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 conienience 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]:

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

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.

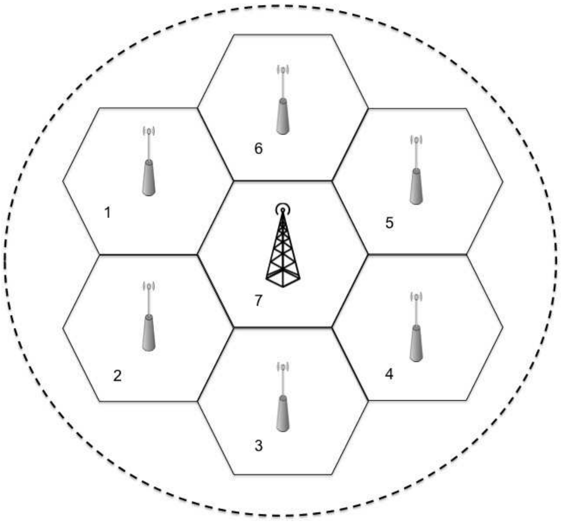

Fig. 1. White Space Model in Dense Area

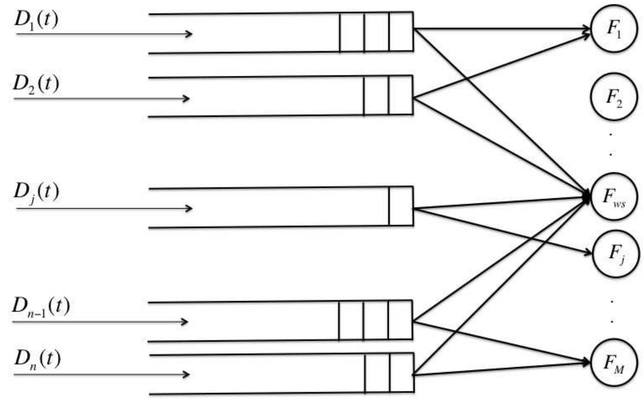

Fig. 2. System Model

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

$$H^f_{i,j}(t) = f(\lambda, t), i \in M, j \in N, f \in (1 + F_w) \qquad (2)$$

λ represents the in-field measured historical data and dynamic sensing information. We use a context-aware method to estimate the j user capacity $H^f_{i,j}(t)$ to an access point i on channel f. We assume the users from the same mesh cell are in a single interference domain, 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.

In this system, the channel capacity $H^f_{i,j}(t)$ is from the SNR according to Friis model and in-field measurements. We consider discrete time with a suitably chosen small time unit. Users scheduled with the same channel will share the time unit. We will assume the channel capacity of the channel schedule keep flat during the time unit. Each user faces F_w+1 options: schedule with the assigned WiFi channel or one of the white space channels. We assume the switching time is negligible. The traffic demand arrive at a user as a Poisson process, with the vector noted as $\boldsymbol{D} = [D_1, D_2, ...D_N]$ and the sum rate $D = \sum_{i=1}^{N} D_i$. The rate D is the aggregate rate of data generated from all users.

Each user has B buffer store the traffic demand. As discussed in [12], the tolerance time of traffic varies from text information, voice information. To address the user tolerance time, we have the waiting time constraint $\mu_j, j \in N$ based on the users traffic demand types. Through this waiting time constraint, the waiting time of a user is limited in a certain time window, which means the traffic of a user will be served during the tolerance time to satisfy the QoS requirements. We assume the buffer B is large enough to store the data during the tolerance time.

B. Problem Formulation

The previous problem is formulated as a discrete-time queuing system as shown in Fig. 2. We list each single channel for the users as a server. Table. I summarizes the notation used in this work. The 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
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
μ	Tolerance time window

TABLE I
TABLE OF NOTATION

In this system, during a time unit, the users need to schedule with an access point on a channel. 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.

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

With a schedule A, the served traffic flow of a user is the minimize value of the queue when then have enough capacity, or the remaining capacity as shown in Eq.4

$$\gamma_j(t) = \begin{cases} \min_{j \in N}(Q_j(t), \sum_{i=1}^{F_M+F_w} A_{i,j}(t) \cdot H_{i,j}(t)) & \sum_{j=1}^{N} \gamma_j(t) \cdot A_{i,j}(t) \le C \\ 0 & \sum_{j=1}^{N} \gamma_j(t) \cdot A_{i,j}(t) > C \end{cases} \qquad (4)$$

The individual queues $Q_j(t), j \in N$ at the end of the time slot t is represented as Eq. 5:

$$Q_j(t) = Q_j(t-1) + D_j(t) - \gamma_j(t) \tag{5}$$

The total transmission time must be smaller than the tolerance time.

$$\sum_{t^*}^{t^*+\mu_j} \gamma_j(t^*) \geq Q(t^*) + D(t^*), j \in N \tag{6}$$

μ_j is the tolerance time of each 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. 7

$$R_i(t) = \begin{cases} 1 & \sum_{j=1}^{N} A_{i,j}(t) \geq 1 \\ 0 & Otherwise \end{cases} \tag{7}$$

The goal is to minimize the channel resource required as shown in Eq. 8:

$$\xi = \min\{\sum_{t}^{t+T} \sum_{i}^{(F_M+F_w)} R_i(t)\} \tag{8}$$

T noted the duration time slots to reduce the resource utilization.

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