WINET: Indoor White Space Network Design

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***Abstract*—The Federal Communications Commission (FCC) released the final rule to approve of TV white spaces (TVWS), *i.e.*, locally vacant TV channels, for unlicensed use in 2010. This TV spectrum will mitigate the shortage of wireless spectrum resources and provide opportunities for new applications. TVWS differ from the conventional Wi-Fi spectrum in three aspects: spectrum fragmentation, spatial variation, and temporal variation. These differences make the network design over TVWS challenging and fundamentally different from Wi-Fi networks. While most prior works on TVWS network design focused on outdoor large-area scenario, the important indoor scenario is largely open for investigation.**

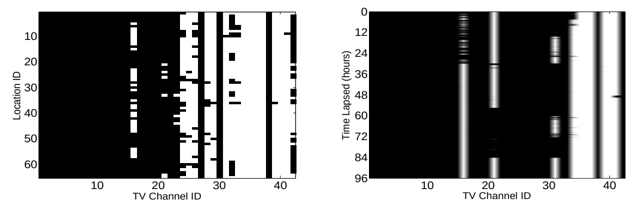
In this paper, we present WINET (for White-space Indoor NETwork), the first design framework for indoor multi-AP white space network. We optimize AP placement, spectrum allocation, and AP association. Spectrum fragmentation, spatial variation, and temporal variation are all tackled in our network design. We build a test-bed and conduct extensive measurements inside an office building across four months to obtain real-world traces. Experimental results show that WINET can increase AP coverage area by an average of 62.2% and obtain 67.9% higher system throughput while achieving fairness among users as compared to alternative approaches.

I. Introduction

The skyrocketing growth of mobile devices and applications has triggered the need for additional wireless spectrum. However, most of the spectrum has been licensed for the privileged users (TV, satellite, celluar, *etc.*). According to a spectrum measurement report [1] by the FCC, most of these licensed spectrum is significantly underutilized. Dynamic Spectrum Access (DSA) is therefore proposed as a potential technology to exploit the inefficiently utilized licensed spectrum without harmful interference to the incumbents, thus mitigating the spectrum scarcity.

A recent application of DSA is in the TV spectrum. On November 4, 2008, the FCC passed a historic ruling to allow unlicensed use of TVWS [2]. On September 23, 2010, the FCC released the final rule for unlicensed operation in the TV bands [3]. The term "TVWS" (or simply white spaces) is used by the FCC to represent the locally unoccupied TV channels located in the VHF and UHF bands [4]. To utilize the TVWS is of great potential for satisfying the increasing demand for wireless spectrum. Moreover, the radio signals in TV spectrum travel farther and penetrate obstacles more effectively than those in the cellular and Wi-Fi ISM bands owing to the lower frequency [5]. Thus using TVWS for communication can bring us some better services, such as providing wireless broadband connectivity for rural areas.

The FCC requires that the unlicensed devices must not interfere with the incumbents and should query a geo-location database to obtain the white space availability. Therefore, for the wireless communication over TVWS, two questions need to be answered, *i.e.,* how to identify TVWS and how to design wireless network over TVWS. We remark that designing TVWS networks is fundamentally different from that for Wi-Fi networks. Compared with Wi-Fi spectrum, TVWS have the characteristics of spectrum fragmentation, spatial variation, and temporal variation. The reason why TVWS are fragmented and have temporal variation is that the FCC mandates non-interference with incumbents who can occupy any portion of TVWS at any time [3]. For the spatial variation, this characteristic exists not only across a wide area due to the distribution of TV transmitters, but also on smaller scales because of severe signal attenuation caused by the indoor obstructions and construction materials. As shown in Figure 1(a), TVWS are not contiguous and vary from one location to another. In addition, TVWS at a given location may change over time as shown in Figure 1(b). These differences make the wireless network design over TVWS challenging and fundamentally different from Wi-Fi networks.



(a) Typical spatial map of white spaces [10]. (b) Typical temporal map of white spaces [10].

Fig. 1: We conduct measurements at 65 indoor locations to obtain the spatial map and a 96-hour continuous measurement at a given indoor location to get the temporal map. White spaces are denoted in white; occupied channels are denoted in black.

Most prior works on TVWS have focused on accurately detecting incumbents and enhancing the geo-location database [6]-[9]. Recently, more works have focused on designing white space network for practical use. [11] established a single wireless link between TV transmitters and users. [12] built a single AP white space network WhiteFi in a campus. [13] extended the study of [12] to a multi-AP white space network WhiteNet. However, their proposed TVWS networks all focus on outdoor large-area scenario. Since 70% of traffic demand comes from indoor environments [17] and there are significantly more TVWS in indoors than those in outdoors [10], it is important to investigate the indoor white space networking issues. So far, research on indoor white spaces is limited to [10], in which a system WISER is proposed to effectively identify and track the indoor TVWS, while there is no work on indoor white

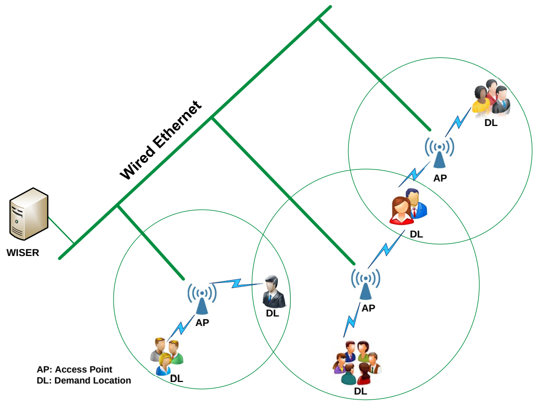


Fig. 2: System Architecture of WINET.

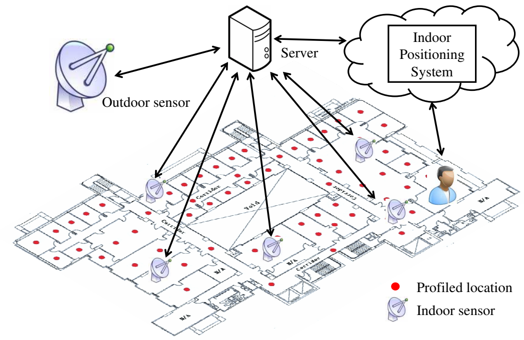


Fig. 3: Architecture of WISER [10].

space network design yet. The fundamental difference between outdoor and indoor TVWS networks is that outdoor TVWS networks usually focus on a large-area scenario and follow the IEEE 802.22 standard [14], while indoor TVWS networks follow the IEEE 802.11af standard [15]. These two standards have very different considerations at almost all levels in the protocol stack [16]. Thus there are big differences between the outdoor and indoor white space network design. For example, designing an actual white space network requires us to characterize the capacity region of the network with unsaturated traffics over random access MAC-layer protocol. The capacity regions are fundamentally different for outdoor and indoor TVWS networks since the outdoor TVWS networks adopt TDMA-like MAC, while indoor TVWS networks are expected to use CSMA. TABLE I summarizes the existing works on TVWS identification and network design.

TABLE I: Existing Works on TVWS

	Identification	Medium Access	Network Design
Outdoor	[6]-[9]	[11]-[12]	[11]-[13]
Indoor	WISER [10]	IEEE 802.11af	This work

Besides, [11]-[13] did not consider the optimization of AP placement in white space network design and [11] ignored the spatial and temporal variation of TVWS. To fill in these gaps, in this paper, we propose WINET, the first design framework for indoor multi-AP white space network with optimized performance. We make the following contributions:

- In Section III-B, we optimize AP placement, spectrum allocation, and AP association in our design. To the best of our knowledge, this is the first work to optimize AP placement in TVWS network design, jointly tackling all three indoor TVWS characteristics, *i.e.*, spectrum fragmentation, spatial variation, and temporal variation. Our experiments based on real-world traces in Section IV-B justify the benefit of performing AP-placement optimization in our design, which was missing in the literature.
- Solving our formulated problem for realistic scenarios requires us to characterize capacity region for a TVWS network with unsaturated traffics over random access MAC-layer protocol, which is a challenging task. We leverage a recent result from [21] to establish an explicit characterization for our indoor TVWS network. It is known that obtaining the capacity region is NP-hard, and we further show that even if the region can be obtained in polynomial time, our formulated indoor white space network design problem is still NP-complete. This observation reveals the inherent challenges of designing optimal indoor multi-AP TVWS networks. Fortunately, in practice, the size of the problem for indoor network design is usually small and thus one can use standard solvers to solve the formulated problem and obtain optimal solutions for AP placement, spectrum allocation, and AP association.
- In Section IV, we carry out extensive measurements across four months inside a typical office building to obtain real-world traces. Evaluation results show that WINET can increase AP coverage area by an average of 62.2% and obtain 67.9% higher system throughput while achieving fairness among users as compared to alternative approaches.

II. System Architecture and Design Challenges

A. System Architecture

As described in Section I, we only focus on the indoor scenario, such as an office building. The indoor TVWS network architecture we adopt has an infrastructure based network topology, as shown in Figure 2. This architecture consists of three key components: an indoor white space identification system WISER, APs, and demand locations. WISER is originally proposed by Ying and Zhang in [10] to efficiently identify indoor TV white spaces. In our system, each demand location can have multiple client devices. All APs and client devices are equipped with multiple cognitive radios, which enables a client device to communicate with the AP using multiple channels simultaneously.

The reason why we adopt WISER to do indoor white space identification instead of the traditional geo-location database is two-fold. First, the geo-location database approach is used for outdoor scenario. This approach uses signal propagation modeling to determine the white space availability and does not consider the obstructions in the modeling. However, there are many construction materials and obstructions in indoor scenario. Hence, this approach is very conservative in the white spaces it reports for a given location and does not apply to indoor scenario. Second, as a comparison, WISER has shown its capability and efficiency in indoor white space identification in [10], which can identify 30-50% more indoor white spaces as compared to alternative approaches. Therefore, in our indoor TVWS network design, we use WISER to obtain and track the indoor white space availability. Since WISER is described in detail in [10], we just briefly outline its architecture and function. Figure 3 shows the architecture of WISER. WISER consists of three components: indoor positioning system, white space database, and real-time sensing module. Indoor positioning system is used to determine users' locations. White space database records the indoor white space availability. Real-time sensing module collects real-time signal strengths of all TV channels at different locations and reports the sensed results to white space database. WISER takes users' locations as the inputs, and outputs the indoor white space availability at the given locations. By querying WISER, we can obtain the white spaces at different indoor locations.

For our proposed indoor TVWS network system WINET, multiple APs are provided to cover all demand locations. And all APs are connected to the wired ethernet network as shown in Figure 2. Similar to Wi-Fi APs, one white space AP can have multiple associated demand locations. In IEEE 802.11af standard [15], CSMA is expected to be used as the MAC protocol. Therefore, in this work, we adopt CSMA/CA protocol for medium access control.

B. Design Challenges

To design such an indoor multi-AP white space network as shown in Figure 2, we need to address three main challenges: AP placement, spectrum allocation, and AP association.

The first challenge is how to do AP placement. AP placement plays a key role in the indoor multi-AP white space network design, and it is constrained by the indoor structure of the buildings. Optimizing AP placement can largely increase AP coverage area and system throughput, and achieve fairness among users, which has been extensively investigated and verified in the Wi-Fi networks [18] [19]. Therefore, it is also important to optimize AP placement in the multi-AP white space network design. The following observations make AP placement challenging. (1) It is hard to figure out the optimum number of APs that should be installed. On one hand, if the number is small, perhaps some demand locations cannot be covered by the APs. On the other hand, if the number is large, the interference among APs might be severe since the APs become dense. Consequently, the network performance will be degraded. (2) It is challenging to determine the optimum locations of the APs. In the conventional Wi-Fi networks, all locations are the same in terms of the channel availability. However, in white space network, we need to consider the spatial and temporal variation of TVWS when determining the locations for the APs. In a word, the number and locations for the APs should be carefully designed.

The second challenge comes from spectrum allocation. (1) An AP cannot naively select channels solely based on its local white space availability. The white space availability at its associated demand locations should also be taken into account due to the spatial variation of white spaces. (2) The TVWS might be fragmented because of the presence of incumbents. To fully utilize the white spaces, one AP may be assigned multiple non-contiguous TV channels rather than just one, which makes spectrum allocation more challenging compared with Wi-Fi networks. (3) As radio signals have different propagation properties under different TV channels, different channels have different interference ranges. As a result, the interference relationship among APs should be significantly various for different TV channels. (4) The spectrum allocated to the AP changes over time due to the temporal variation of white spaces. Therefore it is challenging to do spectrum allocation.

The third challenge is how to associate demand locations with APs. In Wi-Fi networks, users do not need to consider the channels allocated to the APs when deciding which AP to associate with. This is because all channels located in the Wi-Fi spectrum are free at everywhere. However, for the white space network, due to the spatial variation, a user should associate with the AP that has common white spaces with the user location. Besides, the associated AP for each user might change over time due to the temporal variation of white spaces.

III. System Model and Problem Formulation

In this section, we start with our system model and then formulate the indoor multi-AP white space network design problem. Our network design has two phases. At phase I, we figure out the optimal AP placement. At phase II, we conduct spectrum allocation and AP association based on the optimal AP placement.

A. System Model

TABLE II: Key Notations

Notation	Definition
S	Number of AP candidate locations
T	Number of demand locations
R	Number of TV channels
$\overrightarrow{loc^a}$	Set of AP candidate location IDs. $\overrightarrow{loc^a} = \{1, 2, ..., S\}$
$\overrightarrow{loc^d}$	Set of demand location IDs. $\overrightarrow{loc^d} = \{1, 2, ..., T\}$
d_t	Average traffic demand for demand location t
$\mathbb{W}_{(S+T)\times R}$	White space map
$\mathbb{C}_{S\times T\times R}$	Link capacity map
N	Number of offered APs
B	The maximal downlink traffic rate for each AP
$\mathbb{A}_{S\times T\times R}$	AP-Demand association map
$\mathbb{X}_{S\times T\times R}$	Link throughput map

To design the indoor multi-AP white space network, we have the following information in our system model. On the AP's side, we have S AP candidate locations and N APs. AP candidate locations mean the candidate installation locations for the APs. The set of AP candidate locations is $\overrightarrow{loc^a}$. The maximal downlink traffic rate for each AP is B, which is constrained by the network deployment requirements. On the user's side, we have T demand locations. Each demand location may have multiple client devices. The set of demand locations is $\overrightarrow{loc^d}$. The average traffic demand for demand location t is d_t. The number of TV channels is R. To represent the white space availability at all AP candidate locations and demand locations, we define a $(S+T)$ by R matrix $\mathbb{W}_{(S+T)\times R}$ as follows:

$$\mathbb{W}_{ij} = \begin{cases} 1 & \text{if TV channel } j \text{ is vacant at location } i \\ 0 & \text{otherwise} \end{cases}$$

The white space map $\mathbb{W}$ characterizes the spectrum fragmentation and spatial variation of white spaces.

The link capacity map $\mathbb{C}_{S\times T\times R}$ gives the traffic capacity for all possible links in the network. $\mathbb{C}_{str} > 0$ if and only if the following two conditions are true. First, TV channel r is the common vacant channel at both AP candidate location s and demand location t (*i.e.*, $\mathbb{W}_{sr} \times \mathbb{W}_{(S+t)r} > 0$). Second, if we place an AP at AP candidate location s, then this AP can cover demand location t on channel r. Otherwise, $\mathbb{C}_{str} = 0$. Therefore, we can use this capacity map to characterize the coverage relationship between APs and demand locations. Let l_{str} represent the link that the AP at AP candidate location s transmits to demand location t on channel r. When we measure $\mathbb{C}_{str}$, we assume that only link l_{str} exists in the network. Since $\mathbb{C}_{S\times T\times R}$ may change with $\mathbb{W}$, in Section III-B, we use $\mathbb{C}^j_{str}$ to denote the capacity map under the white space map at day j.

For the above parameters, $S, T, \overrightarrow{loc^a}$, and $\overrightarrow{loc^d}$ can be obtained by wireless site survey [20], R is a known number that may vary in different regions, $\mathbb{W}$ can be obtained by querying the indoor white space identification system WISER, and $\mathbb{C}$ can be figured out by ground-truth measurements, while B can be specified based on the network deployment requirements.

To represent the AP installation locations, AP allocated spectrum, and AP association relationship, we define a matrix $\mathbb{A}_{S\times T\times R}$ as follows:

$$\mathbb{A}_{str} = \begin{cases} 1, & \text{if } s \text{ and } t \text{ communicate on channel } r \\ 0, & \text{otherwise} \end{cases}$$

The meaning of $\mathbb{A}_{str}$ is three-fold. First, $\mathbb{A}_{str} = 1$ means that an AP is installed at AP candidate location s. Second, $\mathbb{A}_{str} = 1$ represents that channel r is allocated to the AP at AP candidate location s. Third, $\mathbb{A}_{str} = 1$ describes that the AP at AP candidate location s communicates with demand location t on channel r.

$\mathbb{X}_{str}$ is the estimated actual throughput for link l_{str}. In our network design, we consider the realistic scenario that requires us to characterize the capacity region of our white space network with unsaturated traffics. The link throughput $\mathbb{X}_{str}$ should be within this capacity region. Details on obtaining the capacity region is described in Section III-C.

B. Problem Formulation

In this subsection, we illustrate our indoor TVWS network design by describing how we conduct AP placement, spectrum allocation, and AP association. We divide the network design into two phases. At phase I, our objective is to figure out the optimal AP placement. To achieve this goal, we first carry out one-week TV spectrum measurement for the target building to get the indoor white space map over this week. Using the one-week indoor white space map as the input, we traverse all possible AP placement strategies to find the optimal AP placement that can achieve the best performance over this week. Thereafter, at phase II, we place APs based on the optimal AP placement obtained at phase I, and conduct spectrum allocation and AP association using current white space map. We elaborate on these two phases in the following.

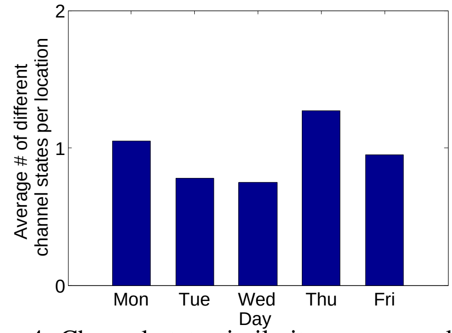


Fig. 4: Channel state similarity across weeks.

Phase I: AP Placement. Let $I = \{i_s | i_s \in \{0, 1\}, 1 \le s \le S\}$ denote a binary vector, representing the AP placement strategy. $i_s = 1$ if and only if an AP is placed at AP candidate location s. The AP placement strategy needs to satisfy $\sum_s i_s \le N$ since we only have N APs. With the objective of **M**aximizing the average **D**emand **F**airness over one week, finding the optimal AP placement strategy I^* can be formulated as the following optimization problem (**MDF**):

$$I^* = \underset{I}{\text{argmax}} \ \frac{1}{D} \sum_{j=1}^{D} \alpha_I^j \quad (1)$$

where D is the number of days in one week, and α_I^j is the demand fairness under AP placement strategy I and white space map at day j. α_I^j is the optimal value of the following **S**pectrum allocation and **AP** association problem (**SAP**). The objective of this SAP problem is to determine the optimal spectrum allocation and AP association given AP placement strategy I, using white space map at day j as the input. The SAP problem is defined as follows:

$$\max \ \alpha_I^j \quad (2)$$

$$\text{s.t.} \quad \max_{t,r} \mathbb{A}_{str} = \mathbf{1}_{\{i_s=1\}}, \forall s \in \overrightarrow{loc^a} \quad (3)$$

$$\sum_s \max_r \mathbb{A}_{str} = 1, \forall t \in \overrightarrow{loc^d} \quad (4)$$

$$\sum_s \sum_r \mathbb{A}_{str} \cdot \mathbb{X}_{str} \ge \alpha_I^j \cdot d_t, \forall t \in \overrightarrow{loc^d} \quad (5)$$

$$\sum_t \sum_r \mathbb{A}_{str} \cdot \mathbb{X}_{str} \le B, \forall s \in \overrightarrow{loc^a} \quad (6)$$

$$\mathbb{A}_{str} \le \mathbf{1}_{\{\mathbb{C}^j_{str}>0\}} \quad (7)$$

$$\mathbb{A}_{str} = \mathbf{1}_{\{\mathbb{X}_{str}>0\}} \quad (8)$$

$$\mathbb{X}_{str} \in CR_I^j \quad (9)$$

The objective (2) is to maximize the demand fairness for a given AP placement strategy I while using the white space map at day j as the input. By maximizing demand fairness α_I^j, we aim to distribute the throughput fairly to all demand locations. $\alpha_I^j > 1$ means that we can provide the demand locations more traffic than that they need. $\alpha_I^j < 1$ means that the demand locations' traffics decrease proportionally as compared to their traffic demands.

Constraint (3) characterizes the AP placement strategy I. $\mathbf{1}_{\{.\}}$ is the indicator function. Constraint (4) states that each demand location should associate with an AP. Constraint (5) maintains fairness by guaranteeing that each demand location must receive at least its fair share of throughput. Demand locations with higher traffic demand get a proportionally larger share of the throughput. Constraint (6) describes that the total traffic rate of all demand locations associated with the same AP should not exceed the maximal downlink traffic rate B provided by this AP. Constraint (7) denotes that if an AP is installed at AP candidate location s and this AP communicates with demand location t on channel r, then the traffic capacity for link l_{str} should be larger than 0. Constraint (8) characterizes the mapping between $\mathbb{A}_{str}$ and $\mathbb{X}_{str}$. Since $\mathbb{X}_{str}$ represents the link throughput for l_{str}, if $\mathbb{X}_{str} > 0$, then the link l_{str} must exist ($\mathbb{A}_{str} = 1$). If $\mathbb{X}_{str} = 0$, then the link l_{str} does not exist ($\mathbb{A}_{str} = 0$). Constraint (9) means that the actual throughput for all links should be within the capacity region. Since the capacity region may change under different AP placement strategies and different white space maps, we use CR_I^j to denote the capacity region under the AP placement strategy I and white space map $\mathbb{W}$ at day j. Details on obtaining the capacity region are discussed in Section III-C.

Phase II: Spectrum Allocation and AP Association. After obtaining the optimal AP placement strategy I^* at phase I, we place APs according to I^* and fix the AP locations ever since. Then we conduct spectrum allocation and AP association based on current white space map and the SAP formulation.

The reason why we separate AP placement from spectrum allocation and AP association, and fix the AP locations is two-fold. First, if we jointly perform AP placement, spectrum allocation, and AP allocation, AP placement will be changed frequently due to the temporal variation of TVWS. However, frequent change of AP placement will cause much inconvenience to the system deployment and is not allowed in practice. Second, we conduct extensive TV spectrum measurements across four months inside a typical office building and obtain the corresponding indoor white space map. Based on the measurement results shown in Figure 4, we observe that there exists strong similarity in indoor white space availability patterns across different weeks for any measurement location. For example, on average, there is only about 0.8 channel state difference on different week's Tuesday at each measurement location. Channel state is either 1 (occupied) or 0 (vacant). We think the reason is that the TV programs are usually broadcasted on a weekly basis. Therefore, the usage patterns of TV channels should be stable across different weeks. This observation indicates that it is sufficient to determine the AP placement using one-week measurement data. And we do not need to change the AP placement in the following weeks. [1]

For the indoor TVWS network design, we determine the optimal AP placement by considering the temporal variation of TVWS over one week. We allocate fragmented TVWS to APs and allow channel reuse, which can improve the spectrum utilization. Moreover, whenever the white space map changes, we will redo spectrum allocation and AP association based on the SAP formulation, to guarantee non-interference with incumbents and maximize the system performance. Therefore, our system WINET is powerful and unique in the way it addresses the indoor TVWS network design challenges described in Section II-B.

[1]Currently we are building an actual TVWS identification system inside an office building and will extend it to other types of buildings, to obtain long-term large-scale measurement results to further validate our observations.

Algorithm 1: Calculating the Capacity Region

1 Find all links l_{str} that exist in the network based on the AP placement strategy and white space map;
2 Calculate θ_{str} for all links;
3 **for** *each channel* r **do**
4   Find all the independent sets for channel r;
5   Calculate the steady-state probability for all independent sets based on equation (10) and (11);
6   Calculate the throughput for all links l_{str} based on equation (12);
7   Impose the constraint $0 \leq \rho_{str} < 1$;

C. Capacity Region

In this subsection, we characterize the capacity region of our indoor multi-AP white space network. According to the IEEE 802.11af standard [15], CSMA/CA-like protocol will be used in the MAC layer of WLAN over TVWS. Based on this observation, we carry out the capacity region analysis based on CSMA/CA protocol.

Capacity region analysis of CSMA/CA networks has attracted a lot of attention in the past years. Most prior works focus on the scenario of saturated traffics. That is, a wireless link always has data to transmit when it is active. However, the traffics are unsaturated (*i.e.*, a link may not have data to transmit even it is active) in realistic settings, including the scenario that we consider in this paper. To this end, the authors in [21] proposed a model for analyzing the capacity region of unsaturated single-hop links in CSMA/CA wireless network in which not all links are within the carrier-sense range. Since in our indoor TVWS scenario, there are only one-hop traffics (from AP to its associated demand locations) and not all links are within the carrier-sense range, we adopt the model from [21] for our analysis.

There are multiple channels in our white space network. In the following, we describe how we compute the capacity region for each channel. In CSMA/CA networks, several links may transmit simultaneously if they cannot hear from each other. We use S to denote the set of links being able to transmit simultaneously, which is called "independent set". S can be obtained by real-world measurements. We model the network state as the independent set. We use π_S to represent the fraction of time that the network is in state S, and $\pi_\emptyset$ to represent the fraction of time that no link is transmitting. By using the result in [21], the steady-state probabilities for all independent sets can be derived as follows:

$$\pi_\emptyset = \frac{1}{\sum_K \prod_{l_{str} \in K} \rho_{str}\theta_{str}} \tag{10}$$

$$\pi_S = \frac{\prod_{l_{str} \in S} \rho_{str}\theta_{str}}{\sum_K \prod_{l_{str} \in K} \rho_{str}\theta_{str}} \tag{11}$$

where K is the independent set, ρ_{str} is the fraction of backoff time when no link is transmitting, θ_{str} is the ratio between the expected transmission time and the expected backoff time for link l_{str}. Let $Th_{\text{single link}}$ be the throughput of an isolated link. Like 802.11, we can get $Th_{\text{single link}}$ by considering

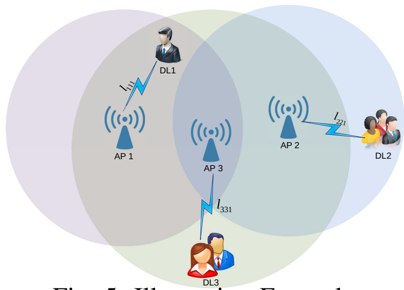


Fig. 5: Illustrating Example.

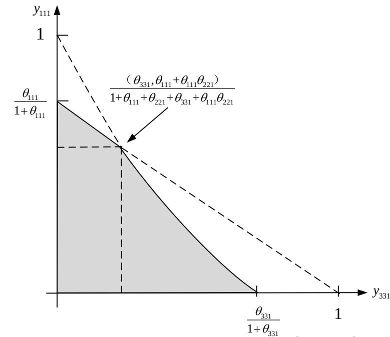


Fig. 6: Capacity region for three links l_{111}, l_{221} and l_{331}. For ease of visualization, only the cross section at $y_{111} = y_{221}$ is shown.

the various header, backoff, and ACK overheads [22]. The average throughput for link l_{str} can be computed as follows by summing over all sets S where link l_{str} is transmitting:

$$\mathbb{X}_{str} = \sum_{S:l_{str}\in S} \pi_S Th_{\text{single link}} \tag{12}$$

Now we discuss how to compute the capacity region for our white space network. As stated in [21], the stability condition for the network is $0 \leq \rho_{str} < 1$ for $\forall s,t,r$. By combining this condition with (10), (11), and (12), we can obtain the capacity region of the network. Algorithm 1 gives the pseudocode for computing the capacity region.

Illustrating Example. To illustrate how we use the result in [21] to obtain the capacity region, we give the following example as shown in Figure 5. We consider a white space network that consists of three APs, three demand locations and one vacant TV channel. This TV channel is vacant at all AP locations and demand locations. Demand locations 1, 2, and 3 associate with APs 1, 2, and 3 respectively. So three links l_{111}, l_{221} and l_{331} exist in the network. Assume that l_{331} is within the carrier-sense range of the other two links, while l_{111} and l_{221} cannot hear from each other. Therefore, the independent sets of this network are $\{\emptyset\}$, $\{l_{111}\}$, $\{l_{221}\}$, $\{l_{331}\}$ and $\{l_{111}, l_{221}\}$. And the steady-state probabilities for all independent sets are as follows:

$$\pi_S = \frac{\prod_{l_{str}\in S} \rho_{str}\theta_{str}}{\Delta}$$

where

$$\Delta = 1 + \rho_{111}\theta_{111} + \rho_{221}\theta_{221} + \rho_{331}\theta_{331} + \rho_{111}\theta_{111}\rho_{221}\theta_{221}$$

Thus the link throughput can be computed as follows:

$$\begin{aligned}
\mathbb{X}_{111} &= (\pi_{\{l_{111}\}} + \pi_{\{l_{111},l_{221}\}})Th_{\text{single link}} \\
&= \frac{\rho_{111}\theta_{111} + (\rho_{111}\theta_{111})(\rho_{221}\theta_{221})}{\Delta} Th_{\text{single link}} \\
\mathbb{X}_{221} &= (\pi_{\{l_{221}\}} + \pi_{\{l_{111},l_{221}\}})Th_{\text{single link}} \\
&= \frac{\rho_{221}\theta_{221} + (\rho_{111}\theta_{111})(\rho_{221}\theta_{221})}{\Delta} Th_{\text{single link}} \\
\mathbb{X}_{331} &= \pi_{\{l_{331}\}} Th_{\text{single link}} \\
&= \frac{\rho_{331}\theta_{331}}{\Delta} Th_{\text{single link}}
\end{aligned}$$

For the convenience of description, let $y_{str} = \mathbb{X}_{str}/Th_{\text{single link}}$. From the stability condition of the system, ρ_{str} should satisfy $0 \leq \rho_{str} < 1$, *i.e.*,

$$0 \leq \rho_{111} = \frac{1}{\theta_{111}} \frac{y_{111}}{1 - y_{111} - y_{331}} < 1$$

$$0 \leq \rho_{221} = \frac{1}{\theta_{221}} \frac{y_{221}}{1 - y_{221} - y_{331}} < 1$$

$$0 \leq \rho_{331} = \frac{1}{\theta_{331}} \frac{y_{331}(1 - y_{331})}{(1 - y_{111} - y_{331})(1 - y_{221} - y_{331})} < 1$$

Based on the three inequalities above, we can easily draw the capacity region as depicted in Figure 6. Links l_{111} and l_{221} impose linear constraints on the capacity region, while link l_{331} imposes an elliptical constraint. This capacity region is clearly *nonconvex*.

D. Complexity Analysis and Solution

To solve our formulated MDF problem, we traverse all AP placement strategies. And for each AP placement strategy, we compute the corresponding average demand fairness over one week by solving the SAP problem. Then we select the AP placement strategy that can achieve the maximal average demand fairness. Thereafter, we fix the AP locations and only conduct spectrum allocation and AP association based on current white space map and the SAP formulation.

Theorem 1. *The SAP problem is NP-complete.*

Proof: First it is easy to know that the SAP problem is NP-hard. This is because we need to find all the independent sets to obtain the capacity region. In fact, searching for all the maximum independent sets is known to be a NP-hard problem [23]. Thus, our problem is at least NP-hard. Even if we can obtain the capacity region in polynomial time, this problem is still NP-complete. We omit the detailed proof here. ■

The above theorem reveals the inherent challenges of designing optimal indoor multi-AP white space network. Fortunately, in our work, we focus on the indoor environments where the number of APs and demand locations are both small. In our experiments, we only need about one minute to solve the SAP problem in MATLAB. We can also accelerate the computation using other high-efficiency programming languages and tools. Therefore, the complexity is not a big problem for us.

IV. PERFORMANCE EVALUATION

In this section, we first describe our test-bed setup, and then use this test-bed to conduct extensive experiments to verify the

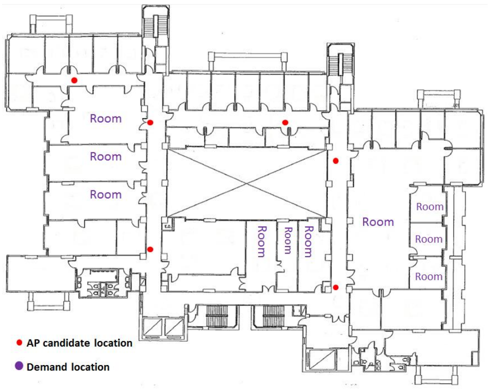


Fig. 7: Test-bed for Experiments. AP candidate locations are denoted as small circles, demand locations are the 10 rooms.

efficacy of our indoor TVWS network system WINET. The outline of our performance evaluation is as follows:

- In Section IV-A, we detail our test-bed setup and parameter settings for the performance evaluation.
- In Section IV-B, we show that WINET can significantly increase AP coverage area and achieve better demand fairness by optimizing AP placement.
- In Section IV-C, we compare WINET with the spectrum allocation scheme NCSAS in Feng et al. [13]. NCSAS requires that any two APs cannot be assigned the same TV channels. In the experiments, we show that WINET largely outperforms NCSAS in terms of system throughput.
- In Section IV-D, we verify the effectiveness of WINET in handling the temporal variation of TVWS. Experimental results show that WINET can well handle the temporal variation and achieve close-to-optimal performance.

A. Experiment Setup

To evaluate WINET, we setup a test-bed on one floor of a typical office building, as shown in Figure 7. In this test-bed, we have six AP candidate locations and 10 demand locations. We use the three non-overlapping channels 1, 6, and 11 in 2.4G ISM band to simulate the TV channels. The reasons we do not directly use TV band for experiments are that TVWS are still not open for unlicensed use in our region and we do not have a license to use TVWS for transmission. Despite all this, we impose white space availability on these three channels to model the spatial and temporal variation of TVWS. We set different transmission power for channels 1, 6, and 11 to simulate the heterogenous propagation properties of TV channels. Thus it is reasonable to use these three channels for our experiments.

Currently five APs are installed in this test-bed and all these APs are connected to a core switch. By conducting continuous traffic monitoring at the switch ports, we obtain the traffic demands for all demand locations. We can also estimate the traffic demands by considering the number of users at each demand location. We obtain the white space map $\mathbb{W}$ by querying WISER. We use the Shannon formula $\mathbb{C}_{str} = B_r \log(1 + \frac{P_{str}}{P_{\text{noise}}})$ to calculate the link capacity map. $\mathbb{C}_{str}$ is the traffic capacity in bits per second, B_r is the bandwidth of channel r in Hz, P_{str} is the received signal power at demand location t on channel r, P_{noise} is the additive white Gaussian noise power. By carrying out measurements for each $< s, t, r >$ pair to get P_{str} and P_{noise}, we can obtain the capacity map $\mathbb{C}$. Referring to Algorithm 1, we can compute the capacity region for our indoor white space network. The maximal traffic rate B provided by each AP can be specified based on our requirements.

B. AP Placement

In this subsection, we evaluate our AP placement strategy. AP placement plays a key role in the indoor multi-AP white space network design. Prior works [12] [13] on white space network design do not optimize AP placement. We refer to this scheme as non-optimization scheme. In this experiment, we compare our AP placement strategy with this non-optimization scheme.

First, we evaluate the metric of AP coverage area, which is defined as the number of covered demand locations. We increase the number of installed APs from one to six, and see how many demand locations can be covered by our design and the non-optimization scheme. From the results shown in Figure 8(a), we can observe that our design WINET can always cover all demand locations in the test-bed when the number of installed APs exceeds one. However, the non-optimization scheme may miss some demand locations. On average, WINET achieves 62.2% more AP coverage area compared with the non-optimization scheme. The intuition is that the non-optimization scheme is just one instance of our feasible solutions, therefore WINET can always achieve a larger AP coverage area, which demonstrates the benefit of optimizing AP placement in white space network design.

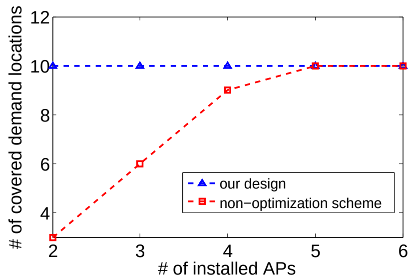
Second, we evaluate the metric of demand fairness. We first use the optimization tool YALMIP [24] to solve our formulated problem in Section III-B to obtain the optimum number and locations of APs. And then for the non-optimization scheme, we place the same number of APs carefully to guarantee that all demand locations can be covered. We increase the traffic demands for all demand locations proportionally. From Figure 8(b), we observe that WINET achieves a better demand fairness than the non-optimization scheme. The reason why demand fairness decreases is that as the traffic demands become larger, we can satisfy the demands less.

From these two test-bed experiments, we have demonstrated the benefit of optimizing AP placement in indoor multi-AP TVWS network design, *i.e.*, significantly increasing AP coverage area and the demand fairness.

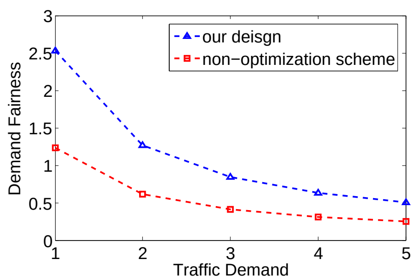
C. Spectrum Allocation

In this subsection, we compare our spectrum allocation scheme with NCSAS in Feng et al. [13]. NCSAS requires that any two APs cannot be assigned the same TV channels. As a comparison, our network design does not have this requirement.

First, we use the ground-truth measurement data as the input to compare our design WINET with NCSAS. WINET obtains 67.9% higher system throughput compared with NCSAS, as shown in Figure 9(a). The reason why WINET outperforms NCSAS is that for NCSAS, any two APs cannot be assigned the same TV channels even if there is no interference among

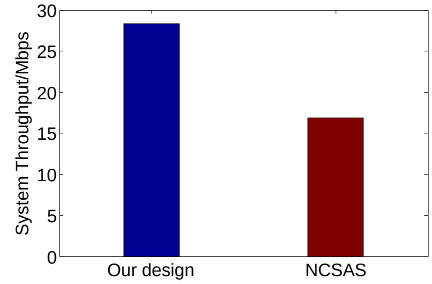


(a) Testbed result: AP coverage area for our design and the non-optimization scheme.

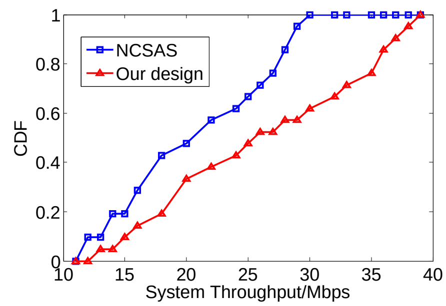


(b) Testbed result: Demand fairness for our design and the non-optimization scheme. For the x-axis, 1 means that we use the ground-truth measurement traffic demands as the input and 2-5 mean that we increase the ground-truth measurement traffic demands by 2-5 times.

Fig. 8: Comparison between our design and the non-optimization scheme.



(a) Testbed result: System throughput for our design and NCSAS. We use the ground-truth measurement data as the input.



(b) Simulation result: CDF curves of system throughput for our design and NCSAS.

Fig. 9: Comparison between our design and NCSAS.

them. This channel allocation scheme results in spectrum underutilization and therefore decreases the overall system throughput.

Furthermore, to see how WINET performs in various network settings, we generate over 20 groups of inputs and plot the CDF curve of system throughput. As shown in Figure 9(b), the maximal system throughput of NCSAS is about 30Mbps. As a comparison, for WINET, nearly 40% of the inputs can achieve system throughput more than 30Mbps. These results demonstrate the effectiveness of our indoor white space network design.

D. Temporal Variation

As we have mentioned in Section I, TVWS have the characteristic of temporal variation. When the white space availability changes over time, the AP locations and AP allocated spectrum may change. For our system WINET, we first select the AP locations that can achieve the averagely best performance. Thereafter we fix the AP locations and only change the AP allocated spectrum when white space availability changes over time.

In our test-bed, we conduct extensive TV spectrum measurements across four months to obtain the white space map of the whole floor at different days. We use the white space map of the first week to obtain the optimum number and locations of APs and then fix the AP locations. Thereafter we update the AP allocated spectrum based on the white space map of current days. Figure 10 shows the result of the next week. The optimal scheme means that we use the current day's white space map to obtain the optimum number and locations of

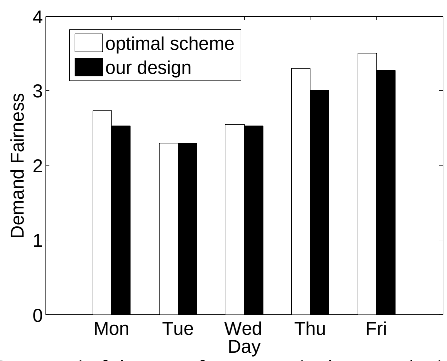


Fig. 10: Demand fairness for our design and the optimal scheme.

APs. On average, WINET only has 4.8% performance loss compared with the optimal one. We can observe from Figure 10 that WINET achieves very similar demand fairness to the optimal scheme. This result indicates that our two-phase network design can well handle the temporal variation and achieve close-to-optimal performance.

V. Related Work

Research on TVWS has attracted a lot of attention since the FCC passed the historic ruling to allow unlicensed use of TVWS in 2008. In general, prior works on TVWS can be classified into two categories, *i.e.,* white space identification and white space network design.

White space identification is significantly important since the FCC requires non-interference with incumbents for the unlicensed operation over TVWS. Currently there are two common approaches to identify TVWS, which are spectrum sensing and propagation modeling. As the name suggests, spectrum sensing based approach first senses the TV spectrum, and then uses energy or feature detection to determine the white space availability. Typical examples of this approach include [6] [7] [8] [10]. [6] used energy detection methodology to conduct experiments on UHF white space band. [7] proposed a mechanism to do fast discovery of opportunistic spectrum. [8] compared the energy detection methodology with feature detection methodology. [10] designed the first indoor white space identification system WISER to effectively identify and track the indoor white spaces in metropolises. Another approach to identify TVWS is propagation modeling. This approach uses terrain information and sophisticated signal propagation modeling to predict the white space availability. Representative work of this approach is [9], which enhanced the white space geo-location database using a combination of an up-to-date database of incumbents and complicated signal propagation model.

In recent years, researchers have started to design wireless network over TV white spaces. Representative works are [11]-[13]. [11] tried to form a single wireless link over TV white spaces. [12] did a pioneering work that implemented and deployed the first Wi-Fi like white space network WhiteFi in a campus. But there is only one AP in their system. [13] followed the step of WhiteFi and designed the multi-AP white space network WhiteNet. However, the TVWS networks in [11]-[13] all focus on the outdoor large-area scenario and abide by the IEEE 802.22 standard. As a comparison, we design the first indoor multi-AP white space network WINET with Wi-Fi like connectivity that follows the IEEE 802.11af standard. Besides, [11]-[13] did not consider AP-placement optimization. We optimize AP placement in our system and show the benefits (*i.e.,* increase AP coverage area and achieve fairness among users).

VI. Conclusions and Future Work

In this paper, we have presented WINET, the first design framework for indoor multi-AP white space network. AP placement, spectrum allocation, and AP association are optimized in our system. We jointly tackle all the three characteristics of TVWS, *i.e.*, spectrum fragmentation, spatial variation, and temporal variation. We demonstrate that our formulated indoor multi-AP white space network design problem is NP-complete. We setup a test-bed and conduct extensive measurements across four months to obtain real-world traces, and use them to evaluate our network design. Experimental results show that WINET can increase AP coverage area by an average of 62.2% and obtain 67.9% higher system throughput while achieving fairness among users as compared to alternative approaches. To the best of our knowledge, this is not only the first work focused on indoor white space network design, but also the first to optimize AP placement as well as tackle the spatial and temporal variation of TVWS in multi-AP white space network.

Several interesting and important directions could be explored in the future. First, it is important to find more efficient approaches to conduct AP placement to reduce the system deployment cost. Second, it will be interesting to build actual white space network when TVWS are unlicensed to satisfy the skyrocketing wireless data demand.

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