WhiteTeris:Hetegeneous Wireless Mesh 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 deployment heterogeneous access points of white space bands and WiFi bands have either not been studied [3]. Specifically, previous work has investigated wireless network deployment in terms of multiradio network, power control, gateway placement, channel assignment, and routing [4]–[6]. However, each of these works focus on the deployment in WiFi bands without considering the white space bands. The white space band could extend the capacity degree and the coverage degree of an access point simultaneous.

In WiFi and white space heterogeneous wireless network, the service area degree of an access point depends on the capacity of radios, the propagation range and the demands of the serving area. The scant frequencies of radios, the propagation distinctive and the demands diversity of population distribution bring the variation of an access point service area. These 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) To what degree can hetergeneous access points benefit the dense population areas and sparsely populated rural areas?*

In this paper, we perform a relaxed linear program which considers the variation of hetergeneous access point service area too find the lower bound total number of access points required to serve a given user demand. Further, we represent an FIXME greedy algorithm to approach the lower bound. Across varying hetergeneous white space and WiFi radios combination, 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. We then evaluate our FIXME, showing the hetergenous band selection across downtown, residential and university settings in urban area and rural areas and analyze the impact of white space and WiFi combinations on a wireless deployment in these representative scenarios.

The main contributions of our work are as follows:

- We develop an optimization framework based on linear programming to jointly leverage white space and WiFi bands approaching the lower bound in terms of numer of access points to serve the demands of a given area.
- We design a FIXME algorithm, which model the problem as a bin package problem. We represent a
- We evaluate the performance of the presented algorim, comparing with the lower bound and the hexagon WiFi access point deployment in sparse rural areas given similar channel resources. The numberic results shows that FIXME.
- We further analysis the performance of hetergenous access point performance in variation of population density. The numberic results shows that hetergenous access point could improve the budget saving in FIXME(dense area/sparse area).

II. Challenges and Problem Formulation

In this section, we illustrate the challenges of hetergenous access point 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 linear program and a FIXME algorithm for estimating the access point 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 [7]. 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 [8]:

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

Here, n varies according to the aforementioned environmental factors with the value of two to five in typical outdoor settings [9].

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 [10]). Prior work has worked to reduce cost through gateway deployment, channel assignment, and routing [5], [11]. Most of existing works try to reduce the intra-network interference or increase the channel usability level of wireless network deployment [3], [12]. However, the access point service area variation becomes an important problem when considering the availability of white space bands. Jointly considering the propagation and single channel capacity, the access points with different configuration (e.g. radios) in the same area, or with same configuration in diverse population density areas (e.g. downtown, rural) could have different service ranges.

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 gaps of WiFi and white space bands (e.g., several 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. A general way to increase the capacity of a single access point is to add channels through radios [13]. The assumption all the channels have the same propagation does not fit for WiFi and white space hetergenous scenario. When a white space band channel added to an access point, the capacity and service range could increase simultaneously. The differences in propagation and constraints of network deployment create 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 [14]. 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. And the deployment cost could be significant reduced through access points with high capacity with more centralized using radios. 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 [15], 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], [14], [16], this paper focuses on hetergenous access point selection for wireless access networks which jointly employ WiFi and white space bands. We propose a relaxed linear program to find the lower bound number of access point, and an FIXME algorithm to approach the lower bound number of access points which serve the traffic demand of a certain area. We assume the service provider has a limited number of spectrum resources and radios have similar configuration. Each radio on an access point operates with a classic protocol model [17]. We further assume that there is a given take rate and traffic demand for a given population (as specified in Section **??**).

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 [18], 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:

$$\sum_{m \in M} C_r^m \geq \sum_{f \in F, k \in K} \bar{D_p} * f * k \tag{2}$$

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 [14]. The object of this work is to find the best possible locations for MNs so that the network has good connectivity and enough capacity to satisfy the traffic demands.

Under the capacity and coverage constraints, the serveice area of a hetergeneous multiband access point varies according to the traffic demand. The service area is limited by the propagation range when the traffic demand is low; and when the traffic demand is high, the service area is limited by the radio capacity. The radius of service area r_s could be represented as:

$$r_s = min\{r_p, r_c\} \tag{3}$$

r_p represents the propagation range of a radio in the access point, r_c is the capacity range of a a radio in the access point. When the traffic demand is distributed uniform in a circle, from Eq. 2 the capacity range r_c could be noted as $r_c = \sqrt{k/\pi}$. Moreover, the propagation range and capacity rang could be determined by the environment, traffic distribution and power control [14]. These factors are out of the scope of this work, but they could easily be added to the model for calculation of a hetergenous access point service area. To simplify the problem and focus on multiband, we assume the traffic demand is uniform distributed and the propagation follow Frii rule as Eq. 1.

When the traffic demand of an area is constant, the degree of a hetergenous access point service area varies with the radios. We assume all the access points have the same number of radios and channel resources. In the low traffic demand scenario, the service radius reaches the radio propagation range. A high frequency WiFi radios will have a smaller service area since the signal attenuate fast; while the white space radio could have a larger service area due to the longer propagation; and a hetergenous access point who has both WiFi radios and white space radios has the same range of as low frequency radios access point. An example is shown in Fig. **??**. In medium traffic demand scenario, hetergenous access points and white space access points will have the same size service area which is larger than high frequency WiFi only access points as shown in **??**. With high traffic demand, all access points will have the same service area due to capacity constraint as shown in **??**. White space bands could reduce the cost of wireless network deployment. Thus, lowest cost for covering a certain area is to use white space bands in all access points based on the analysis. However, spectrum resource is limited, especially the usability of white space bands is restricted in major cities in US [15]. Thus, the trade of between centralized using all white space bands or mixed using white space bands under multiple traffic demands is a question for wireless network deployment. The problem could be modeled as how could we use the minumum number of different sizes of service area according to radio combinations to cover a certain plane area. This problem is a bin package problem [**?**]. The problme is known as a NP-hard problem [?]. We propose a relaxed linear program to get the lower bound of the number of access points and a heuristic algorithm to approach the lower bound.

Given a target area G with the traffic demand distribution γ, the service area of all kinds access points S_t, the coverage rate p, thus the capacity of access point C_t could be calaculated based on the number of radios, Friis model 1 and restriction 3

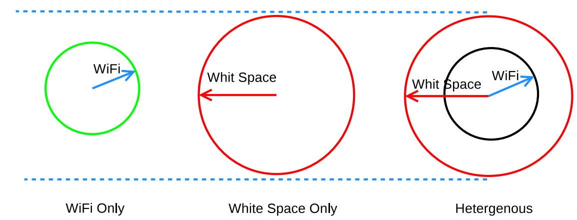

Fig. 1. Low Traffic Scenario

or from in-field measurement [19]. Furthermore, the minimum number of access points could be found through a relaxed linear program as represent in **??**.

Sets: B Set of Bands
T Type of Access Point

Parameters:

G		Target Area
γ		Traffic Demand Distribution
p		Coverage Rate
S_t	$t \in T$	Coverage Area of Type t AP
$O_{b,t}$	$b \in B, t \in T$ $binary$	Channel Occupied by Type t AP
N_b	$b \in B$	Available chennel of a band in Target Area
C_t	$t \in T$	Channel capacity of Type t AP

Variables:

$a_t \leq 0$ $t \in T$ Number of Type t AP

Objective:

$$Min \sum_t a_t \tag{4}$$

Coverage Constraint:

$$\sum_t a_t \cdot S_t \geq G * p \tag{5}$$

Capacity Constraint:

$$\sum_t a_t \cdot C_t \geq G \cdot \gamma \tag{6}$$

Resource Constraint:

$$\sum_t a_t \cdot O_{b,t} \leq N_b \tag{7}$$

The linear program relax the coverage constraint without telling a key parameter *where should we put the access point?*. Moreover, the linear program may provide multiple results since different type of access points could have the same service area, (e.g. in low traffic demand case) The result of the linear program is the lower bound of access points.

In order to find a pratical access points deployment in multiband scenario, we represent a greedy local search algorithm in 1. The service area of access points varies from population distribution. Assume the cost of building an access point is the same as C_a. Thus, we rank the access points type according to their unit price as:

$$p_s = C_a/A_s \tag{8}$$

$A_s = \pi s_r^2$ when a circle coverage model is applied, $A_s = \frac{3\sqrt{3}}{2}$ when a hexagon coverage model is applied. In the framework, the access point type with less unit price is going to deployed first till the available resource is used up. When two types of access points share the same unit price, considering the spacial reuse, access point with high frequency channels will be chosen. The deployment starts from the edge of the given plane. If the combination of unit grid could be covered by an access point, we put the unit grid in the coverage area, until the access point can not access more grid. Then we switch to another available access point. The process is like a Teris game, when a given access point is filled, it will be deleted.

Algorithm 1 Multiband Hetegeneous AP Deployment

Input:

G: Target Area
γ: Traffic Demand Distribution
p: Coverage Rate
S_t: Coverage Area of Type t AP
$O_{b,t}$: Channel Occupied by t Type AP
N_b: Available channels of a Band in Target Area
C_t: Channel Capacity of Type t AP

```
while N_served =!M do
    for all s ∈ S_current do
        Find one-hop nodes in S_Next
        Sort S_Next according to distance from gateway nodes
        for all l ∈ S_Next do
            Calculate 1-hop path interference of link s → l
            Sort the links according to path interference
            Assign(s,l) with the least interference link
            Update N_served, N_unserved
            Update I_active from I
        end for
        S_current = S_Next
    end for
end while
Rank available AP type according to their unit price p_s
Deploy an AP at the left up edge of un-covered area
Fill the AP with one neighbor unit grid and move the AP in the center of the coverage area

The coverage radius of a Multiband Access Point is MinR_p, R_QoS
Apply regular hexagon deployment to get the number of access point for serving given area M
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Output:

The number of Access Points and Deployment

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 [20]–[22]. Prior work does not specifically study the benefits of jointly using white space and WiFi bands in deployment of wireless access networks [23]. 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 [14]. Another work proposes a databased-driven framework for designing a white space network with database of primary user (TV station) locations and channel occupation [24]. 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

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