Leveraging White Spaces Across Diverse Population Densities

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***Abstract*—While many metropolitan areas sought to deploy city-wide WiFi networks, the densest urban areas were not able to broadly leverage the technology for large-scale Internet access. Ultimately, the small spatial separation required for effective 802.11 links in these areas resulted in prohibitively large up-front costs. The FCC has reapportioned spectrum from TV white spaces for the purposes of large-scale Internet connectivity via wireless topologies of all kinds. The far greater range of these lower carrier frequencies are especially critical in rural areas, where high levels of aggregation could dramatically lower the cost of deployment and is in direct contrast to dense urban areas, in which networks are built to maximize spatial reuse. Thus, leveraging a broad range of spectrum across diverse population densities becomes a critical issue for the deployment of data networks with WiFi and white space bands. In this paper, we measure the spectrum utility in the Dallas-Fort Worth metropolitan and surrounding areas and propose a measurement-driven band selection framework, Multiband Access Point Estimation (MAPE). In particular, we study the white space and WiFi bands with in-field spectrum utility measurements, revealing the number of access points required for an area with channels in multiple bands. In doing so, we find that networks with white space bands reduce the number of access points up to 1650% in sparse rural areas over similar WiFi-only solutions. In more populated rural areas and sparse urban areas, we find an access point reduction of 660% and 412%, respectively. However, due to the heavy use of white space bands in dense urban areas, the cost reductions invert (an increase in required access points of 6%). Finally, we numerically analyze band combinations in typical rural and urban areas and show the critical factor that leads to cost reduction: considering the same total number of channels, as more channels are available in the white space bands, less access points are required for a given area.**

I. INTRODUCTION

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].

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. While many works have worked to address multihop wireless network deployment in terms of maximizing served user demand and/or minimizing network costs, the unique propagation characteristics and the interference from coexisting activities in white space bands have either not been jointly studied or assumed to have certain characteristics without explicit measurement [3]. Specifically, previous work has investigated wireless network deployment in terms of gateway placement, channel assignment, and routing [4], [5]. However, each of these works focus on the deployment in WiFi bands without considering the white space bands. Moreover, the assumption of idle channels held in these models fails to match the in-field spectrum utility, which could degrade the performance of a wireless network. These two issues are substantial to designing an optimal network deployment and provide potential commercial wireless services to clients in any location.

Thus, the new opportunities created by white spaces motivate the following questions for wireless Internet carriers, which have yet to be addressed: *(i) 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 *(ii) Where along the continuum of user population densities do the white space bands no longer offer cost savings for wireless network deployments?* In this paper, we perform a measurement study which considers the propagation characteristics and observed in-field spectrum availability of white space and WiFi channels to find the total number of access points required to serve a given user demand. 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 measurement location. With the in-field measured spectrum utility data in metropolitan and surrounding areas of Dallas-Fort Worth (DFW), we calculate the activity level in WiFi and white space bands. Second, we propose a measurement-driven framework to find the number of access points required for areas with differing population densities according to our measurement locations and census data. We then evaluate our measurement-driven framework, showing the band selection across downtown, residential and university settings in urban area and rural areas and analyze the impact of white space and WiFi channel combinations on a wireless deployment in these representative scenarios.

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 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 settings.

- We analyze our framework under capacity and coverage constraints to show that, with white space bands, the number of access points are greatly reduced from WiFi-only deployments by up to 1650% in rural areas.
- We quantify the impact of white space and WiFi channel combinations to understand the tradeoffs involved in choosing the optimal channel setting, given a certain number of available channels from multiple bands.

II. Challenges and Problem Formulation

In this section, we illustrate the challenges of band selection in wireless network deployment and formulate the problem of band selection in mesh network deployments jointly using WiFi and white space bands. Further, we present a measurement-driven framework for estimating the mesh node number to serve the traffic demand of a given population.

A. White Space Opportunity and Challenge

Wireless propagation is the behavior of 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 [6]. 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 [7]:

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

Here, n varies according to the aforementioned environmental factors with the value of two to five in typical outdoor settings [8].

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 [9]). Prior work has worked to reduce interference levels via gateway deployment, channel assignment, and routing [4], [10]. 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. Most of the existing works try to reduce the intra-network interference without regard to the inter-network interference [3]. However, the existence of inter-network interference becomes an important problem when considering the availability of white space bands. While theoretical models describing inter-network interference exist, accurately characterizing a particular region must be done empirically.

When wireless devices operate in WiFi bands, the channel separation is relatively small (e.g., 22 MHz for the 2.4 GHz band). As a result, many works assume that the propagation characteristics across channels are similar. However, with the large frequency differences of WiFi and white space bands (e.g., multiple GHz), propagation becomes a key factor in the deployment of wireless networks with both bands. Here, a frequency band is defined as a group of channels which have small separation meaning similar propagation characteristics. In this work, we consider the diverse propagation and activity characteristics for four total frequency bands: 450 MHz, 800 MHz, 2.4 GHz, and 5.2 GHz. We refer to the two former frequency bands as white space bands and the two latter frequency bands as WiFi bands. The differences in propagation and spectrum utilization creates opportunity for the joint use of white space and WiFi bands in wireless access networks according to the environmental characteristics (e.g., urban or rural and downtown or residential) of the deployment location.

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 [11]. 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 lower-frequency, 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 areas [12], a larger number of white space bands can be leveraged in these areas.

B. Model and Problem Formulation

As opposed to previous works such as [3], [10], [13], this paper focuses on reducing the inter-network interference for various population densities for wireless access networks which jointly employ WiFi and white space bands. We propose a measurement-driven framework to estimate the number of access points required for serving the traffic demand of a certain area. We assume an access point has a limited number of radios which operate on any channel of a fixed number of channels with the same antenna gain. Each radio on an access point operates with a classic protocol model [14]. We further assume that there is a given take rate and traffic demand for a given population (as specified in Section III).

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:

$$A = \frac{S_\theta}{S_a} \quad (2)$$

The capacity of a clean channel is denoted by C. With the protocol model, the capacity of a channel with inter-network interference C_r could be represented as the remaining time of the clean channel capacity according to:

$$C_r = C * (1 - \bar{A}) \quad (3)$$

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 need to be covered

1: Split M in to different type, calculate the traffic demand density f
2: Calculate in-field channel capacity C_r as $C(1 - A)$
3: Get the propagation coverage area radius R_p from Frii model based on n, B, F
4: Calculate the QoS coverage radius R_{QoS} of a Multiband Access Point satisfy the demands of the area
5: The coverage radius of a Multiband Access Point is $MinR_p, R_{QoS}$
6: Apply regular hexagon deployment to get the number of access point for serving given area M

Output:

The number of Access Points

A 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 Internet has been previously characterized [15], 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 access points set M according to:

$$\sum_{m \in M} C_r^m \geq \sum_{f \in F, k \in K} \bar{D_p} * f * k \tag{4}$$

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 [11].

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 point to cover an area is to use multiple orthogonal lower-frequency channels. However, the FCC limits the white space band availability for data communication in most metropolitan areas in the United States [16]. 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 time-domain 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 government statistics [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 space-domain input. Then, we use the measured activity level as the time-domain 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 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 transmit power is adjusted to fulfill the coverage restriction subject to the FCC regulations for maximum-allowable transmit power. A classic regular hexagon deployment process is employed to place the access points.

III. Experiment and Analysis

To evaluate the spectrum utility from in-field measurements, we perform experiments with an off-the-shelf wireless platform and mobile spectrum analyzer. According to the measured data, we apply our MAPE framework to analyze the role of white space and WiFi bands in total access points required for a given deployment area.

A. Experiment 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 with tcpdump for this testbed working as a sniffer and 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, we employ a a spectrum analyzer to form a notion of inter-network interference with finer granularity. We have 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 measure the received signal strength in a short term.

As far as we know, there is no mobile multiband antenna in the market. We use a 700 MHz mobile antenna to perform the in-field experiments. Then, we uniform the mobile antenna measurements across bands by comparing with the indoor measurements from the multiband antenna with our controlled signal source. First we use USRP(Universal Software Radio Peripheral) N210 to generate signals in 450 MHz, 800MHz, and 2.4 GHz [18]. 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 Gatework 2358 with a XR5 radio. Then we connect the signal source to the multiband antenna, and measure the received signal in a fixed distance with the 700 MHz antenna and antennas for different bands to get the

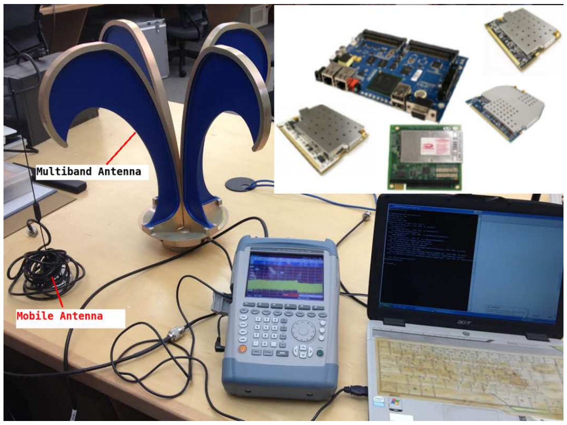

Fig. 1. Multiband Measurement Platform

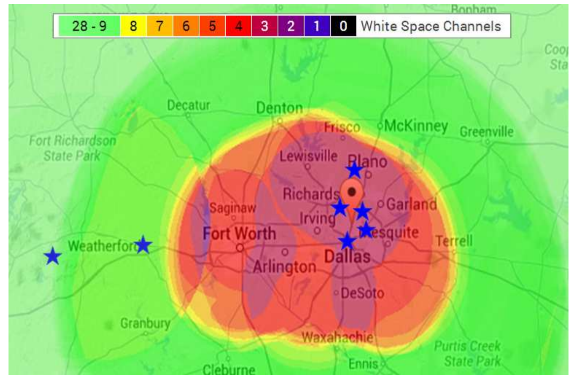

Fig. 2. DFW Metropolitan Measurement Location

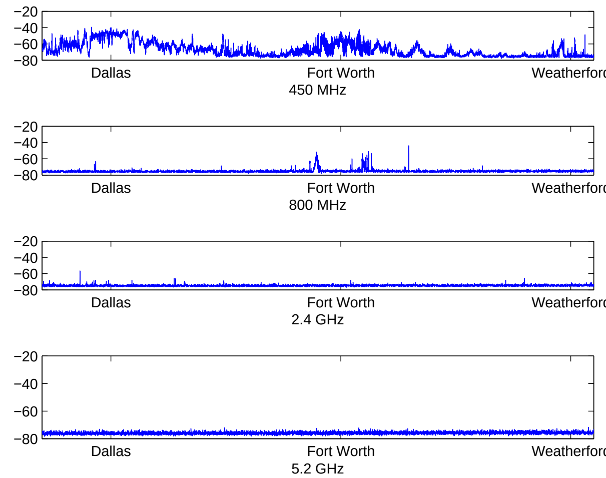

Fig. 3. Spectrum Activity In DFW

antenna loss of all the bands. Then we normalize the received signal strength collected through 700 MHz mobile antenna.

Our experiment platforms are shown in Figure 1. We have 32 samples each second for each band from the spectrum analyzer with time stamps. Gateworks sniffer platform records all the packets received in WiFi bands with time stamps. The duplicated samples in WiFi bands from spectrum analyzer and Gateworks are deleted according to the time stamp. Then we use the data for activity level calculation in WiFi bands. The activity level of white space bands is calculated based on the spectrum analyzer measurements.

We choose experiments locations according to the population distribution in DFW metropolitan. The experiments are performed in Dallas, Weatherford and Millsap marked with stars in Figure 2. We have collected measurements at multiple locations, including the neighborhood, campus and urban area in Dallas. In Weatherford and Millsap, we monitor wireless activities in three locations for 45 minutes on a normal weekday. Downtown, neighborhood and rural area are chosen from Weatherford and Millsap. Then we post-process the data to calculate the activity level of each band in each location.

B. Results and Analysis

In this subsection, we discuss our measurements results and perform our WAPE framework to analyze the influence of white space channels across areas with different population densities.

Figure 2 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).

As an initial experiment, we perform a drive test from Dallas to Weatherford with cruise control set to 60 MPH while on the highway. Part of the result of in-field spectrum measurement is shown in Figure 3. The measured RSSI of 450 MHz is strong in downtown Dallas, downtown Fort Worth; but has less signal activity in the urban and rural area between these cities. The low activity detected in WiFi bands is due to the distance from highway is larger than the propagation range of an indoor wireless router whose transmitting power is limited. The map itself shows the available white space channels in DFW area, more green means more channels. Our in-field measurement matches the FCC restriction showing that less channels means more spectrum utility and tell the spectrum utility levels varying across population distribution. 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-B. Dallas as the central city of North Texas, has the highest activitie level in most of the measured bands, especially in 450 MHz. The measurements of Dallas urban are taken from SMU campus, 2 neighborhoods and city Plano. Our meaurements indicates that 2.4 GHz has a higher activity level in urban area than downtown area. Most schools and their neighborhoods are covered by WiFi today, which explains the high activity level in 2.4 GHz and 5.2 GHz. In Weatherford, all the bands have lower activity levels than in Dallas. And due to the location for measurement collection, the rural area on the west of Weatherford could receive more interference from Fort Worth. Millsap is a typical sparse city with 500 residents total in north Texas. The activity levels across all the bands are lower than in Dallas and Weatherford. In 450 MHz band, the activity level decreases much faster than in other bands in Dallas and Weatherford.

We put these measurement based activity level into our

Bands	Dallas			Weatherford			Millsap		
Area Type	Downtown	Urban	Sparse Area	Downtown	Urban	Sparse Area	Downtown	Urban	Sparse Area
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

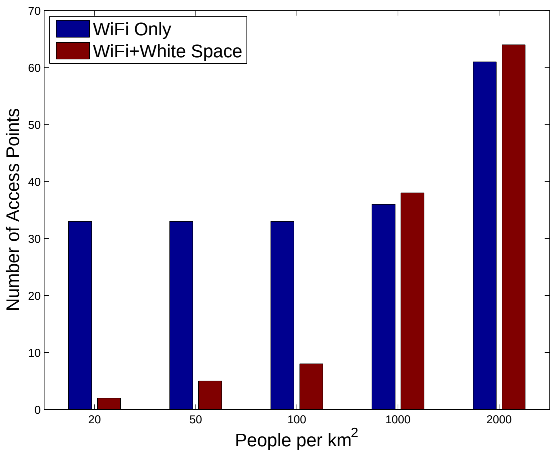

Fig. 4. Number of Access Points need for 13x13 km^2 Area

framework presented in Algorithm 1. We use Millsap sparse area, Millsap downtown, Weatherford urban, Dallas urban, and Dallas downtown measurement as input activity level map to the population density. We input these information to our framework and calculate the number of access point for covering a $13km \times 13km$ area varying population density. The output is shown in Figure 4.

In the calculation, we set the demand request as 2 $Mbps$ per person, the population density as $20, 50, 100, 1000, 2000$ per square kilometers. We assume 30% residents will use this service, the maximum transmit power $30dBm$, path loss exponent 3.5 [19]. For WiFi only, we use 6 channels in 2.4 GHz, and 3 channels in 5.2 GHz. Our experiment platforms are shown in Figure 1. We adopt 802.11n maximum data rate 600 Mbps. For WiFi+ White Space scenario, we use 3 channels in 450 MHz, 2.4 GHz and 5.2 GHz each. Then all the scenarios have the same channels in total. As shown in Figure 4, with the same number of channels, WiFi+White Space gains 1650% comparing to WiFi only in 20 people per square kilometer scenario, and 660% in 50 people per square kilometer and 412.5% in 100 people per square kilometer. But as the population density increase, due to the capacity constraint servicing people in this area, low frequency white space band lose their advantage of larger communication range. And at the same time, the activities of other signal source, such as TV station in downtown area reduce the capacity of white space band, then WiFi+White Space bands perform worse than WiFi only bands combination. If we count the intra-network interference which is out of our scope, the situation could be even worse. Moreover, FCC has stricter policy of white spaces in downtown and urban area. Fewer channels are available in these area which make WiFi bands a better option for population dense areas.

To find the bands combination influence on network deployment, we calculate the number of access points in the area. We select 500 people per square kilometer with Weatherford downtown spectrum utility, and 1500 people per square kilometer with Dallas urban spectrum utility running numerical analysis. We assume the total number of channels is 12. We use the same setup as the previous experiment. The results are shown in II.

No. of Bands	Bands Combination (Hz)	No. of AP 500 population	No. of AP 1500 population
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	450,800 M,2.4,5.2 G	21	44

TABLE II
CHANNEL COMBINATIONS FOR 500 AND 1500 POPULATION DENSITY SCENARIOS

In the table, we compare the number of access points with 12 channels through all the possible combinations of bands. When all the channels are in the same band. as frequency goes up, more access points are need to serve the area due to the limited propagation range. 450 MHz does not outperform 800 MHz in single band at both 500 and 1500 population density cases because 450 MHz channels have larger measured activity level in experiment setup. White space band channels outperform WiFi bands up to 1830% in single band case at 500 population density. But in 1,500 population density, the gain decrease to 543.33%. We distribute equal number of channels to 2 bands combinations and run the experiments in two population and spectrum utility scenarios. The numerical results shows white space bands combination(450 MHz,800 MHz) performs better than WiFi only(2.4 GHz, 5.2 GHz) by 200% in 500 population density and 128.12% in 1,500 population density. White space only(450 MHz, 800 MHz) has almost the same performance as white space + WiFi scenario(450 MHz, 2.4 GHz; 800 MHz, 2.4 GHz) in 1,500 population density. But in 500 population density, white space only is much better than any other 2 bands combinations. White space channels brings up to 87.5% gain in 3 bands combination scenario in 500 population density and up to 33.3% gain in 1,500 population density. And with 4 bands, the number of access points does not outperform using channels in white space bands.

From figure 4 and Table II, we could find as the population density increase, the gain of white spaces decrease. Centralizing channels in white space bands could get more benefit comparing with distribute them into multiband bands. And also, as population and spectrum utility increase, at some point, the performance of white space only could be the same as white space+WiFi combination. Then we may pay less money to get less number of white space channels for wireless net work deployment.

IV. Related Work

Many efforts have been put in wireless network deployment in WiFi bands [4], [20], [21]. These works focus on solving gateway placement, channel assignment, routing problems in wireless network to reduce the interference generated inside the network. However, wireless interference is not only from a new deployment network but also from the existing wireless device. Unfortunately, few of the works in network deployment notice the inter-network interference. Some cognitive radio works discuss the inter-network interference, but most of them focus on point to point communication other than network [22].

As FCC adopt white space bands for wireless communication, new research room comes out for wireless network deployment [23]. The white spaces bring two concerns: large propagation range and existing Inter-network interference from TV station and other device [24], [25]. Previous works fails to discover the white spaces benefit and drawback in network deployment [26]. Many works correlated to white spaces are tareting on opportunistic medium access. However, the application of white space in outdoor environment, such as urban, rural area, has not been recognized. Lacking the quantization discussion of white space in outdoor environment is blocking the development of white space application.

There are some works discuss the propagation variation in both WiFi network and white space network. In [11], Robinson model the propagation variation at the same band in terrain domain. Rohan brings a databased-driven SenseLess framework designing a white space network with database of primary user(TV station) location, channel occupation [27]. However, as far as we know, no work jointly discuss the influence of white space on network deployment in propagation variation of space domain and spctrum utility in time domain.

V. Conclusion

In this paper, we exploited the joint use of WiFi and white space bands for improving the service in multiple type of areas. To do so, we propose an multiband access point estimation framework to find the number of access points in an arbitrary area. We then take spectrum utility measurements in DFW metropolitan area and involve the data to our framework to find the white spaces influence in different type of areas. Through extensive analysis across varying population density, channel combinations across bands, we show that employing channel combination with white space band in rural area gains up to 1650% in the number of access points, 660% in sparse urban area; but fails to get benefit in dense urban and downtown type area. Moreover, we investigate different band combinations in two population density setup. The numerical results show that more white space channels when fix the total number of channels could earn more gains in sparse area. But as the population and spectrum utility increase, white spaces stop outperforming mixed white space plus WiFi channels combination.

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