WhiteMesh: Leveraging White Spaces in Wireless Mesh Topologies

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***Abstract*—Wireless mesh networks were previously thought to be an ideal solution for large-scale Internet connectivity in metropolitan areas. However, in-field trials revealed that the node spacing required for WiFi propagation induced a prohibitive cost model for network carriers to deploy. The digitization of TV channels and new FCC regulations have reapportioned spectrum for data networks with far greater range than WiFi due to lower carrier frequencies. In this work, we consider how these white space bands can be leveraged in large-scale wireless mesh network deployments. In particular, we present an integer linear programming model to leverage diverse propagation characteristics of white space and WiFi bands to deploy optimal WhiteMesh networks. Since such optimization is known to be NP-hard, we design two heuristic algorithms, Growing Spanning Tree (GST) and Band-based Path Selection (BPS), which we show approach the performance of the optimal solution with reduced complexity. We additionally compare the performance of GST and BPS against two well-known multi-channel, multi-radio deployment algorithms across a range of scenarios spanning those typical for rural areas (FCC's target application) to urban areas (original target application for mesh). In doing so, we find gains of up to 160% over existing multi-channel, multi-radio algorithms which are agnostic to diverse propagation characteristics across bands. Moreover, we show that, with similar channel resources and bandwidth, the joint use of WiFi and white space bands can lead to a 140% improvement in served user demand over mesh networks with only WiFi bands or white space bands.**

I. Introduction

About a decade ago, numerous cities solicited proposals from network carriers for exclusive rights to deploy city-wide WiFi, spanning hundreds of square miles. While the vast majority of the resulting awarded contracts used a wireless mesh topology, initial field tests revealed that the actual WiFi propagation could not achieve the proposed mesh node spacing. As a result, many network carriers opted to pay millions of dollars in penalties rather than face the exponentially-increasing deployment costs (e.g., Houston [1] and Philadelphia [2]). Thus, while a few mesh networks have been deployed in certain communities [3], [4], wireless mesh networks have largely been unsuccessful in achieving the scale of what was once anticipated [5].

Around the same time, the digital TV transition created more spectrum for use with data networks [6]. These white space bands operate in available channels from 54-806 MHz, having increased propagation characteristics as compared to WiFi [7]. Hence, the FCC has identified rural areas as a key application for white space networks since the reduced population from major metropolitan areas allows a greater service area per backhaul device without saturating wireless capacity. Naturally, the question arises for these rural communities as well as more dense urban settings: *how can the emerging white space bands improve large-scale mesh network deployments?* While much work has been done on deploying multihop wireless networks with multiple channels and radios, the differences in propagation have not be exploited in their models [8]–[10], which could be *the* fundamental issue for the success of mesh networks going forward.

In this paper, we leverage the diversity in propagation of white space and WiFi bands in the planning and deployment of large-scale wireless mesh networks. To do so, we first form an integer linear programming model to jointly exploit white space and WiFi bands for optimal WhiteMesh topologies. Second, since similar problem formulations have been shown to be NP-hard [11], we design two heuristic algorithms, Growing Spanning Tree (GST) and Band-based Path Selection (BPS). We then show these two algorithms approach the performance of the optimal solution but have a reduced complexity. To assess the performance of our schemes, we compare the performance of GST and BPS against two well-known multi-channel, multi-radio deployment algorithms across a wide range of scenarios, including those typical for rural areas as well as urban settings. Finally, we quantify the degree to which the joint use of both band types can improve the performance of wireless mesh networks in these diverse scenarios.

The main contributions of our work are as follows:

- We develop an optimization framework based on integer linear programming to jointly leverage white space and WiFi bands to serve the greatest user demand in terms of gateway throughput in wireless mesh networks.
- We design a heuristic algorithm called Growing Spanning Tree (GST), which considers the network-wide interference induced by each channel, band, and path choice and attempts to reduce this overall Path Interference induced on the Network (PIN) with these decisions.
- We build a second algorithm, Band-based Path Selection (BPS), which considers the diverse propagation and overall interference level of WiFi and white space bands using a two-stage approach. In the first stage, we prioritize the bands with the greatest propagation to reduce the overall hop count. In the second stage, we compare the interference level of path choices with similar hop count.
- We perform extensive analysis across diverse offered loads, network sizes, and combinations of WiFi and white space band usage to evaluate our algorithms, showing that BPS outperforms existing techniques by up to 160%.
- Given similar channel resources (bandwidth and transmission power), we additionally show that while WiFi-only mesh topologies would largely outperform mesh networks with only white space bands, the joint use of the two types of bands (i.e., WhiteMesh networks) can yield up to 140% improvement in served user demand.

The remainder of this paper is organized as follows. In

Section II, we introduce WhiteMesh network topologies, describe the challenge of diverse frequency band allocation, and formulate the integer linear programming model. In Section III, we develop two heuristic algorithms which consider which bands and multihop paths to select in a WhiteMesh topology. We then validate the performance of the heuristic algorithms versus the upper bound of the optimal solution and compare their performance against two well-known multi-channel, multi-radio algorithms in Section IV. Finally, we discuss related work in Section V and conclude in Section VI.

II. Problem Formulation

In this section, we formulate the problem of how to optimally use WiFi and white space bands in concert when deploying wireless mesh networks. We first describe our system model and illustrate the challenges of such a WhiteMesh architecture. We then discuss how to evaluate WhiteMesh networks and the corresponding goal of both the optimization framework and the heuristic algorithms that we will propose in the following section. Finally, we present our integer linear programming model used to address the problem.

A. WhiteMesh Network Architecture

Wireless propagation is the behavior of the signal loss characteristics when wireless signals are transmitted from a transmitter to receiver. The strength of the receiving signal depends on both the line-of-sight path (or lack thereof) and multiple other paths that are a result of reflection, diffraction, and scattering from obstacles in the environment [12]. The widely-used, Friis equation characterizes the power of the received signal P_r in terms of the power P_t and gain G_t of the transmitting signal, gain of the receiver G_r, wavelength λ of the carrier frequency, distance R from transmitter to receiver, and path loss exponent n according to [13]:

$$P_r = P_t + G_t + G_r + 10nlog_{10}(\frac{\lambda}{4\pi R}) \qquad (1)$$

Here, the path loss exponent n changes according to the aforementioned environmental factors and ranges from 2 to 5 in typical outdoor settings [14].

A common assumption that use many WiFi channels is that the propagation characteristics of one channel is similar to another, since the channel separation is relatively small (e.g., 22 MHz for the 2.4 GHz band). Many works which rely on such an assumption have focused on the allocation of multiple WiFi channels with multiple radios in multihop wireless networks [10]. Here, a frequency band is defined as a group of channels which have similar propagation characteristics. In this work, we consider the diverse propagation characteristics for four total frequency bands: 450 MHz, 800 MHz, 2.4 GHz, and 5.8 GHz. The two former frequency bands, we refer to as white space (WS) bands whereas the two latter frequency bands, we refer to as WiFi bands.

Wireless mesh networks are a particular type of multihop wireless network that are typically considered to have at least two tiers [3]: *(i)* an access tier, where client traffic is aggregated to and from mesh nodes, and *(ii)* a multihop backhaul tier for connecting all mesh nodes to the Internet through gateway nodes. In this work, we focus on how to optimally allocate white space and WiFi bands on a finite set of radios per mesh node along the backhaul tier since we

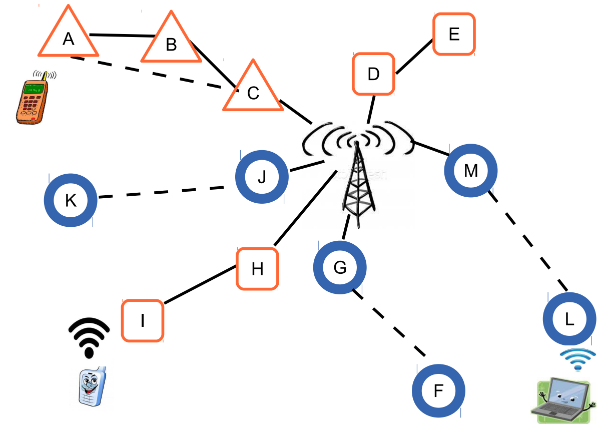


Fig. 1. Example WhiteMesh topology with different mesh-node shapes representing different frequency band choices per link.

assume that client devices will use WiFi (due to the economies of scale). In each of the WhiteMesh topologies studied in Section IV, a sufficient number of orthogonal WiFi channels remain for the access tier to connect to clients using additional radios co-located on the mesh nodes.

Due to the broadcast nature of the wireless medium, greater levels of propagation induce higher levels of interference. Thus, in sparsely-populated rural areas, the lower frequencies of the white space bands might be a more appropriate choice for multihop paths to gateways with reduced hop count. However, as the population and demand scales up (e.g., for more urban regions), the reduced spatial reuse and greater levels of interference of white space bands might detract from the overall deployment strategy. In such urban areas, select links of greater distance might be the most appropriate choice for white space bands, especially since the number of available channels is often inversely proportional to the population (due to the existence of greater TV channels).

Figure 1 depicts an example where mesh node A could connect to mesh node C through B at 2.4 GHz, or directly connect to C at 450 MHz. If 2.4 GHz were used, link D, E might be able to reuse 2.4 GHz if they are out of the interference range. However, if link A, C used 450 MHz, a lower hop count would result for the path, but lower levels of spatial reuse result (e.g., for link D, E). While the issues of propagation, interference, and spatial reuse are simple to understand, the joint use of white space and WiFi bands to form optimal WhiteMesh topologies is a challenging problem.

B. Model and Problem Formulation

Our model is similar to prior multi-channel models [9], [10], [15]. However, in these models, different channels have the same communication range D_c and interference range D_r. While these works would attempt to maximize throughput in a multihop network topology by an optimal channel assignment for a given set of radios, we hypothesize that using radios with a greater diversity in propagation could yield overall network performance gains. Therefore, for a given set of radios, we allow the channel choices to come from different frequency bands (i.e., multiband channel assignment). We assume that the locations of mesh nodes and gateway nodes are given and all mesh nodes have the same transmit power, channel bandwidth, and antenna gain. Each mesh node operates with a classic protocol model [16].

The mesh network could be represented by a unidirectional graph $G = (V, E)$, where V is the set of mesh nodes, and E is the set of all possible physical links in the network. If the received signal (according to Eq. 1) between two mesh nodes i, j for a given frequency band (from the set of all bands B) is greater than a communication-range threshold, then a data link exists and belongs to the set L with a fixed, non-zero capacity γ according to the protocol model. Correspondingly, a connectivity graph C is formed for each band in B such that $C = (V, L, B)$. If the received signal for a given band is above an interference-range threshold, then contention occurs between the nodes. We extend the conflict matrix in [9] according to different interference per band according to $F = (E_{i,j}, I_{Set}, B)$, where $E_{i,j}$ represents the link and I_{Set} includes all the links are physically inside the interference range D_r when operating on each band b.

Therefore, the problem we address is choosing the connectivity graph C which maximizes the served user demand according to the throughput achieved through the gateway (defined below). The challenge is that selecting the optimal channels from the set B leads to a conflict graph F which cannot be known *a priori*. Previous works have proposed a coloring, cluster-independent set, mixed linear integer methodology for a single band b [9], [17], [18]. However, these works do not address reducing hop count or increasing spatial reuse for a set of diverse bands B. In particular, the goal of network backhaul layer is to maximize the amount of mesh user demand served, which can be measured by the total goodput achieved through the gateways. Thus, to evaluate the performance of multiband channel assignment, we use the idea of gateway goodput X, which is defined as:

$$X = \sum_{w \in W, v \in V} T(w, v) \tag{2}$$

Since the bottleneck of mesh network capacity has been shown to be the gateway's wireless connections [19], gateway goodput considers all incoming and outgoing traffic T onto the Internet. We describe the exact calculation of gateway goodput in Section IV and consider gateway placement outside the scope of this work.

C. Mixed Integer Linear Programming Formulation

We now present a mixed integer, linear programming formulation for finding the upper bound on gateway goodput when selecting channels for WhiteMesh topologies across diverse bands. We assume that the set of available mesh nodes V , gateways W and set of available bands B are given. The communication links and conflict graph are given as parameters.

Sets:

V	set of nodes
B	set of bands

Parameters:

$\gamma^b_{i,j}$	$(i, j) \in V, b \in B$	capacity of link i, j on band b
$I^b_{ij,lm}$	$(i, j, l, m) \in V, b \in B$	Interference of link (i, j) on band b
W_i	$i \in V\ binary$	Gateways in network
D_{di}	$i \in V$	Downlink demand of node i
D_{ui}	$i \in V$	Uplink demand of node i

We define a variable time share to represent the percentage of time for a single link as $\alpha^b_{i,j}$, which is the time share for link $i- > j$ in band b.Two flow variables are defined as all uplink and downlink flows on a link $i- > j$ for node k in band b, $uy^b_{i,j,k}, dy^b_{i,j,k}$.

Variables:

$0 \le \alpha^b_{ij} \le 1$	$b \in B, (i, j) \in N$	Time share of (i, j) on band b
$0 \le uy^b_{i,j,k}$	$(i, j, k) \in V, b \in B$	Up link flow of node i on (j, k) at band b
$0 \le dy^b_{i,j,k}$	$(i, j, k) \in N, b \in B$	Down link flow of node i on (j, k) at band b

To maximum the Goodput the objective in the linear program, the objectivecould be represented as:

Objective:

$$Max \sum_i \sum_j \sum_k \sum_b (uy^b_{i,j,k} + dy^b_{j,i,k})\ When\ w_j = 1 \tag{3}$$

If we put the linear program with QoS constraint, all the demands of mesh nodes shoule be satisfied, then the constraints are given as:

Connectivity Constraints:

$$\alpha^b_{i,j} + \alpha^b_{j,i} + \sum_l \sum_m (\alpha^b_{l,m} \cdot I^b_{ij,lm}) \le 1, i \ne j \tag{4}$$

$$\sum_i uy^b_{i,j,k} + \sum_i dyi, j, k^b \le r^b_{j,k} \cdot \alpha^b_{j,k} \tag{5}$$

$$\tag{6}$$

Uplink Constraints:

$$\sum_k \sum_b uy^b_{i,i,k} \le D_{ui}\ When\ w_k = 0, i \ne k \tag{7}$$

$$uy^b_{i,j,k} = 0 w_k = 1 \tag{8}$$

$$\sum_i \sum_b uy^b_{i,j,k} = \sum_m \sum_b uy^b_{j,m,k}\ When\ w_k = 0, i \ne k \tag{9}$$

$$uy^b_{i,j,i} = 0 \tag{10}$$

$$\tag{11}$$

Downlink Constraints:

$$\sum_j \sum_b dy^b_{i,j,i} \leq D_{di} \; When \; w_i = 0 \tag{12}$$

$$dy^l_{i,j,k} = 0 \; When \; w_k = 1 \tag{13}$$

$$\sum_j \sum_b dy^b_{i,j,k} = \sum_m \sum_b dy^b_{j,m,k}, \; When \; w_k = 0, i \neq k \tag{14}$$

$$dy^b_{i,i,j} = 0 \tag{15}$$

In the ILP, (4) is to restrict the link conflict constraint; (5) represent the link capacity distributed by time share α; Constraints (**??**)(9) are to describe relay behavior of the nodes in network. If node i is a mesh, then $Gateway_i = 0$, the total in-coming traffic should equal to the total out-coming traffic; otherwise node i is a gateway, when $Gateway_i = 1$, traffic get into gateway node, in-coming traffic should be greater than out-coming traffic; (10) make sure no loop in the assignment, there is no traffic generated by node i will go back to node i; (**??**),(14),(15) make gateway node provide all the down-link traffic from itself. The in-coming traffic equals to the out-coming traffic for relay traffic on mesh nodes.

Other constraints could be modified according to different objectives. When the objective is to minimum a gateway deployment with QoS constraint, the constraints work for this objective $Min \sum Gateways_i$ with moving the $Gateway$ from parameter to an variable. If the objective is to maximum throughput with fairness, all mesh nodes has the same demand, $Max \sum((uy_i + dy_i), i \in Gateway)$ with parameter $D_{ui} = a, D_{di} = b$, a, b are constant number.

Linear program of network channel assignment and routing has been proved a NP-hard problem [9], [15]. The model itself provide a way to understand the factors need to be considered in channel assignment and provide methodology to achieve the throughput upper bound of a channel assignment. When we have the channel assignment $A^k_{i,j}$, we could modify the objective function, the parameters and the constraints to find the maximum satisfied demand in the network.

III. Path Analysis with Diverse Propagation

In this section, we discuss the influence of diverse propagation characteristics of the wide range of carrier frequencies introduced by white space and WiFi bands. We then introduce two heuristic algorithms for channel assignment in WhiteMesh networks.

A. Path Interference Induced on the Network

In WhiteMesh networks, multihop paths can be intermixed with WiFi and white space bands. To consider which combination is better, we consider which band choices reduce the number of hops along a path and the aggregate level of interference that hop-by-hop path choices have on the network (i.e., Path Interference induced on the Network).

Due to random access, mesh nodes closer to the gateway generally achieve greater levels of throughput at sufficiently high offered loads. To combat such starvation effects, we treat each flow with equal priority in the network when assigning channels. In particular, all nodes along a particular path have equal time shares for contending links (i.e., intra-path interference). At the beginning of a particular channel assignment scheme, assume that h mesh nodes are demanding traffic from each hop of an h-hop path to the gateway. If each link along the path uses orthogonal channels, then each link could be active simultaneously. Consider if each node along the path had traffic demand T_d, and the bottleneck link along the path were closest to the gateway. Then, the total traffic along the path $h \cdot T_d$ must be less than the bottleneck link's capacity γ. In such a scenario, the h-hop mesh node would achieve the minimum served demand, which we call the network efficiency. In general, the active time per link for an h-hop mesh node can be represented by $1, \frac{h-1}{h}, \frac{h-2}{h} \cdots \frac{1}{h}$. The summation of all active times for each mesh node along the path is considered the intra-path network cost.

Considering only intra-path interference, using lower carrier frequencies allows a reduction in hop count and increases the network efficiency of each mesh node along the h-hop path. However, a lower carrier frequency will induce greater interference to other paths to the gateway (i.e., inter-path interference). An example can be seen in Fig. 1, where links in different bands are represented by circles for 450-MHz nodes, rectangles for 2.4-GHz nodes, and triangles for the nodes which can choose between the two. Nodes A and C could be connected through two 2.4-GHz links or a single 450-MHz link. With 2.4 GHz, the interfering distance will be less than using 450 MHz. For example, only link D, E will suffer from interference, whereas H, I would not. However, with 450 MHz, link A, C would interfere with links F, G, M, L, and K, J. At each time unit, the number of links interfering with the active links along the entire path would be the inter-path network cost.

When an h-hop flow is transmitted T_d to a destination node, it prevents activity on a number of links in the same band via the protocol model. The active time on a single link can be noted as $\frac{T}{\gamma_h}$. An interferring link from the conflict matrix F counts as I_h per unit time and contributes to the network cost as: $\frac{hT}{\gamma_1} \cdot I_1 + \frac{(h-1)T}{\gamma_2} \cdot I_2 \cdots \frac{T}{\gamma_h} \cdot I_h$. Then, the traffic transmitted in a unit of network cost for the h-hop node could be represented as:

$$E_\eta = \frac{T}{\sum_{i \in h} \frac{(h-i+1) \cdot T}{\gamma_i} \cdot I_i} \tag{16}$$

Using the concept of network efficiency, the equation simplifies to:

$$E_\eta = \frac{\gamma}{\sum_{i \in h} (h-i+1) \cdot I_i} \tag{17}$$

The meaning of the network efficiency is the amount of traffic that could be offered on a path per unit time. With multiple channels from the same band, I_i will not change due to the common communication range. With multiple bands, I_i depends on the band choice. This network efficiency jointly considers hop count and interference. We define the Path Interference induced on the Network (PIN) as the denominator of Eq. 17, which represents the sum of all interfered links in the network by a given path. We use PIN to formulate both of our heuristic algorithms as to how to assign channels across WiFi and white space bands. To determine when the lower carrier frequency will be better than two or more links at a higher carrier frequency, we consider the average interference $\bar{I}$ of a given path at the higher frequency. The problem could be formulated as:

$$\frac{\gamma}{\frac{h(h-1)}{2}\cdot \bar{I} + I_x} \geq \frac{\gamma}{\frac{h(h+1)}{2}\cdot \bar{I}} \tag{18}$$

Here, when $I_x \leq 2 \cdot h\bar{I}$, a lower-frequency link could be better than two higher-frequency links along the same path. I_x is also a function of hop count in Eq. 17. When the hop count is lower, the threshold would be more strict since the interference would have a greater effect on the gateway goodput.

B. Growing Spanning Tree (GST) Algorithm

In a mesh network, gateway nodes tend to be located at the points of most dense demand [19], [20]. In the mesh topology, the closer a mesh node is to the gateway, the more interference it will likely have due to higher demand. Conversely, edges of the network tend to have more sparse demand, resulting in less interference. Based on this intuition, the Growing Spanning Tree (GST) algorithm (described in Alg. 1) assigns channels to have the least resulting interference on the network (PIN) in a greedy manner. To do so, we first initialize the mesh-node ranking with respect to the physical distance to all gateway nodes. We then consider the one-hop nodes from the gateways (based upon if any carrier frequency of the available bands B is in communication range of the gateway) with least Path Interference induced on the Network (PIN) for these available band. This least-interfering, one-hop node is chosen for channel assignment, and the network is updated for the next step. We term this Phase 1 of the GST, and it resembles the Breadth First Search Channel Assignment (BFS-CA) [21].

In Phase 2 of the GST algorithm, we sort the mesh nodes according to their hop count from the gateway nodes. The algorithm then traverses all the nodes whose hop count are less than the current node. If there are available radio slots for the mesh nodes of lower hop count from the gateway, it is possible to reassign the mesh node to reduce the hop count. We rank all possible options with their PIN. We then choose the lowest one for reassignment of the mesh node. If there exists new links has the same PIN to two or more gateways, we consider the total number of nodes connected to each gateway, selecting the gateway that has fewer connected mesh nodes. Phase 2 process will iterate until no changes in channel assignment occur or up to the total number of mesh nodes.

The GST algorithm greedily assigns a single link to the network (Phase 1) and balances the gateway load in the adjustment process (Phase 2). The breadth first search from Phase 1 for a multiband network has a complexity of $O((N_B \cdot N_V)^2)$, where N_V is the number of nodes V, N_B is the number of bands, sorting of nodes would cost $O(N_B \cdot N_V log(N_B \cdot N_V))$. Hence assigning a node takes $O((N_B \cdot N_V)^2)$ time. When there are N_V nodes, the complexity of an adjust interation is $O(N_B^2 \cdot N_V^3)$. The total interation would be less than N_V since we put an upbound their and in our simulation it does not touch even $\frac{N_V}{2}$. So the complexity of the method would be $O(N_B^2 \cdot N_V^4)$.

Algorithm 1 Growing Spanning Tree (GST)

Input:
- M: The set of mesh nodes
- G: The set of gateway nodes
- C: Communication graph of potential links among all nodes
- I: Interference matrix of all potential links
- B: Available frequency bands

Output:
- CA: Channel Assignment of the Network

```
Initialize S_current = G, N_served = ∅, N_unserved = M, I_active = ∅
Rank mesh nodes according to physical distance from gateway nodes
while N_served =!M do
    for all s ∈ S_current do
        Find one-hop nodes in S_Next
        Sort S_Next according to distance from gateway nodes
        for all l ∈ S_Next do
            Calculate 1-hop path interference of link s → l
            Sort the links according to path interference
            Assign(s,l) with the least interference link
            Update N_served, N_unserved
            Update I_active from I
        end for
        S_current = S_Next
    end for
end while
Sort mesh nodes with their hop counts to gateway nodes N_sorted
while Change of Channel Assignment Exists do
    for all s ∈ N_sorted do
        Traverse all 1-hop arrived nodes have less hop count than node s
        Check if these nodes have radio slots for node s
        Sort path through possible nodes with the path interference
        Choose a new path if it has less interference than the previous one
        If more than one path has the same interference, choose least-leaved gateway node
    end for
end while
Output ChannelAssignment as Solution
```

C. Band-based Path Selection (BPS) Algorithm

The GST algorithm starts from the gateway nodes to generate the channel assignment, in contrast, *Band-based Path Selection* Algorithm starts from the mesh node who has the largest distance from the gateway nodes. When a path is select for such a node, the relay nodes on the path are served. The main idea behind the *Band-based Path Selection* Algorithm is to improve the worst mesh node performance in a path.

The algorithm first sort the mesh nodes in order of their distance to any gateway nodes. Then we select the mesh node has the furthest distance to gateway nodes. In the network, it is impossible traverse all the path with different combination of bands from a mesh node to any gateway nodes. Based on the analysis in III-A, if paths has the same bands combinations, a shortest path most of the time could have the best performance. In the same path under a bands combination, we will choose the link in a channel has the least interference. In case two path has the same path interference, we choose the path who has more high frequency links for spacing re-use. Thus, the next step of the algorithm is to find the shortest path in different bands combinations. Comparing to the number of mesh nodes, the amount of channels N_B in different bands is small. The time complexity of calculation the combination is $O(2^{N_B})$. Then finding the shortest path in Dijkstra algorithm will cost $O(N_E^2)$ [22], N_E is the links in the network. So the total would be $O(N_E^2 \cdot 2^{N_B})$. Then the algorithm calculate PIN of the candidate path and select the path bringing the least interference to the network for the starting mesh node.

After a path is assigned, the algorithm update the network assignment with served nodes, activated links, and nodes' radio information. Then we assign the next node till all the mesh nodes are connected in the network. The *Band-based Path Selection* Algorithm is described in 2.

Algorithm 2 Band-based Path Selection (BPS)

Input:
- M: The set of mesh nodes
- G: The set of gateway nodes
- C: Communication graph of potential links among all nodes
- I: Interference matrix of all potential links
- B: Available frequency bands

Output:
- CA: Channel Assignment of the Network

```
Rank mesh nodes according to physical distance from gateway nodes
Initialize S_current = G, N_served = ∅, N_unserved = M, I_active = ∅
while N_served =!M do
  Select node with largest distance to gateway nodes
  Find the Adjacency Matrix in different band combinations A_c
  for all A_i ∈ A_c do
    Find the shortest path SP_i in the mixed adjacency matrix A
    for all Link l ∈ SP_i in order from gateway node to mesh node do
      Find the link that has less interference
      If there are links have the same interference, choose higher frequency
      Calculate the path interference of path SP_i
    end for
    Store the shortest path SP_i as SP
  end for
  Assign the path in the Network
  Update N_served, N_unserved
  Update I_active from I
end while
Output CA as locally-optimal solution
```

The complexity of the assign a node would be $O(N_E^2 \cdot 2^{N_B})$, if all the nodes could be connected, $N_E = C_n^2$ which is $O(N_V^2)$. Then the complexity of assigning a node could be marked as $O(N_V^4 \cdot 2^{N_B})$. To assign all the node in the network, the complexity would be $O(N_V^5 \cdot 2^{N_B})$.

IV. Experimental Analysis

We now extensively evaluate our proposed heuristic algorithms against the upper bound formed by our integer linear programming model and against prior work. We first introduce the topologies and metric calculation used in the analysis. We then present a set of results based on the gateway goodput.

A. Experiment Design

We consider static wireless mesh networks with n nodes located in a regular grid with distance of $300m$. Today's white space equipment use frequency shift moving signal from white space to WiFi frequency for processing [23]. We set the RSSI threshold as $-160dBm$ for WiFi and $-154dBm$ for White Space Band adjusting the system loss on the radios [24]. Then calculate the communication range and double as the interference range [25]. The gateways are randomly selected $\frac{1}{6}$ from the nodes in the network. We set up to use WiFi band $2.4GHz$, $5GHz$ and white space band $450MHz$, $800MHz$ to generate the network topology.

ISP such as AT&T, T-mobile will charge fee according to the traffic arrived at Internet through wireless network. They are interested in getting the more throughput achieve gateways, which is the throughput arrived at the gateways from all the mesh nodes.

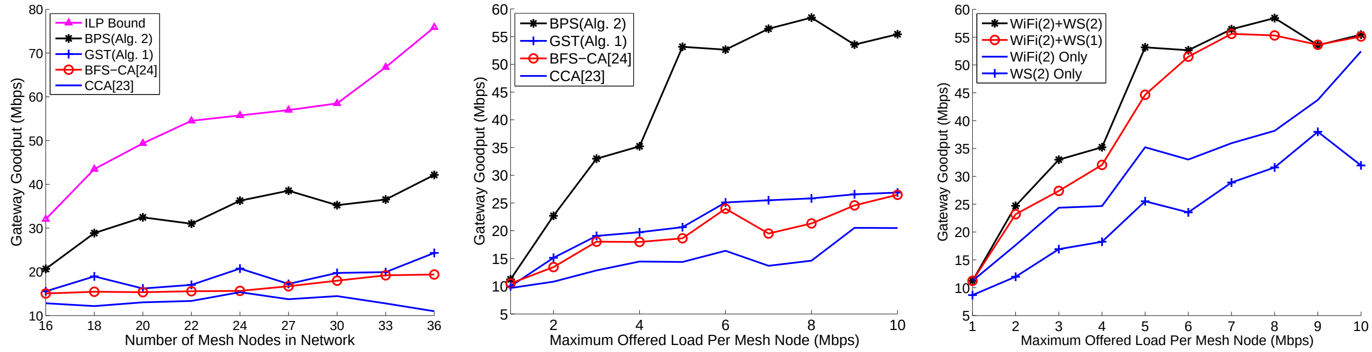
Stefano brings the throughput achieve gateways in the network without considering the interference as maximum throughput to evaluate the channel assignment [26]. However, without considering the interference, the traffic flow in the network is not scheduled.

The throughput achieve gateways binds with multiple factors, such as gateway placement, routing and also channel assignment. To find the best gateway placement, routing associate with channel assignment is out of our scope. In a mesh network, the bottleneck of the network are the links around the gateway nodes [27]. And any traffic transmitted to a wired gateway node is treated equally as throughput achieve gateways. So a methodology to get a scheduler maximum throughput is to serve the nodes close to the gateway nodes first. We first serve the nodes have 1 hop path to the gateway nodes, with the same hop count in the path, choose the path has the least interference on the network and serve the demand as more as possible. Then we satisfy the demand of multiple hop layer nodes and so on, till there is no demand could be satisfied through any path. The calculation process is kind of routing protocol which help us to reach a scrollable maximum throughput achieve gateways of the network. We would not claim it is the best way, for evaluation we keep the same calculation process for all comparable setting. We relax our ILP model to keep the link capacity constraints, given the demand of the mesh nodes as parameter to get an maximum throughput achieve gateways as shown in 2(a). The up-bound is assuming the mesh node could be connect to all the gateways if there is a path. But we limit a mesh node only connect to one gateway in the network, this bring the difference from the up-bound to our calculation.

B. Analysis

Most of the time clients of wireless network have different traffic demand. The uplink and dwon link traffic are equally occupy the channel capacity. Then we randomly assign demand of mesh nodes with a max offer load, calculate the scalable maximum throughput, then repeat the process 20 times. In the ILP bound, we keep the connectivity constraints in II-C. To simiplify the process, we remove the uplink constraints and keep download demand constraints only. Modify the constraint 12 as $\sum_{l\in B}\sum_{j\in V}\sum_{k\in V} dy^k_{j,i,l}$‘ $\sum_{l\in B}\sum_{j\in V}\sum_{k\in V} dy^k_{i,j,k} + D_{di}, i \neq l$. Maximum $\sum_{i\in Gateway}(D_{di} + \sum_{l\in B,j\in V,k\in V} dy^l_{i,j,k}$. The output is the average maximum throughput achieve gateways for the max offer load per mesh node. To evaluate the performance in different size of network, we fix the max offer load of each node as $4MB/s$ and vary the number of nodes in the regular grid network. The performance of the algorithms are shown in 2(a).

The ILP Bound could have multiple gateway connection but other assignment would have only one gateway connection. And ILP optimize both channel assignment and routing



(a) Offered Load Per Mesh Node = 4 Mbps (b) Varying Load, 30-Node Regular Grid (c) BPS (Alg. 2), Varying WS Availability

Fig. 2. Performance in terms of gateway goodput for various offered loads, network sizes, and configurations of WiFi or white space (WS) channels.

Bands/ Algorithms	WiFi Only	WS Only	WS & WiFi	WS & WiFi	WS & WiFi	WS & WiFi	WS & Multi-WiFi	WS & Multi-WiFi	Multi-WS & WiFi	Multi-WS & WiFi	Multi-WS & Multi-WiFi
WS (MHz)		450,800	450	800	450	800	450	800	450,800	450,800	450,800
WiFi (GHz)	2.4, 5		2.4	2.4	5	5	2.4, 5	2.4, 5	2.4	5	2.4, 5
CCA [28]	3.1	7.3	8.2	8.1	8.3	7.8	8.7	9.3	9.0	11.9	14.4
BFSCA [21]	8.9	6.2	7.9	9.0	13.6	13.8	14.9	13.8	14.9	14.3	18.6
GST (Alg. 1)	11.6	6.6	9.3	15.1	15.8	14.4	16.6	14.1	18.8	15.0	25.1
BPS (Alg. 2)	22.2	18.2	28.4	25.0	30.9	25.8	32.00	33.5	34.5	30.9	35.2

TABLE I
THROUGHPUT ACHIEVED THROUGH GATEWAY NODES (MBPS) FOR VARIOUS COMBINATIONS OF WIFI AND WHITE SPACE (WS) MESH TOPOLOGIES (OFFERED LOAD = 4 MBPS, NETWORK SIZE = 30 MESH NODES).

simultaneously. As the number of mesh node increase, CCA lose the ability to handle large size of network. The dips of the curves are resulting from the random demand evaluation setup. We randomly deploy the gateways and offer load of each mesh node, brings the decrease in achieving throughput when the number of mesh node increase.

The performance of the two heuristic algorithms and *CCA* [28], *BFSCA* [21] in a 30-node regular grid topology with 6MB link capacity in each channel are shown in figure 2(b). BPS performs better than the other 3 algorithms since during the channel assignment process, it is already optimize the paths from further nodes to gateways make it possible to ship data from these nodes. But as the max offer load increase, all the channel assignment suffer the bottle neck of link capacity. GST is trying to optimizing the output of BFS-CA, reducing the hop counts and interference of each hop layer. However, since the 1 hop layer has been assigned throughput BFS-CA which is the bottle neck for the capacity of the network. Our results also shows the importance of channel selection of multiband. IV-B shows when 2 radios could be used, the better combination would be a higher frequency and a lower frequency which could combine the advantage of reduce interference in the network through high frequency link and benefit from decrease hop count through low frequency link. Two low frequency channel, as in IV-B, will bring more interference to the network. In this scenario, the performance is even worse than use WiFi channel only. The reason two low frequency channels has better performance than WiFi only in CCA due to the channel assignment fails to connect all mesh node to the gateways make there exist some offer load can not be shipped to gateways. So a smart way to choose channels is to select a set of channels in different band rather than select channels has the same propagation characteristics.

The number of radio equipped on a node in mesh network also abstract ISP attention. The result shows in **??**, BPS has the best performance over other algorithms. Increasing radios do improve the performance of network. As more radios equipped in the network, the benefit would be decrease in most scenario. There is a trade off between performance of more radios and cost increasing. In one radio scenario, BPS outperforms CCA, but fails in completion of BFS-CA and GST. But in multi-radio scenarios, BPS always outperforms the other methods.

In 2(c), the performance of 4 different type of band combination is shown. The four curves are WiFi Only (2.4,5 GHz), WS Only (450,800 MHz), WS (450 MHz) + Multi-WiFi(2.4 GHz), Multi-WS(450, 800 MHz) + Multi-WiFi(2.4, 5 GHz). Increasing radios do help to improve the performance, but with the same radios and bandwidth, WiFi and white space combination could outperform only WiFi and only white space performance.

V. RELATED WORK

Optimization and Game Theory. Optimization frameworks based on linear programming have been used to determine the channel assignment in multihop wireless networks for given link bandwidths and route requests [9]. Since these formulations attempt to solve NP-hard problems, LP relaxation is commonly used to output network flows that potentially are not feasible channel assignments [10]. Game theory has also been used to guide distributed channel assignment and routing algorithms which attempt to balance the load of the network [25], [29]. In such a framework, nodes advertise their dynamically-changing costs to reach their associated gateway according to the residual bandwidth. If a node learns of a less expensive path to the current gateway or another gateway, the appropriate action is taken to construct such a path, but hysteresis must be carefully considered to avoid route flapping.

Multi-Channel, Multi-Radio Algorithms. Many works have studied the channel assignment problem in multihop wireless networks [8], [11], [30]. In addition, multiple radios have been used to improve the routing in multi-channel scenarios [28]. Still others have used static channel assignments where everything is known about the network parameters [31], which is in contrast to dynamic channel assignment where demand and interference are not known *a priori* [21], [32]. We have implemented such channel assignment algorithms (CCA from [28] and BFSCA from [21]) and shown significant gains. Most importantly, all of the aforementioned works have not considered propagation differences of the diverse frequency bands of white space and WiFi, which we show are critical improving the performance of mesh networks.

White Space. To be used effectively, white space bands must ensure that available TV bands exist, and no interference exists between microphones and other devices [33]. Since TV channels are fairly static in their channel assignment, databases have been used to account for white space channel availability (e.g., Microsoft's White Space Database [34]). In fact, Google has even visualized the licensed white space channels in US cities with an API for research and commerical use [35]. In contrast, we study the performance of mesh networks with a varying number of available white space channels at varying population densities (by adjusting the offered load), assuming such white space databases and mechanisms are in place.

VI. Conclusion

In this paper, we exploited the joint use of WiFi and white space bands for improving the served user demand of wireless mesh networks. To do so, we used an integer programming model to find optimal WhiteMesh topologies. We then constructed two heuristic algorithms, Growing Spanning Tree and Band-based Path Selection, to achieve similar performance with reduced complexity. Through extensive analysis across varying offered loads, network sizes, and white space channel availability, we show that our algorithms can achieve up to 160% gains from previous multi-channel, multi-radio solutions since we leverage diverse propagation characteristics offered by WiFi and white space bands. Moreover, we quantify the degree to which the joint use of these bands can improve the served user demand. Our BPS algorithm shows that WhiteMesh topologies can achieve up to 140% more gateway goodput than similar WiFi- or white-space-only configurations.

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