WhiteCell: Leveraging Scant White Space Resource in Dense Area

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***Abstract*—**

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:

II. Model, Assumptions and Problem Formulation

A. Model 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]:

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

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.

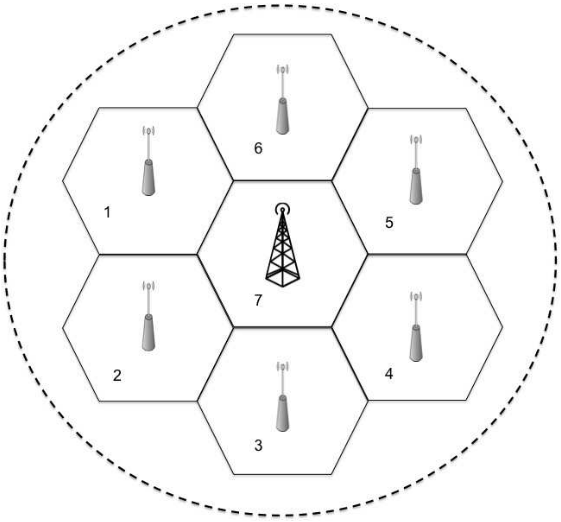

Fig. 1. White Space Model in Dense Area

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. For each user, it has $1+F_w$ channels to be scheduled, the previous WiFi channels and the new white space channels. Then the N users has the options to schedule either WiFi or the new white space channels. The channel capacity of the scheduled channels between the access points and users is noted as a matrix in Eq. 2

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

λ 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. We assume the users from the same mesh cell are in a single interference domain, so these users have to apply a time division for the WiFi channel assigned for this cell. Only one user of the system could occupy a single channel during a time slot. 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 there are enough channel resource given for the system according to worst channel capacity state $H_{i,j}^{f*}(t)$.

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. In [12], a user has a certain patience for waiting. The tolerance time varies across the traffic type, such as text information, voice information. We noted as tolerance time as μ. To simply the problem, we assume an arbitrary average value for μ for the users in the area. The user experience will be worse if the waiting time longer than μ. Another assumption is each user has B buffer store the traffic demand. The buffer is a FIFO system.

In this system, the channel capacity $H_{i,j}^{f}(t)$ is from the SNR according to Friis model and in-field measurements. We

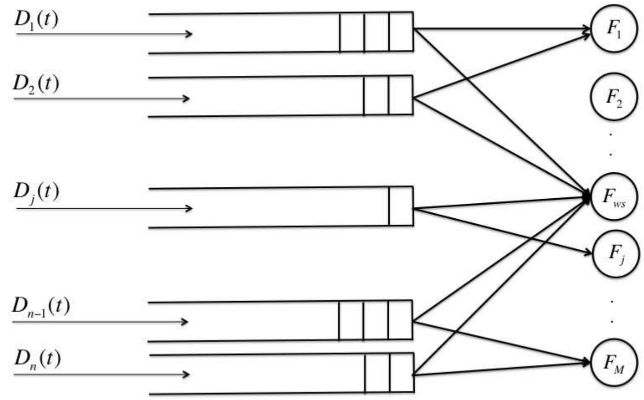

Fig. 2. System Model

consider discrete time with a suitably chosen small time unit. Users scheduled with the same channel will share the time unit through time division inside the time slot. We assume the channel capacity is flat during a time slot. We 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. We assume the user traffic during the tolerance time μ are pre-known. And the last time slot of μ has no traffic of users.

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 a 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_{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
λ	In-Field Measurements
μ	Tolerance time window

TABLE I
TABLE OF NOTATION

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 constraints will be discussed later.

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

With a schedule A, the served traffic flow of a user is the minimize value of the queue with enough channel capacity, or the remaining capacity. The condition ψ as shown in Eq. 4

$$\psi = \sum_{j=1}^{N} \gamma_j(t) \cdot A_{i,j}(t) \tag{4}$$

The served traffic flow is represented as in Eq. 5

$$\gamma_j(t) = \begin{cases} \min\limits_{j \in N}(Q_j(t), \sum\limits_{i=1}^{F_M+F_w} A_{i,j}(t) \cdot H_{i,j}(t)) & \psi \le C \\ 0 & \psi > C \end{cases} \tag{5}$$

The new arrival traffic demand $D_i(t)$ can not be served at the current time slot t. The individual queues $Q_j(t), j \in N$ at the end of the time slot t is represented as Eq. 6:

$$Q_j(t) = Q_j(t-1) + D_j(t) - \gamma_j(t) \tag{6}$$

In the system, the queue must be able to store in the buffer of user as in Eq. 7

$$Q_j(t) \le B \tag{7}$$

B is the buffer size of a user.

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. 8

$$R_i(t) = \begin{cases} 1 & \sum\limits_{j=1}^{N} A_{i,j}(t) \ge 1 \\ 0 & Otherwise \end{cases} \tag{8}$$

During the μ time slot, the system have to transfer all the data coming to and in the buffer. During the μ time slot, to minimize the power consumption is important for the carriers. The goal is represented as shown in Eq. 9:

$$R^*(t) = \min\{\sum_{t=0}^{\mu} \sum_{i=1}^{(F_M+F_w)} R_i(t)\} \tag{9}$$

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

When the total traffic demand of the users are small, one radio in white space could achieve the requirements of the users. However, as the total traffic demand increase with the number of users or the demand per user, we need to the find the feasibility of the system first. The minimize number of operating radios has to fulfill the maximize capacity of each user greater than the remaining buffer and the new coming data as shown in Eq. 10

$$\sum_{j=1}^{F_m+F_b} H_{ij}(T) \ge Q_i(T), \ i \in N \tag{10}$$

Otherwise the buffer will be overflow, and there is no feasible solution of the system.

Instead of an On-off channel, we apply a measurement based channel state estimation $H_{i,j}^{f}(t)$ in the system. The system is designed based on the worst channel state $H_{i,j}^{f*}(t)$ having enough resource for scheduling. Thus, the question is when the channel state $H_{i,j}^{f}$ is better, how many channel resource we can reduce from the system for current time slot t.

III. 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. [13] In [14]. 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 [15]). Google has even visualized the licensed white space channels in US cities with an API for research and commercial use [16]. Previous work discussed the point to point communication with white space bands [17], 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 [18] 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. [**?**] 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 [20]. In [21], the author proves the capacity augmentation bounds for schedulers of parallel tasks. However, these works assume the parallel tasks have uniform servers. In contrast, we study the performance gains of white space channel in varying channel states for a existing mesh networks in power consumption and resource requirement.

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