WhiteCell: Leveraging Scant White Space Resource in Dense Area

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***Abstract*—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 dense areas, where high levels of aggregation could adapt the mobility of users. However, the restriction of white space in dense area limits the available number of white space channels in dense areas. Thus, leveraging the range of spectrum across user mobility becomes a critical issue for the deployment of data networks with WiFi and white space bands. In this paper, we measure the spectrum utility in typical environment of the Dallas-Fort Worth metropolitan. We formulate the heterogeneous wireless network with both WiFi and white space bands as a queuing system. Further, we propose a measurement-driven resource allocation algorithm, Greedy Server-side Replace (GSR). In particular, we study the white space and WiFi bands with in-field spectrum utility measurements, revealing the power consumption required for an area with channels in multiple bands. In doing so, we find that networks with white space bands in dense areas reduce the power consumption by 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. These white space bands operate in available channels from 54-806 MHz, having a far greater propagation range than WiFi bands for similar transmission power [1]. Thus, white space bands could greatly complement the existing WiFi wireless network with a large area. The users in the propagation range of the access point with white space radios has the options to associate with either the WiFi channel of its cell or the white space channel.

The users in multiple locations under the coverage of both the WiFi and white space have *user diversity*. The term user diversity represents the same frequency band at the same time can offer different transmission qualities to different users due to their difference in transceiver design, geographic location, etc. The user diversity comes from two types of diversity gains. One is the temporal diversity which is caused by the environment variation. Another is the spectral diversity which represents the transmission conditions varies across channels. In some moderate number of users, the sum capacity of the fading channel is greater than the sum capacity of a nonfading channel. In the fading channels, the sum capacity of users increase with the number of users in the system [2], [3].

Previous work studied the multi user setting with a single channel [4]. Spectral diversity is isolated for a single user in [5]. In [6], multi-user dynamic channel access is proposed jointly consider the temporal and spectral diversity in a multichannel model. However, none of these works address the channel association problem in multiband scenario.

The larger propagation range of white space channels adapt channel association of users located in large area through time division. When the users distributed in a large area, the temporal diversity and spectral diversity become the key issues of white space applications. Previous work [7] studied the white space application in access network deployment with spectral diversity. However, these works fails to leverage the white space frequency in multi-user diversity in both spectral and temporal scenarios.

In sparse rural areas, plenty of white space channels are able to deploy new white space network. However, in dense area, few white space channels are available for new network deployment, such as none white space channel is available in New York downtown [8]. The carrier have to use WiFi channels to deploy wireless networks in the dense area without any available white space channel. Other than these two extreme cases, most areas of major cities in the United States have one to eight white space channels [8]. Exploiting these limited white space resource to improve the WiFi network in dense area is a perspective option for the dense areas.

The white space frequencies offer more wireless capacity and convenience of access across large area. When the traffic demands of the users are relatively low, a single white space channels satisfy all the user. Then, the WiFi radios could be turned off for saving power. On the other side, when the users have high traffic demand, all the radios, WiFi and white space, have to be operated to serve the users. However, traffic demands generally come across somewhere between these extremes. Thus, the question comes out,a*in what degree the white space help to reduce the power consumptions of an existing WiFi mesh?*

In this work, we study channel schedule in a multi-user multiband setting, where users are not fully backlogged, traffic demand follow a certain arrival process. We focus on the effect of channel schedule of each user between the WiFi or white space band.

In particular, the main contributions of our work are as follows:

- We perform long-term in-field measurements in neighborhoods, campus, downtown business building, and urban business buildings. Through the measurements, we estimate the achieved channel capacity in these area.
- We formulate the channel resource allocation problem as a queuing system. Based on previous works, we propose the response time estimation methods of multiple scenarios for the heterogeneous network.
- We develop a Greedy Server-side Replace algorithm to allocate the channel capacity for the users with minimum power consumption.

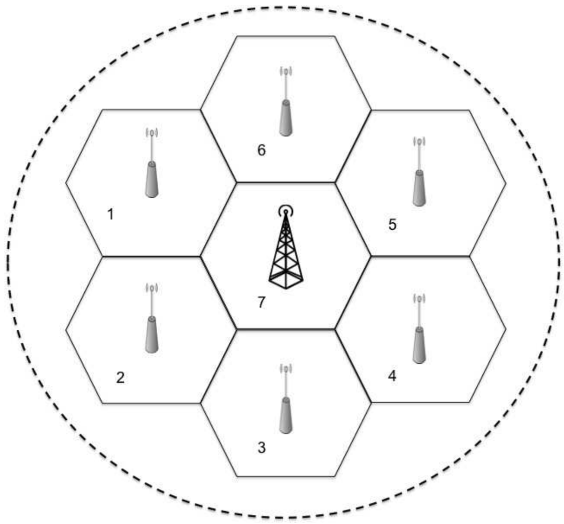

Fig. 1. White Space Model in Dense Area

- We perform measurement-driven simulation to analyze various scenarios of channel resource and users distribution. Our results shows that the white space bands reduce the power consumption in typical city environment by FIXME.

The rest of the paper

II. System, Assumptions and Problem Formulation

A. System and Assumptions

Wireless propagation refers to 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 [9]. 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 [10]:

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

Here, n varies according to the aforementioned environmental factors with a value ranging from two to five in typical outdoor settings [11]. Thus, the channels of white space bands propagates further than the channels of the WiFi bands in free space under the same RSSI threshold, transceiver settings 1. The propagation range of white space channels could be many times of WiFi channels, for instance, 450 MHz channels has more than 12 times propagation range as 5 GHz channels. The larger propagation of white space channels make it possible to assist a WiFi mesh with few white space channels.

Given a WiFi mesh wireless system with M access points and N users as shown in Fig. 1. The users are scheduled with the access point on the single channel $f \in F_M$ located in its own mesh. We consider F_w new white space radios is installed on one of the access points to assistant the existing WiFi network. The capacity of each radio C is a equally restrict number of all the channels. Each radio has enough buffer store the traffic demand. The traffic is served in a FIFO system. For each user, it has $1+F_w$ channels to be scheduled, the previous in-cell WiFi channel and the new white space channels. Instead of assuming the wireless are on-off [12], we apply our measurements to estimate the channel capacity. The capacity of the scheduled channels between the access points and users is noted as a matrix in Eq. 2

$$H^f_{i,j}(t) = G(\zeta, t), i \in M, j \in N, f \in (F_M + F_w) \quad (2)$$

ζ represents the in-field measured historical data and dynamic sensing information. We use a context-aware method to estimate the j user capacity $H^f_{i,j}(t)$ to an access point i on channel f. We assume the users from the same mesh cell are in a single interference domain. Considering the limited number of white space channels in dense area and the fact spatial reuse of white space will make the problem considerably more challenging, we will remains an interesting direction of future research.

We assume the channel capacity is flat during a time slot. We also assume the switching time is negligible. The traffic demand arrive at a user as a Poisson process, with the vector noted as $\boldsymbol{D(t)} = [D_1(t), D_2(t), ...D_N(t)]$ and the sum rate $D(t) = \sum_{i=1}^{N} D_i(t)$. The rate $D(t)$ is the aggregate rate of data generated from all users.

In a time slot, we assume the unscheduled radios remain in sleep mode to save energy. Also we ignore the sleeping energy as well as the amount of energy spent on channel/radio switching. An operating radio will cost equal power during a time unit. Previous work [13] shows a user has a certain patience for waiting. The tolerance time varies across the traffic type, such as text information, voice information. To simply the problem, we assume an arbitrary average value for W of the users in the area. The system apply a first-come-first-serve schedule.

B. Problem Formulation

We formulate the system discussed in II-A as a discrete-time queuing system as shown in Fig. 2. The channels are represented as servers in the queuing system. Table. I summarizes the notation used in this work. The queuing system has N queues and $F_M + F_w$ servers connecting by time-varying channels $H^*(N, F_M + F_w)$.

t	Time slot
N	Set of users
M	Set of Access points
H^f_{ij}	Measurement based Capacity between AP i and user j on channel f
F_m	WiFi Channels with Access Points
F_w	Set of White Space Channels
$A(t)$	User access channel schedule
B	User Buffer
C	Radio Capacity
R	Operating Radio
ζ	In-Field Measurements
W	Tolerance time window

TABLE I
Table of Notations

In this system, during a time unit, the users need to schedule with their achieved channels. Let matrix $\{A_{i,j}(t), i \in (F_M + F_w), j \in N\}$ denote a schedule meets the performance

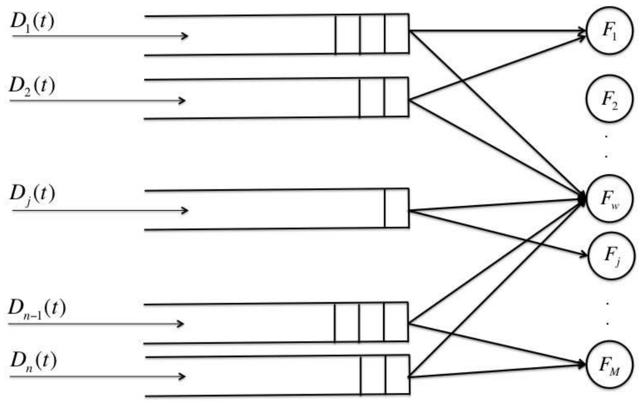

Fig. 2. System Model

constraints will be discussed later.

$$A_{i,j}(t) = \begin{cases} 1 & if\ D_{j \in N},\ is\ scheduled\ with \\ & channel\ i \in (F_M + F_w) \\ 0 & Otherwise \end{cases} \tag{3}$$

To satisfy the users, the system need to keep the expected waiting time of the system w need to be less than the threshold W as shown in Eq. 4

$$E[w] \leq W \tag{4}$$

With the intuition, when the total traffic demand of the users in the system are small, one white space radio in white space could achieve the quality of service for the users. Thus all the WiFi radios could be turned down. However, as the traffic demand increase with the number of users or the demand per user, we need to increase the channel resource from the system to satisfy the user requirements. Another advantage scenario of white space channels are when some of the WiFi cells have more traffic demand, we can spend more white space channel capacity for these cells without building new infrastructure. Then the questions come as, how much power we could save through divide the white space capacity into the WiFi cells? And how much user traffic demand variation we could adapt in one or more cells in the system?

C. Challenges And Analysis

Prior works model similar multi-channel system as $M/M/m$ queuing system for analyzing. Other than prior works, this system is not able to be formulated as a $M/M/m$ queuing system due to the propagation variation across white space bands and WiFi bands. The users in this system can only be served by the white space channels and the WiFi channels assigned in the cell. Moreover, we use a measurement based channel estimation other than an on-off channel model in this work. To design such wireless system, the waiting time constraints have to be satisfied for the quality of service. Previous multi-channel works apply $M/M/m$ queuing model for similar system. However, the spectrum variation and the white space channel splitting in this system remove the equal service capacity in the system. Thus, $M/M/m$ queuing system is not directly applicable to get the minimum channel resource which is the number of servers of the queuing system.

Also a practical system suffer multi-user diversity. Multi-user diversity is a form of diversity inherent in a wireless network, provided by independent time-varying channels across the different users [2]. The user diversity make the channel capacity vary across users. In this system, some WiFi cells may have good white space channels while the others may suffer worth white space performance. Thus, in-field measurements based channel capacity estimation become an important role in such system.

To answer the design question, we first get the channel capacity from the in-field measurement, then we propose a Greedy Server-side Replace (GSR) algorithm to minimize the power consumption and achieve the performance constraints.

The users of the the same WiFi cell are in a heterogeneous queuing system with server of WiFi channels and white space channels with service rate $\mu_1, \mu_2, ...\mu_{(F_w+1)}$. The white space channel capacity could be split into multiple WiFi cells, thus, the capacity of the white space is usually the minimum channel capacity in a WiFi cell. The white space channels in a WiFi cell should be less than the WiFi channel or about equal. Thus, we apply the transformation model in [14] to estimate the response time $\bar{w}$ which should be less than W. In this transformation model, the actual arrival rate for one specific server λ_s is defined as in Eq. 5

$$\lambda_s = D/(F_w + 1) \tag{5}$$

The other parameters are defined in Eq. 6 to 8.

$$\mu_{min} = \min\left(\mu_1, \mu_2, ...\mu_{(F_w+1)}\right) = \bar{\mu} \tag{6}$$

$$\mu_{max} = \max\left(\mu_1, \mu_2, ...\mu_{(F_w+1)}\right) \tag{7}$$

$$k = \lfloor \frac{\mu_{max}}{\mu_{min}} \rfloor \tag{8}$$

When $k = 1$, the system could be treated as a homogeneous system. Otherwise, $k \geq 2$ the average response time of such heterogeneous system could be represented as in Eq. 9 [14]:

$$\bar{w} = \frac{1}{\frac{1}{3}\bar{\mu}(2k+1) - \lambda_s} \tag{9}$$

If the traffic could be served only by part of a single white space channel or the WiFi channel, the users in the cell converge into a $M/M/1$ queuing. Another scenario is when the traffic occupies two or more channels, the system become a $M/M/m$ queuing system. The average response time is calculated as in Eq. 10 and Eq. 11 [15].

$$\bar{w} = \frac{1}{\mu^+ - D} \tag{10}$$

μ^+ is the channel capacity of the single server in queuing system.

$$\bar{w} = \frac{1}{\mu^*}(1 + \frac{c(m,\rho)}{m(1-\rho)}) \approx \frac{1}{\mu^*}\frac{1}{1-\rho^m} \tag{11}$$

μ^* is the channel capacity in the $M/M/m$ queuing system. $\rho = \frac{\lambda}{m\mu^*}$ is the traffic density, and $c(m,\rho)$ is the Erlang-C formula [15].

Through the above analysis, we could calculate the channel capacity need to be spent for certain group of users. To model the power consumption of the system, we assume the power consumption of each operating radio include standby and transmitting power. The operated radios R_i in the system is chosen from the WiFi radios F_M and the white space radios F_w. If the a radio R_i is chosen, $R_i = 1$, otherwise $R_i = 0$, as shown in Eq. 12

$$R_i(t) = \begin{cases} P_s + P_t \cdot \mu & \sum_{j=1}^{N} A_{i,j}(t) \geq 1 \\ 0 & Otherwise \end{cases} \tag{12}$$

For the carrier, reduce the power consumption is important for cost saving. Our goal is, during a certain T time slot, to minimize the power consumption as represented in Eq. 13:

$$R^*(t) = \min \{ \sum_{t=0}^{T} \sum_{i=1}^{(F_M+F_w)} R_i(t) \} \tag{13}$$

R^* represent the minimum operating radios power during T time slots required to satisfy the users in the system.

In this model, the less radio we operate in each time slot, the less power consumption will be cost in the system. To split the white space capacity we propose a Greedy Server-side Replace(GSR) algorithm to approach the minimize number of radios operate in the system. The algorithm output the channel resource allocation to satisfy the waiting time constraint of the system.

For the power consumption, there are two extremes. When the traffic rate D is low, a white space channel could serve all the users in the propagation range. On the other side, when all the WiFi cells have high traffic demand, both the WiFi and white space radios have to work for the users. Between the two extremes, when the user traffic is medium heavy and the location distribution is non-uniform, the white space channels could adapt these cases.

A white space radio is able to replace a WiFi radio if part of the channel capacity could serve the users in the WiFi cell. If each WiFi cell could be served by the least channel resource, the more radios could be turned off. The less capacity assigned for the WiFi cells, the less power will be cost for transmission.

The calculation of channel capacity H will be discussed in Section III. The algorithm starts to reduce the standby power then the transmitting power for each server.

III. Experiment and Analysis

In this section, we introduce the measurements experiments setup and evaluate the process of probabilistic forecasting of channel state.

A. Measurements

We perform measurements in neighborhoods, campus, downtown bussiness office and urban bussiness office for 24 hours on weekdays. The locations we chosen for measurements are shown in Fig. **??**.

We employ a Rohde & Schwarz FSH8 portable spectrum works from 100 KHz to 8 GHz. The portable spectrum analyzer is controlled by a Python script on a laptop to measure the received signal strength. To the best of our knowledge, there is no readily available mobile, multiband antenna from 450 MHz to 5.2 GHz on the market. Thus, we use a 700-MHz mobile antenna to perform in-field measurements. We then normalize the mobile antenna performance across bands with indoor experimentation. To do so, we use a Universal Software Radio Peripheral (USRP) N210 to generate signals at 450 MHz, 800 MHz, and 2.4 GHz. We feed the USRP signals directly to a spectrum analyzer and adjust the configuration of USRP to make the received signal strength the same as the 5.2 GHz signal from Gateworks 2358 with a XR5 radio. Then, we connect the signal source to a fixed multiband antenna (QT 400 Quad Ridge Horn Antenna) and measure the received signal at a fixed distance with the 700 MHz antenna and antennas for different bands to obtain the antenna loss for each band. We adjust the received signal strength collected via the 700-MHz mobile antenna according to the normalization.

Algorithm 1 Greedy Server-side Replace

Input:
N: Users
$H^f_{i,j}$: Vector of channel capacity
D: Traffic Rate
n: Path Loss Exponent
M: WiFi Cells

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Find the WiFi cell with the lowest traffic rate D,break the tie with index
if Check with Eq. 9 10 11 if white space channel satisfy the users, start with the worst/most utilized white space channel then
    Replace the WiFi channel with the white space channel
    Apply half-interval search to find the minimum capacity for the users
else if The WiFi channel satisfy the users then
    Keep the WiFi channel and find the minimum capacity for the users
else if White space channels available then
    Adding white space resource to the cell
else
    Get the response time of the cell with all available resource
end if
Update the system information
Repeat the process for all the cells
Calculate the power consumption
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Output:
The power consumption and the maximum response time

When wireless devices operate in WiFi bands, the channel separation is relatively small (e.g., 5 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 between 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 little frequency separation, meaning they have 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 create opportunities 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.

For spectrum utility and resulting channel availability, we split the measurements every 30 minutes of 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:

$$A = \frac{S_\theta}{S_a} \tag{14}$$

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 free time of the channel capacity according to:

$$C_r = C * (1 - \bar{A}) \tag{15}$$

B. Experiment Setup

C. Results and Analysis

IV. Related Work

Since white space bands were free for wireless communication, many efforts have been put in the area for the application of white space bands. [16] In [17]. the author considered a cognitive method to avoid collision between white space communication and TV broadcasting. Many works increasing the convenience of using white space databases have been published (e.g., Microsoft's White Space Database [18]). Google has even visualized the licensed white space channels in US cities with an API for research and commercial use [19]. Previous work discussed the point to point communication with white space bands [20], and the wireless network deployment with plenty white space channels [7]. However, many of the major cities in the US do not have plenty white space channels, such as most area of Austin, TX has only one white space channel. As far as we know, there is no work discuss these scenarios.

Applying white space in wireless network is similar to the previous multi-channel works other the propagation variation. In [12] a multi-channel system is formulated as a queuing system and Server Side Greedy algorithm is proposed to optimize the throughput with low complexity. In [21], Delay-based Queue-Side-Greedy algorithm is proposed with low complexity for optimal throughput and near-optimal delay. [22] develop a multi-objective optimization framework to minimal energy consumption in a multi-channel multi-radio system. However, these works do not address minimizing the resource for certain quality of service and assume an on-off channel model.

Previous works in real time systems put many efforts to minimize the resources, such as processors [23]. In [24], the author proves the capacity augmentation bounds for schedulers of parallel tasks. However, these works assume the parallel tasks have uniform servers. Previous work [25] investivate the white space in a queuing system without considering the hetergeneous topology. In contrast, we study the performance of a hetergeneous network with both white space channels and WiFi channels in channel utilization.

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