# Achieving Fair Spectrum Allocation for Co-Existing Heterogeneous Secondary User Networks

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***Abstract*—The rapid growth of mobile network traffic has posed a serious challenge to the limited spectrum. The United States Federal Communications Commission (FCC) allowed the utilization of unused TV White Space (TVWS) by unlicensed secondary users (SUs). Particularly, the IEEE 802.19.1 standard is proposed to regulate the coexistence of dissimilar or independently operated SU networks and devices on the TV band. In this paper, we propose a fair spectrum allocation scheme for co-existing SU networks under the IEEE 802.19.1 system architecture. The entire heterogeneous wireless system is divided into two levels, and the spectrum allocation is formulated into a four-stage problem. Unlike previous allocation schemes that maximize the aggregated throughput, the aim of our scheme is to maximize the end user satisfactions within each SU network while maintaining fairness among and within the SU networks. Extensive simulations demonstrate the effectiveness of our spectrum allocation scheme.**

***Index Terms*—Spectrum allocation; fairness; TV white space**

## I. INTRODUCTION

TV White Spaces are frequencies in a particular location at a particular time period that are not being used by licensed services, such as digital television broadcasting. Radio signals at these TV frequencies have two prominent characteristics: a long range and a better penetration ability. Several regulators around the world have been working on the development of new standards that enable unlicensed access to these frequencies, subject to the proviso that primary users (PUs) are not adversely affected. By allowing TV Band Devices (TVBDs) to access these white space frequencies, a more effective and efficient use of the radio spectrum can be envisioned. These standardization efforts include ECMA 392 Wireless Personal Area Network (WPAN) over TVWS [1], IEEE 802.11af Wireless Local Area Network (WLANs) over TVWS [2], IEEE 802.15.4m Local and Metropolitan Area Networks over TVWS [3], IEEE 802.22 Wireless Regional Area Networks (WRAN) over TVWS [4], etc. When multiple wireless networks attempt to share the same spectrum band in the same area, their coexistence may lead to a huge imbalance of bandwidth gain and collisions because (1) the difference in spectrum access design gives them an inherent advantage/disadvantage when competing with each other; (2) networks operated by independent entities cannot communicate to coordinate their access.

IEEE 802.19.1 standard (Wireless Coexistence in the TV White Space) [5] aims to enable the family of IEEE 802 Wireless Standards to most effectively use TVWS by providing radio access technology-independent coexistence methods among dissimilar or independently operated SU networks and dissimilar TVBDs. The architecture of the IEEE 802.19.1 system is shown in Fig. 1, which contains three logical entities: the coexistence discovery and information server (CDIS), the coexistence manager (CM), and the coexistence enabler (CE). The CDIS offers neighbor discovery service, collects and provides coexistence-related control information (CCI) to the CMs. The CMs are the local decision makers for the coexistence; they generate and provide corresponding coexistence requests/commands and control information to CEs. The CEs request and obtain information required for coexistence from SU networks (e.g. via access points or base stations), and serve as the communication interface between the 802.19.1 system and the co-existing SU networks. For simplicity, we will use the general term AP to refer to both the access point in WLANs and the base station in cellular networks. The CDIS is connected to the TVWS database to obtain the information of PUs (and available channels) via backhaul connections. The CM and CE can both be deployed inside the SU network. We assume that the AP is integrated with CM and CE, hence can communicate with CDIS. During the spectrum allocation process, the CDIS will collect and exchange the CCI for all SU networks. Based on the CCI obtained from the CDIS, SU networks make the spectrum utilization decision autonomously. As the frequent exchange of the CCI increases the system overhead, it has to be lightweight, but effective in coordinating the SU networks. Additionally, the CCI cannot contain detailed information that may expose end user privacy.

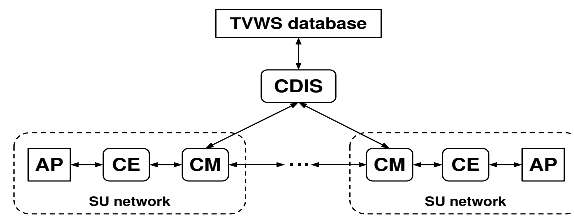



Fig. 1. IEEE 802.19.1 System Architecture

In this paper, we study the coexistence of heterogeneous SU networks in TVWS. By extending the structure of the IEEE 802.19.1 system, we build a two-level system model, in which we take end users into consideration. The spectrum sharing problem is divided into four stages, and we propose a fair and effective spectrum allocation scheme which considers the fairness at both the SU network-level and the end user-level.

Our local allocation algorithm can be used to strike a balance between the end user satisfaction in terms of bandwidth requirements and the fairness. The proposed spectrum allocation scheme is evaluated with extensive simulations.

Our main contributions are listed as follows:

- We study the fair spectrum allocation in TVWS based on the generalized 802.19.1 system architecture, which means that our scheme can be applied to all types of co-existing SU networks.
- Our allocation scheme is semi-distributed, in which SU networks autonomously decide their own spectrum utilization schedules. No end user information is leaked to entities outside the SU network.
- Our model considers the multiple network associations that support simultaneous data transmissions, and the various channel conditions which lead to different data rates over different channels.
- Unlike previous allocation schemes that aim to maximize the aggregated throughput (while meeting fairness constraints), our scheme maximizes the end user satisfactions within each SU network while maintaining fairness among and within SU networks.

## II. Motivation and Related Work

As proposed by IEEE 802.19.1 standard, a group of SU networks may share the same frequency band in TVWS. Given a collection of spectrum requests from co-existing SU networks, a fair spectrum allocation scheme should be able to partition the operational frequencies for the competing SU networks while ensuring fairness. Bian et al. [6] propose the Symbiotic Heterogeneous coexistence ArchitectuRE (SHARE) upon 802.19.1 system, in which the spectrum share of each SU network is proportional to its bandwidth demand and is adjusted by using the interspecific competition process. Bahrak et al. [7] formulate the coexistence decision making in 802.19.1 compliant system as a multi-objective combinatorial optimization problem. Similarly, the spectrum allocation is considered fair if the ratio of the amount of allocated spectrum to the spectrum demand for each of the co-existing networks is the same. Other research [8]–[10] specifically studies the coexistence between LTE and WiFi networks. However, these works only study the SU network-level spectrum partition, while the ultimate goal is to provide better Internet service to end users. Hence, end users should be involved in the spectrum allocation process. Our work proposes a two-level framework, and studies the spectrum allocation at both the SU network-level and the end user-level. Regarding the end user fairness, Cano et. al [11] allocate an equal amount of resources (e.g. channel access time) to all end users. Khalil et. al [12] propose to maximize the minimum bandwidth gain. Hajmohammad et. al [13] consider the average capacity ratio among end users. We assume the knowledge of end user bandwidth demands like [6] [7], and use end user satisfaction as the fairness metric. However, channels are treated identically in [6] [7], and their allocation is counted by the total quantity of channels assigned to each SU network. Instead, we consider the variance of channel conditions, which will result in distinct data rates for links over different channels. Inspired by the technology of concurrent wireless network connections, our model considers that end users may be connected with multiple APs simultaneously for data transmission (detailed in Section III-A).

Other works [14]–[18] have studied the fair client-AP association (two-level) problem in homogeneous wireless networks. The two common fairness metrics adopted are max-min fairness and proportional fairness. The approximation algorithms in [14] provide close to optimal load balancing among APs and max-min fair bandwidth allocation among users. However, the max-min time fairness used in [14] is intended for single-rate WLANs, with no respect to channel condition and diversity. The max-min fairness can lead to a significant sacrifice in aggregate throughput in multi-rate WLANs [15] [16]. Meanwhile, several optimal centralized AP association schemes have been proposed to maximize the aggregate throughput while maintaining proportional fairness among end users in multi-rate WLANs [16]–[18] and cellular networks [15]. Our model under IEEE 802.19.1 system framework differs from these works in four major aspects:

- Semi-distributed scheme: previous works formulate the spectrum allocation into an association optimization problem, in which end users follow the centralized management. However, it is difficult to find a trusted third-party central scheduler who has access to the sensitive information of each specific end user (e.g., traffic load, bandwidth demand). Therefore, we propose a semi-distributed spectrum allocation scheme, in which the CDIS collects and exchanges the coexistence-related information of SU networks (instead of end users), while each individual SU network autonomously determines the spectrum utilization schedule. Synchronization is required, which can be conveniently provided by CDIS to all SU networks. No information of end users is leaked to the CDIS or into other SU networks. End users have to make the association decision on their own.
- Multiple association: the "Multiple Access Point Association" in recent work [17] allows multiple WLANs to collaboratively serve one single end user. Its technical foundation is MultiNet [19], a software-based approach that enables simultaneous connections to multiple WiFi networks by virtualizing a single wireless card. In their simultaneous connections model, only one WLAN can conduct data transmission at a time. Instead, our work consider multiple associations with different types of networks, in which concurrent data transmissions are supported.
- Fairness: these works focus on the fairness among end users within the homogeneous wireless networks, while we study the co-existing heterogeneous SU networks. In our context, we also need to maintain fairness among different SU networks, since they have equal right of access to the TVWS spectrum. Instead, the fairness of end users is handled locally within the SU network, as the bandwidth requests of end users are not available globally (i.e. to CDIS and other

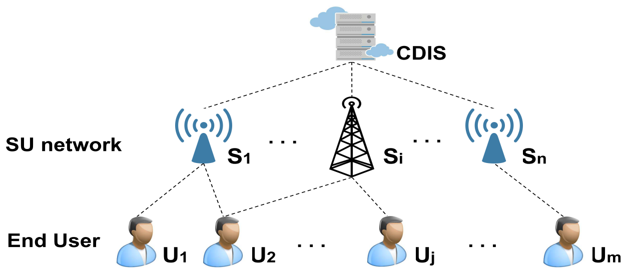



Fig. 2. Architecture of the Heterogeneous System

SU networks).

- System objective: the existing works allocate spectrum to end users in proportion to their data rates, and aim to maximize the aggregate throughput. In our model, we assume that the amount of bandwidth demand of end users are known (as in [6] [7]). This means that end users can make a request for the exact amount of bandwidth to meet their quality of service (QoS) requirement, and SU networks can accordingly make a request for channels based on the needs of associated end users. Therefore, our goal becomes to achieve a high level of end users satisfaction in terms of their bandwidth demands.

## III. System Overview

### A. Association with Multiple SU Networks

Inspired by the novel technologies that enable mobile devices to join different types of networks simultaneously, our model considers concurrent data transmissions over multiple networks. The iOS 7 published in 2013 started to support Mutlipath TCP (MPTCP) [20]–[22], in which a backup TCP connection over cellular data is established alongside the primary TCP connection over WiFi. Although concurrent TCP connections can ensure a continuous TCP data transmission without re-connection gap, the cellular data connection is used only when the WiFi connection becomes unavailable. The Android smartphone Samsung Galaxy S5 released in 2014 came up with download booster technology [23], which combines the WiFi connection and LTE connection to finish one download task. It uses a dual IP stack connection over WiFi and LTE that allows packets to be split up and delivered by both connections simultaneously. This is a pioneer demonstration of integrating different kinds of network technologies for simultaneous transmissions, and it inspires us to model and study the heterogeneous network system in TVWS, where end users can have multiple associations and concurrent data transmissions over different types of SU networks.

### B. System Model

We consider a set of $n$ heterogeneous SU networks $S$ scattered over a large area, each with one AP and belonging to one of the $p$ types of networks (e.g. WiFi, LTE, etc.). For any two SU networks $i$ and $i'$, $p_{ii'}$ is the binary variable that indicates whether they are of the same type: $p_{ii'} = 1$ for the same kind of networks; otherwise, $p_{ii'} = 0$. The co-existing SU networks are operating on TVWS. Let $C$ be the set of $c$ channels of TVWS band. The end users need to be associated

TABLE I
Notations

| Symbol | Description |
|---|---|
| $S$ | Set of all SU networks |
| $n$ | Number of SU networks $n = \|S\|$ |
| $C$ | Set of available channels in TVWS |
| $c$ | Number of available channels $c = \|C\|$ |
| $U$ | Set of all end users |
| $m$ | Number of end users $m = \|U\|$ |
| $r_{ij}^k$ | Data rate between SU network $i$ and user $j$ on channel $k$ |
| $t_{ij}^k$ | Occupancy time of channel $k$ by user $j$ via SU network $i$ |
| $b_{ij}^k$ | Bandwidth achieved by user $j$ via SU network $i$ on channel $k$ |
| $x_{ij}^k$ | Association status of user $j$ to SU network $i$ on channel $k$ |
| $B_j^R$ | Total amount of bandwidth demanded by end user $j$ |
| $B_j^A$ | Total amount of bandwidth achieved by end user $j$ |
| $S_j$ | The set of associated SU networks of end user $j$ |
| $y_j$ | The satisfaction variable of end user $j$ |
| $U_i$ | The set of associated end users of SU network $i$ |
| $B_{ij}^R$ | The total bandwidth request from user $j$ to SU network $i$ |
| $R_{ik}^s$ | The fraction of channel $k$ requested by SU network $i$ |
| $R_{ijk}^u$ | The fraction of channel $k$ intended for user $j$ in SU network $i$ |
| $A_{ik}^s$ | The fraction of channel $k$ allocated to SU network $i$ |
| $A_{ijk}^u$ | The fraction of channel $k$ allocated to user $j$ in SU network $i$ |
| $y_{ij}$ | The satisfaction variable of the bandwidth request from user $j$ to SU network $i$ |
| $\epsilon$ | The variance threshold of user satisfactions within SU network |
| $f_{ik}$ | The fairness value of SU network $i$ on channel $k$ |

with SU networks in order to get Internet or cellular data services. We assume there are a set of $m$ end users $U$, each can be subscribed to multiple SU networks. If the bandwidth requirement can be fulfilled by a single SU network, the end user will only connect to that one SU network; otherwise, an end user may split the large bandwidth demand into several parts and send to selected SU networks respectively. Fig. 2 gives an illustration of our two-level system model: on the upper level, CDIS collects and exchanges information for all SU networks; on the lower level, end users are connected to (multiple) SU networks for Internet or cellular data services. Table I summarizes the notations.

The data rate varies for different links due to several factors, including transmission power, channel condition, modulation scheme, etc. Although the transmission power and modulation scheme can be fixed for a given pair of end users and APs, we consider the diversity of channel conditions. In our multi-rate model, each AP may serve the associated end users with distinct data rates over different channels. Let $r_{ij}^k$ indicate the downlink rate from SU network $i$ to end user $j$ on channel $k$. The value of $r_{ij}^k$ is non-zero if user $j$ is a subscriber of SU network $i$ and $j$ is located inside the communication range of $i$. Otherwise, the $r_{ij}^k$ value would be zero. We assume data rate $r_{ij}^k$ is available to SU networks and end users as in previous works [16]–[18]. For example, the data rate can be estimated through measurements of the channel condition. As the end users could move around and the SU networks may be replaced or reconfigured over time, the data rates $r_{ij}^k$ are updated periodically. The SU networks provide services to end users in rounds. The duration of each round is denoted by $T$, which equals the unit time for simplicity. $t_{ij}^k$ is the transmission time given to end user $j$ by SU network $i$ on channel $k$ ($t_{ij}^k \leq T$). Then, the actual bandwidth achieved by user $j$ via SU network $i$ over channel $k$ can be denoted as $b_{ij}^k = r_{ij}^k \times t_{ij}^k$. In a given round, one channel can be shared in time division multiple access (TDMA) manner by end users from multiple SU networks. Alternatively, we may also view the channels (instead of the time) as divisible. For example, $b_{ij}^k$ can be interpreted as the bandwidth achieved by end user $j$ via SU network $i$ for unit time $T$ over $b_{ij}^k / r_{ij}^k$ fraction of the channel $k$. We define the association binary variable $x_{ij}^k$ to indicate the association status between SU network $i$ and end user $j$ over channel $k$. $x_{ij}^k$ equals 1 if associated; otherwise, $x_{ij}^k$ is 0.

For each end user $j$, let $B_j^R$ and $B_j^A$ be the total amount of bandwidth demand and the bandwidth actually achieved, respectively. The set of user $j$'s associated SU networks is $S_j = \{i | x_{ij}^k = 1, k \in C\}$. We use satisfaction variable $y_j$ to reflect the degree to which the bandwidth demand of end user $j$ is satisfied. Similarly, we define variable $y_{ij}$ to be the satisfaction of the partial bandwidth request of end user $j$ to SU network $i$.

For each SU network $i$, the set of associated end users is $U_i = \{j | x_{ij}^k = 1, k \in C\}$. The amount of channel request of SU network $i$ on a given channel $k$ is $R_{ik}^s$. $R_{ijk}^u$ is the fraction of channel $k$ expected by one of its associated end user $j$, so we have $R_{ik}^s = \sum_{j \in U_i} R_{ijk}^u$. After CDIS has received the channel requests of all SU networks, it will share the information among them. Then, SU networks determine their own share on each channel in terms of the access time and order. To avoid collision, the access of SU networks must follow a certain order, which could be the sequence number of SU networks. Let $A_{ik}^s$ be the fraction of channel $k$ that is actually allocated to SU network $i$. The sum of fractional allocation of channel $k$ must follow $\sum_{i \in S} A_{ik}^s \leq 1$. $A_{ijk}^u$ is the fraction of channel $k$ allocated to end user $j$ through SU network $i$, $A_{ik}^s = \sum_{j \in U_i} A_{ijk}^u$.

## IV. Problem Formulation

We formulate the two-level spectrum allocation issue into three optimization problems. The goal of the upper level is to keep the fairness of spectrum allocation among co-existing SU networks; on the lower level, the goal is to maximize the total end user satisfaction locally within the SU networks with the minimal total channel utilization, while maintaining fairness among associated end users by constraining the variance of user satisfaction values to be lower than a given threshold.

The whole channel allocation process includes four stages: the first stage allows end users to select the SU networks to associate with, and partitions the total bandwidth demands for each of the selected SU networks respectively; in the second stage, each SU network performs the channel utilization planning under the lower-level goal to determine the requests on each specific channel. The planning minimizes the total amount of channel usage to increase the channel utilization efficiency; in the third stage, each SU network decides the actual (fraction of) channels to take autonomously, based on the channel requests of all SU networks. If the total demands for a given channel is larger than 1, the SU networks will compete for that channel following the fairness policy. The actual quantity of channels allocated may be less than the planning; in the last stage, the SU networks allocate the (fractional) channels in possession to the associated end users under the lower-level goal.

### A. Distributed Association Strategy for End Users

In our model, each individual end user wants to achieve the highest satisfaction, but there may be several subscribed SU networks and links available to choose that can satisfy its bandwidth requirement. The dominating association strategy in real-world wireless systems is based on signal strength; this is because an AP with stronger signal can provide a higher bit rate. We adopt a modified version of this strategy to support multiple associations: each end user prefers to be associated with the SU network(s) over certain channels that are able to achieve the highest data rates, to best satisfy its bandwidth demand. From the system perspective, this allows the bandwidth demands to be satisfied with the minimum amount of spectrum usage, and the saved spectrum can be used for other starving end users.

Notice that in order to avoid association conflict and the co-channel interference caused by multiple associations, we must ensure that the selected links (1) are not directing to any two networks of the same type (e.g. a phone cannot transmit data via two LTE or WiFi networks simultaneously); (2) are not using a common channel (e.g. a phone cannot transmit data via two networks over the same channel simultaneously, or they will interfere with each other). In other words, only two kinds of simultaneous transmissions are acceptable: (1) using links directed to the same SU network over different channels, i.e. $i = i', k \neq k'$; (2) using links directed to different types of SU networks over different channels, i.e. $p_{ii'} = 0, k \neq k'$. Each time an end user $j$ wants to select a link for association, it needs to perform the compatibility checking with all previously selected links to eliminate association conflict and co-channel interference. The checking is passed only if that link is compatible with all selected links, then it can be added for association.

The general idea of our multiple association strategy is: for each individual end user $j$, first sort the data rate of all available links to subscribed SU networks over channels $C$ in decreasing order, then select the minimum number of compatible links with the highest data rates and whose total throughput in one round can meet the bandwidth requirement of that end user. Suppose the top $N$ links are selected, the end user $j$ can split the bandwidth demand $B_j^R$ into $N$ parts, each of which is a partial bandwidth request corresponding to one of the $N$ links. The requests over the first $N-1$ links are in the amount of $r_{ij}^k \times T = r_{ij}^k$, which is the throughput achieved through network $i$ on channel $k$ for an entire round (unit time). The bandwidth request over the $N$th link covers the rest of (i.e. unsatisfied) bandwidth demand. Hence, the sum of separate bandwidth requests is exactly the quantity of the total bandwidth demand of that user $j$. If $j$'s demand is huge, all

**Algorithm 1** The Distributed Association (DA) Algorithm

**Input:** Parameters $B_j^R, r_{ij}^k$;
**Output:** Parameters $x_{ij}^k, S_j, B_{ij}^R$;

**Initialize** $x_{ij}^k$ to zero, $\forall i \in S$, $\forall j \in U$, $\forall k \in C$
  $S_j$ to empty set, $\forall j \in U$
  $B_{ij}^R$ to zero, $\forall i \in S$, $\forall j \in U$
**for** each end user j **do**
  Sort the data rate $r_{ij}^k$ between user $j$ and all subscribed SU networks $S$ over all channels $C$ in decreasing order;
  Mark the sorted $r_{ij}^k$ with its sequence number $a$;
  **for** $a = 1$ to $nc$ **do**
    **if** $CC(r_{ij}^k(a), r_{i'j}^{k'}) = true, \forall i', k'$ with $x_{i'j}^{k'} = 1$ **then**
      **if** $B_j^R > 0$ && $r_{ij}^k(a) > B_j^R$ **then**
        $x_{ij}^k = 1$;
        add $i$ into $S_j$ if $i \notin S_j$;
        $B_{ij}^R = B_{ij}^R + B_j^R$; $B_j^R = 0$;
      **else if** $B_j^R > 0$ && $0 < r_{ij}^k(a) \leq B_j^R$ **then**
        $x_{ij}^k = 1$;
        add $i$ into $S_j$ if $i \notin S_j$;
        $B_{ij}^R = B_{ij}^R + r_{ij}^k(a)$; $B_j^R = B_j^R - r_{ij}^k(a)$;
      **else**
        break;

available links will be selected. Note that there may be requests to the same SU network $i$ by a given end user $j$ over multiple channels; these requests are added up and sent as one combined request $B_{ij}^R$. The distributed association (DA) algorithm for end users to select the SU networks and channels to associate with is described in Algorithm 1. Every end user executes the DA algorithm to determine the links to connect, and the quantity of bandwidth request $B_{ij}^R$ sent to the respective associated SU networks.

### *B. Channel Utilization Planning of SU Networks*

In this stage, each SU network collects bandwidth requests from associated end users, then reports the channel requests over all channels to CDIS. The conversion from the bandwidth requests of end user to the channel requests of the SU network is achieved by channel utilization planning. For every SU network $i$, channel utilization planning is used to calculate the quantity of each channel it needs (i.e. channel request $R_{ik}^s$).

Our goal on the lower level is to maximize the total user satisfaction within an SU network at the minimal total spectrum usage, while maintaining fairness in regards to the discrepancy of satisfaction levels among the associated end users. Previous works [16]–[18] have proposed centralized user association and channel allocation schemes to maximize the aggregate throughput while ensuring proportional fairness, in which associated end users on the same channel share the access time equally so that the bandwidth is in proportion to the data rate. However, end users with relatively low data rates may get starved, and those with the lowest data rate cannot even be associated under their goal of maximizing total throughput. In contrast, the maximization of total user satisfaction is set as the objective in our scheme. The satisfaction value can directly reflect the extent to which the bandwidth requests of associated end users are satisfied, so that channel resources will not be wasted on users who have already been served with the requested bandwidth. We maintain fairness by constraining the variance of end user satisfactions to be less than or equal to a given threshold $\varepsilon$. This constraint can guarantee that no user is "ignored". Additionally, a balance can be easily controlled between overall user satisfaction and the fairness level by adjusting the fairness threshold $\varepsilon$. We use the weighted-sum method and $\varepsilon$-constraints method in multi-objective optimization to formulate the channel utilization planning scheme below (program 1):

$$\begin{aligned}
\underset{R_{ik}^s}{\text{maximize}} \quad & w_1 \sum_{\forall j \in U_i} y_{ij} - w_2 \sum_{\forall k \in C} R_{ik}^s \\
\text{subject to} \quad & \mathrm{Var}(y_{ij}) \leq \varepsilon_1 \\
& y_{ij} = \frac{\sum_{k \in C} r_{ij}^k \times R_{ijk}^u}{B_{ij}^R}, \quad \forall j \in U_i \\
& y_{ij} \leq 1, \quad j \in U_i \\
& \sum_{j \in U_i} R_{ijk}^u \leq 1, \quad \forall k \in C \\
& R_{ijk}^u \geq 0, \quad \forall j \in U_i, \forall k \in C \\
& R_{ik}^s = \sum_{j \in U_i} R_{ijk}^u, \quad \forall k \in C
\end{aligned} \tag{1}$$

The objective is to maximize the sum of end user satisfaction values $\sum_{\forall j \in U_i} y_{ij}$ for each SU network $i$ with minimal total channel usage/request $\sum_{\forall k \in C} R_{ik}^s$. We put the total channel requests into the objective function because there could be multiple solutions that can achieve the maximum user satisfaction while satisfying variance constraint. One particular case example is when channel resources are sufficient and all user satisfaction value is 1. If the channel requests are not considered, users may be assigned to low data rate channels and unnecessarily consumes more channel resources. However, the weighted sum method used here does not convert the two objectives into one type. In fact, the exact values of the weights $w_1$ and $w_2$ are irrelevant. We only need to ensure that $w_1$ is much greater than $w_2$, so that the objective on user satisfaction is relatively more important than the objective on channel usage.

The first constraint controls the fairness by restricting the variance of user satisfaction $\mathrm{Var}(y_{ij})$ within a given threshold $\varepsilon_1$. The parameter $\varepsilon_1$ can be used to adjust the maximum tolerable discrepancy of satisfaction among associated end users. The second constraint is the expression of calculating user satisfaction. For a given end user $j$, the bandwidth request to SU network $i$ is $B_{ij}^R$. The total bandwidth that can be achieved equals the sum of the bandwidth achieved over all channels, $\sum_{k \in C} r_{ij}^k \times R_{ijk}^u$. The $R_{ijk}^u$ is the expected occupation time of channel $k$ by user $j$ via SU network $i$, which can also be interpreted as the fraction of channel $k$ that is intended for user $j$. Note that the calculation of $y_{ij}$ here only reflects the expected satisfaction level of partial bandwidth demand $B_{ij}^R$, if user $j$ is associated to multiple SU networks. The third constraint limits the satisfaction value of each user $j$ under SU network $i$ to be no more than 1, as no extra channel resource is allocated once the bandwidth request is met. The fourth constraint restricts the total utilization time of each channel to be less than or equal to 1 (unit time) in each round; otherwise, it will cause co-channel interference. The fifth constraint limits the utilization time $R^u_{ijk}$ of channel $k$ by a single user $j$ via SU network $i$ to be non-negative. The last equation shows that the channel request of each SU network $i$ on channel $k$ equals to the sum of the shares of all associated end users.

### C. Fair Channel Allocation among SU Networks

We consider the fairness of spectrum utilization among co-existing SU networks. In the TVWS spectrum, all competitors are secondary users with equal access to available channels. The fairness can be evaluated by comparing the spectrum share of the SU networks to their channel requests. When there are sufficient spectrum resources, all SU networks get the amount of channels requested. All SU networks are treated equally well and fairness is ensured. However, when channel resources are not enough to meet all requests, some of the SU networks must be left unsatisfied. To preserve fairness, we must guarantee that dissatisfaction is even among all SU networks.

Taking the difference of channel conditions into consideration, we define a channel-level fairness metric named fairness value for each SU network, to represent the level to which a channel request is satisfied. The fairness value is maintained by combining historical records, especially previous rounds in which the channel request is not satisfied. Specifically, we use the variable $f^t_{ik}$ to quantify the proportion of channel request $R^s_{ik}$ satisfied by the allocated amount of channel $A^s_{ik}$ at the current round $r$ on channel $k$.

$$f^r_{ik} = \frac{A^s_{ik}}{R^s_{ik}}, \forall i \in S, \forall k \in C$$

Note that $0 \leq f^r_{ik} \leq 1$, which means that the allocated fraction of channel will not exceed the amount requested. The fairness value is accumulated (multiplied) in rounds. We use $f_{ik}$ to denote the overall fairness value up to the current round on channel $k$.

$$f_{ik} = \prod_{t=1}^{r} f^t_{ik}, \forall i \in S, \forall k \in C$$

Our goal in the upper level is to maintain fairness among all requesting SU networks on each channel. For each SU network, the CCI uploaded to the CDIS and exchanged among SU networks include its channel request $R^s_{ik}$ and the fairness value of the most recently ended round $\hat{f_{ik}}$ on all requested channels. Meanwhile, they receive the CCI of other competing SU networks on each requested channel. The channel allocation is performed on every channel based on CCI, which generates a per-channel access schedule and an updated fairness value $f_{ik}$ for all relevant SU networks. The variance of the fairness values can be used to measure the fairness among competing SU networks on each channel. We formulate the fair spectrum allocation among SU networks as the following program 2:

$$\begin{aligned} \underset{A^s_{ik}}{\text{minimize}} \quad & \text{Var}(f_{ik}) \\ \text{subject to} \quad & \sum_{i \in S} A^s_{ik} = min\{\sum_{i \in S} R^s_{ik}, 1\} \\ & 0 < A^s_{ik} \leq R^s_{ik}, \quad \forall i \in S \\ & f_{ik} = \frac{A^s_{ik}}{R^s_{ik}} \times \hat{f_{ik}}, \quad \forall i \in S \end{aligned} \tag{2}$$

The objective is to minimize the variance of the fairness values $f_{ik}$ of SU networks that are in need of (a fraction of) channel $k \in C$. The first constraint sets the total amount of allocated channels $\sum_{i \in S} A^s_{ik}$ to the smaller value of $\sum_{i \in S} R^s_{ik}$ and 1; if there are sufficient channel resources for allocation, each requesting SU network is allocated with the exact amount of channel demanded, so the total allocated fraction of channel $\sum_{i \in S} A^s_{ik}$ equals to the sum of channel requests $\sum_{i \in S} R^s_{ik}$; otherwise, the entire channel $k$ will be allocated. The second constraint limits the range of allocated fraction of a channel to be between zero and the amount requested. The last equation is the expression to calculate the new fairness value. $\hat{f_{ik}}$ is the fairness value of SU network $i$ on channel $k$ in the last round.

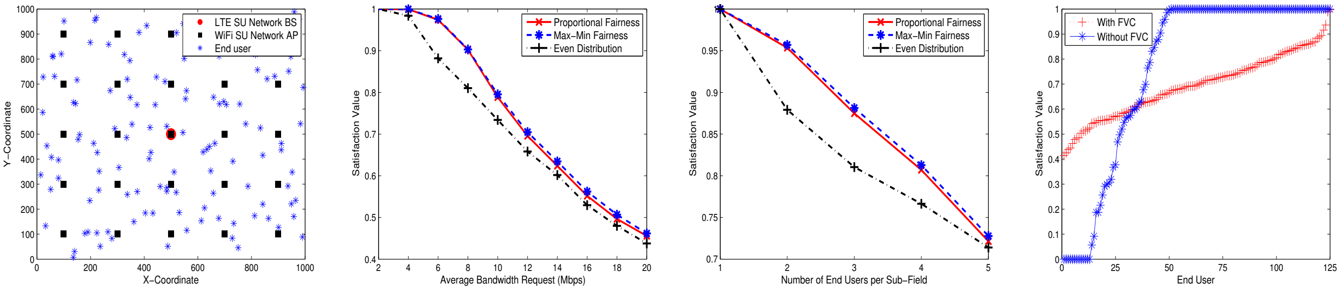
Each SU network solves the above optimization autonomously, and obtains a channel utilization schedule over each channel. Since all competing SU networks receive the identical last-round fairness values and channel requests information, they will get an agreed channel allocation schedule in terms of the utilization time and order (e.g. the access order can follow the pre-defined sequence number of SU networks). On each given channel, SU networks possess the channel following the order for the length of time allocated, therefore the co-channel interference can be completely mitigated.

### D. Actual Channel Allocation within SU Networks

After the SU networks obtain the utilization schedule of requested channels, they will continue to allocate and schedule their channel resources to associated end users in a centralized manner under the lower-level goal. The actual channel allocation within SU networks can be formulated into the following program 3, which is similar to the optimization in stage two.

$$\begin{aligned} \underset{A^u_{ijk}}{\text{maximize}} \quad & \sum_{\forall j \in U_i} y_{ij} \\ \text{subject to} \quad & \text{Var}(y_{ij}) \leq \varepsilon_2 \\ & y_{ij} = \frac{\sum_{k \in C} r^k_{ij} \times A^u_{ijk}}{B^R_{ij}}, \quad \forall j \in U_i \\ & y_{ij} \leq 1, \quad j \in U_i \\ & \sum_{j \in U_i} A^u_{ijk} \leq A^s_{ik}, \quad \forall k \in C \\ & A^u_{ijk} \geq 0, \quad \forall j \in U_i, \forall k \in C \end{aligned} \tag{3}$$

The objective is still to maximize the sum of end user satisfaction values in each SU network $i$. It is not necessary to add channel demands as an objective here since the fraction




(a) Sample Deployment (b) Impact of Bandwidth Request (c) Impact of End User Density (d) Impact of FVC

Fig. 3. Performance Evaluation in Uniform Deployment Scenario

of channels allocated to each SU are less than or equal to the expected (requested) amount, and no waste of spectrum resources would happen. The first constraint restricts the variance of user satisfaction $\mathrm{Var}(y_{ij})$ to be within a given threshold $\varepsilon_2$. The second equation is the expression used to calculate end user satisfaction. $A^u_{ijk}$ is the fraction of channel $k$ allocated to user $j$ through SU network $i$. The satisfaction value $y_{ij}$ equals the ratio of the total achieved bandwidth over all channels $\sum_{k\in C} r^k_{ij} A^u_{ijk}$, to the requested bandwidth $B^R_{ij}$. The third constraint limits the satisfaction value of end users to be no more than 1 as the allocated channel resources will not exceed the requested amount. The fourth constraint restricts the sum of channel shares assigned to end users to be less than or equal to $A^s_{ik}$. The last constraint guarantees that the channel share of each associated user $A^u_{ijk}$ is non-negative.

The above optimization is solved by each SU network during the actual channel allocation stage. Again, $y_{ij}$ only evaluates the satisfaction of the partial bandwidth requests from end user $j$ to SU network $i$. For user $j$ with multiple associations, the total bandwidth achieved is $B^A_j = \sum_{i\in S_j}\sum_{k\in C} r^k_{ij} A^u_{ijk}$. Hence, the overall satisfaction value of end user $j$ is

$$y_j = \begin{cases} 1, \text{ if } B^A_j = B^R_j \text{ (satisfied);} \\ \frac{B^A_j}{B^R_j}, \text{ otherwise (not satisfied).} \end{cases}$$

## V. Evaluation

Our channel allocation scheme contains four stages: end user association, channel utilization planning, fair channel allocation among, and within SU networks. In the first stage, association via links with the highest data rates is widely used in real wireless communication systems. It is also the best option for our distributed decision making design, since the association choice of external end users are unknown (user-specific information like data rates are kept local). In stages two and four, we maintain fairness among end users within SU networks by enforcing constraint to the variance of user satisfaction values. In the third stage, we propose a historical and constrained proportional fair allocation scheme for channel allocation among SU networks. To evaluate the performance of our allocation scheme in terms of average user satisfaction, we compare the following fairness algorithms:

- The constrained proportional fairness algorithm in our scheme. When the variance thresholds are set to 0, it becomes the general proportional fairness algorithm.
- Max-min fairness algorithm. Max-min fairness considers the discrepancy in demands. Those SU networks that intrinsically demand fewer resources than others are prioritized to access the resources.
- Even distribution. If spectrum resource is sufficient, all SU networks obtain the channels demanded. But when there are more demands than resources available, the channels are equally given to requesting SU networks.

We use the Gurobi Optimizer [24] to solve our formulated programs 1, 2 and 3. All the results presented are averaged over 10 simulation runs.

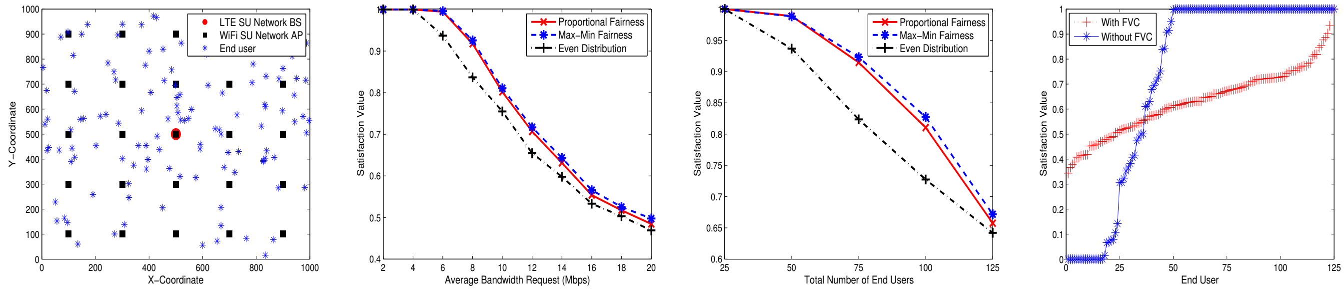
### A. Simulation Setup

We consider a simple heterogeneous wireless system composed of only WiFi and LTE SU networks in our experiments. A total of 26 SU networks are deployed in a 1 km×1 km area including 1 LTE BS and 25 WiFi APs. The whole area can be partitioned into 25 200m×200m sub-fields. The LTE BS is placed at the center of the area and the 25 WiFi APs are placed at the center of the 25 sub-fields, respectively. We test two kinds of end user deployments in stationary scenarios: uniform deployment and random deployment. The difference is that in the uniform deployment scenario, end users are evenly divided into 25 groups, each located in one sub-field. Figs. 3(a) and 4(a) present the sample deployment of the two scenarios.

In the United States, the abandoned television frequencies are primarily in the upper UHF "700-megahertz" band, covering TV channels 52 to 69 (698 to 806 MHz). The total number of channels used in our simulation is 18, each with 6 MHz bandwidth (assumption for experiments).

### B. Empirical Data Rate

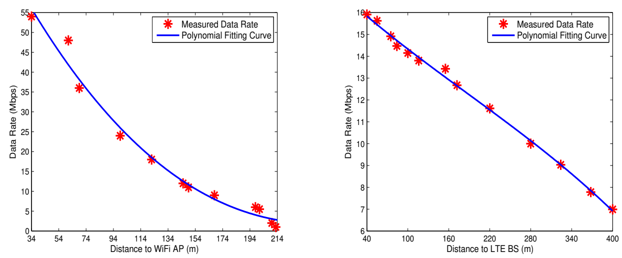
Since the data rates are assumed to be available in our model, we directly use the empirical physical data rate of WiFi and LTE SU networks (as in [14] [16]). We adopt the specification commonly advised by WiFi AP vendors [25], and the data rates measured in real-world LTE cellular systems [26]. The $(data\,rate,\ distance\,to\,AP)$ value pairs adopted are processed with polynomial curve fitting, and the derived polynomial coefficients can be used to calculate an approximate value of the data rate given a distance to AP. Figs. 5(a) and 5(b) are the




(a) Sample Deployment (b) Impact of Bandwidth Request (c) Impact of End User Density (d) Impact of FVC

Fig. 4. Performance Evaluation in Random Deployment Scenario

polynomial functions of WiFi and LTE data rate obtained by curve fitting.




(a) WiFi Data Rate to Distance (b) LTE Data Rate to Distance

Fig. 5. Polynomial Fitting Curve of WiFi and LTE Data Rate

We also consider the variance of channel conditions which result in multi-rate links between a pair of APs and end users over different channels. We model the change of data rate caused by channel conditions using a factor $\alpha$. Let $r_0$ be the original data rate, then the actual achieved data rate becomes $r = r_0(1 + \alpha)$. The value of $\alpha$ is uniformly distributed within [-0.25, 0.25].

## C. Performance Evaluation in Stationary Scenarios

We evaluate the performance of the three fairness algorithms by comparing the average end user satisfaction values. Figs. 3(b) and 4(b) illustrate the impact of end user total bandwidth requests. The bandwidth requests are in poisson distribution, with the mean parameter equal to 2, 4, ..., 20 Mbps. We also study the influence of end user density to end user satisfaction, the results are presented in Figs. 3(c) and 4(c). In the uniform deployment scenario, the user density refers to the number of users in each sub-field. In the random deployment scenario, the user density reflects the total number of users in the whole area. The mean parameter of end user bandwidth requests is set to 8 Mbps. These experiments are conducted for 25 rounds per simulation run. The fairness variance thresholds $\epsilon_1$ and $\epsilon_2$ are usually the same, here we denote them with $\epsilon$, and set it to 0.01.

As shown in these figures, both our constrained proportional fairness and the max-min fairness perform better than the even distribution algorithm in both deployment scenarios. The max-min fairness achieves a slightly larger average user satisfaction rate than our proportional fairness because SU networks are assigned different priorities of access to channel resources (i.e. SU networks with lower demand receive higher priority). However, we argue that it is not proper to use max-min fairness for SU networks because some SU networks intrinsically receive more traffic passing through than others (e.g. public networks and large enterprise networks). Such SU networks may suffer significantly poor end user satisfaction when the total bandwidth demands are too much to fulfill. In contrast, our constrained proportional fairness can guarantee that all SU networks share the resource shortage in proportion to respective demands.

It can also be observed that the performance of the even distribution scheme is very close to the other two fair allocation schemes not only when channel resources are abundant, but also when they are in great shortage. This is because almost no channel wasting can occur if there are too many bandwidth demands left unsatisfied (e.g. every end user has used up the allocated channel resource).

## D. Effect of Fairness Variance Constraint

To maintain fairness within each SU network, we enforce the fairness variance constraint (FVC) among associated end users. The FVC is used to constrain the discrepancy of end user satisfactions in an acceptable threshold. The experiments are conducted in both of the stationary deployment scenarios with a total of 125 end users. The end user bandwidth requests are in poisson distribution with a mean parameter of 8 Mbps. The results are depicted in Figs. 3(d) and 4(d), respectively. In the figures, the end users are sorted in an increasing order of their satisfaction values. As we can see, almost all end users with poor satisfactions are better off when FVC is applied, while the accompanying loss in satisfaction happens primarily to those with high satisfactions. The mean satisfaction value and standard deviation of satisfaction are listed in Table II. In both deployment scenarios, the usage of FVC can increase fairness among end users at the cost of degrading the overall satisfaction level. We test different $\epsilon$ values to illustrate the balance between overall user satisfaction and fairness.

Our scheme can only ensure the satisfaction variance to be lower than the threshold $\epsilon$ within a given SU network. Meanwhile, end user may be associated to multiple SU networks and the overall satisfaction variance could be larger than $\epsilon$. For example, when the variance threshold $\epsilon$ enforced equals 0.01

TABLE II
EFFECT OF FVC ON END USER SATISFACTION

| | Uniform Deployment | | Random Deployment | |
|---|---|---|---|---|
| | Mean | Std | Mean | Std |
| Without FVC | 0.7628 | 0.3671 | 0.7180 | 0.3741 |
| FVC ($\epsilon = 0.1$) | 0.7481 | 0.3153 | 0.6968 | 0.3240 |
| FVC ($\epsilon = 0.01$) | 0.6914 | 0.1325 | 0.6443 | 0.1401 |
| FVC ($\epsilon = 0.001$) | 0.6688 | 0.0856 | 0.6085 | 0.1088 |

(which means the standard deviation threshold is $\sqrt{\epsilon} = 0.1$), the overall standard deviations in the two deployment scenarios are actually 0.1325 and 0.1401 (both larger than 0.1). Even so, the experimental results show that local FVC can also effectively reduce the overall variance of end user satisfaction.

TABLE III
PARAMETERS IN MOBILITY MODEL

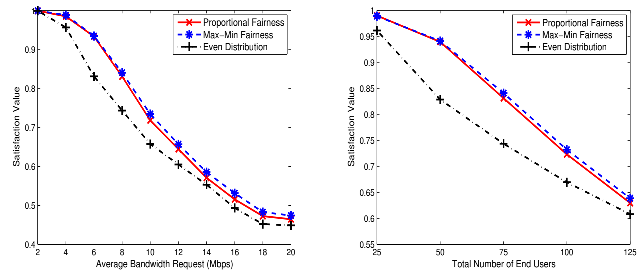
| Parameters | Values |
|---|---|
| X and Y Position Interval | [0, 1000] m |
| Speed Interval | [0, 25] m/round |
| Pause Time Interval | [0, 1] round |
| Simulation Time | 50 rounds |

### *E. Performance Evaluation in Mobile Scenarios*

We also evaluate the performance of the three fairness algorithms in mobile scenarios. At the beginning, mobile end users are randomly scattered over the area. Then, we apply the random way point model to simulate the mobility of end users. The parameters used are listed in Table III. We evaluate the three fairness algorithms with different amounts of end user bandwidth requests and user densities, using the same experimental settings as in stationary scenarios. The results are presented in Figs. 6(a) and 6(b), respectively. Similar to stationary scenarios, the performance of our proportional fairness algorithm and max-min algorithm are very close, and both are better than the even distribution algorithm.

## VI. CONCLUSIONS

In this paper, we presented a two-level coexistence model for heterogeneous secondary user networks sharing the TVWS spectrum. Unlike previous allocation schemes that maximize the aggregated throughput, our new model takes end users into consideration including their bandwidth demands and multiple associations. Our scheme is able to maximize the end user satisfactions within each SU network while maintaining fairness among and within the SU networks. The spectrum allocation is formulated into four stages, namely the association stage, utilization planning stage, and channel allocation stages on the upper level and lower level respectively. On the upper level, the fairness among co-existing SU networks is maintained in historical manner; on the lower level, the user satisfaction is maximized subject to a certain level of fairness among associated end users. Extensive simulations are conducted to evaluate the performance of our spectrum allocation scheme.




(a) Impact of Bandwidth Request (b) Impact of End User Density

Fig. 6. Performance Evaluation in Mobile Scenario

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