50 nodes which are randomly distributed over a $1.25 \times 1.25\ \mathrm{km}^2$ square region. The minimum node separation distance is 150 m and the RF relay capacity is assumed to be $L = 54$ Mbps. The link reliability used in all the experiments is set to $\mathcal{L}_\mathrm{r} = 99.99\%$. The results are presented for two end-user demands $W = 8$ Mbps and $W = 12$ Mbps. As seen in the table, in all instances the GA selected the same number of hybrid gateways as the ILP.

### B. GA Versus Recursive Dominating-Set Based Algorithm

The proposed GA with load balancing is capable of introducing improvements to the problem which was solved in [11] using a recursive dominating-set based algorithm (Recursive_DS). The WMN in [11, Fig. 1], has 93 APs which are randomly distributed over a square region with normalized dimensions of $15 \times 15$. A normalized end-user demand of $W = 1$ and cluster radius $R = 3$ are considered. The relay load and backhauling capacity was taken to be infinity. The Recursive_DS algorithm resulted in eight clusters as shown in [11, Fig. 4]. The GA proposed in Section V-A.2 is used to solve the same problem by setting $V' = \emptyset, T_i = \infty\ \forall i$, when $L = \infty$ and $W = 1$. In this special case, only constraints (5)–(7) are active. The GA results in five clusters as shown in Fig. 4, which is a 35% reduction in the number of gateways.

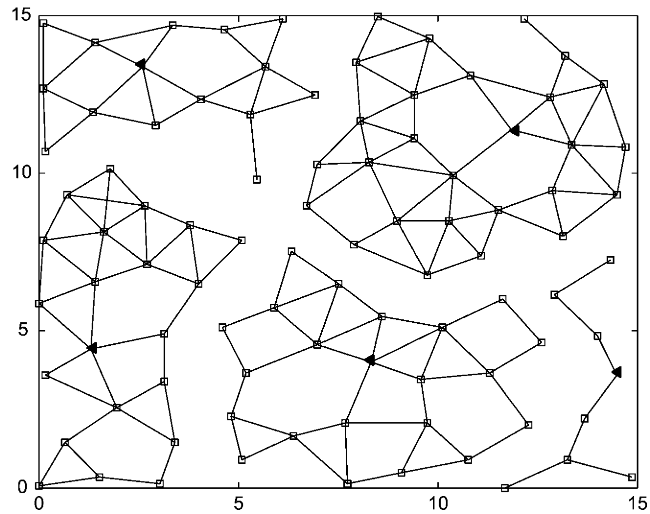

Fig. 4. Resulting 5 clusters for $R = 3$ as obtained by GA with load balancing. (Wired gateway $= \blacktriangleleft$, AP $= \square$).

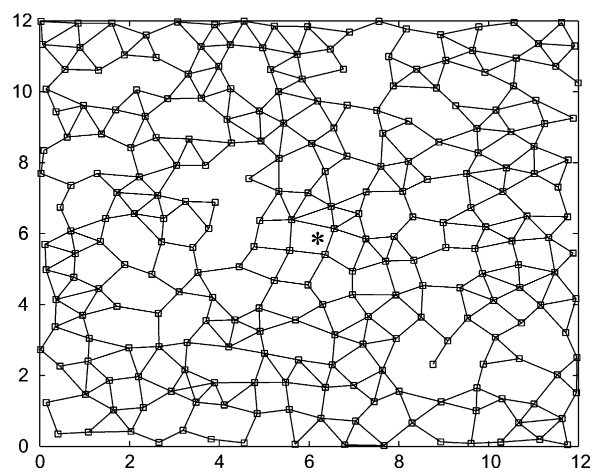

Fig. 5. Topology of the WMN. Note distance is normalized so that each unit of the grid corresponds to 250 m. (ISP $= *$, AP $= \square$).

### C. GA for Larger Networks

For larger WMNs, the GA is used as a practical means to find a gateway assignment. WMNs can vary in size to cover a small dense central business district or extend over very large distances to cover an entire urban core and even rural areas. In this and subsequent sections, the WMN considered extends over a $3 \times 3\ \mathrm{km}^2$ square area with 250 APs which are randomly distributed. Radios are assumed to be omni-directional, but similar results are available for directional links. The data rates assumed over the RF relay links are those available in commercial systems today (e.g., a four-radio IEEE802.11a/g access point has $L = 216$ Mbps with every radio operating at the maximum rate of 54 Mbps). The FSO link reliability is assumed to be $\mathcal{L}_\mathrm{r} = 99.99\%$, as in Fig. 3. In Fig. 5 the connectivity graph is shown for the WMN under consideration. Every AP is represented by a $\square$. The ISP is assumed to be central in this topology and is indicated by a $*$.

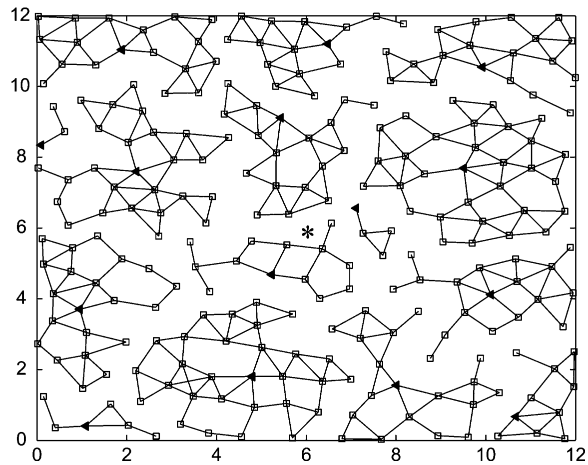

Fig. 6. Wired gateways, $R = 3$, $L = 108$ Mbps, and $W = 4$ Mbps using GA without load balancing. Note distance is normalized so that each unit of the grid corresponds to 250 m. (Wired gateway $= \blacktriangleleft$, ISP $= *$, AP $= \square$).

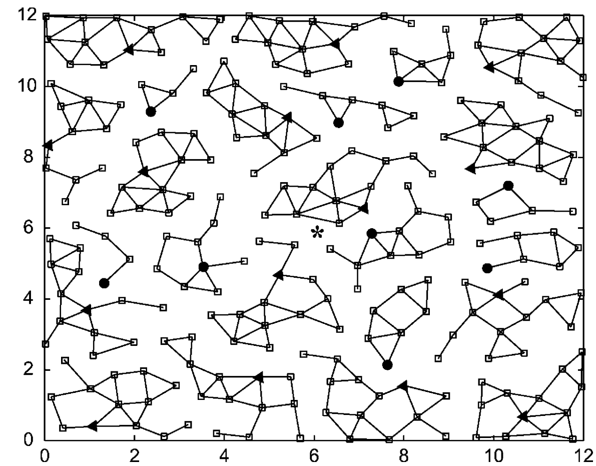

Fig. 7. Wired ($\blacktriangleleft$) and hybrid ($\bullet$) gateways, $R = 3$, $L = 108$ Mbps, and $W = 8$ Mbps using GA without load balancing. Note distance is normalized so that each unit of the grid corresponds to 250 m.

Initially, the WMN is partitioned such that each cluster is serviced by a wired gateway. Practical values for the cluster radius is $R = 3$, and for the RF relay capacity is $L = 108$ Mbps. A uniform end-user demand of $W = 4$ Mbps per AP is assumed. Fig. 6 shows the resulting clustering structure produced by the GA without load balancing where each wired gateway is represented by $\blacktriangleleft$. There are 15 clusters which vary widely in size, however each cluster continues to satisfy all of the constraints. For example, the largest cluster contains 27 APs which saturate the RF relay capacity, whereas the smallest cluster has two APs. It is clear that cluster size is not a function of the location of the wired gateway relative to the ISP.

Consider the case that the end-user demand has increased after the initial deployment causing a violation of the RF relay capacity constraint. System designers may also choose to add an extra cushion to current demands when modifying the WMN so that the new clustering is not sensitive to small changes in the end-user demand. The new end-user demand vector is also assumed to be uniform at $W = 8$ Mbps with all other parameters fixed. The GA without load balancing is used to produce the clustering shown in Fig. 7 where the additional hybrid gateways are represented by $\bullet$ and the ISP is represented by a $*$.

The revised deployment includes nine additional hybrid gateways in addition to the existing 15 wired gateways. Note that the GA places the hybrid gateways close to the ISP since this results in FSO backhaul links of a higher rate. Additionally, clusters serviced by hybrid gateways which are closer to the ISP are larger than those which are positioned further away from the center. Insight into the positioning of the hybrid gateways can be had by defining $d'$ as the distance where $L = \rho(d', \mathcal{L}_{\mathrm{r}})$. Hybrid gateways located at positions $d_i \leq d'$ will not be limited by the FSO rate and they will be constrained by the RF relay capacity and the cluster radius. On the other hand, hybrid gateways with $d_i > d'$ are shown in Fig. 7 to be smaller in size than the ones which are closer to the center since the FSO backhauling rates are lower at these distances.

The variance in cluster size shown in Fig. 6 results in large clusters being sensitive to changes in end-user demand. For example, the largest cluster has 27 APs whereas the smallest cluster has only two. In Fig. 8, the GA with load balancing proposed in Section V-A.2 is used to cluster the WMN shown in Fig. 5, for $R = 3$, $L = 108$ Mbps and $W = 4$ Mbps. Again, there are 15 gateways, however the largest cluster has 24 APs whereas the smallest has eight APs. The locations of the gateways are different when compared to Fig. 6.

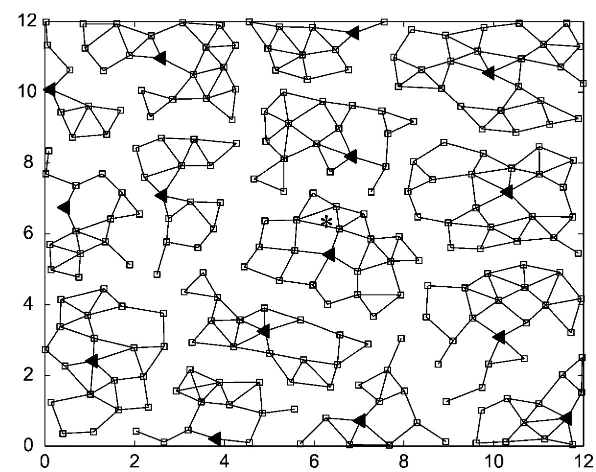

Fig. 8. Wired ($\blacktriangleleft$) gateways with load balancing, $R = 3$, $L = 108$ Mbps, and $W = 4$ Mbps. Note distance is normalized so that each unit of the grid corresponds to 250 m.

In Fig. 9, the GA with load balancing is used to find and locate the minimum number of hybrid gateways after the end-user demand has increased to $W = 8$ Mbps. The resulting clustering requires seven hybrid gateways which compares to nine hybrid gateways shown in Fig. 7 (i.e., using GA without load balancing). Due to more balanced cluster sizes, load balancing helps in producing a better solution in terms of the number of required hybrid gateways.

### D. Effect of Cluster Radius on Gateway Placement

Fig. 10 shows the effect of increasing $R$ on the number of wired gateways produced using the GA with load balancing for end-user demand $W = 4$ Mbps, and for RF relay capacities, $L = 216$ Mbps and $L = 108$ Mbps. For $R \leq 3$, the number

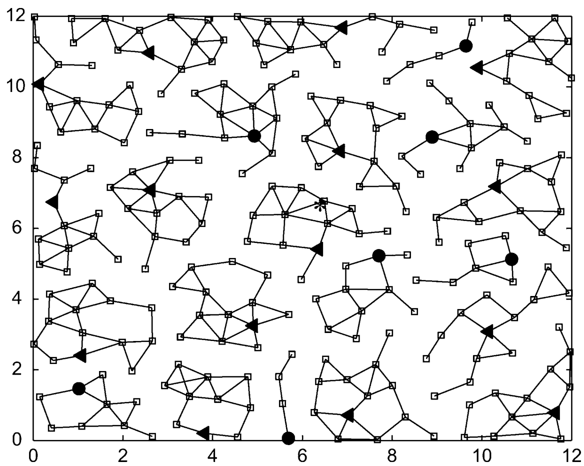


Fig. 9. Wired (◀) and hybrid (●) gateways with load balancing, $R = 3$, $L = 108$ Mbps, and $W = 8$ Mbps. Note distance is normalized so that each unit of the grid corresponds to 250 m.

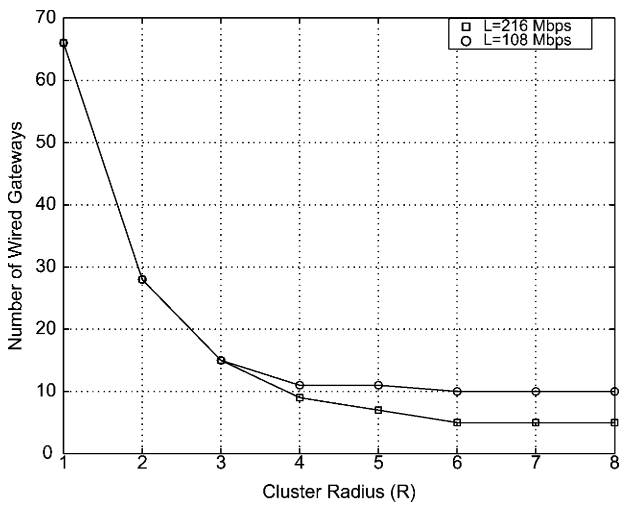


Fig. 10. Effect of cluster radius on the number of wired gateways in a WMN using GA with load balancing.

of wired gateways required is independent of the RF relay capacity and is solely dictated by the cluster radius. For example, a $57\%$ decrease in the number of wired gateways is obtained by changing the cluster radius from $R = 1$ to $R = 2$. This decrease is due to excess backhauling and RF relay capacity at the gateway and APs. When $R \geq 6$, clusters grow in size and the only limiting factor becomes the RF relay capacity. In this region, if $L$ is increased by a factor of two, the number of wired gateways will be halved. For $R = 4$ and $R = 5$, the RF relay capacity and the cluster radius are both active.

In Fig. 11 the number of additional hybrid gateways is shown using the GA with load balancing required to accommodate end-user demands of $W = 8$ Mbps and $W = 12$ Mbps for $L = 108$ Mbps and $L = 216$ Mbps. For small values of $R$, there is excess wireline backhauling and RF relay capacity. For example, when $R = 1$, wired gateways are capable of supporting this increase in $W$ without being supplemented by hybrid gateways. Similarly, when $R = 2$, wireline backhauling capacity and RF relay capacity at the gateway are only an issue when the end-user demand is tripled to $W = 12$ Mbps while

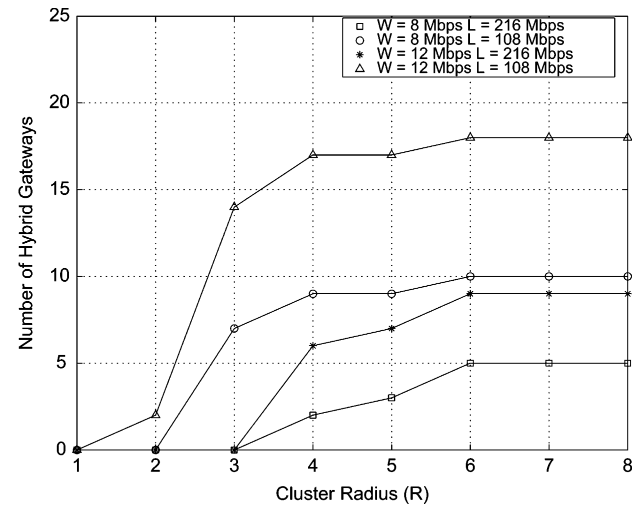


Fig. 11. Effect of cluster radius on the number of hybrid gateways in a WMN using GA with load balancing.

$L = 108$ Mbps. For a given $L$ and $R$, an increased end-user demand results in the placement algorithm partitioning the WMN into a larger number of clusters using more hybrid gateways. For example, when $L = 108$ Mbps and $R = 3$, seven hybrid gateways are required to accommodate $W = 8$ Mbps, whereas 14 hybrid gateways are required for $W = 12$ Mbps.

At large values of $R$, the partitioning of the WMN is only constrained by the RF relay capacity, thus increasing $L$ will significantly impact the number of gateways required. For example, when $R = 8$ and $W = 8$ Mbps, increasing $L$ from 108 Mbps to 216 Mbps halves the number of hybrid gateways required from 10 to five gateways. The GA benefits from large values of $R$ by placing the hybrid gateways close the ISP to achieve the highest possible rate. At close proximity to the ISP, hybrid and wired gateways have similar capacity. However, when the increase in end-user demand is high, the GA is forced to place some hybrid gateways at the periphery of the WMN since relaying will not be sufficient. For example, when $W$ is increased from 8 Mbps to 12 Mbps (i.e., a 50% increase), the GA places some hybrid gateways far away from the ISP where the FSO backhaul rate is decreased. At these distances, wired and hybrid gateways do not have similar capacity and 80% more hybrid gateways are required to accommodate this increase in $W$ regardless of the value of $L$.

## VII. Conclusion

In this paper we have considered the problem of hybrid RF/FSO gateway placement, when FSO links are used to supplement gateway capacity in wireless mesh networks. This is needed when end-user demand evolves and eventually violates the original gateway assignment capacity. To accomplish this, we formulated a joint clustering and gateway placement problem which includes the strong rate-distance dependence of practical FSO links. The formulation incorporates the positions of existing wireline gateways and minimizes the number of additional hybrid-FSO/RF gateways which are needed to satisfy the new capacity requirements. A genetic algorithm was developed which finds and locates the minimum number of hybrid RF/FSO gateways while continuing to use the existing wired gateways. The proposed algorithm can also balance the load carried by each gateway in proportion to its backhauling capacity.

Our approach was found to yield optimal results generated by an ILP for a small WMN with 50 APs. A more reasonable WMN with 250 APs and 15 wired gateways extending over a $3\times3\ \mathrm{km}^2$ area was used to illustrate the feasibility of this approach. It was shown that a 100% increase in the end-user demand can be accommodated using seven additional hybrid gateways when $L = 108\ \mathrm{Mbps}$.

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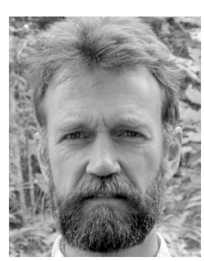

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