# WhiteCell: Leveraging Scant White Space Resource in Dense Area

Pengfei Cui, Dinesh Rajan, and Joseph Camp

Department of Electrical Engineering, Southern Methodist University

***Abstract*—The FCC has reapportioned spectrum from TV white spaces for the purposes of large-scale Internet connectivity via wireless topologies of all kinds. These frequency resource offers more channel capacity and flexibility of propagation for network design. The far greater range of these lower carrier frequencies are especially critical in user mobility adaptation, where high levels of aggregation could dramatically lower the power consumption of network operating. However, the white spaces resource distribution is contrast to the population density, dense area has few white space channels. Thus, leveraging the range of spectrum across user mobility becomes a critical issue for the operating of heterogeneous data networks with WiFi and limited white space bands. In this paper, we present a feasibility analysis for a heterogeneous network resource allocation to reduce the power consumption via queuing theory approach. In particular, we study the spectrum utility across multi-bands and the user mobility across weekdays in typical environment of the Dallas-Fort Worth metropolitan. Moreover, we propose a Greedy Server-side Replace (GSR) algorithm to reduce the power consumption with white space channels application. In doing so, we find that networks with white space bands reduce the power consumption by up to 512.55% in sparse rural area over WiFi-only solutions via measurements driven numerical simulation. In more populated areas. we find an power consumption reduction on average across 24 hours by 24.57%, 46.27%,67.40% over WiFi only network with one to three white space channels respectively. We further investigate the quality of service requirements impacts on power consumption across the number of channels. We find that the power consumption reduction is up to 150.89% with three white space channels in dense areas with large required response time.**

## 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 data 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 greatly complements the existing WiFi wireless network with their large propagation range for user mobility. The users of an WiFi access point have the options to associate with either the WiFi channel of the cell or the large propagation white space channels.

The users in multiple locations under the coverage of both the WiFi and white space have user diversity which represents the difference of transmission qualities of multiple users due to their variations in transceiver design, geographic location, etc. The user diversity comes from two types of reason. One is the temporal diversity which is caused by the environment variation. Another is the spectral diversity which represents the transmission conditions varies across frequencies. In some moderate number of users, the sum capacity of users increase with the diversity in the system [2].

The larger propagation range of white space channels adapt channel association of users located in large area. When the users distributed in a large area, the temporal diversity and spectral diversity become the key issues in white space applications. 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 [3]. 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 [3]. Exploiting these limited white space resource to improve the WiFi network in dense area is a perspective option for wireless networks.

Moreover, the white space frequencies offer more wireless capacity and convenience of access across large area. When the total 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 power saving. On the other side, when the users have highly total 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?* Especially when the WiFi mesh located in dense area with less white space channel availability.

In this work, we study the white space resource impacts on mesh network power consumption via queuing theory model. We describe the heterogeneous network structure with white space bands and WiFi bands and analyze the system with a queuing model. We analyze the heterogeneous structure to get resource required by the waiting time restriction in multiple scenarios of the structure. We further propose a Greedy Server-side Replace (GSR) algorithm to minimize the power consumption for the heterogeneous network structure. We then evaluate the algorithm, showing the power consumption gains across sparse and dense areas and analyze the impact of the number of white space and WiFi channel in these representative scenarios.

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

- We perform 24 hours in-field measurements in neighborhoods, campus, downtown business building, and urban business buildings. Through the measurements, we estimate the achieved channel capacity of these typical area in Dallas area.

- We leverage the user mobility footprint through in-filed WiEye measurements of Dallas on weekdays. Through the measurements, we tell the user distribution in multiple types of areas.
- We formulate the heterogeneous wireless system as a queuing system. Based on previous queuing theory works, we analyze the resource relation of the system waiting time. Based on the analyze, we propose a Greedy Server-side Replace (GSR) algorithm to allocate the channel resource to minimize the power consumption.
- We perform measurement-driven numerical simulation to analyze various scenarios of channel resource and users distribution. Our results shows that the white space bands reduce the power consumption in sparse area by up to 512.55% and 99.57% in weekdays.

The rest of the paper is organized as follows. We describe the system and formulate the problem in II. Then, we present the queuing theory analysis and the Greedy Server-side Replace algorithm also in II. The measurements and measurement-driven numerical simulation is discussed in III. Finally, we conclude our article in V.

## 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 [4]. 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 $\lambda$ of the carrier frequency, distance $R$ from transmitter to receiver, and path loss exponent $n$ according to [5]:

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

Here, $n$ varies according to the aforementioned environmental factors with a value ranging from two to five in typical outdoor settings [6]. Thus, the channels of low frequency white space bands propagates further than the high frequency WiFi bands the same RSSI threshold, transceiver settings according to Eq. 1. The propagation range of low frequency white space channels is times of WiFi channels, for instance, 450 MHz channels has more than 12 times propagation range as 5 GHz channels via Friis model. Thus a single white space access point is possible to serve an area up to hundreds times of a WiFi access point. The larger propagation of white space channels is potentially to be applied for reduction of network deployment cost [7], adaptation of vehicular dynamic access [8], and improvement of network capacity [9]. However, previous works focus on the application of plenty white space channels resource or point to point communication require small amount of white space resource. In wireless network design, as discuss in previous works, the more wireless channel resource means the better performance. Unfortunately, FCC restricts the number of white space channels in most dense populated areas due to the existing TV broadcasting application. Thus, a heterogeneous network with WiFi channels and

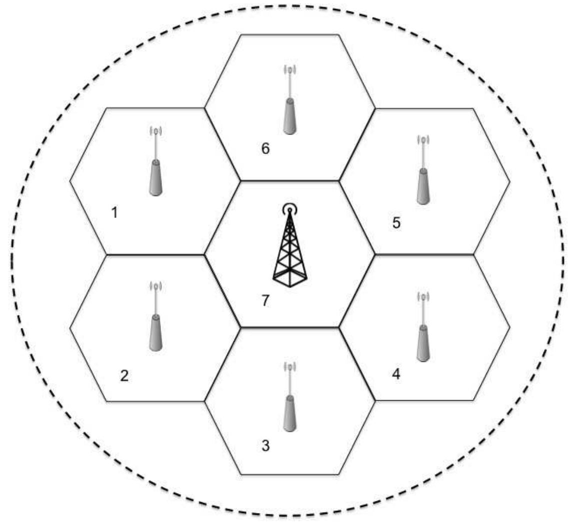


Fig. 1. White Space Model in Dense Area

few white space channels becomes a practical option for these cities.

Here, we introduce a heterogeneous network named as WhiteCell with existing WiFi cells and an access point with few number of white space channels as shown in Fig. 1. Given a WiFi mesh wireless system with $M$ access points and $N$ users. Each of the WiFi cell has access to the white space channels and its own WiFi channel. The reuse of WiFi channels has been discussed in plenty of previous works and it is out of our scope. The users of a WiFi cell are associated with an WiFi channel assigned for the access point in the cell or one of the white space channels. There are $F_w$ 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. There are enough buffer store the traffic demand from the users on each radio. The traffic is served in a first-in-first-out (FIFO) scheduling system. In such a network, each user has $1 + F_w$ channels to be scheduled. One is the previous in-cell WiFi channel and the white space channels. We assume the users in 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.

Instead of assuming the wireless channels are on-off [10] or equally clean, we apply a measurements method to get the achieved channel capacity. The capacity of the channel between the access points and users is noted as a matrix in Eq. 2

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

$\zeta$ represents the in-field measured historical data and dynamic sensing information. We use a context-aware method to estimate the $j$ user capacity $H_{i,j}^f(t)$ to an access point $i$ on channel $f$. The users in a single cell has the same channel status. We assume the channel capacity is flat during a time slot. The switching time is negligible in the system. The calculation of achieved channel capacity is introduced in III-B. 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

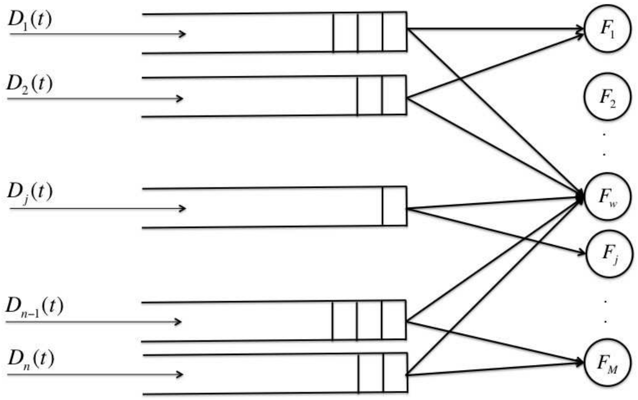


Fig. 2. System Model

$D(t) = \sum_{i=1}^{N} D_i(t)$. The rate $D(t)$ is the aggregate rate of data generated from all users.

During a time slot, 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 in a time unit. Previous work [11] 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 average value for $W$ of all the users in the system. The system applies a first-come-first-serve schedule. The white space channels are able to split for multiple cells.

### B. Problem Formulation

We formulate the system introduced 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 system has $F_w$ white space channels, $F_M$ WiFi channels in total and $N$ users. Thus, 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 |
| $H_{ij}^f$ | 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 |
| $\zeta$ | In-Field Measurements |
| $W$ | Tolerance time window |

TABLE I
TABLE OF NOTATIONS

Let matrix $\{A_{i,j}(t), i \in (F_M + F_w), j \in N\}$ denote the associate meets the tolerance constraint as shown in Eq. 3.

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

The queuing system keeps the expected waiting time of the system $w$ less than the tolerance 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 relatively small, a single white space channel could achieve the quality of service for the users. Thus all the WiFi radios could be turned into sleep mode for power saving. On the other side, as the traffic demand increase with the number of users or the demand per user, we need to increase the channel resource as servers in the system to qualify the user waiting time tolerance requirements. Moreover, when the users are distributed non-uniformly, the white space channels are able to deliver more capacity for the cells with more users to balance the system load without new infrastructure. The flexibility of white space channels offers new opportunity for network design. To apply these white space advantages, the question *how much power we could save via dividing the white space capacity into the WiFi cells?* has to be addressed in this system.

In this work, we focus on the analysis on the power consumption saving of the heterogeneous wireless system. To model the power consumption of the system, we count the power consumption of each operating radio via standby and transmitting power consumption. We assume the sleeping standby power consumption is negligible. We define $R_i$ represents the radios status in the system, $i \in F_w, F_M$. When $R_i$ is working in WiFi channels $F_M$ or white space channels $F_w$, $R_i$ denotes the power consumption with the standby and transmitting cost. Otherwise, $R_i = 0$. The definition is as shown in Eq. 5

$$R_i(t) = \begin{cases} P_s + P_t \cdot \mu & \sum_{j=1}^{N} A_{i,j}(t) \geq 1 \\ 0 & Otherwise \end{cases} \tag{5}$$

Thus, to reduce the power consumption, we need to minimize $R_i$ for all the radios under the quality of service constraints. Our goal, to minimize the power consumption is represented in Eq. 6:

$$R^*(t) = \min \{ \sum_{i=1}^{(F_M+F_w)} R_i(t) \} \tag{6}$$

$R^*$ represent the minimum operating radios power consumption required for the system.

### C. Challenges And Analysis

Prior works model similar multi-channel system as $M/M/m$ queuing system for analyzing [10]. However, this system is not able to be formulated as a $M/M/m$ queuing system due to the non-equal capacity of the assigned channel capacity across white space and WiFi channels. Thus we first analyze the queuing system and apply previous work in $M/M/m$ queuing theory to generate the solution for such system.

Without the white space channels, the users in a cell can only access to the WiFi channel assigned for the cell to get service. The large propagation of white space channels offers more options for all the users. The user could either associate with the white space channels or the WiFi channels. Thus, the white space channels could be splited into several cells. The spliting of the white space channels brings more capacity variation of the servers. The white space channel spliting capacity variation and the spectrum capacity variation of cells might remove the equal service capacity assumption of the system in most scenarios. However, the equal server capacity is the pre-request for a general $M/M/m$ queuing system analysis. Thus, the $M/M/m$ queuing system of a multi-channel version is not directly applicable for this system model.

In the design of the wireless system, the response time $W$ constraints have to be satisfied to keep the quality of service. The users in this system can only be served by the large propagate white space channels or the WiFi channels assigned in the cell. The users located in multiple cells have different channel status in the same white space channels, which is mentioned as part of the multi-user diversity in previous works. Multi-user diversity is a form of diversity inherent in a wireless network, provided by independent time-varying channels across the different users [12]. The diversity could be generated by the interference from device inside the network or out of the network, the environmental variations. The variation among users make the channel capacity among all the cells for white space channels. Thus, some cells may have clean white space channels in the air while the other cells may suffer worse white space channel performance. To address the variation, instead of holding the on-off channel assumption, we implement an in-field measurements based channel capacity estimation approach in this work.

We define an activity level to estimate the achieved channel capacity. We perform measurements to sense the activities in the air through our portable spectrum analyzer. The percentage of sensing samples ($S_\theta$) above an interference threshold ($\theta$) over the total samples ($S$) in a time unit is the activity level ($A$):

$$A = \frac{S_\theta}{S_a} \tag{7}$$

The capacity of a clean channel is denoted by $C$. With the protocol model, the achieved capacity of a channel $C_r$ could be represented as the remaining free time of the channel capacity according to Eq. 8:

$$C_r = C * (1 - \bar{A}) \tag{8}$$

Other than the achieved channel capacity, we also perform in-field measurements of the user mobility footprint. When the total number of the users is a certain value, the user distribution becomes important for wireless network operating. We analyze the dataset from WiEye, an Android application reports the location, velocity and signal information to leverage the mobility pattern of users during week days. The setup and results are shown in Section III.

With thses measurements information, we further analyze the channle capacity allocation for such a system. We first investigate the channel capacity allocation in a single cell. 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 $\mu_1, \mu_2, ...\mu_{(F_w+1)}$. $\mu$ denote the capacity allocated for this cell. The white space channel capacity is splited into multiple WiFi cells, thus, the capacity of the white space is usually the minimum channel capacity in a cell. Thus, there are three cases of the channel capacity in a single cell. The first scenario is several channels of both WiFi and white space works for the cell and the capacity of some white space channel is several time less than other channel capacity since white space channels are splited for many cells. An example here is in a single cell, the white space channel assigned is equally distributed to two cells, while the WiFi channel works in this cell, thus, the capacity of the WiFi channel is about twice of the white space channel capacity in this cell. The second scenario is only the WiFi channel or only part of a single white space channel works for the cell. The third scenario is several channels work for this cell with around equal capacity. The fist case is a heterogeneous server queuing system with inequal capacity servers. The second case is simplified as a $M/M/1$ queuing system. The third case is converted into a $M/M/m$ queuing system.

For the first case heterogeneous server queuing system, we apply the transformation model in [13] to estimate the response time $\bar{w}$. In the transformation model, the actual arrival rate for one specific server $\lambda_s$ is defined as in Eq. 9

$$\lambda_s = D_{cell}/(F_w + 1) \tag{9}$$

$D_{cell}$ is the traffic aggreated from the users in the cell.

The other parameters are noted from Eq. 10 to 12.

$$\mu_{min} = \min(\mu_1, \mu_2, ...\mu_{(F_w+1)}) = \bar{\mu} \tag{10}$$

$$\mu_{max} = \max(\mu_1, \mu_2, ...\mu_{(F_w+1)}) \tag{11}$$

$$k = \lfloor \frac{\mu_{max}}{\mu_{min}} \rfloor \tag{12}$$

When $k = 1$, the system becomes a homogeneous queuing system as in case three. Otherwise, $k \geq 2$ the average response time of such heterogeneous system could be represented as in Eq. 13 [13]:

$$\bar{w} = \frac{1}{\frac{1}{3}\bar{\mu}(2k+1) - \lambda_s} \tag{13}$$

Through the transformation model, we could further calculate the channel capacity required for response time constraints. Further, the power consumption could be calculated for the system. When the traffic could be served by part of a single white space channel or the WiFi channel, as the second scenario, the system converge into a $M/M/1$ queue. The response time $\bar{w}$ could be estimated from Eq. 14 [14].

$$\bar{w} = \frac{1}{\mu^+ - D} \tag{14}$$

$\mu^+$ is the channel capacity of the single channel capacity in queuing system.

In the third scenario, the system could be treated as a $M/M/m$ queuing system. The average reponse time is calculated as in Eq. 15 [14].

$$\bar{w} = \frac{1}{\mu^*}(1 + \frac{c(m,\rho)}{m(1-\rho)}) \approx \frac{1}{\mu^*}\frac{1}{1-\rho^m} \tag{15}$$

$\mu^*$ is the average capacity of channels 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 [14].

In this model, the less radio in operation and the less power consumption will be cost in the system according to Eq. 5. The

**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
Find the WiFi cell with the lowest traffic rate D,break the tie
with index
Calculate the power consumption according to Eq. 13 14 15
if If channel resource feasible then
    List available options
    if Single channel is the best then
        Apply half-interval search to find the minimum capacity for
        the users
    else if Homogeneous is the best then
        Allocate the resource for the cell
        Keep the WiFi channel and find the minimum capacity for
        the users
    else if Heterogeneous is best then
        Adding white space resource to the cell
    end if
else
    Get the waiting 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
```

**Output:**

```
    The power consumption and the maximum waiting time
```

basic idea of power reduction for this heterogeneous system is to replace the WiFi radios via white space channel capacity. To implement the division of the white space capacity we propose a Greedy Server-side Replace(GSR) algorithm to approach the minimize power consumption in the system as shown in Algorithm 1.

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.

The algorithm output the channel resource allocation to satisfy the waiting time constraint of the system.

We integrate the in-field measured data 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.

## 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. 3.

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

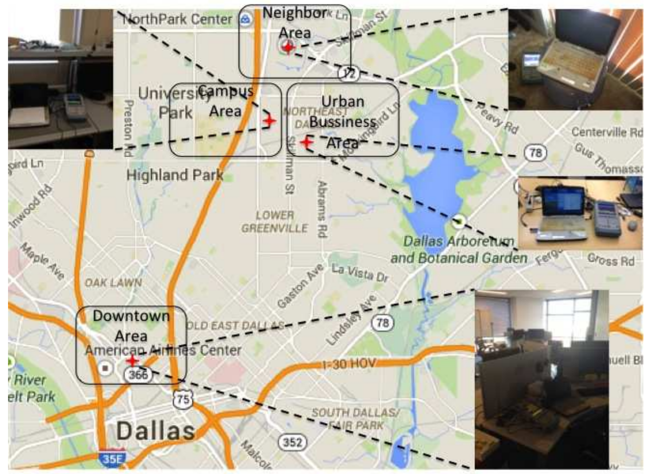


Fig. 3. Long Term Measurements Locations

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.

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.

White space band is in advantage to adapt user moving in the area. To identify the user mobility pattern, we leverage the data from WiEye database and find the user locations across time. WiEye application created for the data collection is currently available for download and usage via the Google Android Market under the name WiEye. The application offers WiFi access points connection quality in both graphical and tabular form. All data collection is done in the background,

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Downtown | 400 MHz | 0:00-11:00 | 23.17 | 23.69 | 23.45 | 22.83 | 23.24 | 23.43 | 23.48 | 23.74 | 23.69 | 23.36 | 23.29 | 23.00 |
| | | 12:00-23:00 | 22.85 | 22.81 | 23.62 | 23.74 | 23.14 | 23.48 | 23.38 | 22.52 | 22.04 | 22.59 | 22.59 | 22.42 |
| | 800 MHz | 0:00-11:00 | 12.63 | 13.20 | 13.08 | 12.94 | 11.55 | 11.48 | 11.60 | 11.38 | 11.86 | 11.72 | 10.47 | 10.32 |
| | | 12:00-23:00 | 12.00 | 11.86 | 10.71 | 11.93 | 12.72 | 12.36 | 11.48 | 11.43 | 11.72 | 11.60 | 11.72 | 11.91 |
| | 2.4 GHz | 0:00-11:00 | 29.04 | 28.66 | 27.29 | 28.15 | 27.89 | 27.72 | 28.18 | 27.38 | 28.18 | 27.74 | 28.15 | 27.96 |
| | | 12:00-23:00 | 27.96 | 29.14 | 28.97 | 28.20 | 28.80 | 29.57 | 29.02 | 27.72 | 27.70 | 27.77 | 29.21 | 28.42 |
| | 5.2 GHz | 0:00-11:00 | 25.41 | 25.29 | 26.32 | 26.49 | 27.23 | 27.28 | 26.99 | 26.27 | 25.36 | 26.13 | 25.81 | 24.88 |
| | | 12:00-23:00 | 26.92 | 26.49 | 26.41 | 27.11 | 25.67 | 26.53 | 26.73 | 26.97 | 26.32 | 25.79 | 27.57 | 26.65 |
| Urban | 400 MHz | 0:00-11:00 | 22.09 | 21.27 | 22.28 | 22.47 | 21.65 | 21.68 | 22.37 | 22.16 | 23.12 | 22.73 | 22.01 | 22.54 |
| | | 12:00-23:00 | 21.80 | 20.86 | 21.80 | 22.54 | 22.35 | 22.61 | 22.45 | 21.58 | 22.18 | 23.09 | 22.11 | 22.09 |
| | 800 MHz | 0:00-11:00 | 12.99 | 12.44 | 12.08 | 12.32 | 11.60 | 11.60 | 12.48 | 12.10 | 11.14 | 11.55 | 11.98 | 11.12 |
| | | 12:00-23:00 | 11.88 | 12.27 | 12.36 | 12.05 | 12.15 | 14.00 | 13.32 | 12.29 | 11.38 | 11.55 | 12.92 | 13.16 |
| | 2.4 GHz | 0:00-11:00 | 29.08 | 29.15 | 29.49 | 28.93 | 29.01 | 28.86 | 28.84 | 29.53 | 29.03 | 28.74 | 29.89 | 29.15 |
| | | 12:00-23:00 | 28.60 | 29.61 | 29.44 | 28.55 | 28.05 | 28.62 | 28.74 | 28.93 | 28.26 | 27.73 | 28.19 | 29.85 |
| | 5.2 GHz | 0:00-11:00 | 27.21 | 27.11 | 26.20 | 25.77 | 26.70 | 26.17 | 25.67 | 26.10 | 25.77 | 25.41 | 26.05 | 26.34 |
| | | 12:00-23:00 | 26.17 | 26.03 | 25.19 | 26.41 | 26.80 | 25.17 | 26.08 | 25.60 | 26.44 | 26.58 | 25.50 | 25.45 |
| Campus | 400 MHz | 0:00-11:00 | 20.29 | 21.56 | 21.41 | 22.52 | 23.12 | 21.97 | 21.65 | 21.63 | 21.87 | 21.22 | 21.17 | 21.39 |
| | | 12:00-23:00 | 22.33 | 22.88 | 22.28 | 21.65 | 22.49 | 22.16 | 21.32 | 22.35 | 21.56 | 21.75 | 21.75 | 20.45 |
| | 800 MHz | 0:00-11:00 | 11.98 | 12.20 | 12.68 | 12.03 | 11.52 | 11.19 | 11.96 | 12.94 | 11.52 | 11.93 | 12.44 | 10.95 |
| | | 12:00-23:00 | 11.26 | 11.62 | 12.12 | 12.70 | 12.34 | 11.62 | 11.57 | 12.17 | 11.55 | 12.08 | 11.88 | 11.98 |
| | 2.4 GHz | 0:00-11:00 | 26.10 | 25.91 | 28.02 | 26.61 | 27.90 | 27.09 | 27.01 | 27.21 | 26.99 | 26.75 | 25.69 | 26.46 |
| | | 12:00-23:00 | 26.58 | 27.23 | 26.92 | 26.29 | 26.10 | 26.13 | 26.25 | 25.53 | 25.79 | 25.84 | 26.13 | 26.46 |
| | 5.2 GHz | 0:00-11:00 | 26.68 | 26.05 | 25.12 | 25.93 | 25.36 | 25.79 | 26.03 | 26.73 | 25.89 | 25.26 | 25.81 | 25.50 |
| | | 12:00-23:00 | 25.19 | 25.60 | 24.52 | 25.00 | 26.08 | 26.17 | 26.85 | 26.53 | 26.10 | 25.53 | 25.89 | 25.31 |
| Neighborhoods | 400 MHz | 0:00-11:00 | 23.17 | 24.35 | 23.82 | 23.75 | 23.44 | 22.76 | 24.08 | 25.26 | 24.54 | 23.87 | 23.82 | 23.70 |
| | | 12:00-23:00 | 23.48 | 22.67 | 23.53 | 23.48 | 23.99 | 24.49 | 23.99 | 22.98 | 22.86 | 23.03 | 23.89 | 23.63 |
| | 800 MHz | 0:00-11:00 | 15.72 | 16.30 | 16.33 | 15.72 | 16.54 | 14.48 | 14.62 | 14.48 | 15.68 | 15.03 | 15.60 | 16.33 |
| | | 12:00-23:00 | 15.72 | 14.74 | 14.74 | 14.38 | 15.41 | 15.00 | 15.84 | 16.25 | 14.84 | 14.69 | 15.51 | 14.93 |
| | 2.4 GHz | 0:00-11:00 | 26.49 | 26.37 | 26.22 | 26.03 | 24.97 | 27.16 | 27.76 | 26.56 | 26.05 | 26.22 | 25.74 | 27.18 |
| | | 12:00-23:00 | 27.01 | 26.34 | 25.79 | 25.48 | 26.53 | 26.29 | 25.33 | 25.86 | 26.92 | 25.98 | 25.48 | 27.66 |
| | 5.2 GHz | 0:00-11:00 | 25.93 | 26.27 | 25.07 | 25.67 | 26.77 | 26.80 | 27.52 | 25.38 | 25.55 | 25.86 | 25.62 | 26.13 |
| | | 12:00-23:00 | 25.29 | 26.49 | 26.70 | 26.77 | 25.31 | 24.59 | 24.78 | 25.91 | 25.67 | 24.73 | 24.73 | 25.21 |

TABLE II
ACTIVITY LEVEL IN MULTIPLE LOCATIONS (TO BE REMOVED)

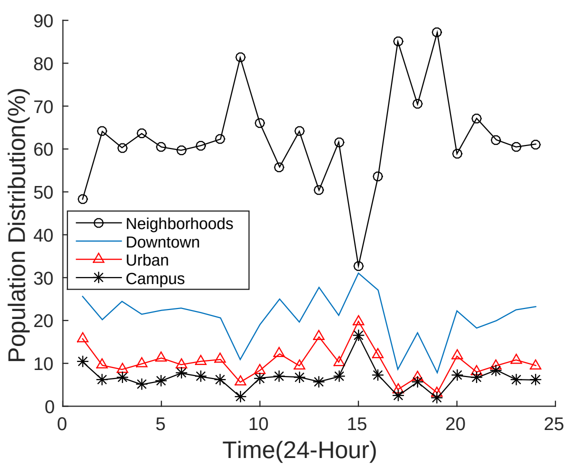

Fig. 4. User Distribution across Time

either continuously while the user is running the application or periodically if the user has opted in to background data collection to SMU research. The data collected has been approved by the Southern Methodist UniversityInstitutional Review Board, a human subjects research committee,ensuring that all ethical precautions have been taken in collectingdata from the users of our application. The dataset we chosen from the WiEye database is measured in the weekdays of around Dallas areas as shown in Fig **??**.

The distribution of the users are shown in Fig 4

### *B. Experiment Setup*

In this subsection, we apply our GSR algorithm with the measurements in a virtual city to investigate white space band impacts on power consumption. The virtual city include a downtown area, a school campus area, two urban bussiness areas and three neighborhood areas. All the areas are in the same size fit for a single WiFi cell. The white space channels has more than 3 times propagation range than WiFi channels cover all the WiFi cells. We assume residents of the city is a constant number. People move from the neighborhoods to the business area and campus in the morning and back in the late afternoon. We assume in a certain weekday all the users are at home.

The transmit power of radios are equal and with the same clean channel capacity. The standby power consumption of a radio is 50 watt and transmit power is 0.5 watt per Mbps. We lookup population distribution from the US census 2010 to calculate the users in the virtual city. We set the demand requested per user as 0.5 Mbps and assume 30% of the users will activate their device (ie. the take rate is 30) from 6:00 to 24:00. From 24:00 to 6:00, 5% of the users device keep working.

The transmit power of radios are equal and with the same clean channel capacity. The standby power consumption of a radio is 50 watt and transmit power is 0.5 watt per Mbps. We lookup population distribution from the US census 2010 to calculate the users in the virtual city. We set the demand requested per user as 1 Mbps and assume 30% of the users will activate their device (ie. the take rate is 30).

### *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. [15] In [9]. the author considered a cognitive method to avoid collision between white space communication and TV broadcasting. Many works increasing

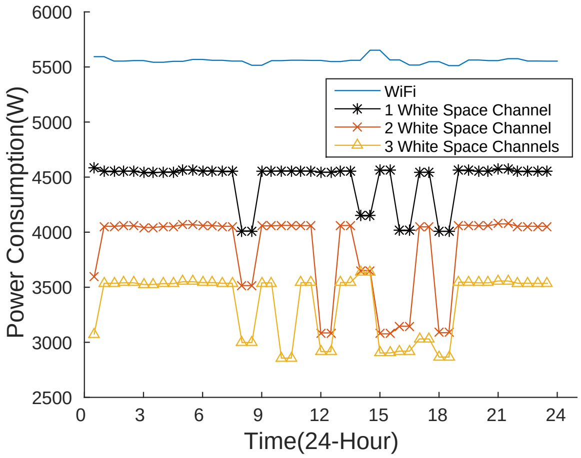


Fig. 5. Power Consumption across Time

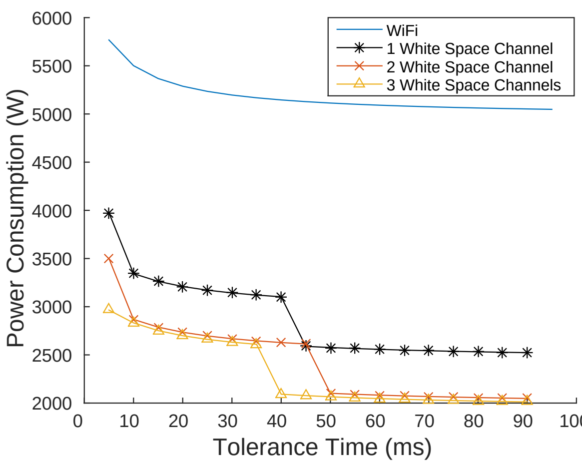


Fig. 6. Power Consumption across Delay Tolerance

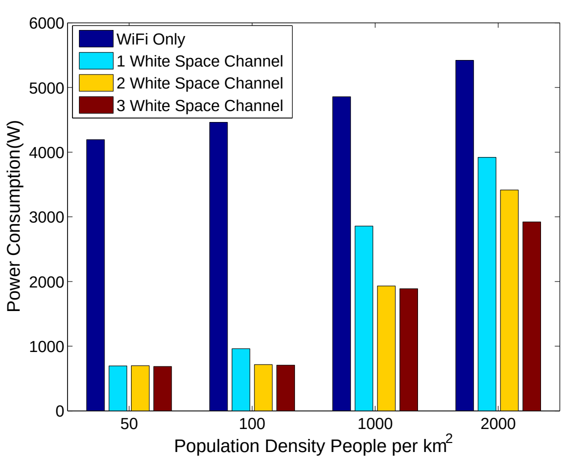


Fig. 7. Power Consumption across Population Distribution

the convenience of using white space databases have been published (e.g., Microsoft's White Space Database [16]). Google has even visualized the licensed white space channels in US cities with an API for research and commercial use [17]. Previous work discussed the point to point communication with white space bands [18], 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 [10] 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 [19], Delay-based Queue-Side-Greedy algorithm is proposed with low complexity for optimal throughput and near-optimal delay. [20] 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 work studied the multi user setting with a single channel [21]. Spectral diversity is isolated for a single user in [22]. In [23], 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. 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.

Previous works in real time systems put many efforts to minimize the resources, such as processors [24]. In [25], the author proves the capacity augmentation bounds for schedulers of parallel tasks. However, these works assume the parallel tasks have uniform servers. Previous work [8] 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.

## V. Conclusion

In this paper

## References

[1] C. A. Balanis, *Antenna theory: analysis and design*. John Wiley & Sons, 2012.
[2] Y. Gan and Y. Wu, "Multiple rayleigh fading channels modeling based on sum-of-sinusoids model," *International Journal of Communication Systems*, vol. 27, no. 11, pp. 2997–3012, 2014.
[3] Google, "Spectrum database," http://www.google.org/spectrum/whitespace/, 2013.
[4] J. B. Andersen, T. S. Rappaport, and S. Yoshida, "Propagation measurements and models for wireless communications channels," *IEEE Communications Magazine*, vol. 33, no. 1, pp. 42–49, 1995.
[5] H. T. Friis, "A note on a simple transmission formula," vol. 34, no. 5, pp. 254–256, May 1946.
[6] T. Rappaport, *Wireless Communications, Principles & Practice*. Prentice Hall, 1996.
[7] D. R. Pengfei Cui, Hui Liu and J. Camp, "A measurement study of white spaces across diverse population densities," *IEEE 10th WiNMeE*, 2014.

[8] S. Chen, A. M. Wyglinski, S. Pagadarai, R. Vuyyuru, and O. Altintas, "Feasibility analysis of vehicular dynamic spectrum access via queueing theory model," *Communications Magazine, IEEE*, vol. 49, no. 11, pp. 156–163, 2011.

[9] P. Bahl, R. Chandra, T. Moscibroda, R. Murty, and M. Welsh, "White space networking with WiFi like connectivity," *ACM SIGCOMM*, vol. 39, no. 4, pp. 27–38, 2009.

[10] S. Bodas, S. Shakkottai, L. Ying, and R. Srikant, "Low-complexity scheduling algorithms for multichannel downlink wireless networks," *Networking, IEEE/ACM Transactions on*, vol. 20, no. 5, pp. 1608–1621, 2012.

[11] S. Niida, S. Uemura, and H. Nakamura, "User tolerance for waiting time," *IEEE Vehicular Technology Magazine*, vol. 5, no. 3, pp. 61–67, 2010.

[12] P. Viswanath, D. N. C. Tse, and R. Laroia, "Opportunistic beamforming using dumb antennas," *Information Theory, IEEE Transactions on*, vol. 48, no. 6, pp. 1277–1294, 2002.

[13] S. Yu, R. Doss, T. Thapngam, and D. Qian, "A transformation model for heterogeneous servers," in *High Performance Computing and Communications, 2008. HPCC'08. 10th IEEE International Conference on*. IEEE, 2008, pp. 665–671.

[14] E. Gelenbe, G. Pujolle, and J. Nelson, *Introduction to queueing networks*. Citeseer, 1998.

[15] "Fcc white space," http://www.fcc.gov/topic/white-space, 2012.

[16] "Microsoft research white space database," http://whitespaces.cloudapp.net/Default.aspx, 2013.

[17] "Google spectrum database," http://goo.gl/NnIFXQ, 2013.

[18] P. Cui, H. Liu, J. He, O. Altintas, R. Vuyyuru, D. Rajan, and J. Camp, "Leveraging diverse propagation and context for multi-modal vehicular applications," in *IEEE WiVeC*, 2013.

[19] B. Ji, G. R. Gupta, X. Lin, and N. B. Shroff, "Performance of low-complexity greedy scheduling policies in multi-channel wireless networks: Optimal throughput and near-optimal delay," in *INFOCOM, 2013 Proceedings IEEE*. IEEE, 2013, pp. 2589–2597.

[20] L. Liu, X. Cao, Y. Cheng, L. Du, W. Song, and Y. Wang, "Energy-efficient capacity optimization in wireless networks," in *INFOCOM, 2014 Proceedings IEEE*. IEEE, 2014, pp. 1384–1392.

[21] S.-S. Tan, D. Zheng, J. Zhang, and J. Zeidler, "Distributed opportunistic scheduling for ad-hoc communications under delay constraints," in *Proceedings of the 29th conference on Information communications*. IEEE Press, 2010, pp. 2874–2882.

[22] T. Shu and M. Krunz, "Throughput-efficient sequential channel sensing and probing in cognitive radio networks under sensing errors," in *Proceedings of the 15th annual international conference on Mobile computing and networking*. ACM, 2009, pp. 37–48.

[23] Y. Liu and M. Liu, "To stay or to switch: Multiuser dynamic channel access," in *INFOCOM, 2013 Proceedings IEEE*. IEEE, 2013, pp. 1249–1257.

[24] G. Nelissen, V. Berten, J. Goossens, and D. Milojevic, "Techniques optimizing the number of processors to schedule multi-threaded tasks," in *Real-Time Systems (ECRTS), 2012 24th Euromicro Conference on*. IEEE, 2012, pp. 321–330.

[25] J. Li, J. J. Chen, K. Agrawal, C. Lu, C. Gill, and A. Saifullah, "Analysis of federated and global scheduling for parallel real-time tasks," in *Real-Time Systems (ECRTS), 2014 26th Euromicro Conference on*. IEEE, 2014, pp. 85–96.