WhiteMesh: Leveraging White Spaces in Wireless Mesh Networks

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***Abstract*—While there were high hopes for multihop wireless networks (mesh) to provide ubiquitous WiFi in many cities, in-field trials revealed the node spacing required for WiFi propagation induced a prohibitive cost model for network carriers to deploy. However, 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 paper, we analyze our in-field measurements in the Dallas-Fort Worth metroplex of channel occupancy in both WiFi and white space frequencies to deploy a wireless multihop backhaul tier. We design a measurement-driven heuristic algorithm, Band-based Path Selection (BPS), to approach optimal channel assignment of both white space and WiFi spectrum with reduced computational complexity. Numerical results show that BPS nearly doubles the served traffic of existing multi-channel, multi-radio algorithms, which are agnostic to diverse propagation characteristics across bands. Most importantly, this paper lays a foundation for the optimal use of white space and WiFi bands in the backhaul tiers of mesh networks across diverse population densities.**

I. Introduction

During the last decade, numerous cities solicited proposals from network carriers for exclusive rights to deploy city-wide WiFi, spanning hundreds of square miles. But many of these attempts failed, as the node spacing prohibited their cost effective implementation. 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 which was once anticipated [4].

Meanwhile, the FCC has approved the use of broadband services in the unused portions of UHF TV bands, noted as white space bands, which were formerly exclusively licensed to television broadcasters. These white space bands are now available for unlicensed public use, enabling the deployment of wireless access networks across a broad range of scenarios from sparse rural areas (one of the key applications identified by the FCC) to dense urban areas [5]. The white space bands operate in available channels from 54-806 MHz, having a far greater propagation range than WiFi bands for similar transmission power and antenna characteristics [6].

The number of available channels in the white space spectrum varies from city to city but is generally inversely proportional to population levels as shown in existing spectral databases (*e.g.*, [7]). Specific to rural areas, the lack of user density and corresponding traffic demand per unit area as compared to dense urban areas allows greater levels of traffic aggregation across larger areas to reduce the total number of required access points, lowering network deployment costs. Conversely, in densely-populated urban areas, the greater concentration of users and higher levels of traffic demand can be served by maximizing the spatial reuse. Considering the increased range of white space frequencies, the following question arises for improving the performance and costs of wireless mesh networks: Where along the continuum of user population densities do the white space bands no longer offer cost savings for wireless network deployments? While much work has been done on deploying multiple channel wireless networks, the differences in propagation among diverse carrier frequencies have not been exploited in their models [8], [9], and the availability of white spaces is not considered, each of which could be fundamental to the growth of mesh networks.

In this paper, we perform a measurement-driven study jointly considers the propagation characteristics and in-field spectrum availability of white space and WiFi channels for optimally building multi-tier mesh networks with limited spectral resources. Driven by these measurements, we design a linear program and a heuristic algorithm, Band-based Path Selection (BPS), to address the channel assignment problem in mesh backhaul tier deployment with both WiFi and white space bands across various aspects including network size, population distribution, and inter-node spacing between access points.

The main contributions of our work are as follows:

- We analyze backhaul tier, wireless network and jointly consider both white space and WiFi band propagation and usage with a linear program model.
- We build a measurement-driven reduced complexity heuristic algorithm, Band-based Path Selection (BPS).
- Through extensive analysis across offered loads, network sizes, and mesh node spacings with WiFi and white space band combinations, we show that the served traffic of users can nearly double when compared with prior multi-channel, multi-radio algorithms.

In Section II, we formulate the channel assignment problem in WhiteMesh networks. In Section III, we introduce our linear program analysis and develop a heuristic algorithm which consider bands and multihop path selection in a WiFi/white space backhaul tier. Related work is discussed in Section IV, and conclusions are drawn in Section V.

II. Leveraging Diverse Unlicensed Bands for Multi-Tier Mesh Networks

In this section, we introduce and analyze wireless access networks which jointly use WiFi and white space frequencies in a multi-tier mesh scenario. A critical aspect of our study is considering the propagation and spectral usage differences and analyzing the impact on various population densities.

A. WhiteMesh Structure and Restrictions

The term WhiteMesh refers to the joint use of WiFi and white space frequencies in the backhaul tier and access tier (whether in a multihop scenario such as mesh networks or even in a single hop scenario such as wireless LAN). The number of white space channels is typically inversely proportional to the population density. The diverse attributes of WiFi and white space bands impact network deployments in unique ways. Sparse populations generate relatively low amounts of traffic demand. The lower traffic demand requires fewer spectral resources for users directly connecting to the access points and may allocate more resources to links between access points (backhaul tier). Conversely, in densely-populated areas, there is likely a greater availability of wired entry points to the Internet. At the same time, the dense population generates more traffic demand requiring greater use of spectral resources for the access tier and less availability of white space, both of which lead to less spectral resources available for the backhaul tier.

The propagation variation of bands is characterized as the received signal power P_r in the Friis model in terms of transmit power P_t, transmitter gain G_t, receiver gain G_r, wavelength λ of the carrier frequency, distance R_p from transmitter to receiver, and path loss exponent n according to [10]:

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

Here, n varies based on the aforementioned environmental factors with a value ranging from two to five in typical outdoor settings [11]. Thus, the propagation range of white space frequencies is longer than WiFi frequencies in nature given the same set up. This effect could be beneficial for sparse areas since the traffic demand from the sparse population is relatively lower. Conversely, a densely-populated area could rapidly saturate the capacity of a single white space channel. As mentioned previously, it is straightforward to solve the band selection problem in network deployment of these two extreme cases: (*i*) in a highly-sparse area, white space bands are better at aggregating the relatively lower traffic demand in larger areas; (*ii*) in a highly-dense area, WiFi bands are better for spatial reuse, and these regions typically have less white space channels available for use. However, the deployment scenario is generally somewhere between these two extremes. To quantify and maximize the benefit of jointly using these bands, our work investigates backhaul tier design of WhiteMesh networks across varying population densities. While we consider the impact of the access tier on backhaul tier design later in this work, we leave the channel selection problem along the access tier for future work due to space constraints.

B. Problem Formulation

Prior work on wireless networks focused on improving the capacity by reducing the intra-network interference [12], [13]. However, many of these works assume uniform propagation characteristics of the multiple channels used in the deployment [13]. In this work, we reduce the overall cost of a multi-tier mesh network design by leveraging: non-uniform propagation across unlicensed frequency bands, varying spectral activities measured in the field, and diverse population densities (leading to diverse traffic demands and white space channel availability).

Spectrum occupancy is a key factor in wireless network design. Despite sufficient levels of received signal, high occupancy can cause channels to be unusable (*e.g.*, due to high levels of packet loss) or unavailable (*e.g.*, due to primary users in a cognitive radio scenario [14], [15]). These interfering spectrum occupants in wireless networks could be divided into two categories according to: (*i*) intra-network interference, generated by nodes in the same network, and (*ii*) inter-network interference, generated by nodes or devices outside of the network.

Backhaul tier design is a critical network deployment issue to increase the traffic served by the carriers. On behalf of a carrier, we denote the total traffic served X, represented as:

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

where $T(w, v)$ represents all delivered traffic between access point $v \in V$ and gateway node $w \in W$. Many factors will influence the total traffic served, such as the network topology, channel assignment, and routing [16]. Here, we focus on the channel assignment problem across WiFi and white space frequency bands. Thus, our objective is to generate a channel assignment CA maximizing the total traffic served.

$$X^* = max\{X\}, given\{Routing, Topology, etc.\} \tag{3}$$

We later discuss the interaction between the access and backhaul tier through the spacing among the access points in III-E.

III. WhiteMesh Backhaul Tier Channel Assignment and Evaluation

In this section, we study the channel assignment problem jointly when using WiFi and white space bands across the backhaul tier of a wireless mesh network. We then present our linear programming model and heuristic, measurement-driven algorithm to address the problem.

A. Linear Programming Formulation

We classify the access points into two sets: mesh nodes (V) which aggregate and forward the traffic from the users, and gateways (W), which serve as ingress points to the Internet. The available frequency bands (B) are pre-known as an input. The conflict graph I is given, and δ_b is the achievable channel capacity estimated from the activity level measurements discussed in previous work [17].

Sets:

N	access points (nodes)
$L = \{i \in N, j \in N : i \neq j\}$	links
$V \subset N$	mesh nodes
$W = N \setminus V$	wired gateway nodes
B	bands

Parameters:

δ^b	$b \in B$	Achievable capacity of band b in target area
$I^b_{ij,\ell m}$	$(i,j),(\ell,m) \in L, b \in B$	Interference matrix based on protocol model of link (i,j) on band b brought by link (l,m)
U_i	$i \in V$	Uplink demand from mesh node i
D_i	$i \in V$	Downlink demand to mesh node i

Variables:

$0 \le \alpha^b_{i,j} \le 1 \quad (i,j) \in L, b \in B$
Link (i,j) time share on band b

$u^b_{i,j,k} \ge 0 \quad (i,j) \in L, k \in V, b \in B$
Uplink flow from mesh node k on link (i,j) at band b

$d^b_{i,j,k} \ge 0 \quad (i,j) \in L, k \in V, b \in B$
Downlink flow to mesh node k on link (i,j) at band b

Connectivity Constraints

$$\alpha^b_{i,j} + \alpha^b_{j,i} + \sum_{b\in B} \sum_{(\ell,m)\in L} (\alpha^b_{\ell,m} \cdot I^b_{ij,\ell m}) \le 1, \quad (i,j) \in L, b \in B \tag{5}$$

$$\sum_{k\in V} u^b_{i,j,k} + \sum_{k\in V} d^b_{i,j,k} \le \delta^b \cdot \alpha^b_{i,j}, \quad (i,j) \in L, b \in B \tag{6}$$

Uplink Constraints

$$\sum_{\{j\in N: j\neq k\}} \sum_{b\in B} u^b_{k,j,k} \le U_k, \quad k \in V \tag{7}$$

$$\sum_{\{i\in V: i\neq j\}} \sum_{b\in B} u^b_{i,j,k} = \sum_{\{i\in N: i\neq j\}} \sum_{b\in B} u^b_{j,i,k}, \quad k \in V, j \in V, j \neq k \tag{8}$$

Downlink Constraints

$$\sum_{\{j\in N: j\neq k\}} \sum_{b\in B} d^b_{k,j,k} \le D_k, \quad k \in V \tag{9}$$

$$\sum_{\{i\in N: i\neq j\}} \sum_{b\in B} d^b_{i,j,k} = \sum_{\{i\in V: i\neq j\}} \sum_{b\in B} d^b_{j,i,k}, \quad k \in V, j \in V, j \neq k \tag{10}$$

In these constraints, (5) ensures that the total time assigned per link is at most 1 and consists of: incoming flows, outgoing flows, and interference time. Constraint (6) ensures that the incoming and outgoing wireless traffic does not exceed the capacity assigned to link (i,j). Constraints (7) and (8) are flow-balance constraints for uplink flow from mesh node k: (7) limits the uplink traffic served to U_k, and (8) ensures that all uplink flow from node k coming into mesh node j from other mesh nodes is distributed out to other nodes (mesh or gateway). Constraints (9) and (10) are the corresponding flow-balance constraints for downlink traffic. Since jointly optimizing channel assignment and routing in a wireless network is NP-hard in general [16], we use an LP model to efficiently find an upper bound on total traffic served for a given channel assignment, and propose a heuristic for solving the joint problem.

B. 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 the resulting starvation effects for downstream nodes, we treat each flow with equal priority in the network when assigning channels. To guarantee the service, all nodes along a particular path have equal time shares for contending links (*i.e.*, intra-path interference). We begin 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 compete with each other. Each mesh node along the path has traffic demand T_d. The bottleneck link along the path would be the one closest to the gateway. Thus, the total traffic along the path $h \cdot T_d$ must be less than the bottleneck link's achievable capacity δ, estimated according to the raw channel capacity less the activity level measured according to the region type. 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.

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 by reducing the interference among the links of its *own* path. However, a lower carrier frequency will induce greater interference to *other* paths to the gateway (*i.e.*, inter-path interference). 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 is denoted 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 time 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 time of network cost for the h-hop path is:

$$E_\eta = \frac{T}{\sum_{i\in h} \frac{(h-i+1)\cdot T}{\gamma_i} \cdot I_i} \tag{11}$$

Through network efficiency, the equation simplifies to:

$$E_\eta = \frac{\gamma}{\sum_{i\in h} (h-i+1) \cdot I_i} \tag{12}$$

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 similar communication range. With multiple bands, I_i depends on the band choice due to the diversity in communication range. Network efficiency jointly considers hop count and interference in the paths. We define the Path Interference induced on the Network (PIN) as the denominator of (12). The parameter represents the sum of all interfering links in the network for a given path.

PIN is used to quantify the current state of a link's 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:

$$\frac{\gamma}{\frac{h(h-1)}{2} \cdot \bar{I} + I_x} \ge \frac{\gamma}{\frac{h(h+1)}{2} \cdot \bar{I}} \tag{13}$$

Here, from (13), when $I_x \le 2 \cdot h\bar{I}$, the performance of a lower-frequency link has better network efficiency than two higher-frequency hops for the same destination node. I_x is also a parameter of hop count in (12). When the hop count is lower to the gateway node, the threshold would be more strict since the interference have a greater effect on the performance.

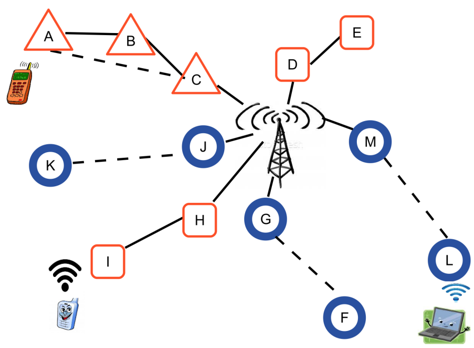


Fig. 1. Example WhiteMesh topology with different mesh-node shapes representing different frequency band choices per link.

C. Band-based Path Selection (BPS) Algorithm

Consider the following example in Fig. 1, the mesh node A could connect to mesh node C relayed by node B with 2.4 GHz, or directly connect to C with 450 MHz. If 2.4 GHz are chosen, link D, E is able to reuse 2.4 GHz when they are out of the interference range. However, along the backhaul tier, if link A, C used 450 MHz, a lower hop count would result for the path, yet lower levels of spatial reuse would 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 done.

Thus, in the backhaul tier, we formulate the problem with a graph-based model. A connectivity graph C is formed for each band in B such that $C = (V, L, B)$. In the protocol model, if the received signal for a given band is above a threshold among nodes, contention occurs for these nodes. We extend the conflict matrix in [8] representing the interference per band according to $F = (E_{i,j}, I_{Set}, B)$, where $E_{i,j}$ represents the potential active links. I_{Set} includes all the links that are physically inside the interference range. D_r represents when there is an active link working on band $b \in B$. Therefore, a key challenge is that selecting the optimal channels from the set B leads to a conflict graph F, which cannot be known *a priori*.

We design a Band-based Path Selection (BPS) algorithm shown in Algorithm 1. The algorithm first chooses the mesh node that has the largest physical distance from the gateway nodes in the network to reduce the total time cost of the network by reducing the hop count. 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. In large-scale mesh networks, it has been proven as an NP-hard problem to traverse all the paths with different combinations of bands from a mesh node to any gateway node. Based on the discussion in Section III-B, 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 paths have the same path interference, we choose the path which has higher-frequency links to keep the potential improvement of spatial reuse and preserve the use of lower-frequency links.

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 $O(2^{N_B})$. The complexity of finding the shortest path via Dijkstra's algorithm is $O(N_E^2)$ [18], where N_E is the number of links in the network. The complexity of the algorithm is $O(N_E^2 \cdot 2^{N_B})$. The algorithm compares the PIN of the paths and selects the path with the least interference on the network. The algorithm iteratively updates the channel assignment of the network after one path is chosen, including served nodes, activated links, and radio information.

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

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 nodes 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
Update CA as the locally-optimal solution
```

D. Experimental Evaluation Setup

We investigate the impact of network size, band availability, and spectrum occupancy on WhiteMesh networks using measurement-driven simulation with 450 MHz and 800 MHz as the white space spectrum and 2.4 GHz and 5.2 GHz as the WiFi spectrum. The communication threshold is set to -100 dBm. The communication range is normalized to the range of the highest frequency band (5.2 GHz), creating a factor of 12.8, 6.2, 2.4, and 1 for 450 MHz, 800 MHz, 2.4 GHz, and 5.2 GHz, respectively. To see the details of our measurement study, refer to [17]. The interference range is set to twice that of the communication range [19]. We perform channel assignment for 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 hexagonal deployment method based on 2.4 GHz [20]. Unless otherwise specified in the analysis, all four bands are used in the WhiteMesh topology studied. For practical application scenarios, more channels could be considered by the BPS algorithm.

To perform the analysis, we generate an equal number of access points (including both gateway nodes and mesh nodes) for each scenario. We specifically calculate the total traffic served through a greedy routing strategy. To maximize the total traffic served for each algorithm and scenario, we start to serve the traffic demand from the gateway nodes. Mesh nodes that have a lower hop count path to the gateways are served first. When mesh nodes have the same hop count, the least interfering mesh nodes are chosen to reduce the cost for the entire network. When the paths have the same level of interference, the ties are broken by the node order.

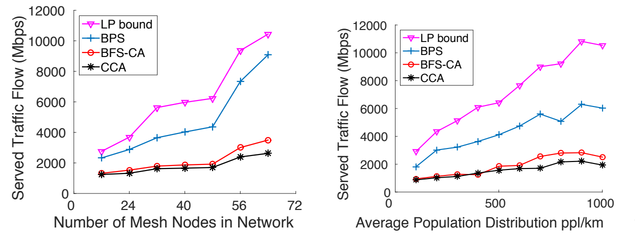
We ran the simulation 20 times for each scenario. To approach the total traffic served upper bound, we relax our LP model to only preserve the link capacity constraints, given the traffic demand of the mesh nodes as a parameter to achieve the maximum throughput at the gateways. We further compare BPS to the *(i)* Common Channel Assignment (CCA) from [21], and *(ii)* Breath First Search Channel Assignment (BFS-CA) from [8] under the same setup. The CCA [21] algorithm assigns a common channel for two nodes when both of them share available radios working on the same channel. In the BFS-CA [8] algorithm, a node will search all the available single-hop connections and then choose the one that has the largest available capacity for a new assignment. These two methods are designed for multi-channel scenarios where each channel has the same propagation characteristics and spectral activity level.

E. Experimental Analysis of WhiteMesh Backhaul

Typically, the traffic patterns of mesh nodes from users are diverse 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 LP bound to larger network sizes, we only consider the download traffic in the analysis.

1) Network Size & Bands Effect: We first consider the network size impact on WhiteMesh networks. The number of mesh nodes is varied from 16 to 64 in the aforementioned regular grid. We choose the wired gateway locations according to the center mesh node of each hexagon of seven mesh nodes in the regular-grid deployment to cover the service area. The service area of each gateway is from the propagation limit of the bands. The number of gateways increase with the number of mesh nodes of the network. In this simulation, the number of gateways is fixed for multiple population distribution configurations. Fig. 2(a) shows the results of the total traffic served when the population distribution is 500 ppl/km^2 for the LP formulation and the heuristic algorithms: *(i)* Common Channel Assignment (CCA) from [21], *(ii)* Breadth First Search Channel Assignment (BFS-CA) from [22], and *(iii)* our BPS algorithm.

In Fig. 2(a), we observe the WhiteMesh network has more total traffic served as the network size increases compared to the multi-channel algorithms (CCA and BFS-CA). To do so, our algorithm which considers diversity across multiple frequency bands (BPS), and an LP bound. As the network size increases, the backhaul tier requires a greater level of traffic. In the LP-bound curve, the larger network size requires



(a) Average Population Distribution = 500 ppl/km^2 (b) Varying Load, 49-Nodes Regular Grid

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

more wired gateways, creating a sharp increase in the total traffic served. For each level of total mesh nodes, however, we keep the number of gateways the same to compare across algorithms. For example, with 56 mesh nodes, there are 10 wired gateways versus 6 wired gateways with 32 mesh nodes, but more than double the total traffic served is achieved by the BPS algorithm. While adding gateways seems like a high-impact method for improving network performance, the CCA and BFS-CA algorithms are not able to fully utilize the gateway capacities. When growing the network from 32 to 48 mesh nodes (keeping the wired gateways fixed at 6), we observe that BPS does not have as a drastic an increase in the total traffic served than when growing the network from 56 to 64 mesh nodes (keeping the wired gateways fixed at 10). Across all mesh node quantities, BPS achieves an average of 76% of the LP bound with respect to the total traffic served and greatly outperforms CCA and BFS-CA. We observe the key inefficiencies of each of the prior algorithms as: (*i*) CCA primarily focuses on finding the available channels, and (*ii*) BFS-CA only optimizes the first-hop connection from the wired gateways without considering other downstream hops.

In Fig. 2(b), we increase the average population density from 100 to 1,000 per km^2, while maintaining a 49-node regular grid topology. The achievable channel capacity is calculated according to the raw channel capacity minus the in-field spectral measurements with the closest population density for a given land use. Over all the population distributions, BPS achieves 60% of the LP bound on average. The total traffic served gap between the LP bound and BPS ranges from 26% to 74%. The BPS gains over the BFS-CA algorithm range from 78% to 186%. The BPS gains over the CCA algorithm range from 104% to 223%. The growth in gain can be seen with the growth in population density because when the traffic demand is low, a channel assignment of similar wireless channels could easily serve the users. However, as the traffic demand increases, the channel assignment, which reserves each band for the certain roles of lowering the hop count (white space) and reducing interference (WiFi), performs much better than these multi-channel algorithms. We can see the importance of considering the diversity in frequency bands as part of the channel assignment for WhiteMesh networks.

To capture the varying degrees of demand and white space availability, we consider three likely scenarios and another scenario for real-world similar comparisons as shown in Table II: *(i)* Four channels in two WiFi bands (2.4 and 5.2 GHz) without any white space channels, *(ii)* four channels in two white space bands (450 and 800 MHz) with no WiFi bands (for comparison), *(iii)* two WiFi band channels (in 2.4 and 5.2 GHz) with two white space channels (in 450 and 800 MHz),

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 ACROSS POPULATION DENSITY

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[24]	1344.0	804.0	792.0	750.0	1014.0	1392.0	1446.0	1836.0	1512.0	1434.0	1824.0
BFS-CA[25]	1578.0	948.0	894.0	1164.0	1362.0	1704.0	2334.0	2022.0	1806.0	1644.0	2196.0
BPS(Alg.1)	2472.0	2046.0	2292.0	2400.0	2124.0	2568.0	3504.0	3894.0	3264.0	3114.0	3786.0

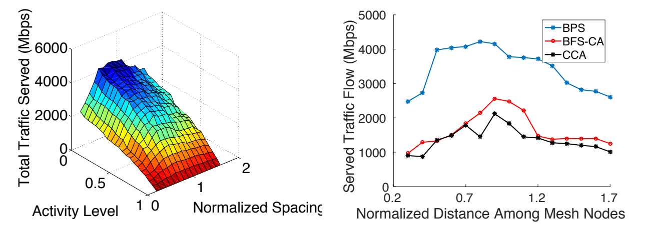
TABLE II
TOTAL TRAFFIC SERVED (MBPS) FOR VARIOUS COMBINATIONS OF WIFI AND AVERAGE POPULATION DISTRIBUTION = 500 ppl/km^2, NETWORK SIZE = 49 ACCESS POINTS).

(iv) three channels in two WiFi bands (2 in 2.4 GHz and 1 in 5.2 GHz) with one white space channel (in 450 or 800 MHz), and *(v)* three channels in two white space bands (2 in 450 MHz and 1 in 800 MHz) with one WiFi channel (in 2.4 or 5 GHz).

In the results, for the two kinds of unlicensed bands, we observe that the WiFi-only scenario has a greater total traffic served than the white-space-only scenario. We can attribute this phenomenon to the WiFi bands having more channel capacity with a lower activity level than white space bands for this particular region. Additionally, the interference and communication ranges of WiFi are less than the white space bands, allowing greater spatial reuse as the user demand increases. Going beyond this comparison between WiFi-only and white-space-only scenarios, a key takeaway is that when both white space and WiFi bands are used, there are large gains in the total traffic served over these two aforementioned scenarios (40% over WiFi only and 56% over white space only, on average). Intuitively, the gains come from allowing the highly-concentrated regions of the service area to have the greater spatial reuse of WiFi. Conversely, distant users with less of a traffic demand concentration can leverage white spaces without dramatically increasing the total cost of the network. With the natural heterogeneity that surfaces in any service area, both aspects can be exploited in one network topology at large.

2) Access Tier Impacts on the Backhaul Tier: The density of access points increases proportionally to the population density to offer enough access capacity for the users. Hence, the distance among the access points and the channel occupancy in the backhaul tier channel assignment should be adjusted accordingly. To investigate the impact of both the inter-AP spacing and the spectrum occupancy in the access tier on the backhaul tier, we simulate a 49-node regular grid WhiteMesh network, as described before.

In Fig. 3(a), we depict the impact of spectrum occupancy through the activity level and inter-AP spacing on a WhiteMesh network. When varying the activity level across the graph, we have the same activity level across all four bands for the purposes of our analysis. We construct a 49-node regular grid with an inter-node spacing which is normalized from 0.2 to 2.1 as introduced in Subsection III-D. In the 3-D figure of Fig. 3(a), we observe that as the activity level increases, the total traffic served decreases in proportion to the reduction of achievable channel capacity. In the spacing dimension, the total traffic served peaks around the normalized



(a) Uniform Activity Level VS. Space Distance (b) Total traffic served with Activity Level & Spacing

Fig. 3. Spacing Impacts on the Backhaul Tier

node spacing of 1. Reduction from the peak total traffic served occurs with small inter-AP spacing due to the low traffic demand that is offered by a smaller service area. Conversely, reduction also occurs with larger inter-AP spacing due to poor performing or broken wireless links across the backhaul tier. In the spectral activity dimension, we find that the general trend in peak total traffic served hold, but are reduced by the available channel capacity at high spectral activity. However, at an activity level between 0.8 and 1, the difference of the total traffic served across inter-AP spacing is marginal.

As discussed in Section II, the optimal spacing between mesh nodes is inversely proportional to the population density. To consider this relationship, we map the largest population distribution in Table I to represent the spacing as a normalized distance of 0.2, and the least population distribution as a normalized inter-node spacing of distance 1.7. In a regular grid the inter-node spacing distance D_s, population distribution P_d, and access point capacity M_c obey $P_d \cdot \frac{D_s}{2}^2 \propto M_c$. We interpolate the activity level for each normalized distance from 0.2 to 1.7 with a 0.1 gap.

In Fig. 3(b), we observe that the total traffic served increases at first, and decreases later as the inter-AP spacing increases. This is a similar notion that is depicted in the 3-D Fig 3(a), but this time the spectral activity is diverse across frequency bands and according to in-field measurements for a specific population density. The best total traffic served occurs when the normalized spacing is 1. When the normalized spacing is greater than 1, channels operating with a carrier frequency of 5.2 GHz break since the distance is larger than its communication range. BPS gains 113% over BFS-CA on average and 142% over CCA on average. At small inter-AP spacing, channels across diverse frequency bands perform similarly as no spatial reuse is required. As the spacing increases, the bands take on specific roles: the lower frequency bands are apportioned to allow greater spatial reuse whereas the higher frequency bands are apportioned to allow lower hop counts. The CCA and BFS-CA have no such distinction in roles and therefore have far lower performance.

Through the simulation analysis, more resources, either wired gateways or wireless channels could greatly improve the network performance. For a WhiteMesh network, improvements come in the following forms: *(i)* Heavily-utilized networks can achieve greater total traffic served by splitting the roles of white space and WiFi bands to allow lower hop counts and greater spatial reuse, respectively. *(ii)* Rural networks can have large inter-AP spacing and still fully serve the user traffic demand with a greatly reduced deployment cost.

IV. Related Work

To be used for data communication, white space bands must ensure that available TV bands exist without interference from microphones and other devices [23]. While white space band availability has to be known in advance of network deployment, TV channels allowed 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 [24]). In fact, Google has even visualized the licensed white space channels in US cities with an API for research and commercial use [7], [25]. 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. Many methods have been proposed to employ these white space bands. For example, Bahl *et al*. introduced WiFi-like white space link implementation on USRP links [23]. The point-to-point communication in a multiband scenario was discussed in [26], [27]. In [28], white space bands were applied to a cognitive radio network for reducing maintenance costs. In contrast, the objective of our work is to maximize the total traffic served of clients in a particular service region with WhiteMesh network topologies.

V. Conclusion

In this paper, we jointly considered the use of WiFi and white space bands in WhiteMesh network deployments. We proposed a measurement-driven Band-based Path Selection (BPS) algorithm for the backhaul tier channel assignment across multiple frequency bands. The simulation showed that our BPS algorithm can achieve 180% of the served traffic flow versus previous multi-channel, multi-radio solutions which assume similarity in channels, since we leveraged diverse propagation characteristics and spectral activity offered by WiFi and white space bands. Moreover, we quantified the degree to which the joint use of these bands can improve the served user demand, even against similar single frequency band scenarios. Our BPS algorithm showed that WhiteMesh topologies can achieve up to 160% of the served traffic flow of similar WiFi or white-space-only configurations.

VI. Acknowledgments

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