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 320% 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 320%.
- 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.

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]:

$$P_r = P_t + G_t + G_r + 10n \log_{10}\left(\frac{\lambda}{4\pi R}\right) \quad (1)$$

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 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).

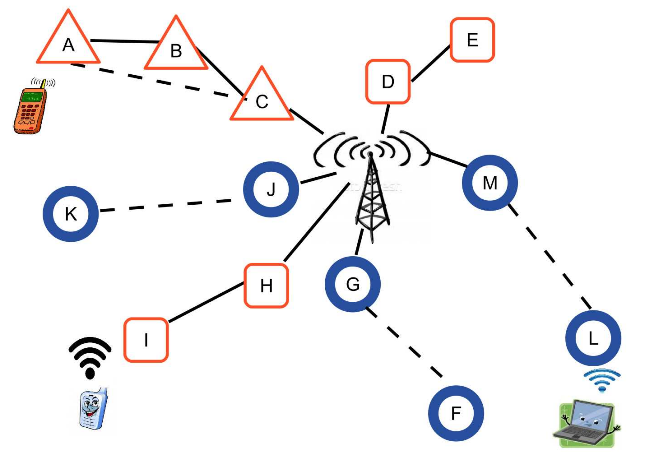


Fig. 1. Example WhiteMesh topology with different mesh-node shapes representing different frequency band choices per link.

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 optimizing gateway goodput when selecting channels for WhiteMesh topologies across diverse bands. We assume that the set of available mesh nodes V , gateways W and 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 time share to represent the percentage of time a single link transmits according to $\alpha^b_{i,j}$ for link i, j in band b. Two flow variables are defined as uplink and downlink flows as below:

Variables:

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

Our objective is to maximize the gateway goodput.

Objective:

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

The constraints for the variables are represented as:

Connectivity Constraints:

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

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

Uplink Constraints:

$$\sum_k \sum_b uy^b_{i,i,k} \le D_{ui}\ When\ w_k = 0, i \ne k \tag{6}$$

$$uy^b_{i,j,k} = 0 w_k = 1 \tag{7}$$

$$\sum_i \sum_b uy^b_{i,j,k} = \sum_m \sum_b uy^b_{j,m,k}\ When\ w_k = 0, i \ne k \tag{8}$$

$$uy^b_{i,j,i} = 0 \tag{9}$$

Downlink Constraints:

$$\sum_j \sum_b dy^b_{i,j,i} \le D_{di}\ When\ w_i = 0 \tag{10}$$

$$dy^l_{i,j,k} = 0\ When\ w_k = 1 \tag{11}$$

$$\sum_j \sum_b dy^b_{i,j,k} = \sum_m \sum_b dy^b_{j,m,k},\ When\ w_k = 0, i \ne k \tag{12}$$

$$dy^b_{i,i,j} = 0 \tag{13}$$

In the ILP, (4) represents the summation of the incoming and outgoing time share and the interfering links' time share, which should all be less than 1. Constraint (5) represents the incoming and outgoing traffic flow, which should be less than the link capacity for link i, j. Uplink constraints (6) and (7) represent that the summation of any flow i, j should be less than the demand of node k. Contraints (8) and (9) are used to restrict the sum of all incoming data flows for a given mesh node k to be equal to the sum of all outgoing flows. Downlink constraints (10) and (11) are similar to (6) and (7) but in the downlink direction. Similarly, constraits (12) and (13) are downlink versions of (8) and (9).

Linear programs which attempt to solve channel assignment and routing in multihop wireless networks have been proved to be NP hard [9], [15]. The model jointly considers factors to be considered in channel assignment and provides the methodology to achieve the upper bound for a channel assignment.

When we have a particular channel assignment $A_{i,j}^k$, we could modify the objective function, parameters, and 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 a 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 is:

$$E_\eta = \frac{T}{\sum_{i \in h} \frac{(h-i+1) \cdot T}{\gamma_i} \cdot I_i} \tag{14}$$

Using network efficiency, the equation simplifies to:

$$E_\eta = \frac{\gamma}{\sum_{i \in h} (h-i+1) \cdot I_i} \tag{15}$$

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. 15, 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:

$$\frac{\gamma}{\frac{h(h-1)}{2} \cdot \bar{I} + I_x} \geq \frac{\gamma}{\frac{h(h+1)}{2} \cdot \bar{I}} \tag{16}$$

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. 15. 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. 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

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 $S_{current} = G$, $N_{served} = \emptyset$, $N_{unserved} = M$,$I_{active} = \emptyset$
Rank mesh nodes according to physical distance from gateway nodes
while $N_{served} =!M$ **do**
  for all $s \in S_{current}$ **do**
    Find one-hop nodes in S_{Next}
    Sort S_Next according to distance from gateway nodes
    for all $l \in S_{Next}$ **do**
      Calculate 1-hop path interference of link $s \rightarrow l$
      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 $s \in N_{sorted}$ **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

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 $S_{current} = G$, $N_{served} = \emptyset$, $N_{unserved} = M$,$I_{active} = \emptyset$
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 $A_i \in A_c$ **do**
    Find the shortest path SP_i in the mixed adjacency matrix A
    for all Link $l \in SP_i$ 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

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 (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, and sorting of the mesh nodes would cost $O(N_B \cdot N_V log(N_B \cdot N_V))$. Hence, assigning a mesh node takes $O((N_B \cdot N_V)^2)$ time. When there are N_V nodes, the complexity of an adjustment iteration is $O(N_B^2 \cdot N_V^3)$. The total iteration would be less than N_V since we have an upper bound. Nonetheless, in our analysis, the complexity does not approach $\frac{N_V}{2}$. Thus, the complexity of the method would be $O(N_B^2 \cdot N_V^4)$.

C. Band-based Path Selection (BPS) Algorithm

While the GST algorithm originates from the gateway nodes to the leaf nodes to assign channels, the Band-based Path Selection (BPS) algorithm (described in Alg. 2) first chooses the mesh node who has the largest physical distance from the gateway nodes. When a path is constructed for the mesh node with the greatest distance, all subsequent mesh nodes along the path are also connected to the gateway. The central concept behind the BPS algorithm is to improve the worst mesh node performance in a path. For large-scale mesh networks, it is impractical to traverse all the paths with different combination of bands from a mesh node to any gateway node. However, based on the analysis in Section III-A, if two paths have the same number of used bands along those paths, then the path with the least hops is likely to have the greatest performance and is chosen. Similarly, if two path have the same path interference, we choose the path who has higher-frequency links for spatial reuse. Thus, the next step of the algorithm is to find the shortest path in different band combinations.

Compared 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 $O(2^{N_B})$. Finding the shortest path in Dijkstra algorithm will cost $O(N_E^2)$ [22], where N_E is the links in the network, and as a result, the total complexity would be $O(N_E^2 \cdot 2^{N_B})$. The algorithm would then calculate the PIN of the candidate path and select the path with the least interference induced on the network for the starting mesh node. After a path is assigned, the algorithm updates the network's channel assignment with served nodes, activated links, and nodes' radio information. Then, we assign the next node until all the mesh nodes are assigned channels in the network.

If all the nodes are connected ($N_E = \binom{n}{2}$ which is $O(N_V^2)$), then the complexity of assigning a channel for a mesh node is $O(N_E^2 \cdot 2^{N_B})$. Then, the complexity of assigning a mesh node is $O(N_V^4 \cdot 2^{N_B})$. To assign *all* the nodes in the network, the complexity would be $O(N_V^5 \cdot 2^{N_B})$.

IV. Evaluation of WhiteMesh Channel Assignment

We now extensively evaluate our proposed heuristic algorithms against the upper bound formed by our integer linear programming model and against prior channel assignment 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

A key aspect of WhiteMesh networks is the diversity in propagation from the lowest white space channels (tens to hundreds of MHz) to the highest WiFi channels (multiple GHz). Thus, to evaluate the performance of our algorithms, we consider a wide range of propagation characteristics from four different frequency bands. For white space bands, we consider 450 and 800 MHz. For WiFi bands, we consider 2.4 and 5.8 GHz. With similar transmission power and antenna gain, the highest carrier frequency would have the shortest communication. Hence, we set a communication-range threshold of -100 dBm, and normalize the communication range with the highest frequency of 5.8 GHz. In particular, the communication range of 450 MHz, 800 MHz, 2.4 GHz, and 5.8 GHz would be normalized to 12.8, 6.2, 2.4, and 1, respectively. The interference range is computed as twice that of the communication range [23]. We deploy static wireless mesh networks of n mesh nodes along a regular, rectangular grid with a normalized distance of 0.8 between the rectangle edges. As a result, we have varying degrees of connectivity in the grid. The gateways are randomly-selected from one out of every six mesh nodes in the network. Unless otherwise, specified in the analysis, all four bands are used in the WhiteMesh topology studied.

The throughput achieved through the gateways is not only critical for network providers (e.g., cellular carriers charge fees for total bandwidth through towers), but also has been used by researchers to evaluate channel assignment [24]. As mentioned previously, the wireless capacity of gateway nodes has been shown to be the bottleneck in mesh networks [25]. Moreover, gateway goodput combines multiple factors, such as mesh node placement, gateway placement, routing, and channel assignment, the latter of which is the focus of our analysis and algorithms.

For the purposes of our analysis, we specifically calculate the gateway goodput first introduced in Section II-B in the following way. Nodes that have a one-hop path to the gateway nodes are the first ones served. Where there are nodes with the same hop count, the least interfering mesh nodes are chosen for channel assignment. Then, the demand of multihop mesh nodes are served until there is no remaining demand to be satisfied through any path. We relax our ILP model to keep the link capacity constraints, given the demand of the mesh nodes as a parameter to achieve the maximum throughput at the gateways. The ILP Bound assumes the mesh nodes could connect to all the gateways if there is a path that exists to each gateway. However, we restrict a mesh node to only connect to one gateway in the network, and this represents the main difference from the ILP Bound to our heuristic algorithms.

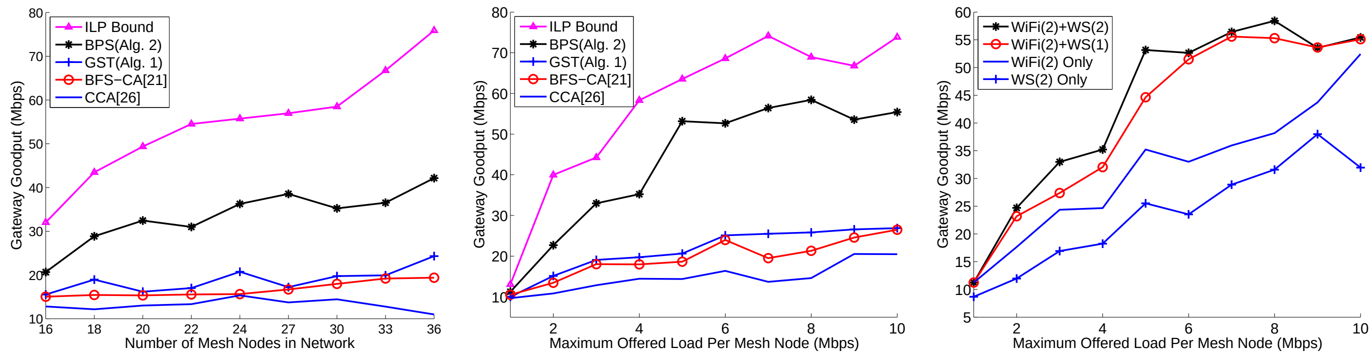
B. Experimental Analysis

Typically, clients and therefore mesh nodes have diverse traffic patterns with the download direction dominating the total traffic demand (e.g., consider service agreements for cellular data or Internet connectivity). Hence, to simplify the analysis and scale the ILP Bound to larger network sizes, we remove the uplink constraints while maintaining the downlink constraints. We then randomly assign demand per mesh node with a maximum offered load as specified in Fig. 2 and Table IV-B. We repeat the process 20 times, averaging the results of each of the algorithms for the given network configuration.

In the first experiment, we consider different network sizes according to the number of mesh nodes in the aforementioned regular grid. In particular, we expect that as the network size grows, so too does the number of gateways, producing a greater total gateway goodput. Fig. 2(a) shows the total gateway goodput when the maximum offered load per mesh node is 4 Mbps for the ILP formulation and four heuristic algorithms: *(i)* Common Channel Assignment (CCA) from [26], *(ii)* Breadth First Search Channel Assignment (BFS-CA) from [21], *(iii)* our first algorithm GST (Section III-B), and *(iv)* our second algorithm BPS (Section III-C). The former two algorithms consider similar propagation characteristics for all channels in the assignment while the latter two algorithms consider the diverse propagation characteristics of the WiFi and white space bands used in the analysis.

In Fig. 2(a), we observe dips in the curves for all algorithms, representing the randomly generated demand. The ILP Bound shows what could be expected, that an increasing number of gateways produces an increase in total gateway goodput. However, we observe that the other algorithms are not able to achieve such behavior for various reasons. First, CCA increases the average hop count the most, meaning that it was unable to find shorter routes to new gateways. Second, while GST slightly outperforms BFS-CA, they both fail to increase the reach of the gateway by attempting to optimize the first hop from the gateway. Conversely, BPS alleviates the strain on these first-hop, bottleneck links, achieving up to 63% of the ILP Bound. The key difference of BPS to the ILP is that BPS only considers one path to a gateway node for each mesh node, wereas the ILP allows multiple paths to gateways.

Next, we consider a different form of scalability in our analysis. Namely, we increase the maximum offered load per mesh node from 1 to 10 Mbps, while maintaining a 30-node regular grid topology. Fig. 2(b) shows that all of the algorithms are able to achieve comparable gateway goodput at 1 Mbps offered load per mesh node. However, as the offered load increases the ILP and BPS diverge greatly from the remaining algorithms. Similar to Fig. 2(a), the wireless capacity around a gateway is quickly saturated if the algorithm is not focused on preserving that resource. Nonetheless, we do observe a leveling off at approximately 6 Mbps offered load due to a similar effect of the saturation of wireless capacity around the



(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 [26]	3.1	7.3	8.2	8.1	8.3	7.8	8.7	9.3	9.0	11.9	14.4
BFS-CA [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	32.0	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).

gateway node. For BPS, this saturation point at 6 Mbps has a gateway goodput from 1.5 to 3.2 times that of the remaining three algorithms, whereas the ILP Bound has between 2.7 and 4.18 times the gateway goodput. BPS has a performance of 75% of the ILP Bound, on average.

WhiteMesh networks will be deployed across a vast array of environments, from rural to urban areas. Each of these areas will have varying amounts of user demand in proportion to the population densitities. However, since a greater number of TV stations exist in urban areas, the available white space bands are often inversely related to the population density. To capture these varying degrees of demand and white space availability we consider three likely scenarios and one final scenario for comparison purposes: *(i)* two WiFi bands (2.4 and 5.8 GHz) with two white space channels (450 and 800 MHz), *(ii)* two WiFi bands (2.4 and 5.8 GHz) with one white space channel (450 MHz), *(iii)* two WiFi bands (2.4 and 5.8 GHz) without any white space channels, and *(iv)* two white space bands (450 and 800 MHz) with no WiFi bands (for comparison).

In Fig. 2(c), we consider the performance of BPS in the four aforementioned scenarios of varying white space availability with varying offered load from 1 to 10 Mbps, representing different population densities. A regular, 30-node grid is also used. Immediately, we observe that the WiFi-only scenario has greater gateway goodput than the white-space-only scenario. This is due to the lack of spatial reuse achieved by white spaces. Interestingly, however, the joint use of both white space and WiFi bands has significant gains over the single type of band scenarios (37% greater than WiFi and 85% over white space, on average). This can be explained because in part because the joint use of WiFi and white space has more total bands to use. However, we will see in Table IV-B that even with the same number of available bands (2), the combination of the two can achieve significant gains over scenarios with only WiFi or white space.

Table IV-B describes the achieved gateway goodput for various combinations of WiFi and white space bands with a maximum offered load of 4 Mbps and a regular 30-node grid. Consider the case where we use a white space band of 450 MHz and a WiFi band of 5.8 GHz. The second reason for the gains in Fig. 2(c) with WiFi and white space is completely isolated in this scenario. Note that, even with the same bandwidth, transmission power, and antenna gain, the joint use of these bands allows 15.8 Mbps of gateway goodput with GST versus 11.6 Mbps for WiFi only and 6.6 Mbps for white space only topologies with gains of 36% and 140%, respectively. With BPS and the same scenario, we achieve 30.9 Mbps of gateway goodput versus 22.2 Mbps with WiFi only or 18.2 Mbps for white space only with gains of 40% and 70%, respectively. If we have on channel in a white space band and one channel in a WiFi band, then we could use the advantage of WiFi for spatial reuse and white spaces to reduce the hop count. These two points become more critical at different points in the WhiteMesh topology. For the sake of completeness, we present many other scenarios which could be interesting for WhiteMesh deployments.

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 [23], [27]. 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], [28]. In addition, multiple radios have been used to improve the routing in multi-channel scenarios [26]. Still others have used static channel assignments where everything is known about the network parameters [29], which is in contrast to dynamic channel assignment where demand and interference are not known *a priori* [21], [30]. We have implemented such channel assignment algorithms (CCA from [26] 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 [31]. 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 [32]). In fact, Google has even visualized the licensed white space channels in US cities with an API for research and commerical use [33]. 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 320% 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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