Interference Management in WLAN Mesh Networks Using Free-Space Optical Links

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***Abstract*—Frequency channels are assigned in wireless local-area network (WLAN) mesh networks subject to strict cochannel interference constraints. Since Wi-Fi may be freely used by other networks, added interference may eventually invalidate the original frequency assignment, making full link activation impossible. In this paper, we address this problem by selectively installing supplementary free-space optical (FSO) links when radio-frequency (RF) link performance has deteriorated. To minimize cost, the number of FSO links that are needed should be as small as possible. We first formulate the channel assignment problem with the objective of maximizing the number of simultaneous link activations while satisfying cumulative RF interference constraints. A proof is given for the NP-completeness of the joint frequency assignment and FSO link placement problem. We then propose an efficient heuristic to solve the channel assignment problem using a genetic algorithm. Results are then presented for various mesh networks which show that the proposed algorithm has good results compared with the computed bounds. The presented results show that the use of FSO links permits WLAN mesh network deployment in interference-prone situations.**

***Index Terms*—Free-space optical link, genetic algorithm, hybrid RF/FSO network, interference mitigation, wireless LAN mesh network.**

I. Introduction

In wireless local-area network (WLAN) mesh networks, frequencies are assigned to links subject to an acceptable radio-frequency (RF) cochannel interference criterion, such as a minimum signal-to-interference (SIR) power ratio. When the network is deployed, the frequency assignment is normally such that all backhaul links can be simultaneously activated. A problem with WLAN mesh deployment, however, is that the available frequencies (both 2.4 GHz IMS and 5 GHz UNI) may be freely used by anyone. This means that as more Wi-Fi is deployed, cochannel interference levels will increase and frequency assignment may eventually be impossible using the frequency set for which the system was originally configured. This problem is exacerbated by the fact that the number of nonoverlapping Wi-Fi channels is limited.

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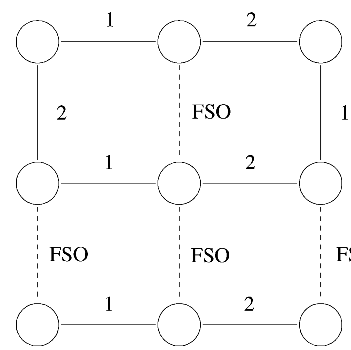

Fig. 1. WLAN mesh network with supplementary FSO links.

In a WLAN mesh network, mesh (APs) provide coverage to mobile users using IEEE 802.11. However, when RF interference becomes unacceptable, the system may operate in a degraded mode using a combination of link-rate reduction and temporal scheduling. In this paper, we address this problem by selectively installing specially designed free-space optical (FSO) links when system performance deteriorates due to unacceptable RF interference. FSO links may replace one or more of the relay links (i.e., those that operate between WLAN mesh points), so that the backhaul network can function as originally configured. A simple example of this is shown in Fig. 1. In this example, we assume that there are only two available WLAN frequencies (1 and 2) and that because of increased interference, their use must be separated by at least one mesh hop. In the figure, the RF links are shown as solid lines with their associated channel allocation. To allow for simultaneous link activation, we have introduced four supplementary FSO links, shown as dashed lines. FSO links are highly directional and do not have the same omnidirectional or antenna steering capabilities as RF links. FSO links provide unregulated bandwidth, low power consumption, and secure and reliable operation over typical WLAN mesh node distances. This paper demonstrates that FSO links are particularly attractive in environments with large external interference.

When FSO links are installed to mitigate RF interference, it is best to minimize the number of deployed FSO links so that installation costs are as low as possible. Clearly if one were considering a new deployment, however, then an option would be to use FSO links for backhaul, exclusively. In this paper, we consider the former case.

The channel assignment problem is formulated with the objective of maximizing the number of simultaneously active RF links while satisfying RF interference constraints and minimizing the number of FSO links that are added to the network.

Practical WLAN mesh networks are usually deployed such that all backhaul links can be simultaneously activated. However, in the future this simultaneous activation may not be possible even with dynamic frequency allocation. When this happens, replacing some of the RF links with FSO links may be one of the only available options. Our objective considers deploying the minimum number of FSO links so that full activation can be restored. The provisioning of an FSO link is clearly a static event. Therefore, a reasonable basis with which to make FSO link replacement selections is for the network to collect link quality measurements over time and to use a static approach to select FSO link positions. It is not our intent to propose a dynamic frequency allocation algorithm, but clearly this can be used to delay the introduction of FSO link replacements.

The problem of joint frequency assignment and FSO-link placement is shown to be an NP-complete problem under a cumulative RF interference constraint. An efficient heuristic is proposed that solves the channel assignment problem using a genetic algorithm. In addition, an integer linear programming (ILP) formulation is used to generate lower bounds for small network sizes. Our comparisons show that the proposed algorithm has good results compared with the computed bounds. The presented results also give an indication of the value of using FSO links in this role. In the ensuing sections, we focus entirely on the point-to-point backhaul links used by the network to relay traffic between mesh points.

The rest of this paper is organized as follows. In Section II, we present some of the related literature from the WLAN mesh and FSO areas. In Section III, we discuss the design parameters of the FSO links used. Sections IV and V describe the graph theoretic formulation of the problem and the ILP bound, respectively. Then in Section VI, a genetic algorithm is proposed for the frequency and FSO link assignment. In Section VII, we discuss the performance of the proposed algorithm and compare it to that of the bounds obtained by solving the ILP. We also include results for the case of explicit external interference in this section. Section VIII gives our conclusions.

II. Background

There are many factors affecting the capacity of wireless mesh networks including end-user mobility, routing, media access control protocol, communication range, and network topology. In [1], theoretic bounds on the throughput of wireless mesh networks are derived, and the throughput of each node diminishes to zero as the number of nodes is increased. In [2], an experimental test bed was used to show that a routing algorithm can select better paths by taking the quality of the wireless links into account rather than selecting paths using minimum hop counts. In [3], adaptive antenna arrays were used in mesh networks using the IEEE 802.11 distributed coordination function (DCF). It was shown that in many cases, the transmit power can be significantly reduced while still maintaining a sufficient link margin. This interference reduction is a key factor in improving capacity. In [4], a media access control protocol is proposed that accommodates the active nulling of cochannel interferers that may arise during the course of ongoing transmissions. The work in [5]–[7] considers the access of nonoverlapping frequency channels in multihop mobile ad-hoc networks. In [8], the channel assignment problem is addressed by minimizing interference, by classifying the neighboring nodes as interfering or not, and the problem is solved using a Tabu search procedure. In [9], a joint channel assignment and routing problem is formulated, taking into account interference constraints, the number of channels, and the number of radios available at each mesh point. In [10], a mesh architecture is proposed that combines spatial separation using directional antennas with frequency separation using different channels.

Free-space optical links have been gaining attention in recent years as an effective means for transmitting at high data rates. The use of FSO links in space-based intersatellite links has been an active area for some time [11]–[15]. FSO intersatellite 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. For example, in [16], an FSO mesh network architecture is proposed for broadband access, which extends home and SOHO xDSL connections. Reference [17] describes a broadband network consisting of densely spaced packet-switching nodes interconnected by FSO links in a multihop mesh arrangement. This work also considers the capacity of the network by looking at the maximum number of virtual connections which can be delivered to the access point such that all quality of service guarantees are maintained. The intent of [17] is to use FSO links to form a backbone network for broadband network access. Although we also use FSO links for backhaul purposes, the use and motivation is quite different. In our case, we add supplementary links, but only enough so that full backhaul link activation can be restored. This requires an interaction between FSO link placement and the frequency allocation for the RF links. In [17], FSO links are used for all backhaul purposes and do not involve RF allocation. The work in [17] is extended in [18] to include routing and load balancing. This previous work does not consider the design of hybrid RF/FSO WLAN mesh networks.

Genetic algorithms are commonly used for solving optimization and search problems [19]. They are particularly useful in scenarios where exhaustively searching the optimization variable range is computationally infeasible. Examples of genetic algorithms' application in wireless communications include clustering and scheduling in wireless sensor networks [20], [21] and frequency assignment [22], [23].

III. Free-Space Optical Links

FSO links are point-to-point connections in which data is transmitted by modulating and detecting the intensity of a laser or light-emitting diode (LED) source. Unlike RF channels, FSO links can only modulate the *intensity* of the carrier and not the amplitude or phase directly. A key advantage of this technology is that large data rates are possible due to the vast available spectrum, which is unregulated world-wide. Additionally, FSO links are immune to interference from other FSO and RF links. Due to their directional nature, FSO links are power efficient and inherently secure. However, the performance of the FSO links is limited by atmospheric and beam-spreading losses.

In this paper, we selectively deploy FSO links as a replacement for certain WLAN mesh network RF links. Since a given

TABLE I
PARAMETERS FOR SHORT-RANGE FSO LINK EXAMPLE

Data Rate		155 Mbps
Link Distance	L	200 m
Beam Divergence	θ_b	10 mrad
Average Transmitted Power	P_t	10 mW
Rx. Aperture Diameter	D_r	0.10 m
Tx. Aperture Diameter	D_t	0.07 m
Wavelength	λ	850 nm
Bit-error rate		10^{-6}
Input referred noise	i_n	14 nA
Responsivity	R	0.6 A/W
Extinction Ratio	r_e	10
Sensitivity		-38.7 dBm

FSO link is installed as a replacement, it is important to ensure that it can reliably provide data rates at least as high as the link that is being replaced. In addition, when the WLAN mesh nodes are battery operated (such as in a solar-powered WLAN mesh [24]–[26]), it is also important that the power consumption of the FSO link does not exceed that of the replaced RF link.

In this section, we present a link budget analysis for a 155 Mbps FSO link over 200 m and demonstrate that a significant link margin exists for these short-range links. The power consumption of such short-range FSO links is estimated using off-the-shelf commercial components.

A. FSO Link Budget

In this section, we provide a link budget calculation for an appropriate short-range FSO link. We show that the intrinsic reliability problems due to atmospheric losses are marginalized due to the short ranges and relatively low data rates existing in WLAN mesh networks. The design parameters chosen for the short-range terrestrial FSO link are summarized in Table I. The link is assumed to operate at 155 Mbps over a range of 200 m, which is chosen as a practical operating distance between WLAN mesh APs. The link design is based on an LED emitter since such units are less expensive, are more robust, and have greater eye-safety as compared to laser emitters.[1] Due to cost constraints, it is assumed that the FSO link does not have any active tracking mechanisms to combat misalignment error. As a result, the beam divergence is set to be quite wide compared to commercial units, $\theta_b = 10$ mrad. The transmitted average optical power and aperture sizes are set to typical values for commercial eye-safe units. The system is set to operate at $\lambda = 850$ nm since inexpensive silicon emitters and detectors exist at this wavelength.

The sensitivity of the receiver is the power required at the input of the receiver in order to provide a BER $= 10^{-6}$. In this case, the sensitivity in Table I is computed as

$$\text{Sensitivity} = 10\log_{10}\left(\frac{4.75 i_n(r_e+1)}{R(r_e-1)} \times 10^3\right) \quad [\text{dBm}]$$

where the responsivity R and input referred noise are taken from commercial components.[2]

The losses inherent in the channel are due to geometric losses in propagation, atmospheric losses as well as system losses, and are summarized in Table II. The received power can be written as

$$P_r = L_f L_m L_o \underbrace{\frac{D_r^2}{(D_t + L\theta_b)^2}}_{L_g} \underbrace{e^{-\sigma L}}_{L_a}$$

where L_f, L_m, L_o, and σ are listed in Table II. Due to the large beam divergence, L_m is assumed to be negligible, while conventional values for L_o and L_f losses are used [27]. The geometric loss L_g is dominated by the wide-beamwidth emitter used to ease pointing restrictions. The atmospheric loss L_a is calculated via the Beer–Lambert law, where the attenuation σ is calculated from an empirical fit to experimental data based on the visibility[3] [28, (6)].

The link margin specifies the extent to which P_r exceeds the minimum required sensitivity to ensure a reliable link. Notice from Table II that a significant link margin exists in all but the worst case of deep fog. The reliability of the link will then depend on the relative frequency of different weather conditions. A recent study using historic weather data for a variety of world cities over a period of 16 years estimated that for ranges on the order of 200 m, a 155 Mbps FSO link was able to maintain a reliable link with an availability of 99.99% [27, Table VI]. Thus, for the short ranges considered in this paper, FSO links can be considered as providing a significant link margin with reliability on par with conventional RF links.

B. Power Consumption Estimate

In order to estimate the power consumption of the transmitter and receiver, commercial components designed for a 155 Mbps fiber link were employed. The combination of a commercial high-speed LED for communication applications and a 155 Mbps LED driver[4] is able to output the required 10 mW output optical signal at a cost of approximately 130 mW of total consumed power. At the receiver, using a high-speed photodiode, a 155 Mbps low-noise transimpedance amplifier and a limiting amplifier to get transistor–transistor logic output levels[5] require approximately 150 mW of consumed power. Thus, an estimate of the total consumed power for such an FSO transceiver is on the order of 280 mW. Notice that this is an overestimate of the power required since the optical components and electronics were not optimized for low-power wireless operation.

[1]OSRAM Opto Semiconductors high-power infrared emitter, part SFH4301: http://www.osram-os.com/

[2]PerkinElmer Optoelectronics silicon PIN photodiode—standard N-type, part C30808E: http://optoelectronics.perkinelmer.com; Maxim Integrated Products, 155 Mbps low-noise transimpedance amplifier, part MAX3657: http://www.maxim-ic.com/

[3]Visibility is defined here as the distance at which the intensity drops to 2% of transmitted value.

[4]Maxim Integrated Products, 270 Mbps SFP LED driver, part MAX3967: http://www.maxim-ic.com/.

[5]$+3.0$ to $+5.5$ V, 125 to 266 Mbps limiting amplifiers with loss-of-signal detector, part MAX3964A: http://www.maxim-ic.com/.

TABLE II
LINK BUDGET FOR EXAMPLE FSO LINK

System Losses		**Atmospheric Losses: L_a**			**Link Margin**
		Condition	Visibility	Attenuation (σ)	
Geometric loss (L_g)	-26 dB	Very Clear	20 km	0.48 dB/km	17 dB
Fading loss (L_f)	-2 dB	Clear	10 km	0.96 dB/km	17 dB
Misalignment loss (L_m)	0 dB	Haze	4 km	2.8 dB/km	16 dB
Optical Losses (L_o)	-3 dB	Light Fog	1 km	13 dB/km	15 dB
		Med. Fog	0.5 km	28 dB/km	12 dB
		Dense Fog	0.2 km	73 dB/km	3 dB
		Deep Fog	0.05 km	309 dB/km	**-44 dB**

By comparison, a conventional (IEEE 802.11a/g) WLAN radio consumes about 780 mW for transmission, 480 mW for receiving/listening, and about 2 mW when in power-save mode [26]. This link operates in half-duplex at a maximum data rate of 54 Mbps. In the worst case, if the RF link were 100% utilized, and transmitting in one direction only, the replacement FSO link would have about a three times data-rate advantage. This means that the FSO link could power save for almost 2/3 of the time at the same aggregate data rate. Therefore, the comparable power consumption for the FSO link would be approximately 93 mW, which is far lower than the power consumption of the RF counterpart. Thus, the power consumption of the FSO link is less than the RF link regardless of its transmit/receive activity.

In the above argument, we have assumed that a single FSO link is replacing a fixed point-to-point RF link. In some cases, more than one FSO link may be required if the replaced RF radio is used to implement more than one RF link using time sharing. In this case, the power consumption and data-rate constraints will still be met since the utilization of the FSO radios can be reduced accordingly.

IV. PROBLEM FORMULATION

In this section, we formulate the joint RF frequency assignment and FSO link placement problem as a graph coloring problem. Consider a multichannel network of N mesh nodes. We represent this network with a *reachability graph* $G = (N, E)$ where each network node represents a node in G and two nodes have an edge (link) between them if they are within communication range. We assume that the communication range of all nodes is equal and all links are bidirectional.

Let $K = \{1, 2, \ldots, k\}$ denote the given set of RF frequencies. We assume that the $|E| \times |E|$ interference matrix $C = (c_{ij})$ is known, where $c_{ij} \geq 0$ indicates the (measured) interference that is caused if links i and j operate on the same frequency, $f \in K$. I_{if} is defined to be the external interference on channel f at link i. We consider the cumulative cochannel interference where a radio frequency $f \in K$ can be assigned to a link i if and only if the total cumulative cochannel interference due to other links' use of the same frequency $f \in K$ is below a predefined threshold B. Note that depending on the value of k, it may be possible to assign a frequency to every link in G satisfying the cumulative interference constraint as described above. When k is not sufficiently large, we place an FSO link on each of the remaining links in G where no radio frequency has been assigned. Note that FSO links are point-to-point and do not interfere with any of the assigned RF channels. The objective is to assign the available RF channels in such a way that we need a minimum number of FSO link replacements. Given the reachability graph and a set $K = \{1, 2, \ldots, k\}$ of radio frequencies, our objective is to maximize the number of links that can be assigned to a given RF channel subject to satisfying the interference constraints as stated above.

We can represent the interference constraints by means of edge weights on an *interference graph* $G' = (N', E')$, which can be derived from the reachability graph G as follows. Each link in G is represented by a node in G' and every pair of nodes i and j in G' share an edge with weight c_{ij}. Then the above channel assignment problem can be modeled as a vertex coloring problem as follows.

Given an undirected graph $G' = (N', E')$ with edge weight c_{ij} for every edge $(ij) \in E'$, the interference threshold B, and the set of available radio frequencies $K = \{1, 2, \ldots, k\}$, the coloring problem is to find a coloring function t such that the maximum number of vertices of G' can be colored with k different colors such that

$$W(i) = \sum_{j \in N' : t(j) = t(i), j \neq i} c_{ij} + I_{it(i)} < B \quad \forall i \in N'. \tag{1}$$

Note that constraint (1) ensures that the total cochannel interference $W(i)$ at a given node i is below the threshold B. In the following, we will now show that the above problem is NP-complete.

A. Complexity Analysis

A graph $T = (P, Q)$ is k-colorable if there exists a coloring of the vertices of T with k colors such that no two adjacent vertices are colored with the same color. It is well known that deciding if a given graph is k-colorable is NP-complete [29]. Given a graph $T = (P, Q)$, the *maximum induced k-colorable* subgraph problem is that of finding a k-colorable subgraph of T with maximum number of vertices. It is well known that finding an approximation to the maximum induced k-colorable subgraph problem is as hard as that of finding an approximation to the *maximum independent set*, for any fixed k [30]. It is also known that the problem of finding an approximation to the maximum independent set within a factor better than $\Omega(n^{1-\epsilon})$, for any $\epsilon > 0$, is NP-complete [31].

To establish the NP-completeness of our problem, we use a reduction from an arbitrary instance of the maximum induced k-colorable subgraph problem on $T = (P, Q)$ to our coloring problem on $G' = (N', E')$, where k is the available number of RF channels. Define $N' = P$ and $E' = Q \cup R$, where R is such that G' becomes a complete graph. Now consider the following weight assignment function $s : Q \rightarrow B$ and $s' : R \rightarrow 0$, which assigns each edge $e \in E'$ a weight equal to B or zero depending on whether $e \in Q$ or $e \in R$, respectively. Note that T with weight B on every edge remains as a subgraph of the graph G'. Clearly, if there exists a polynomial algorithm for solving our coloring problem on G' optimally, that will also result in a maximum induced k-colorable subgraph of T. This can be explained as follows. Since the weights of each edge in Q are B, no vertex can be adjacent to any vertex of its same color in T in any optimal coloring on G' because in that case, the interference constraint (1) will be violated. Even if only one vertex u exists, with an adjacent vertex of its same color in T, the cumulative cochannel interference $W(i)$ in (1) at the vertex u will be equal to the predefined threshold B. Hence this optimal coloring is also an optimal result for the maximum induced k-colorable subgraph problem on T. Thus, the hardness result follows from the hardness of the maximum induced k-colorable subgraph problem.

V. Optimal Link Assignment Formulation

In this section, we formulate the maximum number of vertices of G' that can be colored with k frequencies satisfying the interference constraints given by (1). The problem is formulated as an integer linear programming (ILP) optimization. This allows us to compute the maximum number of links that can be colored with the given set of frequencies. This can only be computed for small problem sizes. The remaining links are assigned to FSO links.

Define a set of binary variables X_{if} where $i \in N'$ and $f \in K = \{1, 2, \ldots, k\}$ as follows:

$$X_{\text{if}} = \begin{cases} 1, & \text{if vertex } i \text{ has been assigned color } f \\ 0, & \text{otherwise.} \end{cases}$$

Similarly, define another set of binary variables Y_i, where $i \in N'$

$$Y_i = \begin{cases} 1, & \text{if } \sum_{f \in K} X_{\text{if}} = 1 \, (\text{vertex } i \text{ has been colored}) \\ 0, & \text{if } \sum_{f \in K} X_{\text{if}} = 0 \, (\text{vertex } i \text{ has not been colored}). \end{cases}$$

Let M be a large value greater than $\sum_{(i,j) \in E'} c_{ij}$. Now our objective is to

$$\max \sum_{i \in N'} Y_i$$

subject to the following constraints:

$$Y_i - \sum_{f \in K} X_{\text{if}} = 0 \quad \forall i \in N' \tag{2}$$

and

$$\sum\nolimits_{j \in N' : j \neq i} c_{ij} X_{\text{if}} + I_{\text{if}} \leq B X_{\text{if}} + (1 - X_{\text{if}}) M \quad \forall i \in N', f \in K. \tag{3}$$

Constraint (2) ensures that each vertex will be assigned at most one frequency. Constraint (3) ensures that channel f is only assigned to vertex i when the cumulative cochannel interference due to other vertices' usage of the same channel is below the predefined threshold B. The term I_{if} accounts for the external interference on channel f at link i.

```
begin
  t[1] ← 1
  // t[i] is the frequency assigned to node_i (i-th node of S)
  No_of_FSO ← 0;
  for i = 2 to |N'| do
    for f = 1 to k do
      t[i] ← f
      for j = 1 to i do
        if t[j] = f then
          if W(j) = Σ_{p∈{1,2,···,i}:t[p]=f:p≠j} c_jp + I_jf < B
          then
            allotment ← yes
          else
            allotment ← No
            break
          end if
        end if
      end for
    end for
    if allotment = No then
      t[i] ← fso_link
      No_of_FSO + +;
    end if
  end for
  return No_of_FSO
end
```

Fig. 2. Fitness function for GA frequency/FSO assignment.

The number of binary variables involved in solving the *self* cochannel FSO placement problem (excluding external interference) is $|N'|k + |N'|$ and the number of constraints is also equal to $|N'|k + |N'|$. In Section VII, this bound is compared to results of the algorithm proposed in the next section.

VI. Frequency and FSO Link Assignment Using a Genetic Algorithm (GA)

In this section, we propose a genetic algorithm formulation for solving the joint frequency and FSO link assignment problem. When using a genetic algorithm, it is required that the parameter set be coded as a finite-length string (or chromosome) over a finite alphabet [19]. A string S is assigned a fitness value using an appropriate fitness function. A collection of M (finite) such strings is called a population. A simple genetic algorithm is composed of three basic operators: i) reproduction or selection, ii) crossover, and iii) mutation [19].

Our implementation of the genetic algorithm is summarized in Fig. 2. It starts with an initial population of randomly generated link orderings, and in each iteration a new (hopefully improved) population of the same size is generated from the current one. Let S_b be the best link ordering (with respect to the fitness value) of the population generated up to iteration t. In the elitist model of genetic algorithm, if S_b or any link ordering better than S_b is not in the population generated in iteration $(t+1)$, then include S_b in the $(t+1)$th population [19]. We apply this technique for solving the joint frequency assignment and FSO link deployment problem.

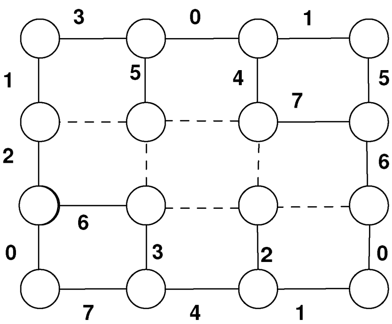

Fig. 3. Frequency assignment for 4×4 mesh with eight frequencies, integer programming results—number of FSOs $= 6$.

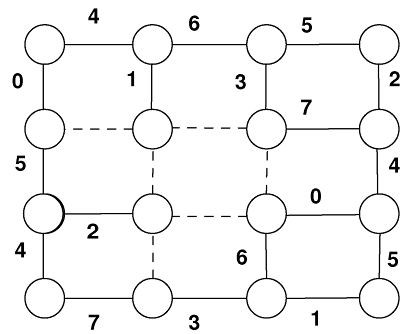

Fig. 4. Frequency assignment for 4×4 mesh with eight frequencies, genetic algorithm results—number of FSOs $= 6$.

Consider the *interference graph* $G' = (N', E')$, where the edge weight represents the interference constraints given by the matrix $C = (c_{ij})$ as described in Section IV. Let $K = \{1, 2, \ldots, k\}$ be the given set of RF frequencies. Consider a random order of the nodes in N' as a link ordering S or chromosome. The fitness of a link ordering S used in our algorithm is described by the function in Fig. 2, which returns the number of FSO links required if frequencies are assigned to nodes of G' following the order as specified by S. Our objective is to find a link ordering for which the fitness value is as small as possible. The procedure can be viewed as a greedy algorithm where the links are considered based on the priority assigned to them by the fitness function. In line 5, we choose the link with the highest priority that has not yet been assigned a frequency and try to assign one in line 7. The interference constraint is checked for that link/frequency pair in line 10. If the interference constraint is satisfied, then the link is operated at that frequency. If the frequency assignment fails (i.e., the interference constraint is not satisfied), another frequency is attempted (lines 6 and 7). The process of attempting frequencies over the chosen link is continued until either the link is successfully assigned a frequency that satisfies the interference constraint or all the frequencies have been attempted. If frequency assignment fails, the RF radio is replaced by an FSO link, as shown in line 20, and the number of added FSO links is incremented in line 21. It is also very easy to extend the GA to handle external interference, i.e., while allocating a particular frequency to a link, the genetic algorithm checks if the summation of cochannel interference and external interference is below the required threshold. Otherwise, the next frequency is tried until all the frequencies are exhausted at which point an FSO link is assigned to that link.

VII. Performance Results

In this section, we compare the results of the genetic algorithm and the integer programming bound for different rectangular mesh sizes. To characterize the algorithm, we first use network examples chosen so that frequency assignment is not possible using the available frequency channel set. This allows us to examine the FSO link assignment ability of the algorithm. We obtain results for SIR values corresponding to the IEEE 802.11 data rates of 1, 11, and 54 Mbps. We also vary the number of frequencies from three up to eight. To calculate the interference matrix, we assume an exponential path loss model corresponding to a propagation exponent of 2.8 when the distance is two hops or less, and 4.5 otherwise.

TABLE III
Number of FSO Links Assigned by GA and ILP

4×4 Mesh				
No. of Frequencies	ILP (11 Mbps)	GA (11 Mbps)	ILP (54 Mbps)	GA (54 Mbps)
3	15	15	18	18
4	12	12	16	16
5	11	11	14	14
6	9	9	12	12
7	8	8	11	11
8	6	6	10	10
5×5 Mesh				
No. of Frequencies	ILP (11 Mbps)	GA (11 Mbps)	ILP (54 Mbps)	GA (54 Mbps)
3	28	28	29	29
4	24	24	26	26
5	20	20	23	24
6	16	16	20	21
7	13	13	18	19
8	10	12	16	16
6×6 Mesh				
No. of Frequencies	ILP (11 Mbps)	GA (11 Mbps)	ILP (54 Mbps)	GA (54 Mbps)
3	42	43	48	48
4	37	38	44	44
5	32	34	40	40
6	28	29	36	36
7	23	25	32	32
8	20	21	28	29

An FSO link assignment example is given in Figs. 3 and 4. Both figures show a 4×4 network (with 11 Mbps links) for which there is no valid frequency assignment, given an eight-frequency set. Fig. 3 shows the resultant assignment of FSO links using the ILP formulation. In all the figures, the RF links are shown as solid lines with their assigned frequency (numbered zero to seven) and the FSO links are shown as dotted lines. The number of full duplex FSO links in this case is three, or six half-duplex FSO links.

Fig. 4 shows the same network with the assignment obtained using the GA algorithm. It can be seen in this example that both algorithms require six FSO links; however, the placement of the links is different in both cases. Clearly, in this example, there are multiple solutions that minimize the number of FSO links while satisfying the RF interference constraint.

In Table III, we compare the results of the GA to the bounds obtained by the ILP for mesh sizes of 4×4, 5×4, and 6×6. For the 4×4 mesh, the results match exactly. The genetic al-

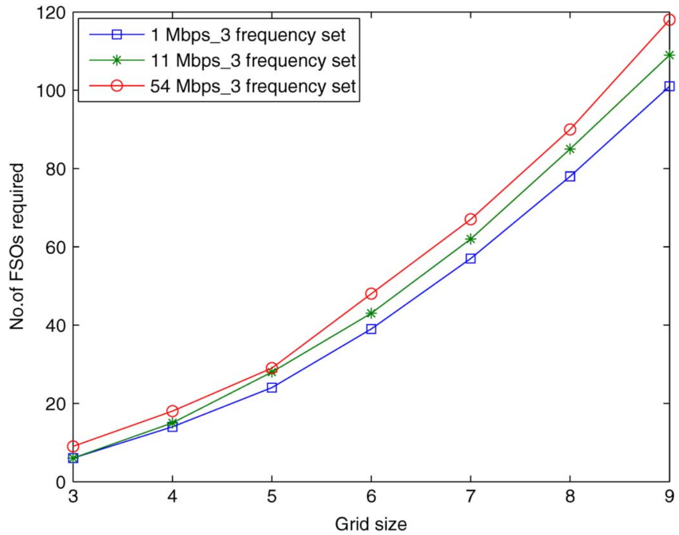

Fig. 5. Genetic algorithm results for three nonoverlapping frequencies.

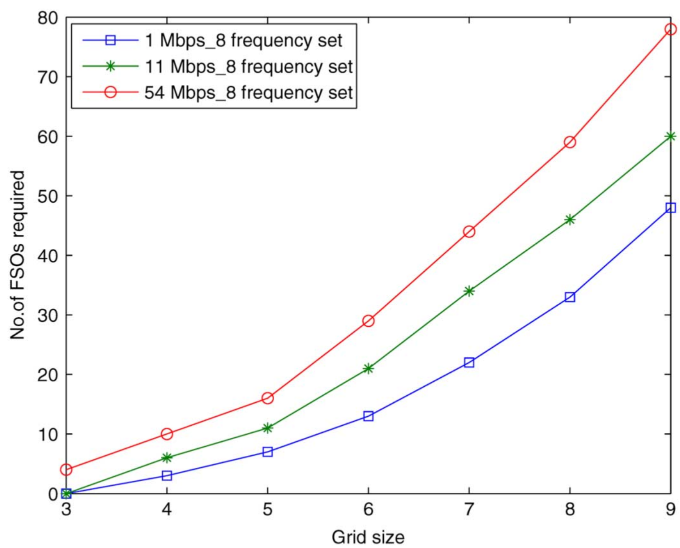

Fig. 6. Genetic algorithm results for eight nonoverlapping frequencies.

gorithm often gives optimal results in very few iterations due to the symmetric structure of the 4×4 network and the small number of link orderings. The results for the 5×5 mesh in Table III show that the number of FSO links obtained using the GA differs by one from the ILP bound for the cases of five, six, and seven nonoverlapping frequencies. However, for three, four, and eight nonoverlapping frequencies, the GA results coincide with the ILP bound. When the number of frequencies is reduced (e.g., three frequencies in a 5×5 mesh), most of the link orderings generated by the GA will not satisfy the interference constraint, leading to a reduced search space. At the other extreme, the availability of eight frequencies provides a higher degree of freedom for the GA such that many possible link orderings can give the optimal result within a small convergence time. The sample that yields the best fitness in the current population keeps propagating in successive generations and hence gives faster convergence. With our initial population size of 100 and a random generator for link orderings, the optimal results

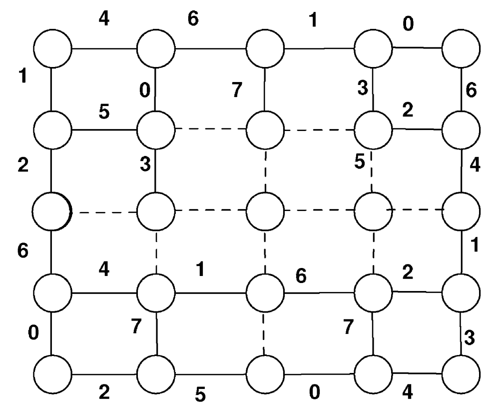

Fig. 7. Frequency assignment for 5×5 mesh with eight frequencies, genetic algorithm results—number of FSOs $= 12$.

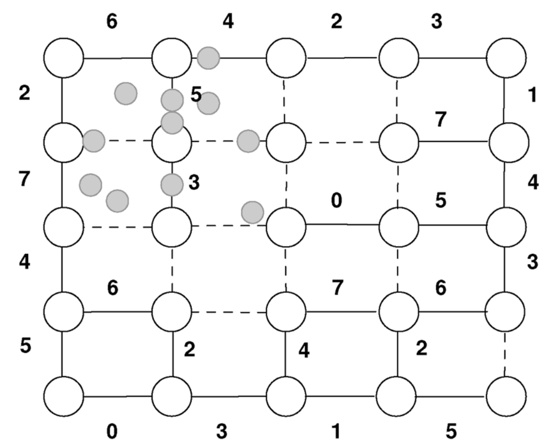

Fig. 8. Frequency assignment for 5×5 mesh with eight frequencies in the presence of external interference, genetic algorithm results—number of FSOs $= 14$.

were obtained in less than 100 iterations for these extreme cases. However, for the five-, six-, and seven-frequency cases, the GA terminates after 7000 iterations without reaching the ILP bounds since within this vast search space no optimal solution existed. The convergence of the GA in the 6×6 mesh to that of optimal results for 54 Mbps is better than that for the 11 Mbps case. In the latter case, the SIR threshold is lower and therefore many link orderings can satisfy the interference constraints; hence a much larger search space requires more iterations for convergence.

Figs. 5 and 6 show how the number of required FSO links increases as a function of the mesh size for different data rates when using three and eight nonoverlapping frequencies and $I_{if} = 0$, i.e., no external interferers. As expected, the number of FSO links required for a 54 Mbps network is always higher than that for 11 Mbps, which in turn is always higher than that for 1 Mbps. This is irrespective of the available number of frequencies since a higher SIR needs to be maintained for higher data rates and hence more FSOs are required. However, for a given mesh size, the difference between the number of FSO links required in the 1 Mbps versus 54 Mbps cases is always smaller in the case of three frequencies in comparison to the eight-frequency case. In the three-frequency case, the percentage of the FSO links out of the entire network is much

TABLE IV
NUMBER OF FSO LINKS ASSIGNED BY GA WITH EXTERNAL INTERFERERS

GA results for 11 Mbps		
No. of frequencies	4×4 Mesh	5×5 Mesh
3	21	31
4	19	27
5	17	23
6	15	20
7	13	16
8	11	14
GA results for 54 Mbps		
No. of frequencies	4×4 Mesh	5×5 Mesh
3	20	32
4	17	28
5	14	25
6	11	22
7	10	20
8	9	17

larger than in the eight-frequency case for any mesh size. It is clear that if a link is feasible under the 1 Mbps SIR constraint, then it has a higher chance of being suitable in the 54 Mbps case in the three-frequency case versus the eight-frequency network.

Thus far, we have considered the use of our results to combat cochannel *self* interference. This is the case when interference is caused by the APs belonging to a single network. However, in practice, cochannel interference may be caused by external interferers. We invoke our GA to accommodate for (3) when the term I_{if} is added to account for external interference.

In Figs. 7 and 8, we present the results given by the GA when applied to a 5×5, 11 Mbps mesh with and without external interferers and eight frequencies. In Fig. 8, the external interferers are operating on frequencies 0 and 1 and are represented by 11 gray-shaded circles. When no external interferers are present, the GA requires 12 FSO links to satisfy the SIR constraint, as shown in Table III. In this case, most of these links are deployed towards the center of the mesh. When external interferers are present, the GA requires 14 FSO links to satisfy the SIR requirement for the same network, as shown in Table IV. The additional links are required to accommodate for the external interferers, which effectively disabled the use of frequencies 0 and 1 in the upper left corner of the grid (i.e., where the interferers are concentrated).

Further results for the external interferer case are shown in Table IV. In the 4×4 case with five frequencies and 54 Mbps links, the number of FSO links required is 14 and is lower than a three-frequency network with no interferers (from Table III), which requires 18 FSO links. It is clear from this table that more FSO links are required when external interferers are present (i.e., compared with the results in Table III). For meshes in which the number of frequencies occupied by external interferers is a significant portion of the assigned frequencies, the use of FSO links is more significant.

VIII. CONCLUSION

In this paper, we have proposed the use of FSO link assignment when unacceptable RF interference occurs after an initial wireless LAN mesh network deployment. We have formulated the FSO link assignment as a graph coloring problem and, after proving the NP-completeness of the problem, solved it using an integer programming approach and a genetic algorithm. Our results show that for small mesh sizes, the genetic algorithm provides comparable results to those of the optimal values given by the integer programming formulation. We have also presented FSO deployment scenarios to mitigate the effect of external interferers. The presented results show that the use of FSO links permits WLAN mesh network deployment in interference-prone situations.

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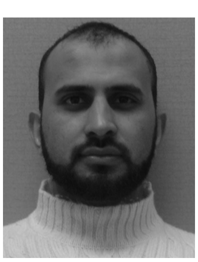

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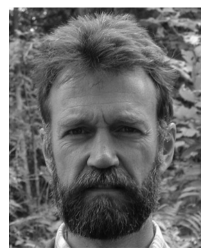

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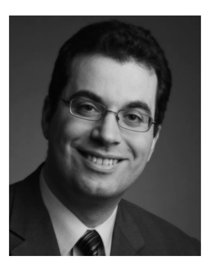

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