WhiteMesh: Leveraging White Spaces in Wireless Mesh Networks

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***Abstract*—The in-field trials revealed 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. Thus, jointly apply the low frequency white space spectrum become an emergency issue for the deployment of data networks. In this paper, we quantify the channel occupancy in both WiFi and white space frequencies through measurements in Dallas-Fort Worth metropolitan, propose a measurement-driven band selection framework, Multiband Access Point Estimation (MAPE), and design a measurement driven heuristic algorithm, Band-based Path Selection (BPS), to approach optimally channel assignment in WhiteMesh networks with both white space and WiFi spectrum with reduced complexity. The numerical result shows that the number of access points reduces by up to 1650% in sparse rural areas over similar WiFi-only solutions. It achieves up to 160% served traffic flow gain competing with 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% over that of mesh networks with only WiFi bands or white space bands, respectively.**

I. Introduction

Network design plays a central role in wireless mesh network. In recent years, many efforts have been put on technical sub problems, such as gateway location selection, channel assignment. And also economic sub problems, such as budget estimation, service of quality. Most of the prior works are focusing on the problems from traditional WiFi based wireless networks deployment.

Since 2009, the FCC has approved the use of broadband services in the white spaces of UHF TV 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 [1]. 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 [2]. These new resources and policy offer opportunities for both the industry and academia.

During the last decade, 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 [3] and Philadelphia [4]). Thus, while a few mesh networks have been deployed in certain communities [5], wireless mesh networks have largely been unsuccessful in achieving the scale of what was once anticipated [6]. 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 spatial aggregation to reduce the total number of required access points, lowering network deployment costs. In densely populated urban areas, the greater concentration of users and higher levels of traffic demand can be served by maximizing the spatial reuse.

The digital TV transition freed more spectrum for data networks with increased propagation range as compared to WiFi [2] as white space sprctrum. These additional channel capacity vares in the line with FFC regulation and existing channel occupancy. As shown in Google database [7], the number of available channels in these spectrum vary from city to city in US. 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?*, *(ii) To what degree can white space bands reduce the network deployment cost of sparsely populated rural areas as opposed to comparable WiFi-only solutions?*, and *(iii) 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 channels wireless networks, the differences in propagation among large scale frequencies have not been exploited in their models [8]–[10], which could be *the* fundamental issue for the success of mesh networks going forward.

In this paper, we perform a measurement based study which jointly considers the propagation characteristics and in-field spectrum availability of white space and WiFi channels to find a possible solution of wireless networks deployment. Across varying population densities in representative rural and metropolitan areas, we compare the cost savings (defined in terms of number of access points reduced) when white space bands are not used. To do so, we first define the metric to quantify the spectrum utility in a given target location. With the in-field measured spectrum utility data in metropolitan and surrounding areas of Dallas-Fort Worth (DFW), we calculate the typical channel occupancy of WiFi and white space bands in multiple types of areas. Second, we propose a measurement-driven framework MAPE (Multiband Access Point Estimation) to find the number of access points required for access tier wireless network deployment in a target area with population densities from our measurements and census data. We then evaluate our measurement-driven framework, showing the band selection across downtown, residential and university settings in urban and rural areas and analyze the impacts of white space and WiFi channel combinations on a wireless deployment in these representative scenarios. We further leverage the diversity in propagation with channel occupancy of white space and WiFi bands in the planning and deployment of large-scale backhual tier wireless mesh networks. To do so, we form an linear program to jointly exploit white space and WiFi bands for optimal WhiteMesh topologies in channel assignment. Then, since similar problem formulations have been shown to be NP-hard problem [10], [11], we build a heuristic measurement driven algorithm, Band-based Path Selection (BPS) based on mathematical analysis to solve the problem. We further apply the approaching method in multiple scenarios with in-field measurement data. Across a wide range of scenarios, including network size, population distribution, deployment distance 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 perform in-field measurements of spectrum utilization in various representative scenarios across the DFW metroplex, ranging from sparse rural to dense urban areas and consider the environmental setting (e.g., downtown, residential, or university campus).
- We develop a measurement-driven Multi-band Access Point Estimation (MAPE) framework to jointly leverage propagation and spectrum availability of white space and WiFi bands for wireless access networks across settings and analyze the framework under capacity and coverage constraints to show that, with white space bands, the number of access points can be greatly reduced from WiFi-only deployments by up to 1650% in rural areas.
- We build a complexity reducing heuristic measurement driven algorithm, Band-based Path Selection (BPS), which considers the diverse propagation, overall interference level of WiFi and white space bands and further perform extensive analysis across offered loads, network sizes, mesh nodes spacing and WiFi/white space band combinations, to compare against previous multichannel multiradio algorithms.
- We study 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 the opportunites and challenge of diverse frequency band in wireless network deployment and then formulate the problem. In Section III, we perform our measurements and analysis. In Section IV, we analyze the access tier network deployment, propose MAPE framework and show the results of white space bands gains. We develop a heuristic algorithms which consider which bands and multihop paths to select in a backhual white space topology and 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 V in several scenarios and conclusions are drawn in Section VII.

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. As opposed to previous works such as [8], [12], [13], we focus on both the access tier network deployment and backhual tier network design.

A. White Space Opportunity and Challenge

Wireless propagation refers to the signal loss characteristics when wireless signals are transmitted through the wireless medium. The strength of the received signal depends on both the line-of-sight path (or lack thereof) and multiple other paths that result from reflection, diffraction, and scattering from obstacles [14]. The widely-used Friis equation characterizes the received signal power P_r in terms of transmit power P_t, transmitter gain G_t, receiver gain G_r, wavelength λ of the carrier frequency, distance R from transmitter to receiver, and path loss exponent n according to [15]:

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

Here, n varies according to the aforementioned environmental factors with a value ranging from two to five in typical outdoor settings [16].

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 each 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 uniform propagation assumption have focused on the allocation of multiple WiFi channels with multiple radios in multihop wireless networks with channels in one band [10]. However, as FCC licensed the white space bands for communication, the propagation variation has to be a consideration in wireless networks. 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 within white space frequency [17].

Wireless mesh networks are a particular type of multi-hop wireless network that provides access for users through wireless links with low cost. Naturally, in wireless network design, there is trade off between the budget and the quality of service. Typically, wireless mesh network is considered to have at least two tiers [5]: *(i)* an access tier, where client traffic is aggregated to and from mesh nodes, and *(ii)* a multihop

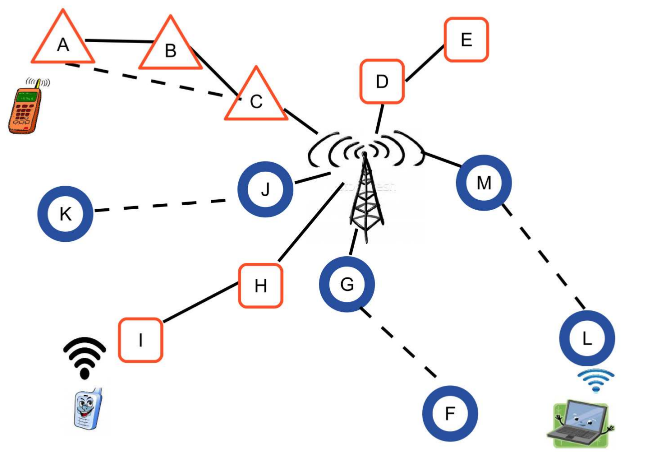


Fig. 1. Example WhiteMesh topology with different mesh-node shapes representing different frequency band choices per link.

backhaul tier for connecting all mesh nodes to the Internet through gateway nodes. To provide better service for more users, the network has to be designed with more access points in the access tier, and offers more capacity in the backhual tier. However, more access points and backhual capacity induce huge cost for network deployment. Fortunately, white space large propagation helps solving these issues. In this work, we explore the white space spectrum application for both access tier network deployment and further focus on optimally allocating white space and WiFi bands on a finite set of radios per mesh node along the backhaul tier.

In the white mesh networks, the white space spectrum offers not only more allowed frequency resources but also a larger service area for a single access point. With the flexible FCC restrictions and artificial activity diversity of white space spectrum, in sparsely-populated rural areas, the lower frequencies of the white space bands might be a more appropriate choice for access point deployment and connections for backhual networks. A white space access point has a larger service area comparing with WiFi access point only counting propagation. Long propagation also reduce the hop counts in backhual networks 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 wireless network deployment strategy. In such urban areas, select links with more spatial reuse ability might be a more appropriate choice, especially since the number of available channels in white space bands is often inversely proportional to the population (due to the existence of greater TV channels).

Larger propagation range results in cost reducing of access points deployment in access tier deployment through larger service area. Figure 1 depicts an example depicts the propagation diversity in white mesh networks. The 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, in backhual tier network 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. In this work, we investigate the diverse propagation characteristics across four frequency bands: 450 MHz, 800 MHz, 2.4 GHz, and 5.8 GHz in theory and measurement-driven simulation. The two former frequency bands are referred as white space (WS) bands, whereas the two latter frequency bands as WiFi bands.

B. Problem Formulation

White mesh wireless network involves the propagation variation and channel occupancy additional to the previous multichannel works. For access tier deployment, the key issue is to reduce the cost for access points with quality of service constraints. In the backhual network, the objective of the deployment is to offer more capacity for the mesh nodes which are the access points in the access tier.

The prior multi-channel models [8], [10] fail to distinguish the propagation range D_c, interference range D_r and channel capacity variation among 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 in both access tier and backhual tier networks. Therefore, in the white mesh model, 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). We assume all channels have the same bandwidth and the same channel capacity of each band with the same transmit power, channel bandwidth, and antenna gain under a classic protocol model [18].

In a typical wireless network deployment, there are 3 sub steps. First step is to learn the electromagnetic environment of the target area for the network design. Next step is to design the access points deployment for the area. The last step is to build the backhual network offering the access to the Internet. We introduce the activity level and then apply the measured parameter to the other steps with constraints in our frameworks.

In sparsely-populated rural areas, the lower frequencies of the white space bands might be a better choice for wireless service in sparsely populated areas for its low utility. However, as the population and traffic demand scales up (e.g., for urban regions), the greater levels of residents traffic demands might detract the white space bands from the overall deployment strategy. That motivate the learning of target area electromagnetic environment in prior of the network design. For spectrum utility and resulting channel availability, we use a long-term measurement for each band. We define the percentage of sensing samples (S_θ) above an interference threshold (θ) over the total samples (S) in a time unit as the activity level (A) of inter-network interference:

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

Based on the in-field measurements, we can further get the achieved channel capacity through the remaining free time according to:

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

The capacity of a clean channel is denoted by δ with the protocol model. The achieved channel capacity is the start point for network design. In a joint white space and WiFi scenario, the activity level varies according to various interfering sources and the propagation characteristics induced by the environmental characteristics of the service area.

Despite sufficient levels of received signal, interference can cause channels to be unusable (e.g., due to high levels of packet loss) or unavailable (e.g., due to primary users in cognitive radios [19]). Prior work has worked to reduce interference levels via gateway deployment, channel assignment, and routing [8], [20]. The interference of a wireless network could be divided into two categories according to the interfering source: *(i)* intra-network interference, caused by nodes in the same network, and *(ii)* inter-network interference, caused by nodes or devices outside of the network. The definition of activity level provides a method to quantify the inter-network interference in the deployment design. We apply the measurements based activity level in both access tier network design and backhual network design.

For the access tier network, a simple method with the least number of access points to cover an area is to use multiple orthogonal lower-frequency channels. However, the FCC limits white space band availability for data networks in most metropolitan areas in the United States [7]. Moreover, the number of channels in each band is limited. Too many lower-frequency channels will cause high levels of intra-network interference for the network, which will be discussed in the backhual network design. We assume that the cost of the network is proportional to the number of access points required for a given user demand (i.e., due to the cost of hardware and installation). Therefore, given a geographical region for a new network deployment, we build a measurement-driven framework called Multiband Access Point Estimation (MAPE)IV to compute the required number of access points.

Most of the existing works try to reduce the intra-network interference without regard to the inter-network interference [13]. However, the existence of inter-network interference becomes an important problem when involving white space bands. While theoretical models which describe inter-network interference exist, accurately characterizing a particular region must be done empirically. To investigate the performance of white space bands, we model the problem as a linear program in V. Further, to reduce the complexity for channel assignment, a BPS(Band-based Path Selection) algorithm is proposed in V, and the measurements driven simulation shows the gain of joint WiFi and white space with BPS and other channel assignment methods.

III. In-Field Measurements

To learn the knowledge of the electromagnetic environment and for future evaluation of the deployment methodology later, we perform in-field measurements in Dallas-Fort Worth metroplex. In this section, we illustrate the experiment setup and show the measurements results with analysis.

A. Experiments Design

We employ a Linux-based 802.11 testbed, which includes a Gateworks 2358 board with Ubiquiti XR radios (XR9 at 900 MHz, XR2 at 2.4 GHz, XR5 at 5.2 GHz) and a DoodleLabs DL475 radio at 450 MHz. We develop shell scripts which

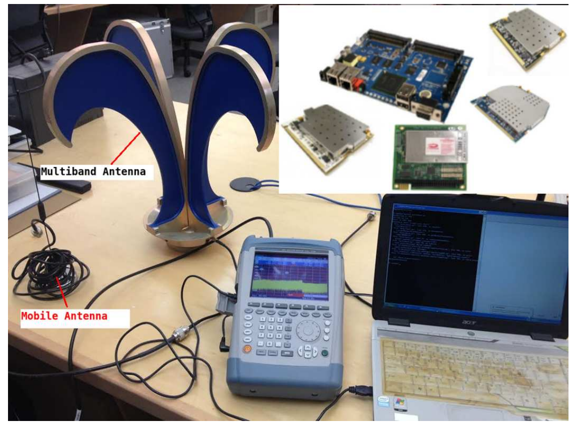


Fig. 2. Multiband Measurement Platform

utilize tcpdump to enable the testbed to work as a sniffer, recording all 802.11 packets. However, since the Gateworks platform only updates its estimate of received signal strength upon the reception of a new packet (and not all relevant channel activity is 802.11 based), we employ a spectrum analyzer to form a notion of inter-network interference with finer granularity. Hence, we also use a Rohde & Schwarz FSH8 portable spectrum works from 100 KHz to 8 GHz. The portable spectrum analyzer is controlled by a Python script on a laptop to measure the received signal strength.

To the best of our knowledge, there is no readily available mobile, multiband antenna from 450 MHz to 5.2 GHz on the market. Thus, we use a 700-MHz mobile antenna to perform in-field measurements. We then normalize the mobile antenna performance across bands with indoor experimentation. To do so, we use a Universal Software Radio Peripheral (USRP) N210 to generate signals at 450 MHz, 800 MHz, and 2.4 GHz. We feed the USRP signals directly to a spectrum analyzer and adjust the configuration of USRP to make the received signal strength the same as the 5.2 GHz signal from Gateworks 2358 with a XR5 radio. Then, we connect the signal source to a fixed multiband antenna (QT 400 Quad Ridge Horn Antenna) and measure the received signal at a fixed distance with the 700 MHz antenna and antennas for different bands to obtain the antenna loss for each band. We adjust the received signal strength collected via the 700-MHz mobile antenna according to the normalization.

Our experimental platform is shown in Figure 2.The mobile spectrum analyzer records 32 samples per second on each band under test with appropriate time stamps. The Gateworks sniffer platform also records all the received WiFi packets according to their time stamps. The duplicate samples in WiFi bands from spectrum analyzer and Gateworks are deleted according overlapping time stamps. Accordingly, we calculate the activity level in WiFi bands. The activity level of white space bands is calculated solely based upon the spectrum analyzer measurements.

Figure 3 depicts a map of the available white space channels with markers where we performed measurements in North Texas. To be representative of a broad range of community types, we consider populations of approximately 25 times one another according to the 2010 U.S. Census, Millsap (500), Weatherford (25K), and Dallas (1.25 M). We have collected measurements at multiple types of locations in Dallas, including a downtown area, a residential area, and a university

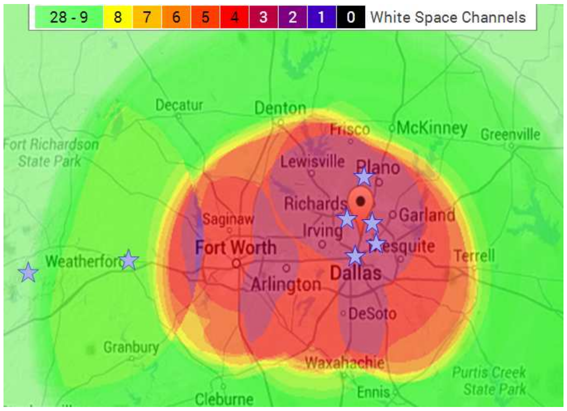


Fig. 3. White Space Channels in DFW Metropolitan and Surrounding Areas.

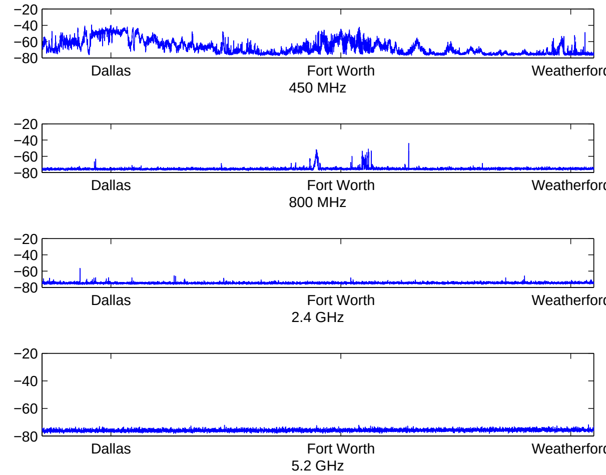


Fig. 4. Spectrum Activity in DFW Metropolitan and Surrounding Areas.

campus. In Weatherford and Millsap, we monitor wireless activities in three locations for 45 continuous minutes on a weekday in downtown, residential, and non-residential areas. Then, we post-process the data to calculate the activity level of each band in each location. First, we parse the SNR from the data logs via Perl scripts. Second, we merge the data from the two platforms according to their respective time stamps and calculate the activity level of each band across these locations. The activity level is then included in our framework as input parameter.

B. Measurements and Analysis

In this subsection, we show our measurements results and analyze the variation of activity level across locations. As an initial experiment, we perform a drive test from Dallas to Weatherford with cruise control set to 60 MPH while on the highway. The result of the in-field spectrum drive test is shown in Figure 4 according to the location and time of the measurement. The measured activity via RSSI of 450 MHz is high in downtown Dallas and Fort Worth but has less signal activity in the urban and rural area between these city centers. The low activity detected in the WiFi bands is due to the distance from the highway being typically larger than the propagation range of predominantly indoor wireless routers.

Our initial in-field measurement matches the FCC restrictions (shown in Figure 3) with less channels available translating to greater spectrum utilization by TV stations. The drive test also shows that the spectrum utilization is roughly proportional to the population density in Figure 4. We use the measurements collected at more fixed locations as marked on the map for the activity level calculation.

The activity level calculated with our measurements are shown in Table III. Dallas, the city with the greatest population in North Texas, has the highest activity level in most of the measured bands, especially at 450 MHz. The Dallas urban measurements are taken from the SMU campus, two neighborhoods, and a densely-populated suburb (Plano). Our measurements indicate that 2.4 GHz has a higher activity level in urban area than the measured downtown area. Most schools and their neighborhoods are covered by WiFi, which contributes to the high activity level at 2.4 GHz and 5.2 GHz. In Weatherford, all the bands have lower activity levels than in Dallas. A peculiarity in the measurements can be seen by the sparse area in Weatherford having more activity than the other regions for 450 MHz. This can be explained due to the measurement location being on the East of Weatherford (closer to Fort Worth, which has a population of approximately 750k). Millsap is a typical sparse rural area with approximately 500 total residents. The activity levels across all the bands are lower than in Dallas and Weatherford. In the 450 MHz band, the activity level decreases much faster than in other bands in Dallas and Weatherford.

Our measurements verify the channel occupation variation in DFW metroplex and quantify the occupation through measurements based activity level. The results induce the spectrum bands are higher occupied in dense populated areas than sparse areas with different levels of utility across bands. The measurements methods and quantification provides the way to get the knowledge of the target environment. We apply these measurements to our MAPE frameworkIV and BPS algorithmsV to further solve the access tier network deployment and multiband channel assignments.

IV. Access Network Deployment

In this section, we introduce the access tier network deployment and our MAPE framework with dynamics of white space bands. We further apply our measurements in III to investigate the white space deployment gain in reducing the number of access point in DFW metroplex.

A. Access Network Model and MAPE

Typically, the deployment of wireless access networks is subject to coverage and capacity constraints for a given region. Coverage is defined with respect to the ability of clients to connect to access points within their service area. We use a coverage constraint ratio of 95% in this work for a target area [21]. Capacity is defined with respect to the ability of a network to serve the traffic demand of clients. Spatial reuse allows improved capacity but increases the cost of deploying a network by increasing the total number of access points required. Hence, for densely-populated areas, the greatest level of spatial reuse possible is often desired. In contrast, sparsely-populated rural areas have lower traffic demand per unit area. Thus, aggregating this demand with the use of lower frequencies via white space bands could be highly effective in reducing the total number of access points required to achieve similar coverage and capacity constraints. Moreover, since less TV channels tend to be occupied in sparsely-populated

Bands	Dallas			Weatherford			Millsap		
Area Type	Downtown	Residential	Suburban	Downtown	Residential	Sparse	Downtown	Residential	Sparse
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 IN MULTIPLE LOCATIONS

areas [22], a larger number of white space bands can be leveraged in these areas.

An access network deployment should ideally provide network capacity equal to the demand of the service area to maintain the capacity constraint. The demand of a service area could be calculated as the summation of individual demands all over the service area $D_a = \sum_{p \in P} D_p$. Since household demand for the Internet has been previously characterized [23], D_a could represent the population distribution f and service area k as $D_a = \sum_{f \in F, k \in K} \bar{D}_p * f * k$. The capacity constraint could be represented with an access point set M according to:

$$\sum_{m \in M} \delta_r^m \geq \sum_{f \in F, k \in K} \bar{D}_p * f * k \quad (4)$$

At the same time, the wireless network must additionally satisfy the coverage constraint in the service area where the access points provide connectivity for client devices. Generally, a coverage of 95% is acceptable for wireless access networks [21].

In a joint white space and WiFi scenario, the activity level varies according to various interfering sources and the propagation characteristics induced by the environmental characteristics of the service area. A simple method with the least number of access points to cover an area is to use multiple orthogonal lower-frequency channels. However, the FCC limits white space band availability for data networks in most metropolitan areas in the United States [7]. Moreover, the number of channels in each band is limited. Too many lower-frequency channels will cause high levels of intra-network interference for the network, which is out of our scope in this work. We assume that the cost of the network is proportional to the number of access points required for a given user demand (i.e., due to the cost of hardware and installation). Therefore, given a geographical region for a new network deployment, we build a measurement-driven framework called Multiband Access Point Estimation (MAPE) to compute the required number of access points.

In the space domain, the advantage of higher-frequency channels is the spatial reuse, while the lower-frequency channels provide greater levels of coverage. Generally, higher frequencies are more appropriate for populated areas, and lower frequencies are more appropriate for sparse areas. The temporal variation of spectrum utilization differs across bands. For an Internet service provider, the service quality which maps to the capacity constraint must be satisfied. Given a metropolitan area, the population distribution can be found according to census data [24]. Then, we can estimate the capacity demand of each type of area with the assumption that users will exhibit average demand. According to the population distribution, we split the area into different types, which compose the spatial input. Then, we use the measured activity level as the temporal input. We have an average channel capacity of each band according to the activity level.

Algorithm 1 Multiband Access Point Estimation (MAPE)

Input:
A: Measured Activity Level
F: Population Distribution
C: Clean Channel Capacity
n: Path Loss Exponent
B: Available Frequency Bands
M: Area to be Covered

1: Split M in to different type, calculate the traffic demand density f
2: Calculate in-field channel capacity δ_r as $\delta(1 - A)$
3: Get the propagation coverage area radius R_p from the Friis model based on n, B, F
4: Calculate the QoS coverage radius R_{QoS} of a multiband access point that satisfies the demands of the area
5: The coverage radius of a multiband access point is $min\{R_p, R_{QoS}\}$
6: Apply a regular-hexagonal deployment to get the number of access points for serving given area M

Output:
The number of access points

With the received signal strength threshold, the Quality-of-Service-constrained coverage area of different types per channel, and the spatial reuse distance can be directly computed. Then, the maximum area an access point could cover can be calculated as the minimal area of the QoS-based coverage area and propagation coverage. Then, the transmission power is adjusted to fulfill the coverage restriction subject to the FCC regulations for maximum-allowable transmit power. A classic regular-hexagonal deployment process is employed to place the access points.

B. Results and Analysis

We use the measurement-based activity levels shown in Table III in our framework presented in Algorithm 1. We specifically use the Millsap sparse area, Millsap downtown, Weatherford residential, Dallas residential, and Dallas downtown measurements as inputs of activity level for a given population density.We then calculate the number of access points for covering a 13 km $\times$ 13 km area, varying the population density. The output is shown in Figure 5.

In the calculation, we set the demand requested per user as 2 Mbps with the population density of 20, 50, 100, 1000, and 2000 users per square kilometer. We assume 30 % of the residents will use this service (i.e., the take rate is 30 %), the maximum transmit power is 30 dBm, and a path loss exponent of 3.5 [25].From Equation 1, we see that the propagation range is proportional to the wavelength with 450 MHz having a propagation range of 11.6 times that of 5.2 GHz. We adopt an 802.11n maximum data rate of 600 Mbps. For the WiFi+White Space scenario, we use 3 channels in each of the 450 MHz, 2.4 GHz and 5.2 GHz bands. For the WiFi Only scenario, we assume 6 channel in the 2.4-GHz band, and 3 channels in the 5.2-GHz band since 2.4 GHz has larger

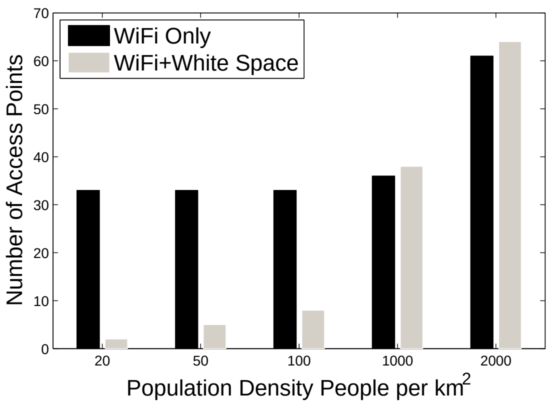


Fig. 5. Number of Access Points Needed for a 13 km x13 km Area.

propagation range than 5.2 GHz. Each of these scenarios have the same channels in total (9). As shown in Figure 5, with the same number of channels, WiFi+White Space reduces the number of access points by 1650% compared to the WiFi Only scenario in the 20 people per square km scenario, 660% in the 50 people per square km, and 412.5% in the 100 people per square km scenario. The large propagation range of the white space bands is approximately 10 times that of the WiFi bands, creating an opportunity for greater coverage. However, as the population density increases, due to the capacity constraint of servicing users in the area, the lower-frequency white space bands lose their advantage of larger communication range due to the reduction in achievable spatial reuse. At the same time, the activities of other signal sources, such as TV stations in downtown areas, reduce the capacity of white space bands. As a result, the WiFi+White Space scenario performs worse than the WiFi Only scenario. If we were to count the intra-network interference (out of scope), the situation could become even worse. Moreover, FCC has stricter policies on white spaces in urban areas. Fewer channels are available in these areas, which makes WiFi a better option for dense areas.

To understand the influence of band combinations on network deployments, we calculate the number of access points in the area when selecting 500 people per square km with a downtown Weatherford spectrum utilization and 1500 people per square km with a residential Dallas spectrum utilization. We assume the total number of channels is 12. We use the same setup as the previous experiment.

No. of Bands	Bands Combination (Hz)	No. of AP 500 ppl/km^2	No. of AP 1500 ppl/km^2
1	450 M	12	35
	800 M	10	30
	2.4 GHz	33	37
	5.2 G	193	193
2	450 M,800 M	11	32
	450 M,2.4 G	23	36
	450 M,5.2 G	23	69
	800 M,2.4 G	20	33
	800 M,5.2 G	20	59
	2.4 G,5.2 G	33	73
3	450 M,800 M,2.4 G	16	33
	450 M,800 M,5.2 G	16	48
	450 M,2.4 G,5.2 G	33	53
	800 M,2.4 G,5.2 G	30	49
4	450 M,800 M,2.4 G,5.2 G	21	44

TABLE II
CHANNEL COMBINATIONS FOR 500 AND 1500 POPULATION DENSITY SCENARIOS

In Table II, we compare the number of access points with 12 channels through all the possible combinations of bands. Since purchasing and deploying access points is the primary cost of a wireless infrastructure, to simplify the calculation, we only count the number of access points as the network's cost. When all the channels are in the same band, as the frequency goes up, more access points are needed to serve the area due to the limited propagation range. However, 450 MHz does not outperform 800 MHz with a single band at both the 500 and 1500 people per square km cases because 450 MHz channels have larger measured activity levels. White space band channels outperform WiFi bands by up to 1830% in the single band case with 500 people per square km, but with 1,500 people per square km, the cost reduction decreases to only 543%. We now distribute an equal number of channels to two-band combinations and run the experiments with the same population densities and spectrum utilization. The results shows the white space band combination (450 and 800 MHz) performs better than WiFi only (2.4 and 5.2 GHz) by 200% and 128% with the people per square km of 500 and 1,500, respectively. In fact, the white space only scenario (450 and 800 MHz) has almost the same performance as the scenarios with one white band and one WiFi band (450 MHz and 2.4 GHz; 800 MHz and 2.4 GHz) with 1,500 people per square km. However, with 500 people per square km, the white space only scenario is much better than any other two-band combination. White space channels provide up to 87.5% cost reduction in three-band combination scenarios with 500 people per square km, and up to 33.3% with 1,500 people per square km. With four bands, the number of access points required does not reduce using white space bands.

From Figure 5 and Table II, we show that as the population density increases, the reduction in number of access points required to meet the same demand diminishes. Note that a more optimal allocation of channels in different bands could offer further cost reductions. We further show that as population and spectrum utilization increase, at some point, the performance of white space only scenario could be the same as a combination of white space and WiFi bands.

V. BACKHUAL NETWORK CHANNEL ASSIGNMENT

In this section, we formulate the channel assignment problem use WiFi and white space bands in concert when deploying wireless backhual networks. We then present our integer linear programming model and heuristic algorithm to address the problem.

A. *WhiteMesh Backhual Architecture*

Many works which rely on such an assumption have focused on the allocation of multiple WiFi channels with multiple radios in multihop wireless networks with channels in one band [10]. However, as white space bands come to this problem, the propagation variation has to be considered in wireless network deployment. The propagation variation brings both spatial and spectrum variation for backhual network design.

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 co-exist 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).

B. Model and Problem Formulation

To distinguish the dynamics of white space bands, we employ the activity level based on multiple measurements in the target area to represent the achieved channel capacity. 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 [8] related to various 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 served traffic flow 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 [8], [10], [26]. 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 [27]. The metric we use to evaluate the proposed algorithm is the served traffic flow. Wireless networks are operated and maintained by vendors, such as AT&T, T-Mobile, who charge the customers based on their data through Internet. In practice, the traffic demand of the user obey Poisson distribution [28], we then generated Poisson distributed numbers to represent clients' traffic demands in our simulation. The served traffic flow is correlated to the population of the area since each user has similar traffic demand in long term average. The employed performance metric of served traffic flow X, is represented the traffic arrived at the gateway nodes, where in Eq. 5:

$$X = \sum_{w \in W, v \in V} T(w, v) \tag{5}$$

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 served traffic flow 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 served traffic flow is described in Section V-I.

C. Linear Programming Formulation

To clarify the problem and approach the optimization solution of the problem, we present a 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 pre-known. The communication links and conflict graph are given as parameters. The capacity δ_b is given as the achieved channel capacity from the activity level measurement calculation in 3.

Sets:

V	set of nodes
B	set of bands

Parameters:

δ^b	$b \in B$	Available 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	$i \in V$ $binary$	Gateway maker in mesh nodes
D_d	$i \in V$	Downlink demand of node i
D_u	$i \in V$	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. 5.

Objective:

$$Max \sum_i \sum_j \sum_k \sum_b (uy^b_{i,j,k} + dy^b_{j,i,k}) \;\; When\ w_j = 1 \tag{6}$$

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

Connectivity Constraints:

$$\alpha^b_{i,j} + \alpha^b_{j,i} + \sum_l \sum_m (\alpha^b_{l,m} \cdot I^b_{ij,lm}) \leq \delta^b, i \neq j \tag{7}$$

$$\sum_i uy^b_{i,j,k} + \sum_i dy^b_{i,j,k} \leq \delta^b \cdot \alpha^b_{j,k} \tag{8}$$

Uplink Constraints:

$$\sum_k \sum_b uy^b_{i,k,i} \leq D_{ui} \; ; w_k = 0, i \neq k \tag{9}$$

$$uy^b_{i,j,k} \cdot w_k = 0 \tag{10}$$

$$\sum_{i \leq j} \sum_b uy^b_{i,j,k} = \sum_{m \leq j} \sum_b uy^b_{j,m,k} \; ; w_j = 0 \tag{11}$$

$$uy^b_{i,j,i} = 0 \tag{12}$$

Downlink Constraints:

$$\sum_k \sum_b dy^b_{i,k,i} \leq D_{di} \;\; ; w_k = 0 \tag{13}$$

$$dy^b_{i,j,k} = 0 \; ; w_k = 1 \tag{14}$$

$$\sum_{i \neq j} \sum_b dy^b_{i,j,k} = \sum_{m \neq j} \sum_b dy^b_{j,m,k} \; ; w_j = 0, i \neq k \tag{15}$$

$$dy^b_{i,i,j} = 0 \tag{16}$$

In the constraints, (7) 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 (8) represents the incoming and outgoing wireless traffic, which should be less than the link capacity for link i, j. Uplink constraints (9) and (10) represent that the summation of any wireless flow i, j should be less than the demand of node k. Constraints (11) and (12) 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 (13) and (14) are similar to (9) and (10) but in the downlink direction. Similarly, constraints (15) and (16) are downlink versions of (11) and (12).

Similar linear programs model is to solve channel assignment wireless networks have been proved to be NP-hard [12]. Our model jointly considers channel assignment factors and multiband scenario which is more complex . When the particular configuration is given, we further choose the objectives, parameters, and relax constraints to find the approaching solution for the network.

D. Path Analysis with Diverse Propagation

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.

E. 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). 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:

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

Using network efficiency, the equation simplifies to:

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

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. 18, 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:

$$\frac{\gamma}{\frac{h(h-1)}{2} \cdot \bar{I} + I_x} \geq \frac{\gamma}{\frac{h(h+1)}{2} \cdot \bar{I}} \tag{19}$$

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. 18. 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.

Algorithm 2 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 $S_{curr} = G$, $N_{srv} = \emptyset$, $N_{unsrv} = M$,$I_{active} = \emptyset$
while $N_{srv} =!M$ **do**
  Select node with largest distance to gateway
  Find the adjacency matrix across band combinations A_c
  for all $A_i \in A_c$ **do**
    Find the shortest path SP_i in mixed adjacency matrix A
    for all Link $l \in SP_i$, ordered from gateway to mesh node **do**
      Find the least interfering path with measured $\delta \times E_n$
      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

F. Band-based Path Selection (BPS) Algorithm

We design a Band-based Path Selection (BPS) algorithm (described in Alg. 2) 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 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 V-E, 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 [29], 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.

G. Evaluation of WhiteMesh Backhual 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.

H. 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. We have 450 MHz and 800 MHz in white space bands and 2.4 GHz and 5.8 GHz in WiFi bands in previous measurement work.

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 [30]. 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 [31]. 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.

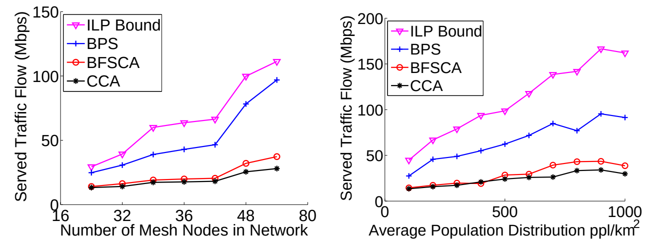
As discussed in V-B, the traffic demand obey Possion distribution. The traffic demand aggregated by a mesh node is independent to others. In the simulation, we generate an equal number of access points (including both gateway nodes and mesh nodes) Possion random numbers with an expect λ according to the population distribution for the target area. Then we map the number to the traffic demand for each access points in the target area. The served traffic flow 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 [32]. As mentioned previously, the wireless capacity of gateway nodes has been shown to be the bottleneck in mesh networks [21].

Moreover, served traffic flow 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 served traffic flow introduced in Section V-B. After the channel assignment process, the network is under a tree based structure. We start to serve the traffic demand from the gateway nodes. 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.

In the simulations, 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 of the target area according to the measurements, 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 LP 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 [33], *(ii)* Breath First Search Channel Assignment (BFS-CA) from [8] under the same simulation setup. In typical CCA [33] 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 [8] algorithm, a node will search all the available single-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 LP 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.

I. 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 LP 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. 7 and Table IV. We average the results of 20 simulations each of the algorithms for the given network



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

Fig. 6. Performance in terms of served traffic flow for various offered loads, network sizes, and configurations of WiFi or white space (WS) channels.

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. 6(a) shows the served traffic flow when the population distribution is 500 ppl/km^2 for the ILP formulation and the heuristic algorithms: *(i)* Common Channel Assignment (CCA) from [33], *(ii)* Breadth First Search Channel Assignment (BFS-CA) from [34], *(iii)* our algorithm BPS (Section V-F).

In Fig. 6(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 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 LP 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 LP 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 $400 ppl/km^2$ to $300 ppl/km^2$ measurements as shown in Table. III. In Fig. 6(b), it shows

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 III
ACTIVITY LEVEL UNDER POPULATION DISTRIBUTION

that as the population distribution increases, the ILP and BPS diverge greatly from the remaining algorithms. Similar to Fig. 6(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 [35]. 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 IV 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 IV 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.

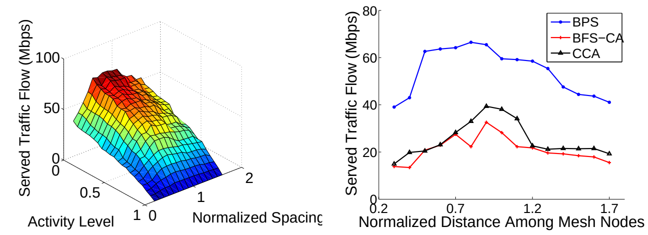
2) Effect of Channel Occupancy: In Fig. 7(a), we show the impacts of channel occupancy through the activity level and spacing variation on wireless white space mesh network. The activity level defined in 3 represent the available channel capacity. The spacing gap is related to the population distribution according to the hexagon deployment for access tier network deployment, the more population distribution, the smaller spacing gap between mesh nodes. In the simulation, 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. III. 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 III 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. 7(b).

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 [33]	22.4	13.4	13.2	12.5	16.9	23.2	24.1	30.6	25.2	23.9	30.4
BFS-CA [34]	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 IV

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. 7.

In Fig. 7(b), as the space gap increase, the multiband network has better performance through spacial reuse matching the simulation analysis shown in Fig. 7(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.

VI. 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. [36] These challenges are distinguished under the topics of channel assignment, cognitive radio, protocol design, etc. [36], [37] Previous works have recognize the impact of interference in wireless mesh network deployment is the key issue [8], [38], [39]. To overcome the challenges, a lot of works have been done to optimize the deployment in increasing throughput, minimize resource, reducing interference, etc. [10], [38], [40] Many works have studied the network deployment problem in multihop wireless networks [11], [36], [41], [42]. In addition, multiple radios have been used to improve the routing in multi-channel scenarios [33], [38]. Both static and dynamic network deployments have been discussed in previous works under the 802.11 WiFi scenario [34], [40], [43]. 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 [44] 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. [8], [20], [21] focus on reducing the gateway mesh nodes. [38], [40] try to reduce the overall interference in the worst case of traffic independent scenario. [39], [45] improve the performance in throughput. However, these works fails to involve the traffic demands of clients in their solutions. [9], [21] 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 [10]. Several works introduce relaxed linear program formulation to find the optimization of multihop wireless networks [8], [38], [46]. Also, game theory methods is another option to solve the problem [30], [47]. Social network analysis is also popular in wireless network design [48]. 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 [49]. 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 [22]). 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. [49] introduce WiFi like white space link implementation on USRP and link protocols.

[50] discuss the point to point communication in multiband scenario. In [46], white space band application is discussed in cognitive radio network for reducing maintenance cost. In [51], 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.

VII. CONCLUSION

In this paper, we jointly considered the use of WiFi and white space bands application for wireless networks deployments. Different from prior work, we first proposed a Multiband Access Point Estimation (MAPE) framework to estimate the number of access points required in a given region for wireless access network and Band-based Path Selection (BPS) algorithm for backhual network based on in-field measurements for wireless access network. We then performed spectrum utilization measurements in the DFW metropolitan and surrounding areas to drive these framework and find the influence of white spaces on network costs in these representative areas. Through extensive analysis across varying population density and channel combinations across bands, we show that white space bands can reduce the number of access points by 1650% and 660% in rural and sparse urban areas versus the same cost savings are not achieved in dense urban and downtown type area. As the population and spectrum utilization increase, the cost savings of white space bands diminish to the point that WiFi-only channel combinations can be optimal. The simulation shows that our BPS 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 served traffic flow of similar WiFi or white-space-only configurations.

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