Leveraging White Space Opportunity in Metropolitan Area

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***Abstract*—Wireless Mesh Network is an efficient and low cost solution for large-scale Internet connectivity in metropolitan areas. To deploy new wireless mesh network, knowing the existing signals in the air is a must. The existing signal information is important for all the problems in wireless mesh network, such as gateway deployment, channel assignment, and routing. Many work has been done to approach the interference model. However, there is no model fit for all metropolitan cities. Moreover, FCC regulations have reapportioned spectrum for data communication with far greater range than WiFi in lower carrier frequencies. Thus, leveraging the spectrum utility and finding the proper bands become an urgent task for metropolitan cities who want to deploy wireless mesh network. In this work, we measure the spectrum activities in DFW area and propose a measurement driven band selection framework Multiband Access Point Estimation (MAPE) which explore the white space bands with in-field spectrum utility telling the number of access points required to serve an area with channels in different bands. In doing so, we find gains of white space bands application over existing multi-channel, multi-radio application in reducing the number of access points up to 1650% in sparse rural area, 660% in rural area, and 412% in sparse urban area. Moreover, due to the heavy used white space band, the spacial reusable WiFi bands gains 6.25% reducing the number of access points in urban area, and 6.6% in downtown area. Moreover, we use our MAPE framework numerical analyze band combination in typical urban area and the result shows with the same number of channels, the more channels in white space band, the less access points needs for a candidate areas.**

I. Introduction

Numerous cities are pursing city-wide WiFi deployment since the beginning of 21st century. Wireless Mesh Network is an ideal solution for the coverage target. Both academies and industries are putting efforts on providing Internet connection for metropolitan areas [1]. While a few mesh networks have been deployed in certain populated communities [2], [3], wireless mesh networks have largely been unsuccessful in achieving the scale of what was once anticipated [4]. As a result, many network carriers opted to pay millions of dollars in penalties rather than facing the exponential-increasing deployment costs [5]. Part of the reasons are the cost of building tons of access points and the failure of cooperation with existing wireless instrument.

Around the same time, the digital TV transition created more spectrum for using with data networks [6]. These white space bands operate in available channels from 54-806 MHz, having increased propagation characteristics as compared to WiFi [7]. The large scale communication range help the network carriers reducing the number of access points for covering a certain area. Hence, the FCC has identified rural areas as a key application for white space networks since the reduced population from major metropolitan areas allows a greater service area per backhual device without saturating wireless capacity. Naturally, the question arises for these rural communities as well as more dense urban settings: *how can the emerging white space bands improve large-scale mesh network deployments?* While much work has been done on deploying wireless networks the differences in propagation and the coexisting activities in white space bands have not been exploited simultaneously [8]. Recognizing the coexisting signals in both WiFi channels and white space band channels is an prerequisite for applying wireless network in all the topics. Previous work has investigate multi-channel, multi-radio wireless network in gateway placement, channel assignment, and routing problems. However, these works fail to involve white space band in their wireless network. Moreover, the clean channel hypothesis held in these works fails to match the in-field spectrum utility, which could slash the performance of mesh network in their models.

In this paper, we apply in-field measurement spectrum utility across WiFi bands and white space bands in multiband scenario to leverage the diversity in propagation and spectrum utility in the deployment of large-scale wireless mesh networks. To do so, we first form a metric quantify spectrum utility. Second, we proposed a measurement driven framework for finding the number of access points for multiple type of dense areas. Then, with in-field measured spectrum utility data in Dallas-Fort Worth area we tell the activity level in these WiFi and white space bands. We apply our framework with the measurement results and shows the band selection variation in downtown area, neighborhood, university campus, urban area and rural area. Finally, we analyze the white space band channels in band combination performance improve for a typical urban area.

The main contributions of our work are as follows:

- We design and perform in-field spectrum utility measurement in DFW metropolitan. Then we analyze the measurement results in multiple type dense areas.
- We develop a measurement driven multi-band wireless mesh deployment framework to jointly leverage white space and WiFi bands for serving wireless mesh networks in an arbitrary area.
- We perform extensive analysis across diverse propagation, existing spectrum utility under capacity and coverage constraints with our measurements and framework, showing that with white space band, the number of access points outperforms WiFi only deployment by up to 1650% in sparse rural area.
- Given similar channel resources, we additionally analyze the white space band performance in multiple combination of channels.

II. Problem Formulation

In this section, we formulate the problem of band selection in wireless mesh network deployment jointly using WiFi and white space bands. We first illustrate the challenges of band selection in deploying wireless network. Then we discuss the number of access points estimation in deploying wireless mesh network. Finally, we present measurement driven estimation framework to address the problem.

A. White Space Opportunity and Challenge

Wireless communication have changed the world since the day it was discovered. Today, wireless signals fill up the world across all the frequency bands. These signals help people improving their lives but also bring interference to each other. In any topic of wireless communication, the interference of existed signals have to be considered as an important part. Such as yielding primary users is a key issue in cognitive radio [9]. Researchers have put many efforts in solving issues of wireless network in gateway deployment, channel assignment, routing, etc. [10], [11]. Most of the works in wireless network solutions assume the channels are clean which unfortunately is not true.

The interference of a wireless network could be divided into two catalog according to the interference source. One is the *Intra-network intereference* which the nodes in the network interference each other. The other *Inter-network interference* is from signal sourse who is not in the network. The assumption make the recent works of wireless network deployment focus on the allocation of intra-network interference [8]. However, the ignorance of inter-network interference becomes an problem when white space bands come in to data communication. The inter-network interference of TV station and other signal source is a basic issue in network deployment.

Wireless propagation is the behavior of the signal loss characteristics when wireless signals are transmitted in the medium. The strength of the received signal depends on both the line-of-sight path (or lack thereof) and multiple other paths that are a result of reflection, diffraction, and scattering from obstacles in the environment [12]. The widely-used, Friis equation characterizes the power of the received signal P_r in terms of the power P_t and gain G_t of the transmitting signal, gain of the receiver G_r, wavelength λ of the carrier frequency, distance R from transmitter to receiver, and path loss exponent n according to [13]:

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

Here, the path loss exponent n varies according to the aforementioned environmental factors and ranges from 2 to 5 in typical outdoor settings [14]. Before FCC release white space bands, the channel separation is relatively small (e.g., 22 MHz for the 2.4 GHz band), many works assume the propagation of these channels are the same which match the restriction. Now, as white space bands come to data communication, the variation of propagation has to be counted in wireless network deployment.

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. The two former frequency bands, we refer to as white space (WS) bands whereas the two latter frequency bands, we refer to as WiFi bands. The difference of bands in propagation and in spectrum utility brings more variation to address for band selection with WiFi and white space bands.

Deploying wireless mesh network has to fulfill coverage and capacity constraints. Connectivity constraint requires all clients could be connected to access points. When access points locations are unknown or not yet selected, the possible access points need to cover all the area with a coverage constraint. We assume the coverage constraint is 95% for a target area [15]. Moreover, wireless bandwidth is shared among all clients, which is desirable to limit the number of potential shares of the scarce wireless spectrum. This capacity constraint limits the number of clients could be served. Spacial reuse helps to improve the capacity but increases the cost of deploying a wireless network. When a wireless network is deploying, both the coverage and capacity constraints have to be satisfied.

Avoiding interference is a primary target in wireless deployment. Many previous works focus on resolving the Intra-network interference [8], [16], [17]. But few trys to address the inter-network interference. Due to the distribution nature of the Inter-network interference, it is impossible to have a theoretic model to describe and estimate the activities of existing wireless signals. Measurement is the best and probably the only way to tell the Inter-network interference. The broadcast nature of the wireless medium make greater levels of propagation induce higher levels of interference, as both Inter-network and Intra-network interference. To smart use of WiFi and white space band adapting different demands of rural area and urban areas is a key issue in wireless network deployment. Thus, in sparsely-populated rural areas, the lower frequencies of the white space bands might be a more appropriate choice for wireless service in huge sparse areas. However, as the population and demand scales up (e.g., for more urban regions), the reduced spatial reuse and greater levels of Inter and Intra interference in white space bands might detract from the overall deployment strategy. In such urban areas, select links of greater distance might be the most appropriate choice for white space bands, especially since the number of available channels is often inversely proportional to the population (due to the existence of greater TV channels).

The distribution of inter-network interference vary in different types of area. We did measurement driving through Dallas, Fort Worth, and Weatherford in north Texas as the blue line shown in Figure 1. The driving spectrum measurement is shown in Figure 2. The signal strength of 450 MHz is strong in downtown Dallas, downtown Fort Worth; but has less interference in the urban and rural area between these cities. The low variation of 5.2 GHz and 2.4 GHz due to the limited transmitting range. The map itself shows the available white space channels in DFW area, more green more channels. Our driving measurement matches the policy restriction less channels means more spectrum utility. When we drive in the highway, the distance from our car to the weak signal source of

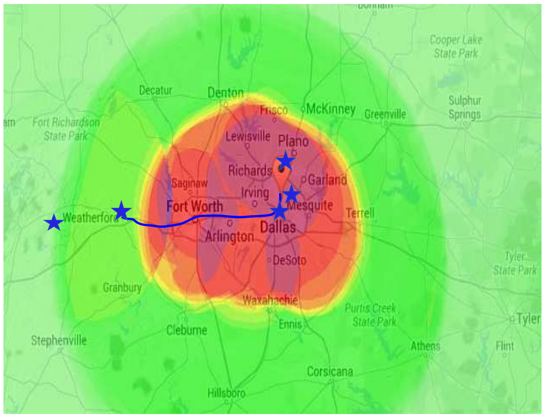

Fig. 1. DFW Metropolitan Measurement Location

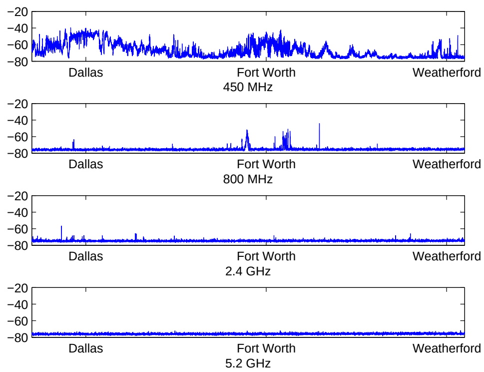

Fig. 2. Spectrum Activity In DFW

these bands is too large to be detected making low activities in WiFi bands. We did more fixed location measurement to quantify the spacial distribution.

Figure 3 depicts an example spectrum utility in activity level defined in II-B in our urban lab with the platform introduced in III. The activity level from data collected in the same location shows the difference in time domain. The existing signals occupy 25.83 percentage of time in 450 MHz, 26.49 percentage of time in 800 MHz, 34.95 percentage of time in 2.4 GHz and 35.46 of time in 5.2 GHz. The Inter-network interference of these existing signals is what we have to count in wireless network deployment. There is around 10% difference from white space band to WiFi band in our lab. This gap brings variation in band selection for wireless network deployment.

B. Model and Problem Formulation

Oppose to previous works, this paper focus on bands adaptation of Inter-network interference and multiple types of populated areas [8], [11], [18]. We propose a measurement driven framework to get the number of access points for serving a certain area with QoS requirement. We hypothesize that using radios with a greater diversity in propagation could achieve overall network performance gains. Therefore, for a given set of radios, we allow the channel choices to come from different frequency bands (i.e., multiband channel assignment).

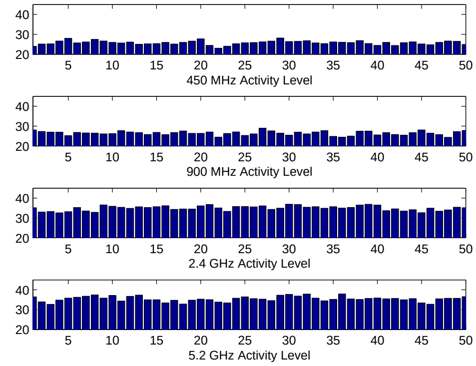

Fig. 3. Wireless Activity in Urban Lab

We assume that all access points have the same channel bandwidth, and antenna gain. Each access point operates with a classic protocol model [19].

Generally, Internet data request comes with population and Finland government even announce broadband is an individual 'legal right' [20], [21]. Providing a community wireless Internet service have to satisfy its traffic demand of multiple population distribution. In populated urban area, more people need more network capacity in which case WiFi band spatial reuse is better than white space band who limit its capacity in one NIC for the whole area. However, in populated urban area, more Inter-network interference comes from existing devices in WiFi bands could reduce the capacity of a spatial reuse WiFi network. Here we are trying to answer the question in a certain Inter-network interference, what is the band or bands combination we should use to provide network service for a community.

Since mathematical formula is difficult to describe the activities of signal on the air even in an arbitrary area. We use long term measurement represent the activities in each band is a good estimation. We define the the percentage of sensing samples S_θ above a interference threshold θ over the total samples S in a time unit as the $ActivityLevel$ A of Inter-network interference shown in equation 2

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

The capacity of a clean channel is C, with protocol model, the capacity of a channel with Inter-network interference C_r could be represented as in equation 3

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

The lower bound of a network deployment is to provide network capacity equal to the demand of the service area. The demand of a service area could be calculated as the summation of individual demand all over the service area $D_a = \sum_{p \in P} D_p$. Since individual or family Internet data demand is marked as government statistics [21], D_a could be remarked with population distribution f and service area k as $D_a = \sum_{f \in F, k \in K} \bar{D_p} * f * k$. The network deployment lower bound of access point M could be represented in equation 4

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

Also, the network has to satisfy the coverage constraint. The access points provide single-hop connectivity for client devices. Generally a coverage of 95% is good for outdoor mesh network [15].

In multiband scenario, the activity level varies with to different interference source and the propagation characteristics bring the service area variation. The simplest way to cover an area is to use multiple orthogonal lower frequency channels, however, FCC limit the white space band utility in most metro area in US [22]. Moreover, channel in each band is limited. And too many lower frequencies channels will bring huge Intra-network interference for the network which is out of our scope. To answer the question given an area for a new network, the number of access points which equals to how much funding should be risen, we build the measurement driven framework *Multiband Access Points Estimation* to approach the number of access points for an arbitrary area.

In space domain, the advantage of high frequency channel in network is the spatial reuse, the low frequency channel is better in large scale coverage. Generally high frequency fit for populated area and low frequency fit for sparse area. The time domain variation of spectrum utility could be seen in Figure 3. For an ISP, the service quality which maps to the capacity constraint has to be satisfied. Given an area of metropolitan, the population distribution could be found in government and academy resources [23]. Then we have the capacity request of each part of the area with the assumption everyone has the same Internet demand. According to the population distribution, we chop the area into different types. These are the space domain input. Then we count the measured activity level as input in time domain. We have an average channel capacity of each band with the activity level. With received signal strength threshold, the QoS coverage area of different type per channel and the reuse distance could be computed. Then the maximum area an access point could cover can be calculated as the minimize area of the QoS coverage area and propagation coverage. Then the transmitting power is adjusted to fulfill the coverage restriction. A classic regular hexagon deployment process is employed to put the access points.

With this framework, we combine our measurement and public population data to evaluate white space band application in dense populated area, sparse area in section III.

Algorithm 1 Multiband Access Points Estimation

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: Chop 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

III. Experiment and Analysis

To study spectrum utility in multiple area types, we developed experiments on off-the-shelf wireless platform and remote controlled spectrum analyzer measurement platform. We do measurement in typical areas of DFW metropolitan carrying these platform. According to the measured data, we apply our Multiband Access Points Estimation framework to analyze the performance of white space band application in typical populated areas.

A. Experiment Design

To ensure the results are applicable, we employ a Linux-based 802.11 testbed [24]. The platform 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 [24], [25]. We developed shell script with tcpdump for this testbed working as a sniffer recording all 802.11 packets. The experiments taken in downtown Dallas, SMU campus, neighborhood show there is no 802.11 packets dected in white space bands. And in DFW area, as far as we know, we are the only group holds FCC license of white space bands. Our experiments verify that these bands have not been used for wireless data communication. However, we observed that Gateworks platform only update its received signal strength when received a new packet. It is not good for inter-network interference measurement. To cover the gap, we employ a spectrum analyzer, multiband antenna, mobile antenna and a laptop developing a spectrum sensing system. There is no mobile multiband antenna in market. We compare the multiband antenna measurement and mobile antenna measurement across bands in lab with our controlled signal source. Then normalize the received signal strength for mobile antenna measurement.

Our experiment platforms are shown in Figure 4. We has 32 samples each second from the spectrum analyzer system with time stamp of all bands. Gateworks sniffer platform record all the packet received with time stamp. The duplicated samples are unique through the time stamp. Then we use the uniformed data for activity level calculation.

We choose typical location according to population distribution and free white space bands from Google spectrum database [22]. The location chosen for experiments are Dallas, Weatherford and Millsap marked with stars in Figure 1. In Weatherford and Millsap, we monitor wireless activities in 3 location for 45 minutes in static on a normal weekday. The three locations of a city include downtown, neighborhood and rural area. In Dallas, we have multiple measurement in neighborhood, campus and sparse density area. Then we post-

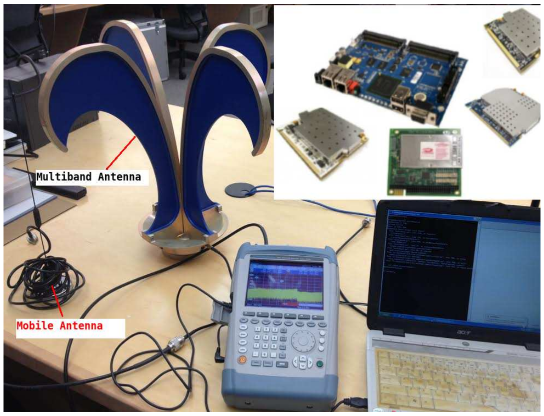

Fig. 4. Multiband Measurement Platform

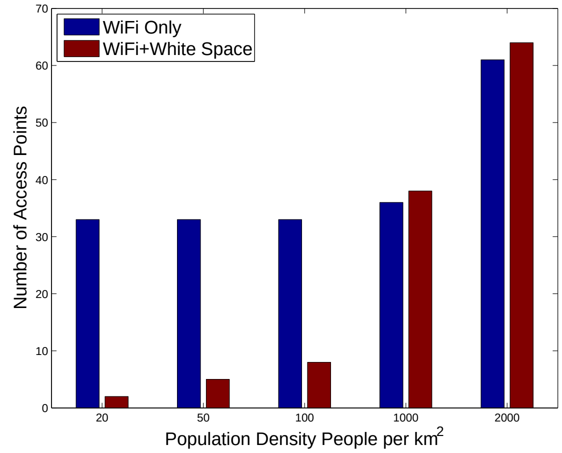

Fig. 5. Number of Access Points need for 13x13 km^2 Area

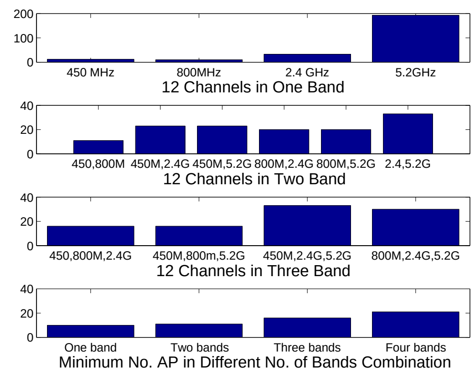

Fig. 6. Bands Combinations of The Same No. of Channels in 500 Population Density

process these data to get the activities level for each band in all the location. Moreover, through our framework, the number for covering an arbitrary area is calculated and discussed in III-B.

B. Results and Analysis

In table III-B, we show our measurement results in multiple locations of DFW metro. Dallas as the central city of North Texas, has the highest activities 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. We average these data finding 2.4 GHz is more active in urban area rather than downtown area. Most of schools campus and neighborhoods are covered by public or private WiFi today, which bring more activities in 2.4 GHz and 5.2 GHz. In Weatherford, all the bands have less activities than Dallas. And due to the measurement location we chosen, the rural area we chose on the west of Weatherford where could get more interference from Fort Worth. Millsap is a typical sparse city has 500 residents total in north Texas. The activities across all the bands are lower than Dallas, and Weatherford. For 450 MHz, the activity reduce much faster than other bands in Dallas and Weatherford.

We put these measured activity level into our framework presented in 1. We use Millsap sparse area, Millsap downtown, Weatherford urban, Dallas rural and look up the population density on-line. We input these information to our framework and calculate the number of access point for covering a $13km \times 13km$ area in different types. The output is shown in Figure 5.

We set the demand request as $2Mbps$ per person, the population density as $20, 50, 100, 1000, 2000$ per square kilometers. We assume 30% residents will use this service. For WiFi only, we use 6 channels in 2.4 GHz, and 3 channels in 5.2 GHz. 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 5, 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. Moreover, if we count the intra-network interference, the situation could be even worse.

To find the best bands combination, we select 500 people per square kilometer scenario and use Weatherford downtown spectrum to calculate the number of access points in this area. We assume the total number of channels is 12. The other setup of the experiment is the same as the previous configuration. The results are shown in 6.

The first subplot in the Figure is the number of access points needs for 12 channels in one band. As frequency goes up, more access points need to serve this area. 450 MHz does not outperform 800 MHz since in this population density, they have the same service area. Subplot 2 shows if we have equal channels in 2 bands, white space bands combination performs better than WiFi by 63.64% and WiFi + white space bands by 56.52%. In this scenario, the more white space bands channels are used, the better performance will be got.

We reset the population as 1500. And Dallas urban spectrum activity is used in7. In this scenario, using all channels in white

Bands	Dallas			Weatherford			Millsap		
Area Type	Downtown	Urban	Sparse Area	Downtown	Urban	Sparse Area	Downtown	Urban	Sparse Area
450 MHz	24.3667	25.8274	23.7667	6.050	12.50	14.0333	7.0000	0.0667	0.0215
800 MHz	4.4000	16.4940	4.7667	5.2167	5.0667	4.4333	3.8667	4.2000	3.6000
2.4 GHz	15.8667	34.9488	2.6000	2.0333	2.0333	2.7667	2.0667	1.6000	0.8000
5.2 GHz	19.7000	35.4571	1.5333	1.9333	1.9333	1.3333	1.2667	2.0667	2.1000

TABLE I
ACTIVITY LEVEL IN MULTIPLE LOCATIONS

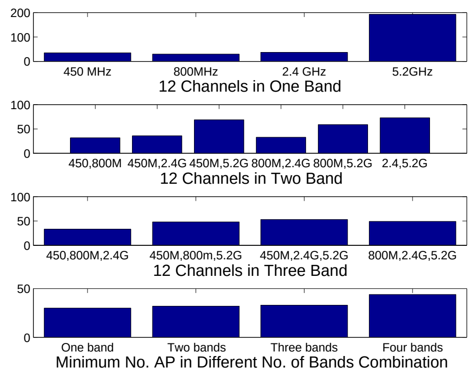

Fig. 7. Bands Combinations of The Same No. of Channels in 1500 Population

space band has the same performance comparing to WiFi+ White space bands. And generally white space band still have benefit reducing the number of access points by 23.33% and 9.19%. As population density increase, the gain brought by white space decrease. The best band combination is still the combination with white space bands.

IV. RELATED WORK

Many efforts have been put in wireless network deployment issues, such as in gateway placement, channel assignment, routing and jointly optimization [10], [17], [26]. These works focus on wireless network issues in WiFi bands and propose many algorithms for the solving these problems.

However, as FCC regulations have reapportioned spectrum for data networks with white space bands, questions come out for wireless network with these new bands. Two new characters of wireless network are brought by white space bands: propagation difference and Inter-network interference. [27], [28]. Previous work provide solutions for WiFi network but fails to cover these two factors.

White space band application is a new research hot spot. Follow FCC's policy, white space capacity of continental USA is quantified in [29]. White space is targeting on opportunistic medium access for data transmission and the opportunity is experimental verified indoor [30]. However, the best application of white space is to serve rural area with its long propagation range other than indoor application. Our target is to quantify the opportunity of outdoor backhual network.

There are some works talked about the propagation variation in both WiFi network and white space network. In [15], Robinson model the propagation variation in the same band for terrain domain. Rohan bring a databased-driven SenseLess framework for operating a white space network with database of primary user location, channel occupation [31]. However, as opportunistic medium access, the most important application of white space bands are focus on or related to the time domain. It is impossible to build a mathematical model of white space bands due to the variation of FCC rules in multiple metropolitan. Measurement is the best way to tell the current state of bands utility. We propose the measurement framework with in-field data for wireless network deployment band selection.

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 coverage frame to find the number of access points in an arbitrary area. We then take spectrum activities measurement in DFW metropolitan area and involve the data to our framework to find the best best band combination for different type of areas. Through extensive analysis across varying population density, channel availability across bands, we show that employing white space band in rural area gain 1650% reducing the number of access points, 660% in sparse urban area; but fails to get benefit in density urban and downtown type area. Moreover, we investigate different band combination in sparse urban area, even with high existing spectrum activities, white space bands still bring benefit for these areas.

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