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 and fundamental equation for path loss 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 from transmitter to receiver and path loss exponent n according to [13]:

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

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 in works 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 reasonable 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.

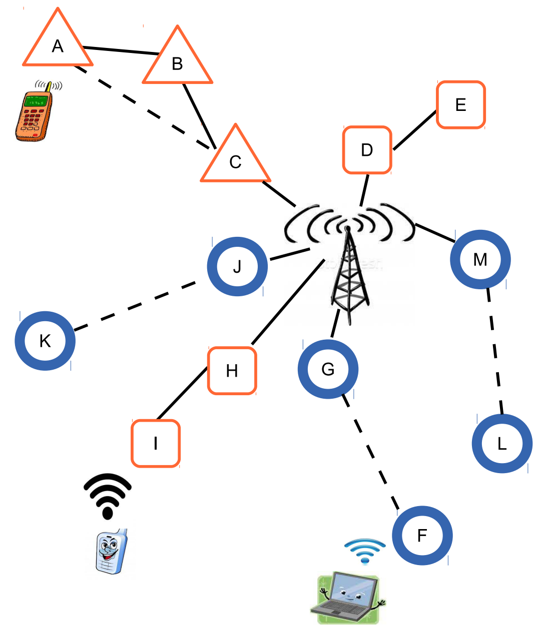

Fig. 1. Varying Multiband Communication and Interference Range

The broadcast nature of the wireless medium makes it generate multiple access interference in wireless network. Employing White Space Band in lower frequency brings advantages for mesh network, 1) more orthogonal bandwidth reduce the contention and conflict in the network, 2) the propagation variation brings flexible topology by reducing connection hop counts in the network. However, at the same time, links in White Space Band also increase the interference range in the network making space reuse of the white space band channel difficult. There is an example in figure 1, node A could connect to node C through relay of node B in higher frequency 2.4 GHz band, or directly connect by lower frequency 450 MHz band channel with larger communication range. If under higher frequency band, link between node D, E could reuse the higher frequency since they are out of the interference range of this high frequency band; however, if A, C connected with lower frequency 450 MHz band in less hop counts, then the channel could not be reused for node D, E. To balance the larger communication range and interference range of white space band in mesh network is a key issue in *Multiband Mesh Network* from *Multiradio* scenario.

B. Model and Problem Formulation

Channel Assignment is to assign radios between nodes in mesh network creating virtual links for network communication with minimum interference. Our objective is to get a channel assignment for a wireless mesh network formed by a set of static mesh nodes and wired gateway nodes. Each node in the network is equipped with one or more radios could work in one of the permitted bands. We also assume all the nodes have the same transmitting power, antenna with the same gains and other configurations. To model the connectivity, we adopt classical *Protocol Model* from Gupta [15]. If the received signal is above the threshold, the link would have a communication capacity, otherwise, the link could not exist. The interference exist as conflict contention when the received signal strength of other links are above the threshold; otherwise, the link will not be interfered by other links.

The *Gateway Nodes* and *Mesh Nodes* locations are given. Transmitting power, antenna gains, communication and interference threshold are given. From *Friis Model*, we could get *Communication Range* and *Interference Range* of each band. Multiband multi-radio wireless network could be represented as an undirected graph $G = (V, E)$ according to the communication range and interference range. V is noted as the nodes, and E marked as the links in the network.

The channel assignment is represented as *Connectivity Graph*, $C = (V, L, B)$, L denotes the set of links, B denotes the set of frequency bands. In protocol model, the channel capacity between two nodes in a channel is noted as LC. If the RSSI from a node to another node is above the threshold, LC is a constant value, otherwise, it is zero.

We extend the *Conflict Matrix* from Jain's work [9] with a flexible approach for interference, $CM = (E_{i,j}, I_{Set}, B)$. $E_{i,j}$ represents the link, I_{Set} includes all the links are physically inside the interference range D_r.

Our model is similar to Multichannel Model in many previous works [9], [10], [16]. However, in Multichannel Model, the Communication Range D_c and Interference Range D_r of different channels in the same band have the same value. The Multichannel Model is unnecessary to consider the variation of communication and interference range due to band propagation. Multiband Channel Assignment work toward the same target as Multichannel Channel Assignment to provide richer connectivity with minimum interference with channel variation in more bands.

The difficulty of the problem is that we can not know the interference before we assign channel to each node. Previous works have proposed *Coloring, Cluster, Independent Set, Mixed Linear Integer* methodology to approach the solution of *Multichannel Channel Assignment* [9], [17], [18]. However, these work fails to deal with the minimize hops and more frequency space reuse embedded in multiple bands scenario. Our work focus on multiband channel assignment without explicitly considering network traffic/load [19]. We present a mixed linear integer model to understand the multiband scenario. We also analyze the relation between the *Hop Counts* and *Space Reuse*, then propose two heuristic algorithms approaching solution of this problem.

C. Evaluation Metric

The goal of network backhual layer is to maximize its overall good put within a unit time. To evaluate the assignment, we use the idea of *Gateway Good put* of the network. The gateway good put X of a network is defined as the traffic achieve gateways.

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

In [20], Robinson proves the bottle neck of mesh network capacity is the gateway wireless connection. The gateway good put is the traffic arrive at the gateway node and relay to the wired Internet. The good put performance is correlated with gateway placement, channel assignment and routing. The calculation of *Gateway Good put* is described in IV .Jointly optimization of channel assignment, gateway placement, and routing is out of the scope of this paper.

D. Mixed Integer Linear Formulation

We now present a *Mixed Integer Linear Program* formulation for the *Multiband Multi-Radio* wireless mesh network described in section II to model the problem and provide a way to approach the upbound a network throughput achieve gateways.

Assume that we are given the nodes and available bands as the variable set. The communication links and conflict graph are given as parameters.

Set:

V	set of nodes
B	set of bands

Parameters:

$LC_{i,j}^k$	$(i, j) \in V, k \in B$	capacity of link i, j on band k
$I_{ij,lm}^k$	$(i, j, l, m) \in V, k \in B$	Interference of link (i, j) on band k
$Gateway_i$	$i \in V$ *binary*	Gateways in network
D_{di}	$i \in V$	Down link demand of node i
D_{ui}	$i \in V$	Up link demand of node i

We define *Time Share* variable to represent the time division of a single link as $\alpha_{i,j}^k$ which is the time share for link $i -> j$ in band k. Two flow variables could be defined as up-link and down-link flow on a link $i -> j$ for node k in band l, $uy_{i,j,k}^l, dy_{i,j,k}^l$.

Variables:

$0 \le \alpha_{ij}^k \le 1$	$k \in B, (i, j) \in N$	Time share of (i, j) on band k
$0 \le uy_{i,j,k}^l$	$(i, j, k) \in V, l \in B$	Up link flow of node i on (j, k) at band l
$0 \le dy_{i,j,k}^l$	$(i, j, k) \in N, l \in B$	Down link flow of node i on (j, k) at band l

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

Constraints:

Connectivity Constraints:

$$\sum_i \alpha^k_{i,j} + \sum_i \alpha^k_{j,i} + \sum_l \sum_m (\alpha^k_{l,m} \cdot I^k_{ij,lm}) \leq 1, i \neq j \quad (3)$$

$$\sum_i uy^l_{i,j,k} + \sum_i dyi, j, k^l \leq r^l_{j,k} \cdot \alpha^l_{j,k} \quad (4)$$

Uplink Constraints:

$$\sum_k \sum_l uy^l_{i,i,k} \geq D_{ui} - J \cdot Gateway_i \quad (5)$$

$$uy^l_{i,j,k} \leq J(1 - Gateway_i) \quad (6)$$

$$\sum_j \sum_l uy^l_{i,j,k} - \sum_m \sum_l uy^l_{i,k,m} \leq Gateway_i \cdot J, i \neq k \quad (7)$$

$$\sum_j \sum_l uy^l_{i,j,k} - \sum_m \sum_l uy^l_{i,k,m} \geq 0, i \neq k \quad (8)$$

$$uy^l_{i,j,i} = 0 \quad (9)$$

Downlink Constraints:

$$\sum_j \sum_l dy^l_{i,j,i} \geq D_{di} - J \cdot Gateway_i \quad (10)$$

$$dy^l_{i,j,k} \leq J(1 - g_k) \quad (11)$$

$$\sum_j \sum_l dy^l_{i,j,k} - \sum_m \sum_l dy^l_{i,k,m} \geq -Gateway_i \cdot J, i \neq k \quad (12)$$

$$\sum_j \sum_l dy^l_{i,j,k} - \sum_m \sum_l dy^l_{i,k,m} \leq 0, i \neq k \quad (13)$$

$$dy^l_{i,i,j} = 0 \quad (14)$$

In these constraints, J is a large value to represent the different behavior of gateway nodes and mesh nodes in linear. In implementation we will use the sum of link capacity of *Gateway* as J.. In the ILP, (3) is to restrict the link conflict constraint; (4) represent the link capacity distributed by time share α; Constraints (7)(8) 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; (9) make sure no loop in the assignment, there is no traffic generated by node i will go back to node i; (12),(13),(14) 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], [16]. 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. More details will be discussed in section IV

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 on WhiteMesh networking planning. According to the analysis, we develop two algorithms for *Channel Assignment* in multi-band multi-radio scenario.

A. Path Interference Induced on the Network

In network, the definition of a link is a wireless channel from one node to another, a path is a combination of links connecting two nodes. In *Multiband Multiradio Network*, a multihop path could be mixed with higher frequency links have less interference range and lower frequency links have less hop count. This is a significant difference from previous *Multi-Channel Multi-Radio* work. A key issue of path selection in multi-band network is to answer which link combination is better.

To discuss this problem, we pick up a multihop path from wireless mesh network and analyze its performance. In wireless mesh network, generally a path would have a bottleneck in the link closest to gateway. Generally the nodes close to gateway should have more traffic demand in gateway placement process and a gateway itself should have the most connectivity population. To simplify the model, we assume each node equally binding with the same traffic demand. Under this assumption, all the nodes in the path equally share the time of the common links. First, we introduce the *Intra-Path* traffic. In path, the mesh nodes have only one h hop path arrived at a gateway node. Assume the links in a path are in different bands, thus they could work simultaneously, or normalized links in the same band but share the time equally. Each node has equal traffic demand T_d, as normalized uplink or downlink since both of them occupy link capacity without difference. And the total traffic on the path $\sum T_d$ is less than the bottle neck link capacity LC.

We define the minimum transmission rate on a path as *Network Efficiency*. The last node in the path has the minimum transmission rate with the assumtion all the nodes have the same traffic demandT_d. The first link close to gateway in the h hop path woule be active for the whole time unit, the sencond would be $\frac{h-1}{h}$, and so on. Then the acitve time in a time unit of each link in the path can be represented as $1, \frac{h-1}{h}, \frac{h-2}{h} \cdots \frac{1}{h}$. The summation of each link active time in the path is counted as total cost time of network.

When only counting the interference generated in the path, an intuition of benefit from using lower band is to reduce the hop count which increase the minimum time utility rate which is the active time of the last link over the total active time of the path. Furthermore, as hop count goes up, the area will be interferenced increase too. An example shown in Fig. 1, the picture shows links in different bands, circles nodes could be connected by 450 MHz links, rectangle nodes could be connect through 2.4 GHz, trangle nodes are the links we talking. In the figure, the link in the figure does not represent the real distance or interference range accurately. Node A, C could be connected through two 2.4 GHz links or a single 450 MHz link; with 2.4 GHz links, the interference distance will be less than using 450MHz, only link D, E will be interferenced, H, I would not; however, with 450 MHz A, C link, more links, $F, G; M, L; K, J$ will be interferenced.

To combine this *Inter-Path Interference* with previous Intra-Path Interference, we define a unit time of each link is counted as a unit time of *Network Time*. When a h hop path transmitting traffic T_d for the destination node, it prevent activity on a number of links in the same band in protocol model. In a path, when the traffic arrived at the furthest destination node, previous links have served for these traffic. The active time on a single link can be noted as $\frac{T}{LC_h}$. With interference link counts I_h from the conflict matrix CM: the *Network Time* counted as $\frac{hT}{LC_1} \cdot I_1 + \frac{(h-1)T}{LC_2} \cdot I_2 \cdots \frac{T}{LC_h} \cdot I_h$, then the traffic transmitted in a unit *Network Time* for the endding node could be represented as:

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

With protocol model, if link exist, then they have the same capacity $LC_1 = LC_2 \cdots = LC_h = c$. The definition of *Network Efficiency per Node* in equation 15 could be represented as:

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

The meaning of the *Network Efficiency* is that in a unit time, the traffic could be loaded by this path. In multichannel scenario, the links will have a common communication range, the I_i will not change according to bands, this parameter equals to the conflic graph in many multichannel works [11]. Since we count only one channel not multiple possible links, the parameter also could be seen as an extention of a single link *Link Load* defined in [8].

The *Network Efficiency per Node* connect hop counts and interference in one equation. The denominator is defined as the *Path Interference induced on the Network* (PIN) which is the summation of interference links amount in the network. Then we have to find an answer when a lower *White Space Band* is better to be used in a path. In a path, we use an average interference count $\bar{I}$ replace each interference count with assumption the links in the path all in one higher frequency band. Assume there is a *White Space Band* could be used to replace two links in the path as a single link with interference count I_x represent one of the factor $i \cdot I_i$. The problem could be formulated as:

$$\frac{LC}{\frac{h(h-1)}{2} \cdot \bar{I} + I_x} \geq \frac{LC}{\frac{h(h+1)}{2} \cdot \bar{I}} \tag{17}$$

From the inequation 17, when $I_x \leq 2 \cdot h\bar{I}$ a lower band link could be better than 2 high frequency links. I_x is also a function of hop order in 16, generally the path order lower, the threshold would be more stricter. It matches the intuition the hop order is small, it close to the gateway, it may interference more links so it needs a stricted constraint.

According to these analysis, to improve the performance of a channel assignment in multi-band multi-radio scenario has two ways. First is to reduce the hop count, second is to reduce the interference among links. And at the same time, we have to trade off between the hop count reduction and single link interference which does not happen in multi-channel multi-radio scenario.

The discussion in subsection III-A provide the methodology to balance hop counts and low frequency long distance links in channel assignment. But the difficulty of channel assignment is that before the process has been done, it could no be evaluated to tell which is better. To approach the solution, we propose two local search based heuristic algorithms to adapt the multiband scenario.

B. Growing Spanning Tree (GST) Algorithm

In a mesh network, gateway nodes always building in the most busy location [20], [21]. As the service tree rooted at a gateway grows, the links closer to the gateway, the more interference will happen. And in the edge of the network, it is less populated in which cases reduce hop count through lower frequency may bring more benefit. The main idea behind the *Growing Spanning Tree* Algorithm is to find the link has least interference on the network for each node in a greedy manner at each step. The hop count for gateway nodes themselves are defined as 0. We first initialize the mesh nodes ranking with the distance to all the gateway nodes. In the ranking order of the mesh nodes, the 1 hop links from gateway nodes ranking with the *Path Interference induced on the Network*. Then select the lowest interfered link for this node and update the assignment information for next steps. Iterate these steps to assign channels for all mesh nodes. This process is phase 1 of our algorithm which is similar to but not exactly the same as the breadth first search channel assignment.

In phase 2 of the algorithm, we sort the mesh nodes with their hop count to gateway nodes. The algorithm traverses all the nodes whose hop count are less than the current node. If there are radio slots for the less hop nodes, it is possible to re-connect the mesh node to reduce the hop count. We rank all possible option with their PIN, then choose the lowest one re-connect for the mesh node. If there exist new link has the same PIN, we count the number of nodes has connected to the gateway nodes, select the gateway has less node connected. Phase 2 process will be iterated till no changes in the network or upto the number of nodes.

The *Growing Spanning Tree* Algorithm is described in 1.

The *Growing Spanning Tree* Algorithm greedy assign a single link to the network and balance the gateway load in the adjust process. The BFS in a multiband network complexity is $O((bn)^2)$, n is the number of nodes V, b is the number of bands, sorting of nodes would cost $O(bnlog(bn))$. Hence assigning a node takes $O((bn)^2)$ time. When there are n nodes, the complexity of an adjust interation is $O(b^2n^3)$. The total interation would be less than n since we put an upbound

Algorithm 1 Growing Spanning Tree (GST)

Input:
M: The set of all 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
Initial $S_{current} = G$, $N_{served} = \emptyset$, $N_{unserved} = M$,$I_{active} = \emptyset$
Rank mesh nodes according to their distance to 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, shorter distance first
    for all $l \in S_{Next}$ **do**
      Calculate one-hop path interference of link $s \to l$
      Sort the links, choose the one has the least 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 Exist **do**
  for all $s \in N_{sorted}$ **do**
    Traverse all the 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 the gateway node has least leaves nodes
  end for
end while
Output $ChannelAssignment$ as Solution

their and in our simulation it does not touch even $\frac{n}{2}$. So the complexity of the method would be $O(b^2n^4)$.

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 b in different bands is small. The time complexity of calculation the combination is $O(2^b)$. Then finding the shortest path in Dijkstra algorithm will cost $O(E^2)$ [22], E is the links in the network. So the total would be $O(E^2 \cdot 2^b)$. 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 all 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 their distance to gateway nodes
Initial $S_{current} = G$, $N_{served} = \emptyset$, $N_{unserved} = M$,$I_{active} = \emptyset$
while N_{served} =!M **do**
  Select the node has the largest distance to gateway nodes
  Find the Adjacency Matrix in different bands 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 has less interference
      If there are links have the same interference, choose high frequency
      Calculate the path interference of path SP_i
    end for
    Store the shortest path SP_i in 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 $O(E^2 \cdot 2^b)$, if all the nodes could be connected, $E = C_n^2$ which is $O(n^2)$. Then the complexity of assigning a node could be marked as $O(n^4 \cdot 2^b)$. To assign all the node in the network, the complexity would be $O(n^5 \cdot 2^b)$.

IV. Experimental Analysis

We performed a set of simulations to evaluate the performance of the heuristic algorithms and leverage the white space band influence on mesh network. The experiment set up is introduced in IV-A with the topology, metric calculation. A set of result is shown in IV-B and analysis is presented with the throughput achieve through gateways. CCA simplily pick two nodes have common channel to build links which also could be used in multiband scenario. In BFS-CA, we adopt the ranking standard as single link interference numbers, utilization of channels to fit multiband scenario.

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. 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-D. To simiplify the process, we remove the uplink constraints and keep download demand constraints only. Modify the constraint 10 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.

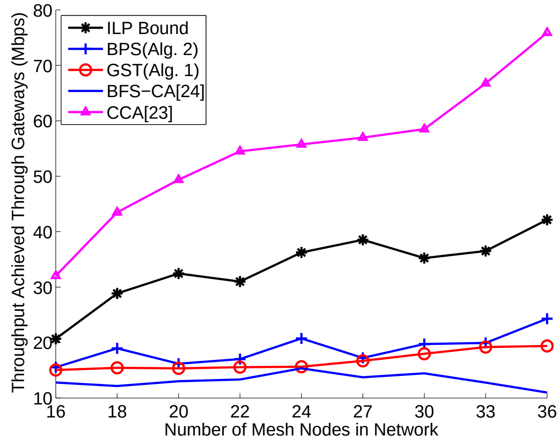

Fig. 2. Uniform offered load per mesh node of 4 Mbps.

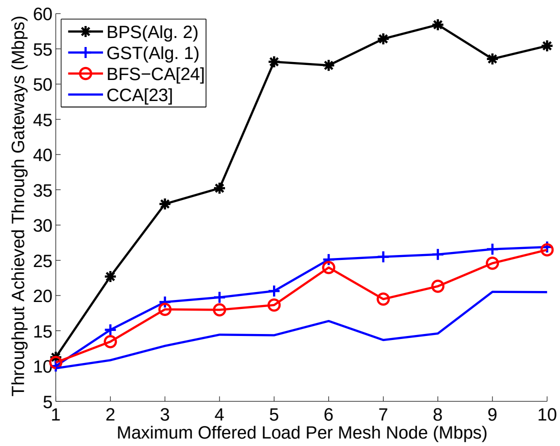

Fig. 3. Varying maximum offered load for a 30-node regular-grid mesh topology.

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 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* [29] in a 30-node regular grid topology with 6MB link capacity in each channel are shown in figure 3.

BPS performs better than the other 3 algorithms since during the channel assignment process, it is already optimize the paths

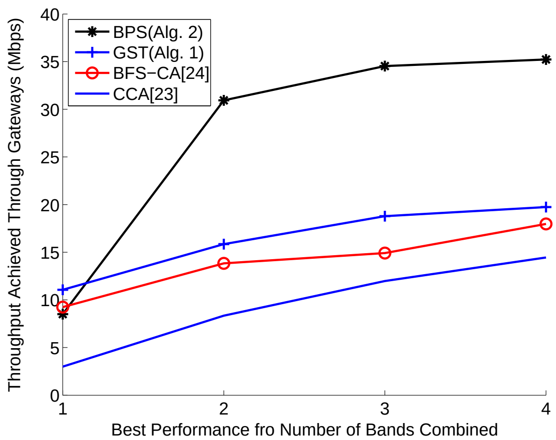

Fig. 4. Varying radios in 30-node regular-grid of 4 Mbps.

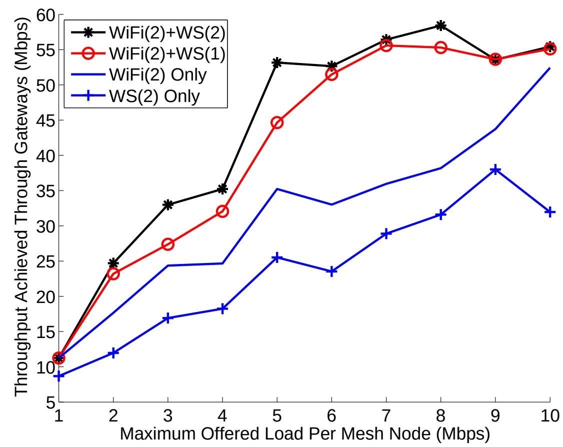

Fig. 5. BPS (Alg. 2) performance with two total channels of WiFi or white space (WS) with varying offered load from x mesh nodes.

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 4, 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 5, 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], [30]. 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], [31]. 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 [32], which is in contrast to dynamic channel assignment where demand and interference are not known *a priori* [29], [33]. We have implemented such channel assignment algorithms (CCA from [28] and BFSCA from [29]) 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. Coloring methodology assume all the color equal failing to process multiple topology generating by bands combination [19]. **White Space.**

White space bands are fundamentally different from conventional Wi-Fi along spatial variation [34]. Spatial variation gives rise to new challenges for implementing a wireless network in this band. Government department FCC has licensed white space bands in US [6]. Microsoft build *Microsoft Research White Space databas* for white space application reference [35]. Google even visualize the licensed white space

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 [29]	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).

channels in cities all over US and provide API for research and commerical users [36]. The white space potential and the open free spectrum database provide chance to improve the mesh network performance in combining these UHF channels and Wi-Fi channels. In this work, we study the performance of mesh network with varying number of available white space channels at varying population densities as offerload to offer solution for white space channel application in mesh networks.

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. In future work, we will adapt our algorithms to be used with dynamically-changing network conditions, in the field on large-scale WhiteMesh networks.

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