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. While dense areas might still benefit from the use of WiFi for spatial reuse, white space spectrum becomes increasingly important as the population density decreases, especially since the availability of these white spaces are often inversely proportional to population density. In this paper, we perform measurements in Dallas-Fort Worth metroplex to analyze channel occupancy in both WiFi and white space frequencies. Based on these measurements, we propose a measurement-driven band selection framework, Multiband Access Point Estimation (MAPE) to quantify the benefit of jointly using WiFi and white space frequencies along the access tier. Further, to deploy heterogeneous 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 MAPE reduces access point by up to 1650% in sparse rural areas over similar WiFi-only solutions. Also, BPS achieves up to 180% in the served traffic flow of existing multi-channel, multi-radio algorithms, which are agnostic to diverse propagation characteristics across bands. Most importantly, this paper lays a foundation for optimal use of white space and WiFi bands in the access and 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 of what was once anticipated [4]. 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.

Meanwhile, the FCC has approved the use of broadband services in the unused portions 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 [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 [6]. These new resources and policies offer opportunities for both industry and academia.

As shown in the spectrum white space databases (e.g., [7]), the number of available channels in these spectrum varies from city to city in the US but generally is inversely proportional to population levels. Hence, the question arises for improving the performance and costs of wireless mesh networks: *(i) how can the 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 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, which could be fundamental issues for the success of mesh networks going forward.

In this paper, we perform a measurement-driven study which jointly considers the propagation characteristics and in-field spectrum availability of white space and WiFi channels for optimally building the access and backhual tiers of a wireless mesh network. As a representative metropolitan area, we measure the spectral activity data in the metropolitan and surrounding areas of Dallas-Fort Worth (DFW). We propose a measurement-driven framework, Multi-band Access Point Estimation (MAPE), to find the number of access points required for wireless network deployments in certain target areas with population densities from our in-situ measurements and census data. Further, we design a linear program and a heuristic measurement-driven algorithm, Band-based Path Selection (BPS), to address the channel assignment problem in wireless network deployment with both WiFi and white space bands.

The main contributions of our work are as follows:

- We perform in-field measurements of spectrum utilization in various representative scenarios across the Dallas-Fort Worth metropolitan area, ranging from sparse rural to dense urban areas, considering 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 environmental settings. We then 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 reduced complexity heuristic-based measurement-driven algorithm, Band-based Path Selection (BPS). BPS considers the diverse propagation and overall interference level of WiFi and white space bands. We further perform extensive analysis across offered loads, network sizes and mesh nodes spacing across WiFi/white space band combinations to evaluate the performance versus prior multi-channel, multi-radio algorithms.
- We study the channel occupancy and node spacing impacts on mesh performance given similar channel resources (bandwidth and transmission power). The results show the total traffic served improvement of BPS in typical configurations, achieving up to 180% of previous multi-channel algorithms.

The remainder of this paper is organized as follows. In Section II, we introduce the challenge of deploying diverse frequency bands in wireless networks. In Section III, we perform our DFW measurements to drive our algorithms and analysis for diverse populations. In Section IV, we analyze the access tier network deployment, propose the MAPE framework, and discuss the white space bands impact. In Section V, we develop a heuristic-based algorithm which consider which bands and multihop paths to select in a backhaul white space topology. We then evaluate the performance of the heuristic algorithm versus the upper bound of the optimal solution and compare their performance against two well-known multi-channel, multi-radio algorithms in several scenarios. Related work is discussed in Section VI and conclusions are drawn in Section VII.

II. WhiteMesh Networks

In this section, we define and introduce WhiteMesh networks which jointly use WiFi and white space frequencies in a wireless mesh network. We then discuss the influences of WiFi and white space frequencies in wireless mesh network design. Further, we describe the two tiers we consider in wireless mesh network deployments: access and backhaul tier.

A. WhiteMesh Structure and Restrictions

Here, the term WhiteMesh refers to a heterogeneous wireless network which jointly exploits both WiFi and white space frequencies. Thus, variation in frequency bands allows diverse capacity and service areas in network design. The white space bands were originally assigned to analog TV broadcasting. The number of white space channels is typically less in dense areas than in the rural areas to protect the existing TV broadcasting networks. An example of available channels acroos a metropolitan area is shown in Fig. 1 (DFW). The diverse attributes at WiFi and white space bands impact network deployments in unique ways. In sparse rural areas, the number of wired entry points to the Internet is like to be more restricted. At the same time, sparse populations generate relatively low amount of traffic demand. The lower traffic demand requires resources for users directly connecting 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 to 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, leading to less using available for the backhaul tier. As shown in Fig. 1, the spectral resources in dense areas are also less available than in the sparse area. When there are more spectral resources reserved for the access tier, few spectral resources can be used for the backhaul tier.

Moreover, white space frequencies have longer wavelengths than WiFi frequencies. 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 [10]. 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 [11]:

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

Here, n varies according to the aforementioned environmental factors with a value ranging from two to five in typical outdoor settings [12]. Thus, the propagation range of white space frequencies is longer than WiFi frequencies given a similar environment. For the same transmit power, greater propagation levels leads to larger service area. This effect could be beneficial for sparse areas since the traffic demand from the sparse population is relatively lower.

The network deployment is constrained by the coverage area of a single access point. The large propagation regions of white spaces help to greatly reduce the number of access points and corresponding network cost. Conversely, a densely-populated area could saturate the capacity of a single white space channel. However, WiFi has smaller interference range and propagation range. The smaller interference range increases the spatial reuse of WiFi bands. In a densely-populated area, the network deployment is constrained by the capacity of a single access point. 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 ally regions are less of available white spaces. However, the deployment is generally somewhere between these two extremes. To quantify and maximize the benefit of jointly using these bands, our work focuses on access and backhaul design of WhiteMesh networks across varying population densities.

B. Wireless Mesh Network Deployment

Wireless mesh networks have multihop paths between access points to reduce the number of wired entry points to the Internet and reduce network costs. The key objective of wireless network deployment is to serve the traffic demand of the population at a minimal financial cost, thereby increasing the

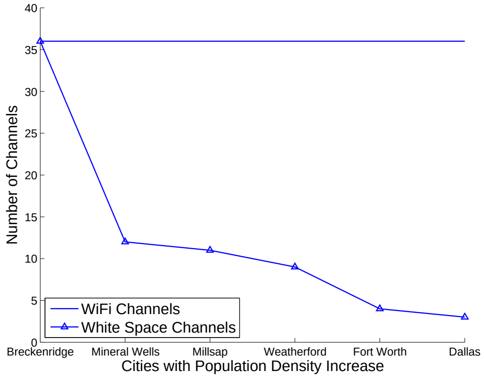


Fig. 1. WiFi and White Space Channels in North Texas

long-term usability of the network. Many wireless networks have been implemented in school campuses, office buildings, and even mobile scenarios. Typically, wireless mesh networks have at least two tiers [3]: *(i)* an access tier, where users directly communicate to access points, and *(ii)* a multihop backhaul tier for connecting all access points to the Internet through gateway nodes.

Access Tier. An access point should ideally provide network capacity equal to the demand of the service area. The deployment of the access tier is subject to the coverage constraint of a given area and the capacity constraint of the users in the area. The coverage constraint is defined with respect to the ability of users to connect to access points within their service area. The capacity constraint is defined with respect to the ability of a network to serve the traffic demand of users. Spatial reuse allows improved capacity but increases the cost of deploying a large-scale network by increasing the total number of access points required.

Backhual Tier. Access points may communicate directly to one another to form a backhaul tier which forwards traffic to and from gateway points to reach the wired or wireless Internet entry points. Prior work focused on improving the capacity by reducing the interference among the links [9], [13]. However, many of these works assume a uniform propagation ability of the multiple channels used in the deployment. [9]. In this work, we study the wireless network deployment across WiFi and white space frequencies, which have diverse propagation and availability based on the deployment location.

III. In-Field Spectral Measurements

To characterize the spectral footprint of a representative and diversely-populated area, we perform spectral analysis measurements in the Dallas-Fort Worth metroplex. In this section, we discuss the experimental setup and quantify the measurement-driven spectral activity.

A. Wardriving Experimental 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 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

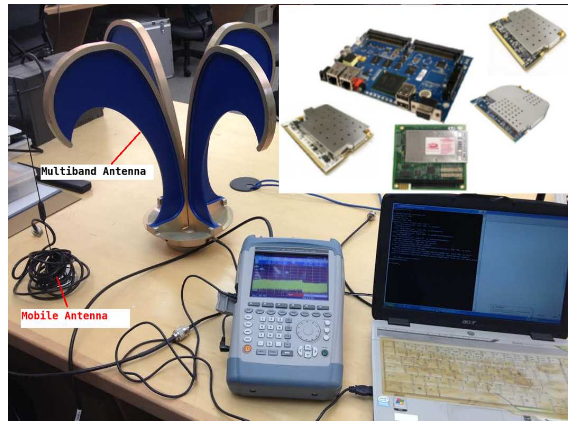


Fig. 2. Multiband Measurement Platform

finer granularity. Hence, we also use a Rohde & Schwarz FSH8 portable spectrum which operates 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.

Interference is a key issue in wireless network design. 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) [14]. The interference in wireless networks 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.

We define an activity level to quantify the spectrum utilization. The activity level is the percentage of time which the interfering signal could impact an active wireless link. In practice, we use the 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:

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

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 spectral analysis 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 in the receiver side 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. We compare the received signals from the antennas designed for each band with known gains to obtain the antenna loss for each band. We further adjust the received signal strength collected via the 700-MHz mobile antenna according to the normalization data set.

Our experimental platform is shown in Fig. 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

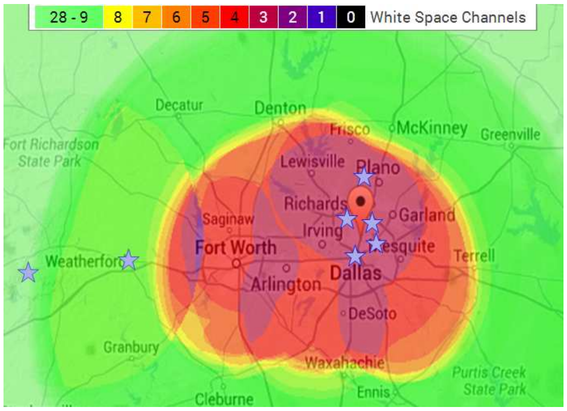


Fig. 3. White Space Channels in DFW Metropolitan and Surrounding Areas.

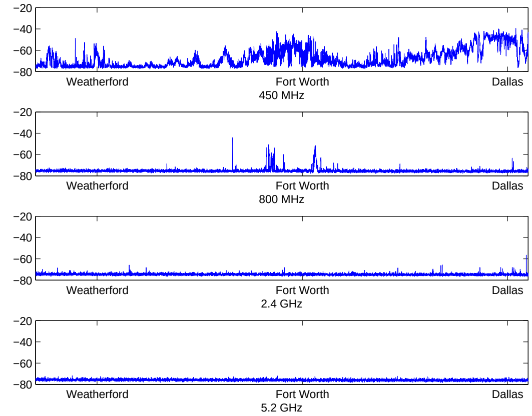


Fig. 4. Spectrum Activity in DFW Metropolitan and Surrounding Areas.

to their time stamps. The duplicate samples in the WiFi bands reported by the spectrum analyzer and Gateworks are removed according to overlapping time stamps to calculate the activity level in the WiFi bands. The activity level of white space bands is calculated solely based upon the spectrum analyzer measurements since it is assumed that device operating in the white space bands is not yet 802.11 compliant.

Fig. 3 depicts a map of the FCC-approved 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 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 at 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. Highway Speeds to Fixed 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 Fig. 4 according to the location of the measurement. The measured activity via RSSI of 450 MHz is high in downtown Dallas and Fort Worth but has less spectral 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 spectral analysis measurements agree with the the FCC restrictions (shown in Fig. 3), greater spectrum utility by TV bands induce less spectral availability. The drive test also shows that the spectrum utilization is roughly proportional to the population density in Fig. 4. We use the measurements collected at 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 the aforementioned urban areas 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 side 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 occupancy variation in the DFW metroplex and quantify the occupancy through a measurement-based activity level. The results show the spectrum bands have greater occupancy in densely-populated areas. The measurements methods and resulting quantification provides the way to understand a typical deployment environment. We apply these measurements to our MAPE framework in Section. IV and BPS algorithms in Section. V to further design access tier network deployments and backhaul tier multiband channel assignment, respectively.

IV. Access Network Deployment Algorithm and Evaluation

In this section, we study the access tier network deployment and propose our measurement-driven MAPE framework with the dynamics of WiFi and white space bands. We further apply our MAPE framework with the measurements shown in Section III to investigate the the access tier gain of WhiteMesh in reducing the number of access point in the Dallas-Fort Worth metroplex.

A. Access Network Model and MAPE

Access tiers must satisfy both the coverage and capacity constraints to provide service for users. The coverage con-

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

straint could be calculated according to the propagation model of Eq. 1. Generally, a coverage of 95% of access tier is acceptable for wireless access networks [15]. We represent the capacity constraint according to the demand of a service area, which 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 [16], 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:

$$\sum_{m \in M} \delta_r^m \geq \sum_{f \in F, k \in K} \bar{D}_p * f * k \tag{3}$$

Through the measured activity level, the achieved channel capacity could be calculated through the free time according to:

$$\delta_r = \delta * (1 - \bar{A}) \tag{4}$$

Here, the capacity of a clean channel is denoted by δ under the protocol model. With the achieved channel capacity, we could further estimate the capacity of an access point in the access tier and link capacity in the backhaul tier.

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, which will be discussed in the next backhaul tier section. 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 spatial 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 [17]. 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. 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 regular-hexagonal deployment process is employed to place the access points.

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

B. Results and Analysis

We use the measurement-based activity levels shown in Table III as an input to Alg. 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 Fig. 5.

In the calculation, we set the demand requested per user to be 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, with a path loss exponent of 3.5 [18]. From Eq. 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.

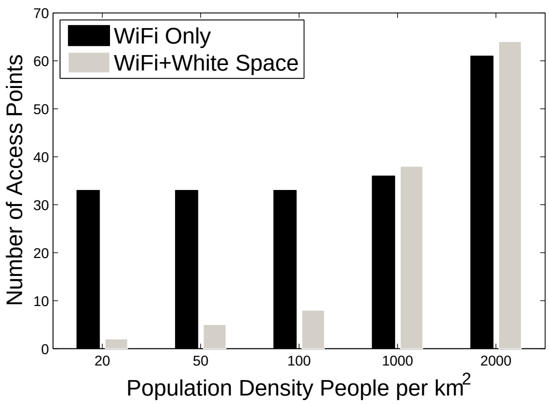


Fig. 5. Number of Access Points Needed for a 13 km x13 km Area.

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 a greater propagation range than 5.2 GHz. Each of these scenarios have the same channels in total (9). As shown in Fig. 5, with the same number of channels, the WiFi+White Space scenario 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 as in the following section, the situation could become even worse. Moreover, FCC has stricter policies on white spaces in urban areas. Fewer channels are available in the downtown and urban areas, which makes WiFi a better option for these 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.

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 show that 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.

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

From Fig. 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 ALGORITHM AND EVALUATION

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

A. Linear Programming Formulation

The function of the backhual tier is to wirelessly provide end to end traffic to and from the user and Internet. In practice, the traffic demand of the users obeys a Poisson process [19]. Most of the carriers charge users based on the traffic being tranferred oner the Internet. The traffic demand of the users delivered to or from the Internet are noted as the total traffic served. In particular the total traffic served X, is represented as:

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

$T(w,v)$ nodes all delivered traffic between access point $v \in V$ and gateway node $w \in W$.

Here, we present a linear programming formulation to approach the optimal channel assignment in along the backhaul tier of a WhiteMesh network. We leverage the nodes into consider the set of available access points (V) which aggregate the traffic from the users, and gateways (W) as ingress points to the Internet. The available frequency bands (B) are pre-known as an input. The conflict graph I is given as parameters. δ_b is the achieved channel capacity estimated from the activity level measurements introduced in Section. III.

Sets:

V	set of nodes
B	set of bands

Parameters:

δ^b	$b \in B$	Achieved 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 marked with access point set
D_d	$i \in V$	Downlink demand of node i
D_u	$i \in V$	Uplink demand of node i

The variable time share $\alpha^b_{i,j}$ represents the assigned percentage of a single link transmitting time for link i,j between node i and node j in band b. The two variables, $uy^b_{i,j,k}$ and $dy^b_{i,j,k}$ are defined as uplink and downlink flows:

Variables:

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

The objective is to maximize the total traffic served (X) of all the gateways, X is defined in Eq. 5. It is represented with the variables:

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 this LP formulation, the constraints are presented as connectivity, uplink, and downlink sections here:

Connectivity Constraints:

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

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

Uplink Constraints:

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

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

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

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

Downlink Constraints:

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

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

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

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

In these constraints, (7) represents the total time assigned for the incoming flows, outgoing flows, and the interfering time which should all be less than 1. Constraint (8) represents that the incoming and outgoing wireless traffic are less than the capacity assigned for link i,j. Uplink constraints (9) and (10) represent that the total traffic flow on link i,j from i is less than the demand of node i. Constraints (11) and (12) restricts the sum of incoming data flows for a given access point k equal to the total outgoing flows from the node. Downlink constraints (13) and (14) represent similar restrictions as (9) and (10), but in the downlink direction. Similarly, constraints (15) and (16) are downlink versions of (11) and (12). Since linear programming models for multiple channels has been proved to be NP-hard [20], in this work, we choose small set of cases to achieve the optimal solution.

B. Path Interference Induced on the Network

In WhiteMesh networks, it is possible that multihop paths are intermixed with WiFi bands for more spatial reuse and white space bands with hop count reduction. We analyze the band choices reducing the number of hops along a path and the aggregate level of interference on that hop-by-hop path choice has on the network (i.e., Path Interference induced on the Network).

Mesh nodes closer to the gateway generally achieve greater levels of throughput at sufficient-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. In the worst case, 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. We note each node along the path had 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 achieved capacity δ, estimated according to the measurements. The h-hop access point would achieve the minimum-served demand, which we define as the network efficiency. In general, the active time per link for an

h-hop access point 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 access point along the path is considered the intra-path network cost.

Using lower carrier frequencies allows a reduction in hop count and increase the network efficiency of each access point along the h-hop path by reducing the interference among the links of the 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 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 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 node is:

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

Through network efficiency, the equation simplifies to:

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

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. 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 Eq. 18. The parameter 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. 19, when $I_x \leq 2 \cdot h\bar{I}$, 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 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.

C. Band-based Path Selection (BPS) Algorithm

Consider the following motivation example in Fig. 6, the access point A could connect to access point C relayed by node B with 2.4 GHz, or directly connect to C at 450 MHz. If 2.4 GHz were chosen, link D, E is able to reuse 2.4 GHz when they are out of the interference range. However, along the backhual tier, if link A, C used 450 MHz, a lower hop count would result for the path, yet 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

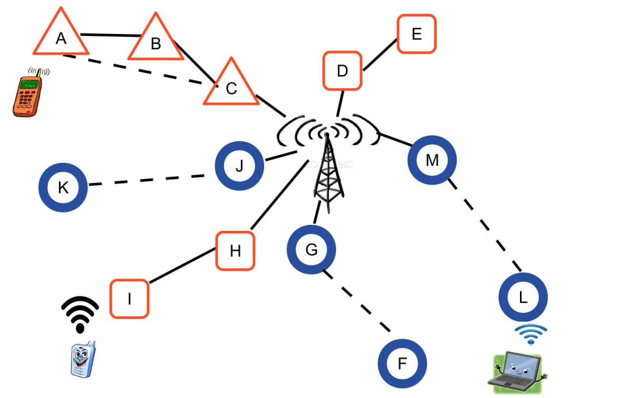


Fig. 6. Example WhiteMesh topology with different mesh-node shapes representing different frequency band choices per link.

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 $C = (V, L, B)$. 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 the 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: choose the connectivity graph C' which maximizes the total traffic served from the access tier. 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 Alg. 2. The algorithm first chooses the access point that has the largest physical distance from the gateway nodes in the network to most greatly reduce the total time cost of the network. When a path is constructed for the access point with the greatest distance, all subsequent access points along the path are also connected to the gateway. In large-scale mesh networks, the complexity makes it impractical to traverse all the paths with different combination of bands from an access point to any gateway node. It has been proved as an NP-hard problem. However, based on the discussion in Section. V-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 path have the same path interference, we choose the path which has higher-frequency links to keep the potential improvement of spatial reuse. Thus, the next step of the algorithm is to find the shortest path across band combinations.

In the algorithm, compared to the number of access points, 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 $O(N_E^2)$ [21], where as N_E is the set of possible links in the network. As a result, the total complexity would be $O(N_E^2 \cdot 2^{N_B})$. The algorithm will compare the PIN of the candidate paths and select the path with the least interference channel induced on the network for the source access point.

Algorithm 2 Band-based Path Selection (BPS)

Input:
- M: Set of access points
- 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 access points 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 access point **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
Update CA as the locally-optimal solution

The algorithm updates the channel assignment of the network after the path is chosen. Then, the set of served nodes, activated links, and radio information are updated. The process will repeat iteratively to assign channels for all the access points in the network.

The complexity of assigning a channel for an access point 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 an access point is $O(N_V^4 \cdot 2^{N_B})$. To assign *all* the access points 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 (mesh group) for a wireless network assignment.

D. Experimental Evaluation Setup

WhiteMesh networks have the diversity in propagation from the lowest white space channels (tens to hundreds of MHz) to the highest WiFi channels (multiple GHz). We consider a wide range of propagation characteristics from four different frequency bands to set up the experimental evaluation. We use 450 MHz and 800 MHz of white space bands and 2.4 GHz and 5.2 GHz of WiFi bands data from the spectral analysis in Section. III.

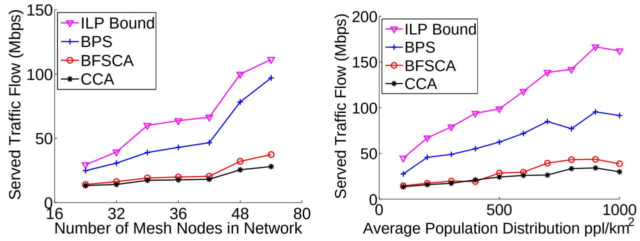
According to the population density for a given deployment location, we consider the spectral activity observed for the population density from our in-field measurement. We input the measurements to both the LP and heuristic-based algorithm to compare the performance in various scenarios. The communication threshold is set as -100 dBm. The communication range is normalized with the highest frequency of 5.2 GHz. Then, the communication range of 450 MHz, 800 MHz, 2.4 GHz, and 5.2 GHz would be normalized to 12.8, 6.2, 2.4, and 1, respectively in the Friis model (as Eq. 1). The interference range is set to twice that of the communication range [22]. We deploy static wireless mesh networks of n access points 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 [23]. 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 BPS algorithm.

The traffic demand aggregated by an access point is independent to others and obeys a Poison distribution per unit time. In the simulation, we generate an equal number of access points (including both gateway nodes and access points) Poison random numbers with a mean of λ. Then, we assign as the traffic demand for each access points in the target area. As mentioned previously, the achieved wireless capacity of gateway nodes has been shown to be the bottleneck in mesh networks [15]. Moreover, the amount of total traffic served is affected by access point placement, gateway placement, routing, and channel assignment. For the purposes of our analysis, we specifically calculate the total traffic served through a greedy strategy. We study the channel assignment process under a tree-based structure. To maximize the total traffic served, 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 access points have the same hop count, the least interfering access points are chosen to reduce the cost for the whole network. When the paths have the same level of interference, the ties are broken by the nodes order. The process repeats until no remaining traffic demand of users is unserved or no remaining channel capacity exists on any path.

We investigate the impacts of network size, band availablity, and channel occupancy on WhiteMesh networks in the simulations. We assume 30% of the residents will use the service. An individual user would have a 2 MBps traffic demand on average. Each radio has 600 MBps capacity as previous configuration. We assign the traffic demand to users under the same Poison setting and run the analysis of each case 20 times. To approach the total traffic served upper bound, we relax our LP model to only keep the link capacity constraints, given the traffic demand of the access points as a parameter to achieve the maximum throughput at the gateways. We further compare BPS with the *(i)* Common Channel Assignment (CCA) from [24], and *(ii)* Breath First Search Channel Assignment (BFS-CA) from [8] under the same setup. The CCA [24] 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 free capacity for a new assignment. These two methods are designed for multi-channel scenarios where each channel has tha same propagation characteristics and spectral activity level of the algorithms.

E. Experimental Analysis of WhiteMesh Backhaul

1) Network Size & Bands Effect: Typically, the traffic patterns of access points from users are diverse with the download direction dominating the total traffic demand (e.g., consider service agreements for cellular data or Internet connectivity).



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

Fig. 7. Performance in terms of total traffic served for various offered loads, network sizes, and configurations of WiFi or white space (WS) channels.

Hence, to simplify the analysis and scale the LP Bound to larger network sizes, we only consider the download traffic in the simulations.

We investigate the network size impact on WhiteMesh networks. The number of access points is varied from 16 to 64 in the aforementioned regular grid. The gateways through the hexagonal gateway node deployment with the network size. Fig. 7(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-based algorithms: *(i)* Common Channel Assignment (CCA) from [24], *(ii)* Breadth First Search Channel Assignment (BFS-CA) from [25], AND *(iii)* our algorithm BPS (Section V-C).

In Fig. 7(a), we observe the total traffic served increases with the network size. The multiband wireless network has a similar communication and interference performance with the multi-channel wireless network with a small network size for all algorithms. However, as the network size or population increases, the performance diverges between BPS and CCA/BFS-CA. The nodes of a small network are located in a single interference space of all the bands. The communication range variation of the bands impact on the network performance when the inter-node spacing become diverse. The LP Bound shows the upper-bound of total traffic served increases with the network size. The multi-channel algorithms assign channels without considering the channel capacity diversity and thepropagation differences per band. Hence, the performance is remains low across population densities. CCA fails to employ the communication range variation to find the most efficient multi hop paths. BFS-CA optimizes the first-hop connection 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 LP Bound. The gap of BPS to the LP is partly because BPS only considers a fixed multihop path to a gateway node for each access point, whereas the LP considers multiple paths to the gateways. For BPS and other heuristic-based algorithms, a dynamic assignment version could be implemented through updating the assignment as after path emerge.

Then we investigate 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. The achieved channel capacity is mapped to the spectral analysis with the closest population distribution. Fig. 7(b) shows the correlation of the population distribution and total traffic served. Similar to Fig. 7(a), as shown in the figure, the wireless channel capacity of a gateway is saturated quickly when the algorithm fails to reduce the interference via resource allocation among the channels. Also, the results show how the achieved channel capacity impacts on the performance. As the population density increases, the measurement-based channel capacity varies among multiple bands. When the population density reaches 1,000 ppl, the total traffic served decreases due to the high measured activity level and the saturation of wireless channel capacity around the gateways. BPS 60% achieve of the upper bound on average. The results shows that CCA and BFS-CA perform worse than BPS with limited recogination of propagation variation in the joint WiFi and white space scenarios.

WhiteMesh networks are able to deploy 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. 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 5.2 GHz) channels with two white space channels (450 and 800 MHz), *(ii)* three channels in two WiFi bands (2.4 and 5.2 GHz) with one white space channel (450 MHz), *(iii)* Four channels in two WiFi bands (2.4 and 5.2 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 total traffic served for various scenarios of WiFi and white space bands with an offered load of 5 Mbps as mean value of Possion process from 500 ppl/km^2 in a regular 49-node grid. We study the performance of BPS in the four aforementioned scenarios of varying white space availability. In the simulation, we keep total 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). In the results, we observe that the WiFi-only scenario has greater total traffic served than the white-space-only scenario. This is due to the lack of spatial reuse achieved by white spaces bands. White space has larger communication range to shorten the hop counts as well as has larger interference reducing the spatial reuse. Another reason is that the achieved channel capacity of 500 ppl/km^2 in white space bands are worse than WiFi bands. These two reasons make the performance of white space only worse in all channel assignment methods applied here. 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 Table IV, that with the same number of bands (2), the combination with similar propagation characters, the cleaner channels combination has better performance. With similar achieved channel capacity, lower frequency offers more option for connection path perform better in channel assignment. If we have one channel in a white space band and one channel in a WiFi band, then we could employ the advantages of both WiFi for spatial reuse and white spaces to reduce the hop

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

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]	22.4	13.4	13.2	12.5	16.9	23.2	24.1	30.6	25.2	23.9	30.4
BFS-CA [25]	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
TOTAL TRAFFIC SERVED (MBPS) FOR VARIOUS COMBINATIONS OF WIFI AND AVERAGE POPULATION DISTRIBUTION = 500 ppl/km^2, NETWORK SIZE = 49 ACCESS POINTS).

count in channel assignment.

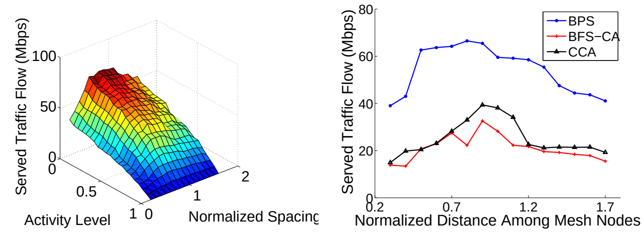
2) Access Tier Impacts on Backhaul Tier: The density of access points increase proportional to the population density to offer enough access capacity for the users. Hence, the distance among the access points and the channel occupancy in backhual tier channel assignment need to be leveraged. To investigate impacts of the spacing variation and channel occupancy in the access tier on the backhaul tier, we perform simulation on a 49-node regular grid WhiteMesh network as described before.

In Fig. 8(a), we show the impacts of channel occupancy through the activity level and spacing variation on wireless white space mesh network. In the results, all the bands have the same activity level in the 49-nodes regular grid with normalized multiple inter-node spacing from 0.2 to 2.1 as discussed in Subsection V-D. In the 3-D figure, as the activity level increases, the total traffic served decreases due to the reduction of achieved channel capacity. In the spatial dimension, when the nodes have extremely small spacing, lacking the propagation diversity of multiple bands and spacial reuse make the total traffic served limited as we have analyzed in Fig 7(a). While as the spacing gap increases, the high frequency bands bring higher total traffic served via more spacial reuse. As the spacing gap increase, the high frequencies stop communicating due to the limited communication range. The number of available channels reductioneleads the total traffic served reduce sharply as shown in the figures.

We further study the real world spacing gap variation through BPS with in-field measurements. 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 access point capacity M_c obey $P_d \cdot \frac{D_s}{2}^2 \propto M_c$. We interpolate activity level for each normalized distance from 0.2 to 1.7 with gap 0.1. The results of the heuristic-based algorithms and the results are shown in Fig. 8(b).

In Fig. 8(b), as the spacing increases, the WhiteMesh network has the best performance in all methods through spatial reuse, matching the simulation analysis shown in Fig. 8(a). As the distance increases up to normalized distance 1, one of the 5 GHz channels stops working in the network since the distance is larger than its communication range. That makes the performance decrease sharply.

Through these analysis, a mixed WiFi and white space



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

Fig. 8. Spacing Impacts on the Backhaul Tier

wireless WhiteMesh network improves the performance in the following achieve aspects: *(i)* Heavily utilized networks can get more capacity from spatial reuse and flexible path reducing hop count through diverse links. *(ii)* Rural networks have large mesh spacing to be deployed with a reasonable network performance with a fair more reduce of budget. We are able to find an approaching of optimal WhiteMesh deployment based on this analysis.

VI. RELATED WORK

There are significant challenges in wireless mesh network deployment, such as user priorities, user behaviors, long term throughput estimation, interference and energy efficiency, etc. [26] Previous works have recognize the impact of interference in wireless mesh network deployment is the key issue [8], [27], [28]. To overcome the challenges, previous works have been done to optimize the deployment in increasing throughput, minimize resource, reducing interference, etc [9], [27], [29]. Many works have studied the network deployment problem in multihop wireless networks [26], [30]–[32]. Both static and dynamic network deployments have been discussed in previous works under the 802.11 WiFi scenario [25], [29], [33]. However, all of the aforementioned works have not considered propagation variation of the diverse frequency bands among white space and WiFi, which we show are critical improving the performance of mesh networks. Frequency agility in multiband scenario brings more achieved channel capacity to wireless network deployment as well as more complexity of resolving the interference issues.

To be used effectively, white space bands must ensure that available TV bands exist but no interference exists between microphones and other devices [34]. 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 [35]). 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. [34] introduce WiFi like white space link implementation on USRP and link protocols. [36] discuss the point to point communication in multiband scenario. In [37], white space band application is discussed in cognitive radio network for reducing maintenance cost. In this work, the objective is maximizing the served traffic flow of clients in the wireless network.

VII. Conclusion

In this paper, we jointly considered the use of WiFi and white space bands application for wireless networks deployments. We first perform our in-field measurements study in the DFW metropolitan area and surrounding areas. We then propose a measurement-driven Multiband Access Point Estimation (MAPE) framework to estimate the number of access points required in a given region for wireless access network. Further, we propose measurement-driven Band-based Path Selection (BPS) algorithm for backhual tier channel assignment. 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% of the served traffic flow 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.

References

[1] M. Reardon, "EarthLink pays 5 million to delay houston Wi-Fi buildout," http://news.cnet.com/8301-10784_3-9768759-7.html, 2007.

[2] J. Cheng, "Philadelphia's municipal WiFi network to go dark," http://arstechnica.com/gadgets/2008/05/philadelphias-municipal-wifi-network-to-go-dark, 2008.

[3] J. Camp, J. Robinson, C. Steger, and E. Knightly, "Measurement driven deployment of a two-tier urban mesh access network," in *ACM MobiSys*, 2006.

[4] R. Karrer, A. Sabharwal, and E. Knightly, "Enabling large-scale wireless broadband: the case for TAPs," in *HotNets-II*, 2003.

[5] C. Inc., "Fcc certifies carlson wireless technologies tv white space radio," http://www.carlsonwireless.com/rural-connect-press-release.html, 2014.

[6] C. A. Balanis, *Antenna theory: analysis and design*. John Wiley & Sons, 2012.

[7] "Google spectrum database," http://goo.gl/NnIFXQ, 2013.

[8] J. Tang, G. Xue, and W. Zhang, "Interference-aware topology control and QoS routing in multi-channel wireless mesh networks," in *ACM MobiHoc*, 2005.

[9] M. Doraghinejad, H. Nezamabadi-Pour, and A. Mahani, "Channel assignment in multi-radio wireless mesh networks using an improved gravitational search algorithm," *Journal of Network and Computer Applications*, vol. 38, pp. 163–171, 2014.

[10] J. B. Andersen, T. S. Rappaport, and S. Yoshida, "Propagation measurements and models for wireless communications channels," *IEEE Communications Magazine*, vol. 33, no. 1, pp. 42–49, 1995.

[11] H. T. Friis, "A note on a simple transmission formula," vol. 34, no. 5, pp. 254–256, May 1946.

[12] T. Rappaport, *Wireless Communications, Principles & Practice*. Prentice Hall, 1996.

[13] W. Si, S. Selvakennedy, and A. Y. Zomaya, "An overview of channel assignment methods for multi-radio multi-channel wireless mesh networks," *Journal of Parallel and Distributed Computing*, vol. 70, no. 5, pp. 505–524, 2010.

[14] S. Haykin, "Cognitive radio: brain-empowered wireless communications," *Selected Areas in Communications, IEEE Journal on*, vol. 23, no. 2, pp. 201–220, 2005.

[15] J. Robinson, M. Singh, R. Swaminathan, and E. Knightly, "Deploying mesh nodes under non-uniform propagation," in *IEEE INFOCOM*, 2010.

[16] G. Rosston, S. Savage, and D. Waldman, "Household demand for broadband internet service," *Communications of the ACM*, vol. 54, no. 2, pp. 29–31, 2011.

[17] "People and households," http://www.census.gov/people/, 2014.

[18] R. Meikle and J. Camp, "A global measurement study of context-based propagation and user mobility," in *Proceedings of the 4th ACM international workshop on Hot topics in planet-scale measurement*. ACM, 2012, pp. 21–26.

[19] T. L. Saaty, *Elements of queueing theory*. McGraw-Hill New York, 1961, vol. 423.

[20] J. Yuan, Z. Li, W. Yu, and B. Li, "A cross-layer optimization framework for multihop multicast in wireless mesh networks," *IEEE JSAC*, vol. 24, no. 11, pp. 2092–2103, 2006.

[21] B. Golden, "Shortest-path algorithms: A comparison," *Operations Research*, pp. 1164–1168, 1976.

[22] A. Raniwala and T. Chiueh, "Architecture and algorithms for an IEEE 802.11-based multi-channel wireless mesh network," in *IEEE INFOCOM*, 2005.

[23] S. Meguerdichian, F. Koushanfar, G. Qu, and M. Potkonjak, "Exposure in wireless ad-hoc sensor networks," in *Proceedings of the 7th annual international conference on Mobile computing and networking*. ACM, 2001, pp. 139–150.

[24] R. Draves, J. Padhye, and B. Zill, "Routing in multi-radio, multi-hop wireless mesh networks," in *ACM MobiCom*, 2004.

[25] K. N. Ramachandran, E. M. Belding-Royer, K. C. Almeroth, and M. M. Buddhikot, "Interference-aware channel assignment in multi-radio wireless mesh networks." in *IEEE INFOCOM*, 2006.

[26] E. Z. Tragos, S. Zeadally, A. G. Fragkiadakis, and V. A. Siris, "Spectrum assignment in cognitive radio networks: A comprehensive survey." *IEEE Communications Surveys and Tutorials*, vol. 15, no. 3, pp. 1108–1135, 2013.

[27] R. E. Irwin, A. B. MacKenzie, and L. A. DaSilva, "Resource-minimized channel assignment for multi-transceiver cognitive radio networks," *Selected Areas in Communications, IEEE Journal on*, vol. 31, no. 3, pp. 442–450, 2013.

[28] S. Chieochan and E. Hossain, "Channel assignment for throughput optimization in multichannel multiradio wireless mesh networks using network coding," *Mobile Computing, IEEE Transactions on*, vol. 12, no. 1, pp. 118–135, 2013.

[29] A. P. Subramanian, H. Gupta, S. R. Das, and J. Cao, "Minimum interference channel assignment in multiradio wireless mesh networks," *IEEE TMC*, vol. 7, no. 12, pp. 1459–1473, 2008.

[30] K. Jain, J. Padhye, V. N. Padmanabhan, and L. Qiu, "Impact of interference on multi-hop wireless network performance," *Wireless networks*, vol. 11, no. 4, pp. 471–487, 2005.

[31] I. F. Akyildiz, X. Wang, and W. Wang, "Wireless mesh networks: a survey," *Computer networks*, vol. 47, no. 4, pp. 445–487, 2005.

[32] A. Raniwala, K. Gopalan, and T.-c. Chiueh, "Centralized channel assignment and routing algorithms for multi-channel wireless mesh networks," *ACM SIGMOBILE MCCR*, vol. 8, no. 2, pp. 50–65, 2004.

[33] X. Wu, J. Liu, and G. Chen, "Analysis of bottleneck delay and throughput in wireless mesh networks," in *IEEE MASS*, 2006.

[34] P. Bahl, R. Chandra, T. Moscibroda, R. Murty, and M. Welsh, "White space networking with WiFi like connectivity," *ACM SIGCOMM*, vol. 39, no. 4, pp. 27–38, 2009.

[35] "Microsoft research white space database," http://whitespaces.cloudapp.net/Default.aspx, 2013.

[36] P. Cui, H. Liu, J. He, O. Altintas, R. Vuyyuru, D. Rajan, and J. Camp, "Leveraging diverse propagation and context for multi-modal vehicular applications," in *IEEE WiVeC*, 2013.

[37] I. Filippini, E. Ekici, and M. Cesana, “A new outlook on routing in cognitive radio networks: minimum-maintenance-cost routing,” *IEEE/ACM Transactions on Networking (TON)*, vol. 21, no. 5, pp. 1484–1498, 2013.