WhiteTeris: Wireless Mesh Hetegeneous Deployment

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***Abstract*—While many metropolitan areas have plan to deploy city-wide WiFi networks, the densest urban areas where not able to broadly leverage the technology for large-scale Internet access within limited budget. Ultimately, the small spatial separation required for effective 802.11 links in the areas resulted in prohibitively large upfront 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 heterogeneous structure 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 model the heterogeneous white space and WiFi deployment problem . propose a relaxed ILP to get the lower bound of the amount of access point under resource limitations and a heuristic approach of the problem. In particular, we map the problem as a Bin packing problem and resolve it with a fixme method. In doing so, we find that networks with white space bands reduce the number of a cess points up to fixme**

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).
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- We analyze our framework under capacity and coverage constraints
- We quantify the impact of white space and WiFi channel

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]:

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

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 **??**).

For spectrum utility and resulting channel availability, we use a long-term measurement for each band. We define the percentage of sensing samples S_θ above an interference threshold θ over the total samples S in a time unit as the activity level A of inter-network interference:

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

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:

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

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].

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

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. Related Work

With new FCC regulations on the use of white space bands, there are two factors to consider with such bands: large propagation range and existing inter-network interference from TV stations and other devices such as microphones [18]–[20]. Prior work does not specifically study the benefits of jointly using white space and WiFi bands in deployment of wireless access networks [21]. Additionally, prior work related to white spaces target opportunistic media access. However, the application of white spaces across diverse population densities has not been fully explored.

Finally, some works discuss the propagation variation in both WiFi bands and white space bands. For example, Robinson et al. models the propagation variation at the same band in terrain domain [11]. Another work proposes a databased-driven framework for designing a white space network with database of primary user (TV station) locations and channel occupation [22]. However, these works do not jointly study the influence of white space and WiFi bands on network deployment according to their resulting propagation variation and spectrum utilization.

IV. Conclusion

In this paper, we jointly considered the use of WiFi and white space bands for deploying wireless access networks across a broad range of population densities. To consider network deployment costs, we proposed a Multiband Access Point Estimation framework to find the number of access points required in a given region. We then performed spectrum utilization measurements in the DFW metropolitan and surrounding areas to drive our framework and find the influence of white spaces on network costs in these representative areas. Through extensive analysis across varying population density and channel combinations across bands, we show that white space bands can reduce the number of access points by 1650% and 660% in rural and sparse urban areas, respectively. However, the same cost savings are not achieved in dense urban and downtown type area. Finally, we investigate different band combinations in two population densities to show that greater access to white space channels have greater total savings of mesh nodes when the total number of channels used in the network is fixed (i.e., given a total number of allowable WiFi and white space channels). 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.

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