Leveraging White Space Opportunity in Metropolitan Area

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***Abstract*—The interference widely exists in Wireless Mesh Networks, e.g. gateway placement, channel assignment, and routing. Many work has been done to resolve the problems in WiFi network. However, there is a gap between the hypotehsis and in-field spectrum utility. Moreover, the digitization of TV channels and new FCC regulations have reapportioned spectrum for data communication with far greater range than WiFi due to lower carrier frequencies. Thus, leveraging the spectrum utility is a prerequisite for applying existing methodology and developing new algorithms. In this work, we propose measurement driven band selection framework which shows the opportunity of white space band in rural area and WiFi advantages in downtown area. We perform the framework with measured data in DFW Metropolitan and white space band outperforms percent in rural area and WiFi outperforms FIXME in downtown area.**

I. Introduction

Numerous cities are pursing city-wide WiFi deployment. Both academies and industries are putting efforts on providing Internet connection for metropolitan areas for this opportunity [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 soolars 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 use 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 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 backhaul 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 activities in white space bands have not been exploited simultaneously [8]. The existing signals in both WiFi channels and white space band channels is an issue for all the topics in wireless network deployment. The clean channel hypothesis held in previous models fails to match the in-field spectrum utility, which could slash the performance of mesh network.

In this paper, we leverage the diversity in propagation and spectrum utility of white space and WiFi bands in the deployment of large-scale wireless mesh networks. To do so, we first from a metric jointly exploit propagation and spectrum utility. Second, we proposed a measurement driven framework for finding the lower bound number of access points for multiple type of areas. Then, with in-field measured data in Dallas-Fort Worth area we shows the band selection variation in downtown area, neighborhood, university campus, urban area and rural area. Finally, we quantify the degree to which the joint use of both band types can improve the performance of wireless mesh networks in these diverse scenarios.

The main contributions of our work are as follows:

- We develop framework based on in-field measurement to jointly leverage white space and WiFi bands to serve the demand in terms of multiple type of areaswireless mesh networks.
- We design and perform in-field measurement in multiple type populated areas in Dallas-Fortworth metro. Then we apply the measurement in band selection for wireless network deployment and leverage the diversity in multiple populated areas.
- We perform extensive analysis across diverse propagation, band availability, Inter-network interference, demand population fitting for multiple metro areas. We additionally show that the joint use of the two types of bands (i.e., WhiteMesh networks) can yield up to FIXME saving for wireless mesh network deployment.

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 minimum number of access points in deploying wireless mesh network. Finally, we present measurement driven estimation model used to address the problem.

A. White Space Opportunity and Challenge

Today, wireless signals exist everywhere in the world and all over the frequency bands. When talking about wireless communication, the interference of existed signals have to be considered as an important part for the conversition. Such as yielding primary users is a key issue in cognitive radio [9]. Researchers have put many efforts in developing algorithms a series of issues in wireless network, for instance gateway placement, channel assignment [10], [11]. These works assume the channels are clean for deploying new network which unfortunitely is not true.

Wireless propagation is the behavior of the signal loss characteristics when wireless signals are transmitted from a transmitter to receiver. The strength of the receiving 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 changes according to the aforementioned environmental factors and ranges from 2 to 5 in typical outdoor settings [14].

Since 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. The works rely on such an assumption have focused on the allocation of multiple WiFi channels with multiple radios in multihop wireless networks and provide solution for intra-network interference [8]. Here, a frequency band is defined as a group of channels which have similar propagation characteristics. Moreover, the activities in multiple bands vary from downtown area to rural area, such as more activities of WiFi bands than white space frequencies in downtown area, and rural area, more white space band activities than WiFi activities. This character brings more options for band selection in WiFi and white space. 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.

There are several constraints for wireless mesh network deployment. For backhual tier connectivity constraint require all access points can be connected to gateway. When gateway locations are unknown or not yet selected, the possible gateways need to cover all the area with a coverage constraint. We assume the coverage constratint is 95% [15]. Moreover, wireless bandwidth is shared amongst all clients, which is desirable to limit the number of potential shares of the scarce wireless spectrum. Spacial reuse helps to improve the capacity constraint. When a gateway is serving an area, it has to satisfy the demand of the residents which related to the area type. We hold the residents demand as capacity constraint.

Avoiding interference is the primary target in wireless deployment. There exist two kinds of interference for wireless network. The first kind is the *Inter-network interference* comes from existing wireless devices. The second interference is *Intra-network interference* comes from wireless network deployment itself. Previous work focus on resolve the Intra-network interference [8], [16], [17]. Due to the distribution nature of the Inter-network interference, it is impossible to have a theoritic 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, both for Inter-network and Intra-network interference. To smart use

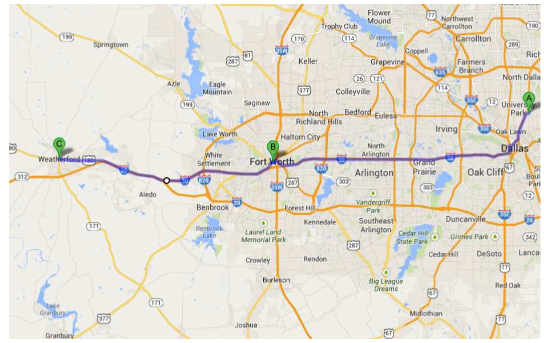

Fig. 1. DFW Drive Test Map

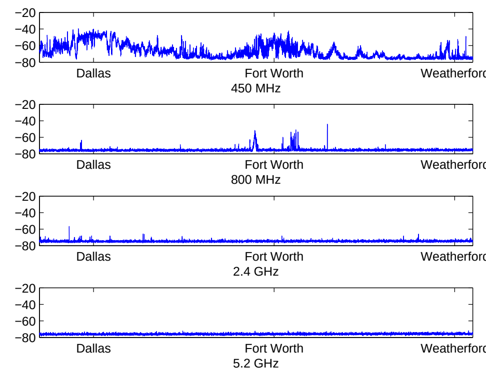

Fig. 2. Wireless Activity in Urban Lab

of WiFi and white space band adapting different demands of rural area and urban areas is a key issue in wireless network. 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 of 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 downtown, urban and rural area. A drive spectrum measurement is shown in Figure **??**. We drove through Dallas, Fort Worth, and Weatherford in north Texas **??**. 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. When we drive in the highway, the distance from our car to the weak signal source of these bands is to large to detect these signals. We did more fixed location measurement to quantify the spactial distribution. We define measured percentage activity time in a unit time to quantify the

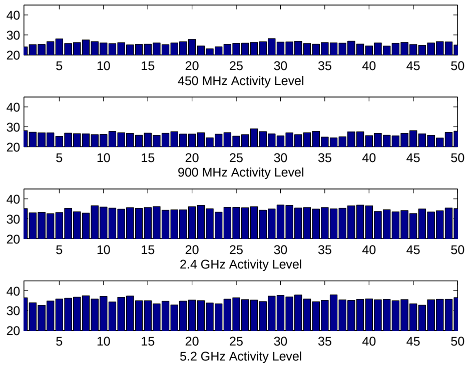

Fig. 3. Wireless Activity in Urban Lab

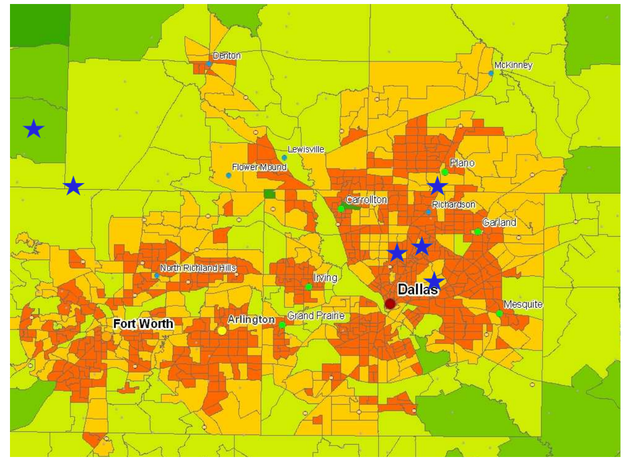

Fig. 4. Dallas-Fort Worth Population Distribution

Inter-network interference II-B. Figure 3 depicts an example activity level in our urban lab with the plaform introduced in III. The interference across varies in time domain. 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 avoid in wireless network deployment. There is around 10% difference from white space band to WiFi band in our lab. This gap is an opportunity to improve wireless network deployment.

B. Model and Problem Formulation

Oppose to previous works, this paper focus on bands adaptation of Inter-network interference and multiple populated areas [8], [11], [18]. We propose a measurement driven framework to get the lower bound amount 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). We assume that all mesh nodes have the same transmit power, 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 anounce broadband is an individual 'legal right' [20], [21]. Providing a community wireless Internet service have to satisfy its traffice demand of multiple population distribution. Figure 4 depicts the population distribution of Dallas-Fort Worth metropolitan area. Population increase with red color and decrease with green color in the map. 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 fomular is diffcult 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 tier provides single-hop connectivity from client devices to a mesh node. 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 simpliest 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

Algorithm 1 Number of 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

Output:

CA: Lower Bound of Mesh Nodes

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

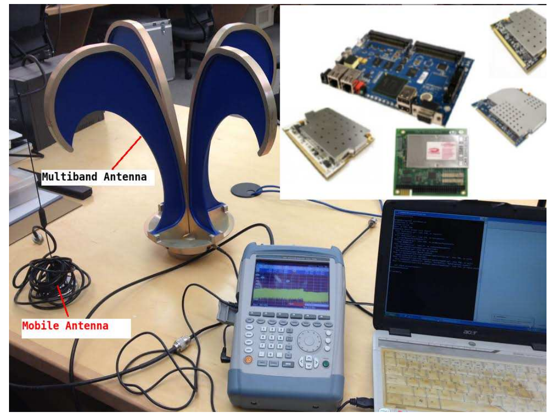

Fig. 5. Experiment Platform

Intra-network interference for the network which is out of our scope. To answer the question given an area for a new network, at least how many access point or how much funding should be risen, we build the measurement driven framework to approach the lower bound.

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 lowe freqency fit for sparse area. The time domain variation could be seen in Figure **??**. For an ISP, the service quanlity 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 restrition. A classic regular hexogan deployment process is employed to put the access points.

III. Experiment Design

To study band selection in multiple area types, we developed static and driving experiments on off-the-shelf wireless platform and remote controlled spectrum analyzer platform. According to the measured data, we apply our access point deploymnet framework to analyze white space band performance in typical downtown, urban, rural and intercetion areas.

To ensure the results are applicable, we employ a Linux-based 802.11 testbed [24]. The platform includes a Gateworks 2358 node 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 shows there is no 802.11 packets in 450 MHz and 900 MHz. As far as we know, we are the only group holds FCC license to use white space bands in DFW area. Our measurements verify that these bands have not been used for WiFi. 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 and a laptop developing a spectrum sensing system. We compare the Our platforms are shown in Figure 5. We has 64 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 uniqued through the time stamp. Then the uniformed data are used 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 marked with stars in Figure **??**. We monitor wireless activities in each location for 2 hours in static or driving mode on a normal weekday. Then we post-process these data to get the activities level for each band in all the location. For our convinience, and urban areas are the most interesting in white space bands application, we choose campus, neighborhood and bussiness area for the measurement.

In Figure **??**, we show the activity level of white space bands and WiFi bands in these locations.

Based on the measured data, we apply our framework to tell the minimum access point for cover a certain area in different type of areas. We apply our framework in a x by x area in downtown, urban, urban+downtown, urban+ rural, rural area. An access point could not occupy all the frequency spectrum, an access point could have up to 4 radios in legal bands. In Figure **??** we show the lower bound of access point we could use to cover such an area with different bands combinations.

In rural area, white space band is better than any other options due to the limited traffic demand; in downtown area in downtown+urban area in urban neighbor area in urban bussiness area in urban campus in urban+rural area

In Figure **??**, when given an area mixed with urban and rural type, as urban area increase the band selection

In Figure **??**, when given an area with 50% rural and 50% urban area, as the urban population density varies

In Figure **??**, as white space channels number increase, the access point number

IV. Results and Analysis

V. 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 spcae 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 demain. 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.

VI. Conclusion

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