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 describe the multi-band multi-radio wireless mesh network architecture, and formulate the key research issue in channel assignment. Then we propose a linear program to understand the architecture, illustrate the challenges of the problem. Then we leverage the influence of multi-band in wireless network.

A. Multiband Wireless Mesh Network Architecture

Wireless Mesh Network could be chopped as two-tiers: Access layer, consists of traffic aggregation mesh nodes for clients, and backhual layer for interconnection from mesh nodes to gateway nodes with wired Internet connection [12]. In this paper, we talk *Multiband Wireless Mesh Network* in the backhual layer, since access layer always need ISM band channels providing access to client's Wifi devices, such as iPhone and laptops. To simply the analysis, we assume the access layer uses different channels in ISM band.

A lot of efforts have been put on the similar architecture Multichannel Multi-radio Mesh Network focusing in *Channel Assignment, Multihop Routing, Gateway Placement* problems [10]. These works, the definition of multi-channel is channels has small gap with the same propagation performance, for instance the orthogonal WLAN channels in 2.4GHz from 2.412GHz to 2.484GHz with 22MHz gap. We refer *Multiband* as a combination of different channels with large gap whose propagation characteristics are different, such as a two channel set of one channel in 2.4GHz and one channel in 450MHz.

Wireless propagation is the behavior of the signal loss characteristics when wireless signals are transmitting from one point to another. The rules of radio propagation are complex and diverse, such as the daily changes of environment, weather, and atmosphere changes due to cosmos activities. In most propagation models there are three basic propagation mechanisms: reflection, diffraction, and scattering [13]. For multiband mesh backhual network, the nodes are usually installed on the top of buildings or towers to get the best line of sight propagation. A line of sight propagation model is a reasonable hypotheses in wireless mesh network. In popular *Friis* propagation model, the received signal power of a node is represented as:

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

Path-loss exponent α is used to describe the environment factors, typically in outdoor environments range from 2 to 5. [14]. In equation 1, in the specific environment with a common path-loss exponent and P_t, G_t, G_r configuration, the received signal vary according to the band represented by wavelength λ. Since wireless radios have the same received signal threshold, lower frequency band could have a larger communication range R, and also a larger interference range I_r.

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. In figure **??**, node *N1* could connect to node *N3* through relay of node *N2* in higher frequency band, or directly connect by lower frequency band channel with larger communication range. If under higher frequency band, link between node *N4* and node *N5* could reuse the higher frequency since they are out of the interference range of this high frequency band; however, if *N1* and *N3* connected with lower frequency band in less hop counts, then *N4* and *N5* could not reuse these lower frequency channels due to the larger interference range. To balance the larger communication range and larger interference range of white space band is a key issue in *Multiband Mesh Network Channel Assignment* different from *Multichannel* 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 configuration, each radio works under the same transmitting power, antenna with the same gains. 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. In *Protocol Model*, 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. Other input information includes, transmitting power, antenna gains, communication and interference threshold. From *Friis Model*, we could get *Communication Range* and *Interference Range* of each link in different band. Multiband multi-radio wireless network could be formulated 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. The capacity between two nodes in common channel is noted as $C_{lb}, l \in L, b \in B$. If they are

α	Path Loss Exponent
R	Communication Range
I_r	Interference Range

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).

physically located within each others communication range of a band, the value of C_{lb} would be a constant value, otherwise, it is zero.

The associated interference range is larger than the communication range for each node. We extend the *Conflict Matrix* from Jain's work with a flexible approach for interference, $CG = (L_{i,j}, I_{Set}, B)$. $L_{i,j}$ represents the active link, I_{Set} includes all the links are physically inside the interference range.

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

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 distinguish the trading off between minimize hops and more frequency space reuse among multiple bands. Our work focus on the *traffic-independent* without explicitly considering network traffic/load [19]. To approach the optimization channel assignment, we develop a mixed linear integer model to understand the multiband scenario. We also analyze the intra-relation between the *Hop Counts* and *Space Reuse*, then propose two heuristic approaching for this problem.

C. Evaluation Metric

Mesh Network is designed to provide service for clients. The goal of a backhual network is to maximize its overall good put within a unit time. This enables the network to support more end-user flows, and in turn more number of users. 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

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

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* fixed wireless mesh network described in II.

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

N set of nodes
B set of bands
Parameters:

$r^k_{i,j}$	$(i,j) \in N, k \in B$	capacity of link i,j on band k
$I^k_{ij,lm}$	$(i,j,l,m) \in N, k \in B$	Interference of link (i,j) on band k
g_i	$i \in N$ *binary*	Gateway placement
$uy^l_{i,j,k}$	$(i,j,k) \in N, l \in B$	UL of node i on (j,k) at band l
$dy^l_{i,j,k}$	$(i,j,k) \in N, l \in B$	DL of node i on (j,k) at band l

In order to the link constraints, we define a *Time Share* variable to represent the time division of a single link as $\alpha^k_{i,j}$ which is the time share for link $i->j$ in band k. Two flow variables are defined as up-link and down-link flow on a link $i->j$ for node k in band l, $uy^l_{i,j,k}, dy^l_{i,j,k}$.

Variables:

α^k_{ij}	$k \in B, (i,j) \in N$	Time share of (i,j) on band k
λ_i	$i \in N$	Satisfied demand of node i

The constraints is given as:

Constraints:

Variable-Type Constraints:

$$\alpha_{i,j}^k \leq 1 \tag{3}$$

$$uy_{i,j,k}^l \geq 0 \tag{4}$$

$$dy_{i,j,k}^l \geq 0 \tag{5}$$

Connectivity Constraints:

$$\sum_i \alpha_{i,j}^k + \sum_i \alpha_{j,i}^k + \sum_l \sum_m (\alpha_{l,m}^k \cdot I_{ij,lm}^k) \leq 1, i \neq j \tag{6}$$

$$\sum_i uy_{i,j,k}^l + \sum_i dyi,j,k^l \leq r_{j,k}^l \cdot \alpha_{j,k}^l \tag{7}$$

Uplink Constraints:

$$\sum_k \sum_l uy_{i,i,k}^l \geq \lambda u_i - J \cdot g_i \tag{8}$$

$$uy_{i,j,k}^l \leq J(1 - g_i) \tag{9}$$

$$\sum_j \sum_l uy_{i,j,k}^l - \sum_m \sum_l uy_{i,k,m}^l \leq g_i \cdot J, i \neq k \tag{10}$$

$$\sum_j \sum_l uy_{i,j,k}^l - \sum_m \sum_l uy_{i,k,m}^l \geq 0, i \neq k \tag{11}$$

$$uy_{i,j,i}^l = 0 \tag{12}$$

Downlink Constraints:

$$\sum_j \sum_l dy_{i,j,i}^l \geq \lambda d_i - J \cdot g_i \tag{13}$$

$$dy_{i,j,k}^l \leq J(1 - g_k) \tag{14}$$

$$\sum_j \sum_l dy_{i,j,k}^l - \sum_m \sum_l dy_{i,k,m}^l \geq -g_i \cdot J, i \neq k \tag{15}$$

$$\sum_j \sum_l dy_{i,j,k}^l - \sum_m \sum_l dy_{i,k,m}^l \leq 0, i \neq k \tag{16}$$

$$dy_{i,i,j}^l = 0 \tag{17}$$

In these constraints, J is a large value to represent different behavior of mesh node and gateway node in linear. In implementation we will use the total link capacity of *Gateway* as J to reduce the computation complexity. In the ILP, 6 is to restrict the link conflict constraint; 7 represent the link capacity distributed by time share α; 10 11 is to describe relay behavior of the network. If node i is a mesh, then $g_i = 0$, the total in-coming traffic should equal to the total out-coming traffic; otherwise node i is a gateway, when $g_i = 1$, traffic get into gateway node, in-coming traffic should be greater than out-coming traffic; 12 make sure no loop in the assignment, there is no traffic generated by node i will go back to node i; 15, 16, 17 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. The constraints above are need to be satisfied, otherwise the channel assignment could not be scheduled.

Other constraints could be modified according to different objectives. When the objective is to find the maximum throughput with fairness, $Max \sum(\lambda u_i + \lambda d_i), \lambda u_i = \lambda u_j, \lambda d_i = \lambda d_j, i \neq j$, constraints 8,9 could be represented as above. If the node is a mesh, the summation out-coming flows should be greater or equal to the demand of node i, otherwise as a gateway, it transfers data to wired Internet directly without out-going traffic flow for up-link traffic; Constraints 13, 14, restrict the down-link behavior of the network nodes similar to the up-link constraints. For mesh nodes, the in-coming flows should be greater or equal than the demand of node i, a gateway node has no out-coming traffic for itself.

Similar linear program has been proved as 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 $A_{i,j}^k$, 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 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 over Network

A link is a wireless channel from one node to another. A path is a combination of links to connect two nodes far away from each other. 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. That's the significant difference from *Multi-Channel Multi-Radio* since the multi-channel in the same band will have the same communication range and interference range. A key issue of multihop path in multi-band network is to answer which combination is better.

To discuss this problem, we pick up a multihop path from wireless mesh network and analyze its performance with worst case satisfied throughput hypothesis. In wireless mesh network, such 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. We assume each node equally binding with the same demand. Under this assumption, all the node in the path equally share the time of the common links. First, we introduce the *Intra-Path* traffic. In a spanning tree, the mesh nodes on the path have only one h hop path arrived at a gateway node. The links in a path are in different bands could work simultaneous or normalized links in the same band but share the time equally. Each node has traffic T, no matter uplink or downlink since both of them occupy link capacity with no difference. And the total traffic on the path $\sum T$ is less than the bottle neck link capacity C.

We define the minimum transmission rate on a path as *Network Efficiency*. With the fairness restriction, the last node in the path has the minimum transmission rate. Then the acitve time in a time unit of each link can be represented as $1, \frac{h-1}{h}, \frac{h-2}{h} \cdots \frac{1}{h}$. The unit time of each link in the path is counted as total cost time of network.

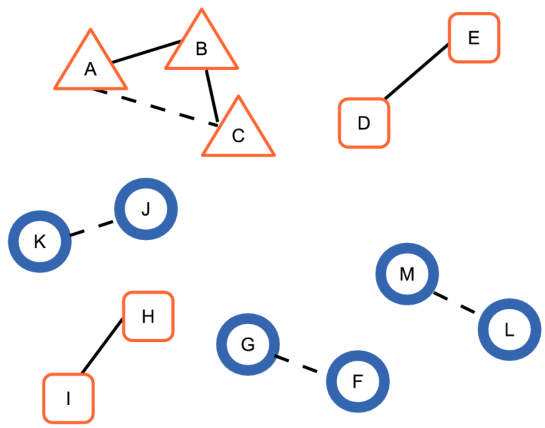

Fig. 1. Path Efficiency Introduction Solid Wire notes 2.4GHz link, Dashed line notes 900MHz

Without considering *Inter-Path* interference which represent interference with links out of the path, an intuition of benefit from using lower band is to reduce the hop count to 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 interference range increase too. An example shown in Fig. 1, the picture shows links in different bands. The links are in 2.4GHz and 900MHz. As a sketch map, the link in the figure does not represent the real distance. Node A, C could be connected through two 2.4GHz links or a single 900MHz link; with 2.4GHz links, only link D, E will be interferenced,H, I would not; however, with 900MHz A, C link, link F, G; M, L; K, J will be interferenced.

To quantization this *Inter-Path Interference*, the unit time of each link is counted as a unit time of *Network Time*. When a h hop path transmitting traffic T for the destination node, it stops activity on a number of links in the same band. In a multihop path, when the traffic arrived at the last destination node, all the previous links are serving for these traffic. The active time on a single link can be noted as $\frac{T}{c_h}$. With interference counts I_h from the conflict matrix: the *Network Time* counted as $\frac{hT}{c_1} \cdot I_1 + \frac{(h-1)T}{c_2} \cdot I_2 \cdots \frac{T}{c_h} \cdot I_h$, then the *Path Efficiency over Network* is defined the traffic of the node over the *Network Time* and could be represented as:

$$E_{PEN} = \frac{T}{\sum_{i \in h} \frac{(h-i+1) \cdot T}{c_i} \cdot I_i} \tag{18}$$

With protocol model, if link exist, then they have the same capacity $c_1 = c_2 \cdots = c_h = c$. The *Path Efficiency over Network*could be represented as:

$$E_{PEN} = \frac{c}{\sum_{i \in h} (h-i+1) \cdot I_i} \tag{19}$$

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

The *Path Efficiency over Network* connect hop counts and interference. The denominator is defined as the *Path Interference* (PIN) which is the summation of interference links amount in the network. Then we are going to 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 freq band. Then a *White Space Band* is used to replace two links in the path as a single link with interference count X represent one of the factor $i \cdot I_i$. The problem could be formulated as:

$$\frac{c}{\frac{h(h-1)}{2} \cdot \bar{I} + X} \geq \frac{c}{\frac{h(h+1)}{2} \cdot \bar{I}} \tag{20}$$

From the inequation 20, when $X \leq 2 \cdot h\bar{I}$ a lower band link could be better than 2 high frequency links. X is also a function of hop order in 19, 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 ř efsubsec:PEN provide the methodology to improve 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 each step. The hop count for gateway nodes themselves are 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*. 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 breath 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 path interference, then choose the lowest one re-connect the mesh node. If there exist new link has the same path interference, 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.

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

Algorithm 1 Multiband 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 $s \rightarrow l$
      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

The *Growing Spanning Tree* Algorithm greedy assign a single link to the network and balance the gateway load in the adjust process. The BFS complexity is $O(n^2)$, sorting of nodes is $O(nlogn)$. Hence assigning a node takes $O(n^2)$ time. Thus the complexity of the assignment is $O(n^3)$.

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 node on the path is served. The main idea behind the *Band-based Path Selection* Algorithm is to improve the worst path in the network.

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 $O(2^b)$. The second path of 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 the *Path Interference* of the candidate path and select the path will bring 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 $O(E^2 \cdot 2^b)$, which could be marked as $O(n^2 \cdot 2^b)$, n is the mesh node number. To assign all the node in the network, the complexity would be $O(n^3 \cdot 2^b)$.

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.

A. Experiment Design

We consider static wireless meshnetworks with n nodes located in a regular grid with distance of $300m$ distance. Today's white space equipment use frequnecy 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 relese 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 3. The upbound 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 upbound to our calculation.

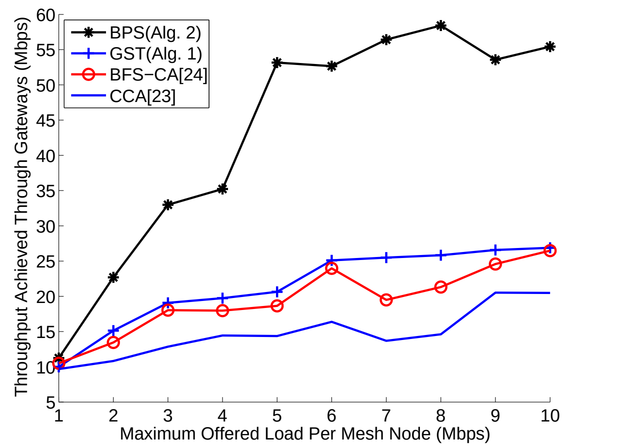

Fig. 2. Varying maximum offered load for a 30-node regular-grid mesh topology.

B. Analysis

Most of the time clients of wireless network have different traffic demand. We first deploy a number of gateways according to number of mesh nodes randomly, Then we randomly assign demand of mesh nodes with a max offer load, calculate the scalable maximum throughput, then repeat the process 20 times. The output is the average maximum throughput achieve gateways for this max offer load per mesh node. 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 2.

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.

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 3.

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 evaluation setup. We randonly deploy the gateways and offer load of each mesh node, brings the decrease in achieving throughput when the number of mesh node increase.

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

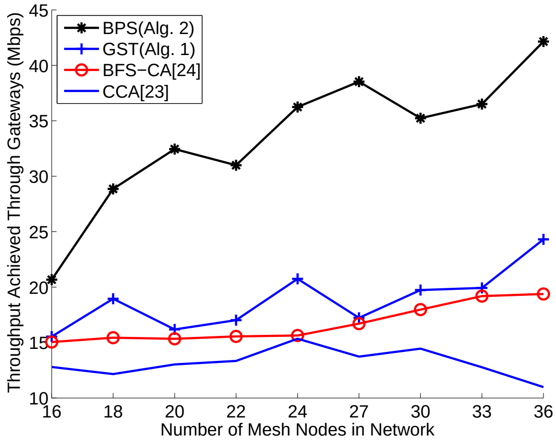

Fig. 3. Uniform offered load per mesh node of 4 Mbps.

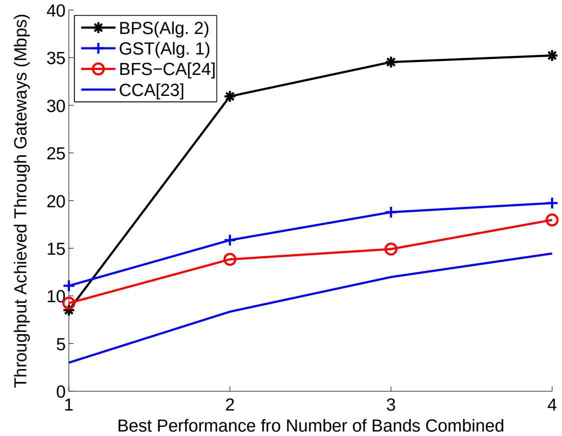

Fig. 5. Varying radios in 30-node regular-grid of 4 Mbps.

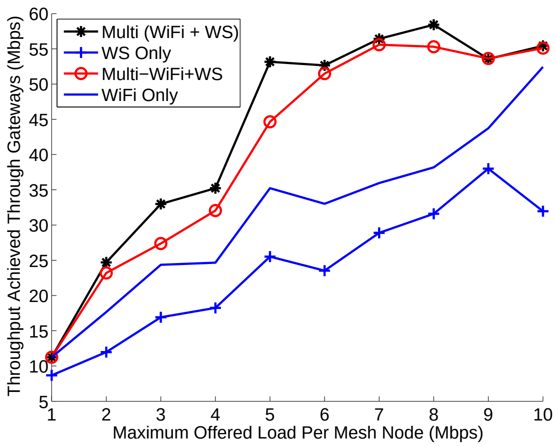

Fig. 4. WiFi White Space Combination Performance in BPS

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.

In 4, 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 overperform only WiFi and only white space performance.

The number of radio equipped on a node in mesh network also abstract ISP attention. The result shows in 5, 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 tradeoff between performance of more radios and cost increading. 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.

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 [**?**]. 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], [12]. 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* [29], [32]. 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.

White Space. We need to cite some work by Microsoft on white spaces (SIGCOMM 2009 and other Ranveer Chandra papers). Talk about databases for available white space channels and say that in this work, we study the performance of mesh networks with 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

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)		450,900	450	900	450	900	450	900	450,900	450,900	450,900
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 II
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).

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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