WhiteMesh: Leveraging White Spaces in Wireless Mesh Networks

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. Also, channel occupancy of change the performance of wireless network across both ISM bands and white space bands. In this work, we consider how these white space bands can be leveraged in large-scale wireless mesh network deployments with in-field measured channel capacity. In particular, we present an integer linear programming model to leverage diverse propagation characteristics and the channel occupancy of white space and WiFi bands to deploy optimal WhiteMesh networks. Since such problem is known to be NP-hard, we design a measurement driven heuristic algorithm, Band-based Path Selection (BPS), which we show approaches the performance of the optimal solution with reduced complexity. We additionally compare the performance of BPS against two well-known multi-channel, multi-radio deployment algorithms across a range of scenarios spanning those typical for rural areas to urban areas. In doing so, we achieve up to 160% traffic achieved gateways gain of these 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 achieve a served user demand of 170% that of mesh networks with only WiFi bands or white space bands, respectively. Further, through the result, we leverage the channel occupancy and spacing impacts on white mesh network and study the general rules of band selection.**

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 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], wireless mesh networks have largely been unsuccessful in achieving the scale of what was once anticipated [4].

Around the same time, the digital TV transition created more spectrum for use with data networks [5]. These white space bands operate in available channels from 54-806 MHz, having increased propagation range as compared to WiFi [6]. 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. At the same time, the new allowed white space channels offers more capacity all over the US. The propagation diversity and additional channel capacity are the two key impacts on wireless network performance of white space bands. The additional channel capacity vary according to FFC regulation and existing channel occupancy. As shown in Google database [7], the additional the number of available white space frequency channels vary from city to city in US. Existing channel occupancy discussed in previous work [8] has shown that the occupancy of frequency impacts on wireless network deployment. Naturally, the question arises for improving the performance as well as the optimization of utilization: *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 been exploited in their models [9]–[11], which could be *the* fundamental issue for the success of mesh networks going forward.

In this paper, we leverage the diversity in propagation and channel occupancy 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 program to jointly exploit white space and WiFi bands for optimal WhiteMesh topologies in channel assignment. Second, since similar problem formulations have been shown to be NP-hard problem [11], [12], we design a heuristic measurement driven algorithm, Band-based Path Selection (BPS) based on mathematical analysis to solve the problem. We then apply the approaching method in multiple scenarios with in-field measurement data. Across a wide range of scenarios, including network size, population distribution, deployment gap, we exploit the general rules of emerging white space bands in mesh networks. The performance of our scheme is compared against two well-known multi-channel, multi-radio channel assignment algorithms across these scenarios, including those typical for rural areas as well as urban settings. We further discuss the channel occupancy impacts on wireless networks and show the comparison of our algorithm and previous methods in typical scenarios. Finally, we quantify the degree to which the joint use of both band types can improve the performance of wireless mesh networks.

The main contributions of our work are as follows:

- We analyze the white space bands application in wireless network deployment and develop an optimization framework based on integer linear programming to jointly leverage white space and WiFi bands to advantages and disadvantages in wireless mesh networks.
- We build a heuristic measurement driven algorithm, Band-based Path Selection (BPS), which considers the diverse propagation, overall interference level of WiFi and white space bands with measurement adjust.
- We perform extensive analysis across offered loads, network sizes, mesh nodes spacing and WiFi/white space band combinations, to compare against previous multi-

channel multiradio algorithms. And we further exploit the general rules of white space bands application in wireless network.

- We discuss the channel occupancy and mesh spacing impacts on the performance given similar channel resources (bandwidth and transmission power), We show the improvement of our BPS in typical configurations up to %180 vs. previous multichannel algorithms.

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 analyze the WhiteMesh network and develop a heuristic algorithms which consider which bands and multihop paths to select in a WhiteMesh topology. We then evaluate the performance of the heuristic algorithm versus the upper bound of the optimal solution and compare their performance against two well-known multi-channel, multi-radio algorithms in Section IV in several scenarios and analyze the result for answering where WhiteMesh is better. 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 introduce the multiband mesh network system model and illustrate the challenges of such a WhiteMesh architecture in propagation and channel occupancy. We then discuss the network performance in economic view to evaluate WhiteMesh networks and the corresponding goal of both the optimization framework and the heuristic algorithm that we 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 [13]. The widely-used Friis equation characterizes the power of the received signal P_r in terms of the power P_t and gain G_t of the transmitting signal, gain of the receiver G_r, wavelength λ of the carrier frequency, distance R from transmitter to receiver, and path loss exponent n according to [14]:

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

Here, the path loss exponent n changes according to the aforementioned environmental factors and ranges from 2 to 5 in typical outdoor settings [15].

A frequency band is commonly defined as a group of channels which have similar propagation characteristics with small frequency separation. A common assumption in previous 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., 5 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

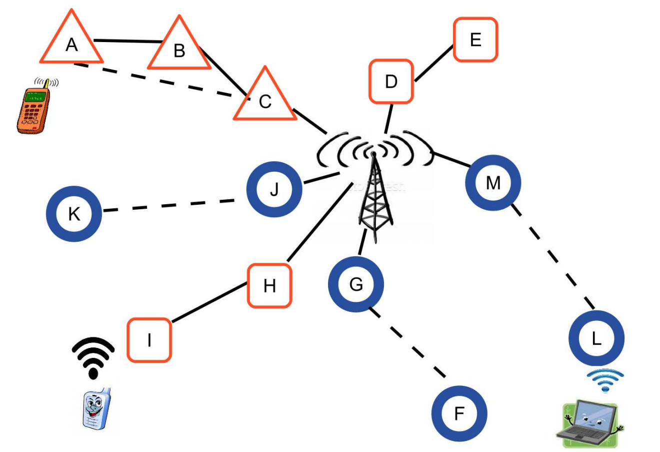

Fig. 1. Example WhiteMesh topology with different mesh-node shapes representing different frequency band choices per link.

multiple radios in multihop wireless networks with channels in one band [11]. However, as FCC licensed the white space bands for communication, the propagation variation has to be considered in wireless network.

Moreover, the FCC has flexible rules all over the states because of the existing TV stations and devices working in white space bands [7]. These existing channel occupancy has to be considered in the wireless communication with white space frequency [16]. To quantify the channel occupancy, we have the concept activity level from [17] as defined in Eq. 2. The concept is defined based on a long-term measurement as the percentage of sensing samples (S_θ) above an interference threshold (θ) over the total samples (S) of each band (b) during a unit time.

$$A = \frac{S_\theta}{S_a} \tag{2}$$

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 optimally allocating white space and WiFi bands on a finite set of radios per mesh node along the backhaul tier, since we assume that client devices will use WiFi (due to the economies of scale) along access tier. In each of the WhiteMesh topologies studied in Section IV, a sufficient number of orthogonal WiFi channels remain for the access tier clients connection through additional radios co-located on the mesh nodes.

In this work, we consider the diverse propagation characteristics for four frequency bands: 450 MHz, 800 MHz, 2.4 GHz, and 5.8 GHz. We refer to the two former frequency bands as white space (WS) bands, whereas the two latter frequency bands as WiFi bands. Due to the broadcast nature of the wireless medium, greater levels of propagation induce higher levels of interference. Also, the more allowed frequency channels and low level signal activity of white space bands coexist in sparse areas. Thus, in sparsely-populated rural areas, the lower frequencies of the white space bands might be a more appropriate choice for multihop paths to gateways having reduced hop count with more capacity. However, as the population and demand scales up (e.g., for urban regions), the reduced spatial reuse and greater levels of interference of white space bands might detract from the overall channel assignment strategy. In such urban areas, select links of greater distance might be the most appropriate choice for white space bands, especially since the number of available channels is often inversely proportional to the population (due to the existence of greater TV channels).

Figure 1 depicts an example where mesh node A could connect to mesh node C through B at 2.4 GHz, or directly connect to C at 450 MHz. If 2.4 GHz were used, link D, E might be able to reuse 2.4 GHz if they are out of the interference range. However, if link A, C used 450 MHz, a lower hop count would result for the path, but lower levels of spatial reuse also result (e.g., for link D, E). While the issues of propagation, interference, and spatial reuse are simple to understand, the joint use of white space and WiFi bands to form optimal WhiteMesh topologies is challenging since the optimization is based on the knowledge of prior channel assignment which is not available before the work has been finished.

B. Model and Problem Formulation

Multiband wireless network involve the propagation variation and channel occupancy additional to the previous multichannel scenario. Thus, we improve the prior multi-channel models [9], [11] to adopt the new parameters. In these previous models, they fail to distinguish the communication range D_c, interference range D_r and channel capacity variation across frequency bands. While these works would attempt to minimize the interference in a multihop network topology by an optimal channel assignment for a given set of radios, we hypothesize that using radios with a greater diversity in propagation could yield overall network performance gains. Therefore, for a given set of radios, we allow the channel choices to come from multiple frequency bands (i.e., multiband channel assignment, which also includes multiple channels in the same band). In this work, we assume all channels have the same bandwidth and adjust the channel capacity of each band through the measured channel occupancy parameter activity level 2. In practice, we could easily calculate the proportional ratio of channels in each band according to their bandwidth. We assume that the locations of mesh nodes and gateway nodes are given and all mesh nodes have radios with the same transmit power, channel bandwidth, and antenna gain. Each mesh node operates with a classic protocol model [18].

A mesh network could be represented by a unidirectional graph $G = (V, E)$, where V is the set of mesh nodes, and E is the set of all possible physical links in the network. If the received signal (according to Eq. 1) between two mesh nodes i, j for a given frequency band (from the set of all bands B) is greater than a communication-range threshold, then a data link exists and belongs to the set L with a fixed, non-zero capacity δ with a protocol model. Due to the frequency occupancy, the available channel capacity could be calculated through Eq. 3.

$$\delta_r = \delta * (1 - \bar{A}) \tag{3}$$

The capacity of a clean channel is denoted by δ. Under the protocol model, the capacity of a channel with interference of existing signals δ_r could be represented as the remaining free time of the channel capacity according to the measured activity level A. We employ the activity level based on multiple measurements in the target area to represent the average inter-network interference. Correspondingly, a connectivity graph C is formed for each band in B such that $C = (V, L, B)$. If the received signal for a given band is above an interference-range threshold, then contention occurs between nodes. We extend the conflict matrix in [9] related to different interference per band according to $F = (E_{i,j}, I_{Set}, B)$, where $E_{i,j}$ represents the link and I_{Set} includes all the links are physically inside the interference range D_r when operating on each band $b \in B$.

Therefore, the problem we model is: to choose the connectivity graph C' which maximizes the metrics obey the constraints of multiband wireless network (defined below). A key challenge is that selecting the optimal channels from the set B leads to a conflict graph F which cannot be known *a priory*. Previous works have proposed several coloring, cluster-independent set, mixed linear integer methodology for a single band b [9], [11], [19]. However, these works do not address a reduction in hop count or an increase in spatial reuse and channel occupancy for a set of diverse bands B.

In network application, the bottleneck of mesh network capacity has been shown to be the gateway's wireless connections [20]. The metric we use to evaluate the proposed algorithm is the traffic arrived at gateway nodes. Networks are operated and maintained by vendors, such as AT&T, T-Mobile, who charge the customers based on their data through Internet. Thus, we use random generated numbers to represent clients' traffic demands. The traffic arrived at gateway nodes correlated to the population of the area since people have almost traffic demand in long term average. The employed performance metric of traffic arrived gateway X, is represented the traffic arrived at the gateway nodes, where in Eq. 4:

$$X = \sum_{w \in W, v \in V} T(w, v) \tag{4}$$

The traffic arrived gateway node $w \in W$ considers all incoming and outgoing wireless traffic from access node $v \in V$ as T onto the Internet. Obviously, the traffic arrived gateway is also related to the routing and other factors, we use a simple routing method to keep the maximum the traffic arrived at the gateway nodes, the exact calculation of gateway traffic arrived gateway is described in Section IV and consider where to put the gateway nodes are outside the scope of this work.

C. Mixed Integer Linear Programming Formulation

To clarify the problem and approach the optimization solution of the problem, we present a mixed integer, linear programming formulation for optimizing channel assignment in multiband scenario. We assume that the set of available mesh nodes (V), gateways (W), and available bands (B) are preknown. The communication links and conflict graph are given as parameters. The capacity δ_b is given as the available channel capacity according to activity level measurement noted in 3.

Sets:
V set of nodes
B set of bands

Parameters:

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

In the variable set, we define a time share represents the percentage of time a single link transmits according to $\alpha^b_{i,j}$ for link i,j between node i and node j in band b. There are two terms $uy^b_{i,j,k}$ and $dy^b_{i,j,k}$ defined as uplink and downlink flows:

Variables:

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

Our objective is represented for maximizing the traffic arrived at gateway (X) described in Eq. 4.

Objective:

$$Max \sum_i \sum_j \sum_k \sum_b (uy^b_{i,j,k} + dy^b_{j,i,k}) \ \ When\ w_j = 1 \quad (5)$$

In the ILP, the connectivity, uplink, and downlink constraints are represented as:

Connectivity Constraints:

$$\alpha^b_{i,j} + \alpha^b_{j,i} + \sum_l \sum_m (\alpha^b_{l,m} \cdot I^b_{ij,lm}) \leq \delta^b, i \neq j \quad (6)$$

$$\sum_i uy^b_{i,j,k} + \sum_i dy^b_{i,j,k} \leq r^b_{j,k} \cdot \alpha^b_{j,k} \quad (7)$$

Uplink Constraints:

$$\sum_k \sum_b uy^b_{i,i,k} \leq D_{ui}\ when\ w_k = 0, i \neq k \quad (8)$$

$$uy^b_{i,j,k} = 0 w_k = 1 \quad (9)$$

$$\sum_i \sum_b uy^b_{i,j,k} = \sum_m \sum_b uy^b_{j,m,k}\ when\ w_k = 0, i \neq k \quad (10)$$

$$uy^b_{i,j,i} = 0 \quad (11)$$

Downlink Constraints:

$$\sum_j \sum_b dy^b_{i,j,i} \leq D_{di}\ when\ w_i = 0 \quad (12)$$

$$dy^l_{i,j,k} = 0\ when\ w_k = 1 \quad (13)$$

$$\sum_j \sum_b dy^b_{i,j,k} = \sum_m \sum_b dy^b_{j,m,k},\ when\ w_k = 0, i \neq k \quad (14)$$

$$dy^b_{i,i,j} = 0 \quad (15)$$

In the constraints, (6) represents the summation of the incoming and outgoing wireless time share and the interfering links' wireless time share, which should all be less than 1. Constraint (7) represents the incoming and outgoing wireless traffic, which should be less than the link capacity for link i,j. Uplink constraints (8) and (9) represent that the summation of any wireless flow i,j should be less than the demand of node k. Constraints (10) and (11) are used to restrict the sum of all incoming data flows for a given mesh node k to be equal to the sum of all outgoing flows. Downlink constraints (12) and (13) are similar to (8) and (9) but in the downlink direction. Similarly, constraints (14) and (15) are downlink versions of (10) and (11).

Similar linear programs model is to solve channel assignment wireless networks have been proved to be NP-hard [21]. Our model jointly considers channel assignment factors and provides the methodology to achieve the optimization solution. When the particular configuration is given, we further choose the objectives, parameters, and relax constraints to find the approaching solution for the network.

III. Path Analysis with Diverse Propagation

In this section, we discuss the influence of diverse propagation characteristics of the wide range of carrier frequencies of white space and WiFi bands in wireless networks. We then introduce our measurement driven heuristic algorithm for channel assignment in WhiteMesh networks.

A. Path Interference Induced on the Network

In WhiteMesh networks, multihop paths can be intermixed with WiFi for more spacial reuse and white space bands with less hops. To deal with the trade-off, we consider analyze the band choices reduce the number of hops along a path and the aggregate level of interference that hop-by-hop path choices have on the network (i.e., Path Interference induced on the Network).

Mesh nodes closer to the gateway generally achieve greater levels of throughput at sufficiently high offered loads. To combat such starvation effects, we treat each flow with equal priority in the network when assigning channels. In the worst case, all nodes along a particular path have equal time shares for contending links (i.e., intra-path interference). We start the channel assignment assuming that h mesh nodes are demanding traffic from each hop of an h-hop path to the gateway. If each link along the path uses orthogonal channels, then each link could be active simultaneously, otherwise they will complete with each other. We note each node along the path had traffic demand T_d, obviously the bottleneck link along the path would be the one closest to the gateway, and then next. Thus, the total traffic along the path $h \cdot T_d$ must be less than the bottleneck link's capacity δ estimated from the measurements. In such a scenario, the h-hop mesh node would achieve the minimum served demand, which we define as the network efficiency. In general, the active time per link for an h-hop mesh node can be represented by $1, \frac{h-1}{h}, \frac{h-2}{h} \cdots \frac{1}{h}$. The summation of all active times for each mesh node along the path is considered the intra-path network cost.

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

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

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

Using network efficiency, the equation simplifies to:

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

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

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

Here, from Eq. refeq:benefit when $I_x \leq 2 \cdot h\bar{I}$, the performance of a lower-frequency link is better than two higher-frequency hops for the same destination node. I_x is also a parameter of hop count in Eq. 17. When the hop count is lower which closer to the gateway node, the threshold would be more strict since the interference would have a greater effect on the performance.

B. Band-based Path Selection (BPS) Algorithm

We design a Band-based Path Selection (BPS) algorithm (described in Alg. 1) which first chooses the mesh node that has the largest physical distance from the gateway nodes to reduce the whole time cost of the network. When a path is constructed for the mesh node with the greatest distance, all subsequent mesh nodes along the path are also connected to the gateway. The intuition behind the BPS algorithm is to improve the worst mesh node performance in a path. In large-scale mesh networks, it is impractical to traverse all the paths

Algorithm 1 Band-based Path Selection (BPS)

Input:
- M: Set of mesh nodes
- G: Set of gateway nodes
- C: Communication graph of potential links among all nodes
- I: Interference matrix of all potential links
- B: Available frequency bands
- δ: Measurements based Channel Capacity

Output:
- CA: Channel Assignment of the Network

```
Rank mesh nodes in Set M according to physical distance from gateway nodes G
Initialize S_curr = G, N_srv = ∅, N_unsrv = M, I_active = ∅
while N_srv =!M do
    Select node with largest distance to gateway
    Find the adjacency matrix across band combinations A_c
    for all A_i ∈ A_c do
        Find the shortest path SP_i in mixed adjacency matrix A
        for all Link l ∈ SP_i, ordered from gateway to mesh node do
            Find the least interfering path with measured δ × E_n
            If equally-interfering links, choose higher frequency
            Calculate the path interference of SP_i
        end for
        Store the shortest path SP_i as SP
    end for
    Assign the path in the network
    Update N_srv, N_unsrv
    Update I_active from I
end while
Output CA as the locally-optimal solution
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with different combination of bands from a mesh node to any gateway node since it is a NP-hard problem. However, based on the discussion in Section III-A, if two paths have the same number of used bands along those paths, then the path with the least hops is likely to have the greatest performance and is chosen. Similarly, if two path have the same path interference, we choose the path which has higher-frequency links for spatial reuse. Thus, the next step of the algorithm is to find the shortest path across band combinations.

To run the algorithm, compared to the number of mesh nodes, the amount of channels N_B in different bands is small. The time complexity of calculating the combination is $O(2^{N_B})$. Finding the shortest path in Dijkstra algorithm will cost $O(N_E^2)$ according to [22], where N_E is the set of possible links in the network, and as a result, the total complexity would be $O(N_E^2 \cdot 2^{N_B})$. The algorithm would then calculate the PIN of the candidate path and select the path with the least interference channel induced on the network for the source mesh node. After a path is assigned, the algorithm updates the network's channel assignment with served nodes, activated links, and radio information. Then, we iteratively assign channels for all the mesh nodes in the network.

If all the nodes are connected to gateway nodes ($N_E = \binom{n}{2}$ which is $O(N_V^2)$), then the complexity of assigning a channel for a mesh node is $O(N_E^2 \cdot 2^{N_B})$. Then, the complexity of assigning a mesh node is $O(N_V^4 \cdot 2^{N_B})$. To assign *all* the nodes in the network, the complexity would be $O(N_V^5 \cdot 2^{N_B})$. The complexity is polynomial time of the number of traffic demands points (client group) for a wireless network assignment.

IV. EVALUATION OF WHITEMESH CHANNEL ASSIGNMENT

We now extensively evaluate our proposed measurement-driven heuristic algorithm against the upper bound approaching formed by our integer linear program and versus prior channel assignment strategies. We introduce the topologies and metric calculation used in the analysis and present a set of results based on the linear program and heuristic algorithm.

A. Experimental Evaluation Setup

A key aspect of WhiteMesh networks is the diversity in propagation from the lowest white space channels (tens to hundreds of MHz) to the highest WiFi channels (multiple GHz). Thus, to evaluate the performance of our measurement-driven algorithm, we consider a wide range of propagation characteristics from four different frequency bands. For white space bands, we choose 450 and 800 MHz, for WiFi bands, we choose 2.4 and 5.8 GHz according to the measurements from [8]. In the 9 measurements from [8], we map the population density from US census [23] to the activity level for each bands as Table. I. The measurements connect the relation of population distribution, traffic demand, and available channel capacity in multiple bands. We input the measurements to the ILP and heuristic algorithm to calculate the available channel capacity δ for our algorithm which makes the available channel capacity of all the bands more practical. With the same transmission power and antenna gain, the highest carrier frequency would have the shortest communication range. Hence, we set a communication-range threshold of -100 dBm, and normalize the communication range with the highest frequency of 5.8 GHz. In particular, the communication range of 450 MHz, 800 MHz, 2.4 GHz, and 5.8 GHz would be normalized to 12.8, 6.2, 2.4, and 1, respectively according to Eq. 1. The interference range is computed as twice that of the communication range [24]. We deploy static wireless mesh networks of n mesh nodes along a regular grid with a normalized distance of 0.8 between rectangular edges. The gateways are chosen through a typical cell hexagon deployment method based on 2.4 GHz [25]. Unless otherwise, specified in the analysis, all four bands are used in the WhiteMesh topology studied. For practical application scenarios, more channels could be involved in the algorithms.

The throughput achieved through the gateways is not only critical for network vendors (e.g., cellular carriers charge fees for total bandwidth through towers), but also has been used by researchers to evaluate channel assignment [26]. As mentioned previously, the wireless capacity of gateway nodes has been shown to be the bottleneck in mesh networks [27]. Moreover, traffic arrived gateway is affected by multiple factors, such as mesh node placement, gateway placement, routing, and channel assignment, the latter of which is the focus of our analysis and algorithms. For the purposes of our analysis, we specifically calculate the traffic arrived gateway first introduced in Section II-B in the following way. Mesh nodes that have a close hop count path to the gateway nodes are the first ones served. Where there are nodes with the same hop count, the least interfering mesh nodes are chosen for serving. Then, the demand of multihop mesh nodes are served until there is no remaining demand to be satisfied or there is no remaining channel capacity through any path.

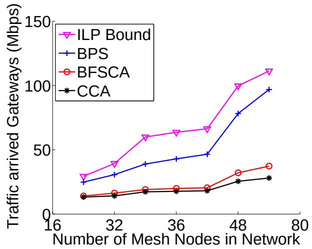
Through the algorithms, we investigate the impacts of network size, bands availability, and channel occupancy on wireless white mesh networks. We vary the average population distribution and the available channel capacity according to [8] of the target area, assuming 10% of the residents will use our service. An individual would have a 100 KB/s traffic demand on average. Then, we assign the demand to users randomly under the same average value across the area and run the analysis of each case 20 times as the simulation configuration. Through the assignment, the traffic arrived at gateway nodes and the network throughput are calculated. To approach the traffic arrived gateway up-bound, we relax our ILP model to keep the link capacity constraints, given the demand of the mesh nodes as a parameter to achieve the maximum throughput at the gateways. We compare BPS with the *(i)* Common Channel Assignment (CCA) from [28], *(ii)* Breath First Search Channel Assignment (BFS-CA) from [9] under the same configuration. In typical CCA [28] algorithm, two nodes will assign a common channel for each other when both of them share free radios working in the same channel. In BFS-CA [9] algorithm, a node will search all the available one-hop connections then choose the one has the largest available capacity for a new assignment. These two methods focus on multi-channel assuming the existing links are equal when there is no assignment on the channel. In BPS, we both consider and leverage propagation differences of diverse bands. The ILP Bound calculation make the mesh nodes activate all possible connection the gateways if there exists a path. However, the three heuristic algorithms provide assignment each mesh node has connection only to one gateway in the network, and this reduce the dynamic changes for the assignment, which could be implemented by updating the assignment in a short term through the heuristic algorithms.

B. Experimental Analysis of WhiteMesh Backhaul

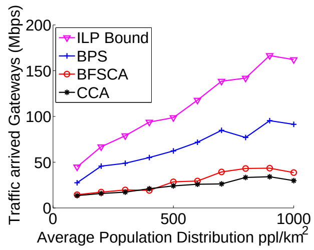
1) Network Size & Bands Effect: Typically, clients and mesh nodes have diverse traffic patterns with the download direction dominating the total traffic demand (e.g., consider service agreements for cellular data or Internet connectivity). Hence, to simplify the analysis and scale the ILP Bound to larger network sizes, we only consider the download traffic while maintaining the simulations. We then assign distributed download traffic demand randomly per mesh node with a maximum offered load to simulate the practical scenario as specified in Fig. 3 and Table II. We average the results of 20 simulations each of the algorithms for the given network configuration and compare the results to analyze multiband application in wireless network.

First, we investigate network sizes impacts on wireless white mesh network. The number of mesh nodes is varied from 16 to 64 in the aforementioned regular grid. As the network size grows, so too does the number of gateways through the hexagon gateway nodes deployment. Fig. 2(a) shows the total traffic arrived gateways when the population distribution is 500 ppl/km^2 for the ILP formulation and the heuristic algorithms: *(i)* Common Channel Assignment (CCA) from [28], *(ii)* Breadth First Search Channel Assignment (BFS-CA) from [29], *(iii)* our algorithm BPS (Section III-B).

In Fig. 2(a), we observe as the network size increase, the performance gap among BPS and CCA/BFS-CA goes up. When the network size which represent the size of target area, the multiband wireless network has similar communication and interference performance with the multi-channel wireless



(a) Average Population Distribution = 500 ppl/km^2



(b) Varying Load, 49-Nodes Regular Grid

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

network since all the nodes are located in a limited space where could be communicated/interfered by all the bands. As network size increase, the connection/interference variation among multiple bands makes the performance of multi-channel algorithms stay in low level. The ILP Bound shows what could be expected, that an increasing number of gateways/mesh nodes produce an increase in total traffic arrived gateways. However, we observe that CCA, BFS-CA algorithms are not able to achieve such behavior for various reasons. CCA fails to employ the communication range variation and find the most efficient hop connections which increase the average hop count. BFS-CA optimizes the first connection hop from the gateway, but fails to deal the whole path from the gateway to destination node. Conversely, BPS alleviates the strain on these first-hop, bottleneck links, achieving average 76% of the ILP Bound. The gap of BPS to the ILP is part from that the BPS only considers static one path to a gateway node for each mesh node, whereas the ILP allows multiple paths to the gateways. For BPS and other heuristic algorithms the dynamic assignment could be implemented through updating the assignment in a short term.

Next, we consider a different form of scalability in our analysis. Namely, we increase the average population distribution from 100 to 1,000 per km^2, while maintaining a 49-node regular grid topology. In the simulation set up, we map the channel capacity to the closest population measurement results. If there are measurements has the same distance to the current set up, the lower population measurement will be chosen, for instance, we map $400ppl/km^2$ to $300ppl/km^2$ measurements as shown in Table. I. In Fig. 2(b), it shows that as the population distribution increases, the ILP and BPS diverge greatly from the remaining algorithms. Similar to Fig. 2(a), the wireless channel capacity around a gateway is quickly saturated if the algorithm is not focused on preserving that resource. Another factor of the performance is the channel capacity, as population increase the measured channel capacity vary in different bands. As the population reaches 1,000, the traffic arrived gateways decrease due to the channel capacity and the saturation of wireless channel capacity around the gateway nodes. BPS has an average performance of 60% of the ILP Bound, on average. CCA and BFS-CA fails to serve more traffic demand through the jointly WiFi and white space wireless network.

WhiteMesh networks could be deployed across a vast array of environments, from rural to urban areas. Each of these areas will have varying amounts of user demand traffic in proportion to the population densities. However, since a greater number of TV stations exist in urban areas, the available white space bands are often inversely related to the population density due to the FCC rules [5]. Also the available channel capacity is related to the existing signal activities in the area. To capture these varying degrees of demand and white space availability we consider three likely scenarios and one final scenario for comparison purposes: *(i)* two WiFi bands (2.4 and 5.8 GHz) channels with two white space channels (450 and 800 MHz), *(ii)* three channels in two WiFi bands (2.4 and 5.8 GHz) with one white space channel (450 MHz), *(iii)* Four channels in two WiFi bands (2.4 and 5.8 GHz) without any white space channels, and *(iv)* four channels in two white space bands (450 and 800 MHz) with no WiFi bands (for comparison).

Table II describes the achieved traffic arrived gateways for various combinations of WiFi and white space bands with a maximum offered load of 5 Mbps from 500 ppl/km^2 in a regular 49-node grid. We consider the performance of BPS in the four aforementioned scenarios of varying white space availability. A regular, 49-nodes grid is again used. In the simulation, we keep 4 channels for each method, such as in the combination of 2.4 GHz and 5 GHz, we put 2 channels in both bands. In the triple bands combinations, we set each band has a channel, and put the other channel in the highest frequency band. (In 2.4 GHz, 5GHz, 800 MHz combination, we put the extra channel other than the 3 channel each band in 5 GHz). Immediately, we observe that the WiFi-only scenario has greater traffic arrived gateways than the white-space-only scenario. This is due to the lack of spatial reuse achieved by white spaces. White space has larger communication to shorten the hop counts as well as has larger interference reducing the spatial reuse. Another reason is that the available channel capacity of 500 ppl/km^2 in white space bands are worse than WiFi bands. This two reasons make the white space only has worse performance no matter what channel assignment methods are applied. Interestingly, however, the joint use of both white space and WiFi bands has significant gains over the single type of band scenarios with the same number of channels (40% greater than WiFi and 56% over white space, on average).

In 500 ppl/km^2 scenario, 5 GHz channel is cleaner than 450 MHz which makes the combination of 2 channels in 5 GHz, 1 channel in 2.4 GHz and 800 MHz has better performance than WiFi(2)+WS(2) in some cases. Obviously, in Table II that with the same number of available bands (2), when the combination has similar propagation characters, such as one in WiFi band, one in white space band, the combination has clean channels have better performance. With similar channel capacity, lower frequency offers more option for connection path could output a better channel assignment. If we have one channel in a white space band and one channel in a WiFi band, then we could use the advantage of both WiFi for spatial reuse and white spaces to reduce the hop count.

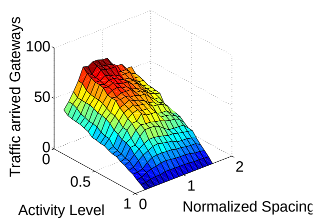
2) Effect of Channel Occupancy: In Fig. 3(a), we show the impacts of channel occupancy through the activity level and spacing variation on wireless white space mesh network. The activity level defined in 2 represent the available channel capacity. The spacing gap is related to the population distribution according to the hexagon deployment for access tier network deployment, the more population distribution, the smaller spacing gap between mesh nodes. In the simulation,

Frequency Bands	Population Distribution ppl/km^2								
	1500	1000	500	300	200	150	100	20	10
450 MHz	24.37	25.83	23.77	6.05	12.50	14.03	7.00	0.07	0.02
800 MHz	4.40	16.49	4.77	5.22	5.07	4.43	3.87	4.20	3.60
2.4 GHz	15.87	34.95	2.60	2.03	2.03	2.77	2.07	1.60	0.80
5.2 GHz	19.70	35.46	1.53	1.93	1.93	1.33	1.27	2.07	2.10

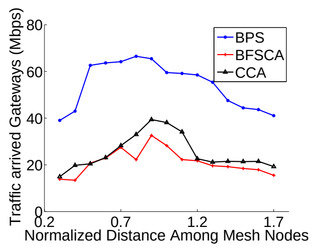
TABLE I
ACTIVITY LEVEL UNDER POPULATION DISTRIBUTION

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]	22.4	13.4	13.2	12.5	16.9	23.2	24.1	30.6	25.2	23.9	30.4
BFS-CA [29]	26.3	15.8	14.9	19.4	22.7	28.4	38.9	33.7	30.1	27.4	36.6
BPS (Alg. 1)	41.2	34.1	38.2	40.0	35.4	42.8	58.4	64.9	54.4	51.9	63.1

TABLE II
THROUGHPUT ACHIEVED THROUGH GATEWAY NODES (MBPS) FOR VARIOUS COMBINATIONS OF WIFI AND AVERAGE POPULATION DISTRIBUTION = 500 ppl/km^2, NETWORK SIZE = 49 MESH NODES).



(a) Uniform Activity Level VS. Space Distance



(b) Traffic arrived Gateways with Activity Level & Spacing

Fig. 3.

we assume all the bands have the same activity level and use the 49-nodes regular grid with normalized multiple spacing distance gap from 0.2 to 2.1. From the 3-D figure, we could see as the activity level increase, the traffic arrived gateways decrease due to the deduction of available channel capacity. In the spacing dimension, when the nodes have small spacing gap, all the bands could not be applied for spacial reuse, the traffic arrived gateways is small. But as the spacing gap increase, the spacial reusing is available for high frequency bands, the traffic arrived gateways increase. Then, as the spacing gap increase over the high frequency communication range, the number of usable channels start to decrease according to protocol model, the traffic arrived gateways decrease in the figure.

We further investigate the spacing gap variation under in-field scenario. The in-field measurement mapping is listed in Table. I. We keep the white mesh network as 49-nodes regular grid, assume each mesh node has 4 radios in each band. As clarified, a larger spacing gap between mesh nodes means less population. We map the largest population distribution in Table I to represent the spacing as normalized distance 0.2, and the least population distribution as normalized distance 1.7. In a regular grid the spacing distance D_s, population distribution P_d and mesh node capacity M_c should obey $P_d \cdot \frac{D_s}{2}^2 \propto M_c$. The 9 measured data sets are mapped to generate the matrix sets. Then according the data in the matrix we interpolate activity level for each normalized distance from 0.2 to 1.7 with gap 0.1. These data sets are put into the heuristic algorithms and the results are shown in Fig. 3(b).

In Fig. 3(b), as the space gap increase, the multiband network has better performance through spacial reuse matching the simulation analysis shown in Fig. 3(a). As the distance increase up to normalized distance 1, one of the channel in 5 GHz could not be applied in the network since the distance is larger than its communication range under the protocol model, that makes the performance decrease quickly. Through this investigation, we can conclude that in sparse area when the number of mesh nodes is small, lower frequency for the back-hual network could have better performance. However, in dense area when the mesh nodes are deployed closely, have higher frequency for spacial reuse is better than the low frequency white space bands.

Through these analysis, a mixed WiFi and white space wireless network could improve the performance in the scenarios as follow: *(i)* Larger network has more mesh nodes, which need more capacity from spacial reuse and flexible path to reduce hop count through more links. *(ii)* Rural area whose spacing gap among mesh nodes is larger. Not only for the number of mesh nodes reducing but also for hop count reducing. However, as we discussed, the flexible paths and the interference among these links become more critical at different points in the WhiteMesh topology. For the sake of completeness, we need cautious selection of frequency bands in wireless network deployment.

V. RELATED WORK

Wireless mesh network deployment is to design wireless architecture for offering Internet service in an target area. There are significant challenges in wireless mesh network deployment, such as user priorities, user behaviors, long term throughput estimation, selfish clients, interference and energy efficiency, etc. [30] These challenges are distinguished under the topics of channel assignment, cognitive radio, protocol design, etc. [30], [31] Previous works have recognize the impact of interference in wireless mesh network deployment is the key issue [9], [32], [33]. To overcome the challenges, a lot of works have been done to optimize the deployment in increasing throughput, minimize resource, reducing interference, etc. [11], [32], [34] Many works have studied the network deployment problem in multihop wireless networks [12], [30], [35], [36]. In addition, multiple radios have been used to improve the routing in multi-channel scenarios [28], [32]. Both static and dynamic network deployments have been discussed in previous works under the 802.11 WiFi scenario [29], [34], [37]. However, 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. Frequency agility in multiband scenario brings more traffic capacity to wireless network deployment as well as more complexity of resolving the interference issues.

Previous work [8] involve the inter-network interference in multiband scenario, but did not offer the solution of intra-network interference. As a new designed wireless network, intra-network interference is more important for performance estimation. Previous work focus on WiFi wireless networks proposed several methods to reduce the interference targeting on multiple metrics. [9], [27], [38] focus on reducing the gateway mesh nodes. [32], [34] try to reduce the overall interference in the worst case of traffic independent scenario. [33], [39] improve the performance in throughput. However, these works fails to involve the traffic demands of clients in their solutions. [10], [27] consider the QoS requirements in the WiFi network design. Our work also consider the traffic demands from the client as part of our network design to satisfy both customers and vendors.

The wireless network deployment problem has been proved as a NP-hard problem [11]. Several works introduce relaxed linear program formulation to find the optimization of multihop wireless networks [9], [32], [40]. Also, game theory methods is another option to solve the problem [24], [41]. Social network analysis is also popular in wireless network design [42]. In this work, we model the problem to a linear program to approach the optimal solution and generate heuristic algorithms to find a practical solution for the problem.

To be used effectively, white space bands must ensure that available TV bands exist but no interference exists between microphones and other devices [43]. White space bands availability has to be known in prior of network deployment. TV channels freed by FCC are fairly static in their channel assignment, databases have been used to account for white space channel availability (e.g., Microsoft's White Space Database [44]). In fact, Google has even visualized the licensed white space channels in US cities with an API for research and commercial use [7]. In contrast, we study the performance of mesh networks with a varying number of available white space channels at varying population densities, assuming such white space databases and mechanisms are in place. As FCC release these bands for research, many methods have been proposed to employ these frequency bands. [43] introduce WiFi like white space link implementation on USRP and link protocols. [17] discuss the point to point communication in multiband scenario. In [40], white space band application is discussed in cognitive radio network for reducing maintenance cost. In [45], the white space is proposed to increase the data rates through spectrum allocation. In our work, we focus on maximizing the throughput of the wireless network.

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 in pratical scenarios. To do so, we used an integer programming model with in-field measurements to find optimal WhiteMesh channel assignment. We then constructed a measurement driven heuristic algorithm, Band-based Path Selection, to approach optimal performance with reduced complexity. Through extensive analysis across varying offered loads, network sizes, and white space channel availability, we show that our algorithm can achieve 180% the served user demand versus previous multi-channel, multi-radio solutions in multiband scenarios, 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 160% of the traffic arrvied gateways of similar WiFi- or white-space-only configurations.

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