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 III).

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 number of access points 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 target area is given, we could get the service area of each access point type through 3, then we adjust the transmit power of each radio to reduce the interference among each other.

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. 1. 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 2. With high traffic demand, all access points will have the same service area due to capacity constraint as shown in 3. 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 to deploy different size of cells in a given palen, which is a NP-hard bin package problem [19]. 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.

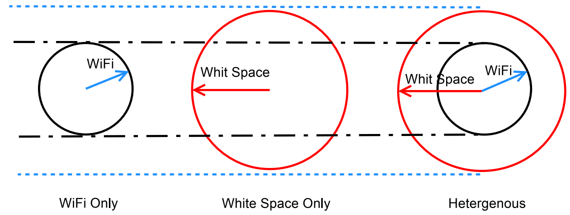

Fig. 1. Low Traffic Scenario

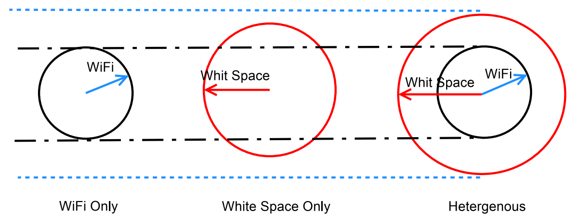

Fig. 2. Medium Traffic Scenario

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 or from in-field measurement [20]. When the target area is served, the reward of the area could be knows as a constant number R. However, the reward does not influence the optimal deployment since the total reward is a constant. Furthermore, the minimum number of access points could be found through a relaxed linear program as fllowing.

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 channel of a band in Target Area
C_t	$t \in T$	Channel capacity of Type t AP

Variables:

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

Objective:

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

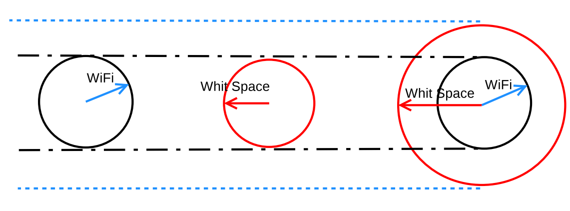

Fig. 3. High Traffic Scenario

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:

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

Spatial Constraint:

$$a_t < \frac{G}{S_t} \cdot \frac{2}{3} \cdot N_b \tag{8}$$

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 multi-band 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. When an access point is built, the more service area is better. Thus hetegenous access point could always have better performance. However, since there are a limit number of spectrum resource, we have to balance the usability of hetegenous access point who reduce the cost of building access points, and single radio access point who may cover more areas.

In linear program, the reward R is a constant of the area G. But for a single hetergenous access point deployment, we have to compare its reward and cost to seperately using the radios. In a certain area, a hetegenous AP has radius r_1. If we sperately using the radios with radius $r_2, r_3, \dots r_n$, the reward is uniformly distributee, the hetegenous reward is defined as:

$$H_r = (n-1)C_a - \frac{R}{G} \cdot \sum f_s(r_n) \tag{9}$$

$f_s(r)$ is the area calculation function, e.g. $f_s = \frac{3\sqrt{3}}{2}r^2$ when a hexagon coverage model is applied. In the framework, the access point type with more reward 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 and we use protocol model to find the available access point type. 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.

Generally, we employ access point with larger coverage capacity fill in the area, then for the Through the algorithm, we could cover the target area by the most efficient access point type step by step. The minmum number of access points and a pratical multiband wireless deployment.

Algorithm 1 Multiband Hetegeneous AP Deployment

Input:

G: Target Area
R: Reward of 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 $\sum A \cdot S_t < p$ **do**
  Rank available AP type according to their unit price H_r
  Rank available AP type according to radio numbers
  if The reminder area G_r is larger than all the available AP **then**
    Choose the AP has the largest coverage area S_t
  else
    Find the available AP type whose coverage area $S_t = minS_t > G_r$
  end if
  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
  Update Channel Resource $O_{b,t}, N_b$
  Update Output Access Point A
end while

Output:

The number of Access Points and Deployment

III. Numerical Evaluation and Analysis

To evaluate the performance of hetegenous wireless network deployment, we perform numberical evaluation with linear program, and MHAPD algorithm to analyze the role of white space and WiFi bands in total access points required for a given deployment area.

A. Experimental Setup

In the evaluation, we set the demand request as 2 Mbps per person with the population density from 20 to 2000 per square kilometer. We assume 30% residents will use this service, the maximum transmit power is 30 dBm, and a path loss exponent of 3.5 [21].

We adopt an 802.11n maximum data rate of 600 Mbps. In the protocol model, the interference range is as twice as the communication range. We investigate both traffic demand and the number of white space channel influence on heter-geneous wireless network deployment. We have interference free scenario, each band has at least 3 channels, which fits for most rural areas and some cities, such as Houston [22]. In this scenario, it is possible to use all hetergeneous access points since hetergeneous access point could serve more area. However, in the field, there are some cities has area only one or two licened white space channel, such as Salt Lake City [22]. In these scenario, only part of the access points could be hetergeneous. We run numerical simulation of both the scenarios and analyze the hetergeneous access points amount of the results.

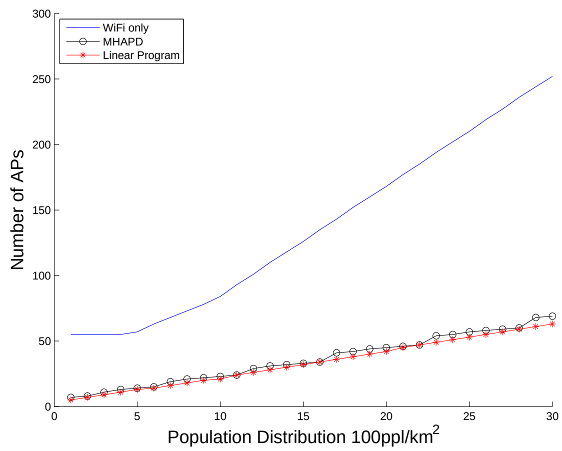

Fig. 4. Sufficient White Space Channels Scenario

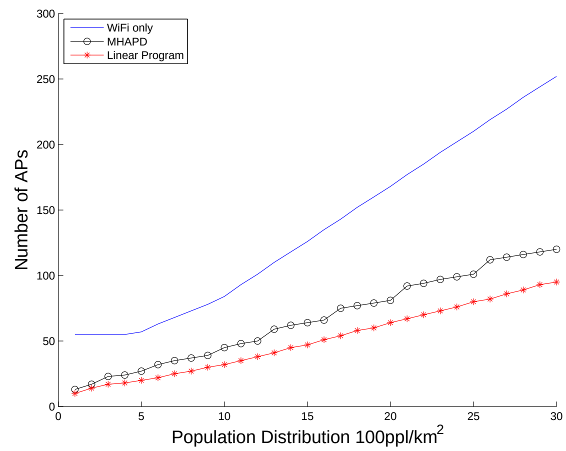

Fig. 5. One white channel

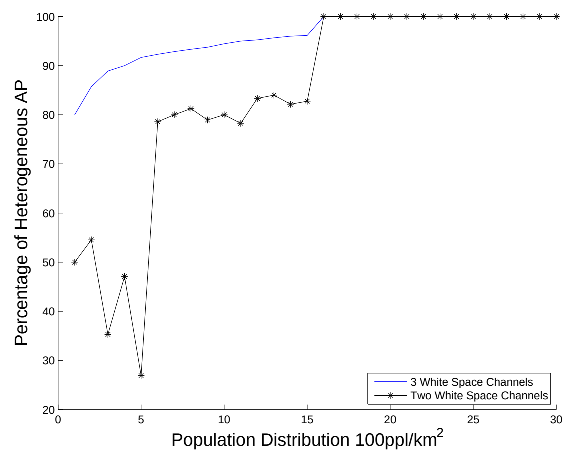

Fig. 6. Percentage of Heterogeneous Access Points

We given the target area as 15×15 square kilometers. In the numerical simulation, we assign orthogonal WiFi channels in 2.4 GHz,5.8 GHz and white space channels in 450 MHz, 800MHz. Then we calculate the service area of access point according to their radio combinations as described in II-B with a hexagon model. Then we run our linear program and MHAPD mehtods to investigate the benefit from white space band and in what degree hetergeneous access point is beter than single radio access point.

B. Results and Analysis

Figure 4 shows access point number to serve the target area when the area has more than 3 white space channels, which means white space radios could be used on all access points in hexagon deployment model. In the simulation, we set 3 white space channels in 450 MHz. In this scenario, at the beginning, the served area of WiFi only access point is restricted by the communication range. As the population distribution increase, the served area of WiFi only access point will be limited by the traffic demand instead of the communication range. The curve keeps flat untill the traffic demand becomes the limitation of the served area. In the hetergeneous deployment, the served area is restricted by the traffic demand at the beginning, the number of access point increase as the traffic demand increase. Also since there are enough channels can be reused, our algorithm use almost the same number of access point to serve the target area. In this scenario, as population distribution increase, the gain of adding white space channels in our algorithm comparing with WiFi only(2.4 GHz) decrease from 686% to 248% and keep around the value 260%. The gain is from the large propagation range of white space bands at low population distribution. As the population distribution increase, which means the traffic demand increase, some of the gain comes from more capacity of hetergeneous access point.

With few white space band channes(less than 3 channels), in the hexagon model, only one or two neighbor access point could use white space channel. Figure 5 shows the simulation result of one 450 MHz channel deployment. Shortage of white space channels make the number of access points much more than the linear program calculation. The gain from white space channel is from 323% to 86%.

In these sufficient and shortage of white space channel scenarios, the highest gains are from low population distribution. This result represent that white space band fits rural or suburban area where has few residents. When the population distribution increase, the benefit of white space channels is from their bandwidth, which is the same as adding more WiFi channels.

In Figure 6, we investigate the percentage of hetergeneous access points in 3 white space channels scenario and two white space channels scenario in our algorithm. With sufficient white space channels, we prefer hetergeneous access point and there is no limitation of the hetergeneous access point deployment. The percentage of hetergeneous access points is higher than 80%. In two white space channels scenario, at the beginning the number of hetergeneous access point is restricted by the interference range. As the population increase, no more hetergeneous access point could be added in the target area, we have to add more WiFi access point which makes the hetergeneous points percentage decrease. When the population distribution reach the threshold which the traffic demand restrict the service area of hetergeneous access point, the percentage increases. When the service area shrink as the WiFi access point, since they have more capacity, all the access points become hetergeneous.

IV. 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 [23]–[25]. Prior work does not specifically study the benefits of jointly using white space and WiFi bands in deployment of wireless access networks [26]. 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 [27]. 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.

V. Conclusion

In this paper, we jointly considered the use of WiFi and white space bands for

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