Frequency Hopping for Fair Radio Resources Allocation in TVWS

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***Abstract*—Using frequency hopping for fair resources allocation in TV white spaces is proposed and evaluated in this paper. The degree of fairness is judged by the achieved throughput by different secondary users. The throughput of the secondary users is determined by their permissible transmission power and the interference from the TV and other secondary users. The permissible transmission power for secondary users in TV white spaces in different channels is investigated. The main concern of calculating the permissible secondary user transmission power is protecting the primary TV receivers from harmful interference. With the aid of SPLAT (RF Signal Propagation, Loss, And Terrain analysis tool), the received TV signal power in a study case of the surroundings of the city of Gävle is fetched. The interference from the TV transmission into the free channels is measured in six different locations. The simulated system is a deployed Wi-Fi access points in a building representing an office environment in an urban area. Moreover, the size of the hopping set and the number of APs influences are investigated.**

Keywords–TV white spaces; Wi-Fi Access Points; Secondary Spectrum Access; Frequency Hopping; Throughput.

I. INTRODUCTION

Using cognitive radio (CR) enables flexible access to the wireless spectrum, which can improve efficiency in spectrum utilization significantly. CR is proposed at first in [1] to mitigate the spectrum scarcity problem by enabling dynamic spectrum access (DSA), which allows unlicensed users, so called secondary users (SUs,) to identify unutilized channels in the licensed spectrum and utilize them opportunistically as long as they do not cause any harmful interference to the communication by the legacy spectrum primary users (PUs). The temporarily unused portions of spectrum are called spectrum white spaces (WS) that may exist in time, frequency, and space domains.

In [2], using geo-location database for accessing spectrum holes is proposed instead of performing spectrum sensing, which has extensively used in literature. With a geo-location database approach, the SU need to reports its location into a database, which then tells the SU the available spectrum to use with the associated transmission parameters. Geo-location database is attractive when the activity pattern of the PU is highly predictable or slowly varying over time as the terrestrial TV transmission where the free of use channels are called TV white space (TVWS).

It is important to bear in mind that SU should not cause any harmful interference to the PUs. In the case of terrestrial TV broadcasting, it means that the SU cannot use the same channel. However, interference caused by SUs is not only limited to co-channel interference. In particular, in short-range scenarios, the adjacent channel interference is an equally severe problem. In [3], an indoor home scenario with cable, rooftop antenna and set-top antenna reception of TV was analyzed. The spectrum reuse opportunities for SUs have been determined, using the number of channels where it is possible to transmit without causing harmful interference to TV receivers as performance measure. A consequence is that the transmission capacity will depend on which of the free channels a SU is assigned. Free channels that are exposed to interference from either local or neighbouring TV masts will have lower throughput. One way to allocate the available channels in a fair way among the users is to switch channels using a pseudo random sequence i.e., using frequency hopping.

In the literature, the most related work is reported in [4] and [5]. In [4], the potentials and performance of Wi-Fi like networks deployment in TVWS are studied. In [5], the attainable throughput of Wi-Fi systems deployed in TVWS is studied compared to the current deployment approach in ISM band.

In contrast of the related work in the literature, this paper considers TV reception protection, TV transmission interference into free channels and the secondary to secondary interference to provide a full picture for a secondary access scenario. Moreover, a combination of measured data together with simulations are used to have a realistic representative environment. Furthermore, in this paper frequency hopping is adopted as a way to distribute the available free channels among the secondary users. Most observably, the spectrum leakage from the active TV channels into the free channels is empirically evaluated, which is a distinct contribution of this paper.

The rest of this paper is organized as follows. Section II introduces the system model including TV as a primary system, SU power assignment and propagation model. In Section III, the frequency hopping framework is motivated and presented. The methodology of obtaining the parameters and performance evaluation is presented in Section IV. Section V shows the numerical results and their interpretations. Finally, Section VI concludes the paper.

II. SYSTEM MODEL

A. Secondary Access to the Terrestrial TV Band

The terrestrial TV broadcasting band lies between $470-862$ MHz and divided into 49 channels 8 MHz each. These channels are indexed with the numbers $21-69$. A single TV

 ISBN: 978-1-61208-433-6

transmitter serves a coverage area of a radius of $30-50$ km using a transmission power of $40-50$ dBW. Due to the high power of the TV transmitter, neighbouring TV transmitters use different broadcasting channels. Accordingly, in each geo-location, there exist a number of TV channels which are unoccupied and potentially usable for secondary operation. These unoccupied TV channels are called TVWS.

Techno-economic studies reported in [6] have concluded that Wi-Fi like short range indoor wireless systems are the 'sweet point' for secondary operation in TVWS. Therefore, Wi-Fi access points (APs) are considered in the studies carried out in this paper. It is assumed here that among the unoccupied TV channels, a specific number of channels M are available for the deployed APs.

B. APs Permissible Transmission Power

The permissible transmission power model is based on TV receivers adjacent channels interference tolerance, which minimally guarantees a certain level of TV reception quality. In [7], the adjacent channels interference has been experimentally evaluated. The aggregate interference coming from multiple SUs into channel L at a specific location coordinates (x, y) is denoted as $I_{tot}(x, y)$, which is calculated as

$$I_{tot}(x,y) = \sum_{\substack{k \\ k\neq 0}} \sum_{j=1}^{N} I_{j,k+L}(x,y), \tag{1}$$

where (x, y) are evaluated with a reference $(0, 0)$ for the TV transmitter mast location, N is the total number of SUs, $I_{j,k+L}(x, y)$ is the interference generated by the j^{th} SU occupying channel $k + L$ into a TV receiver located at (x, y).

If the TV received power on channel L at location (x, y) is $S_L(x, y)$ and the minimum acceptable signal-to-interference ratio (SIR) is γ, then in order to meet the TV reception requirements, we should satisfy.

$$S_L(x,y) \geq \gamma + I_{tot}(x,y). \tag{2}$$

where all quantities in (2) are in the logarithmic scale.

To determine the maximum permissible transmission power on channel $k + L$, one needs to count for the aggregate interference from multiple SUs. Hence a margin of δ dB can be used to compensate for that adjacent interference. Accordingly, the maximum permissible transmission power for a SU in channel $k + L$ at location (x, y), call it $P^t_{k+L}(x, y)$ is found as

$$P^t_{k+L}(x,y) = S_L(x,y) - \gamma - \zeta(k) - \delta \tag{3}$$

where $\zeta(k)$ is the k^{th} adjacent channel power ratio (ACPR), which represents the difference between the power received in a specific channel and the leaked power from the adjacent channel k into that channel.

C. Received Power at SU Terminals

To obtain the received power at each SU terminal, a propagation model is needed. In [8], a propagation model based on combining COST 231 [9] model and ITU-R P.1238 [10] is developed. The model calculates the path loss between the SU transmitter and receiver as

$$PL(d,f) = PL_{FS} + \alpha d + n_w L_w + n_f L_f + A, \tag{4}$$

where $PL(d, f)$ is the path loss when the transmitter operates at a frequency f MHz and located at a distance of d meters from the receiver. n_w, n_f, L_w and L_f are the number of penetrated walls, number of penetrated floors, loss per wall and loss per floor respectively, α and A are constants. Table I shows the model parameters for the case of an office environment.

To count for the shadow fading, the received power at channel $k + L$ in location (x, y) is denoted as $P^r_{k+L}(x, y)$ and modelled as a log-normally distributed random variable with a mean $(P^t_{k+L}(x, y) - PL(d, f))$ and standard deviation σ.

III. Fair Radio Resources Distribution

A. Heterogeneous Free Channels

Applying (3) to determine the maximum permissible AP transmission power at a specific location gives different values for different channels due to the following reasons. At first - and most important - there are different adjacent channels indices, therefore $\zeta(k)$ takes different values for different channels depending on which channels are used by the TV transmitter. Secondly, different used TV channels use different transmission power, which gives different values of $S_L(x, y)$.

Not only the AP transmission power that is different for different channels, but also the PU interference into different unoccupied channels considerably varies. Measuring this interference in a specific area is a stand alone contribution of this paper as explained in Section V. This PU interference can be originated from TV transmitter non-linearities in forms of spectral leakage and intermodulation products. Spectral leakage basically affects the first adjacent channels while intermodulation products are found in different channels. Moreover, channels used by neighbouring TV transmitters can also be interfered. Even though PU interference is more severe in outdoor operation, yet, our measurements results shown in Section V show that the PU indoor interference into free TV channels is not neglectable and considerably affects the performance of the SUs.

Having different permissible APs transmission power with different PU interference at different channels would result in tern of having wide range of quality achieved when using different channels. Following subsection proposes frequency hopping as a solution provides fairness distribution of the available channels among the APs.

B. Frequency Hopping

In order to distribute the available heterogeneous free TV channels in a fair way among the APs, frequency hopping is proposed in this paper. By frequency hopping it is meant that the APs hop between the available channels in a random uncentralized manner. By frequency hopping it is assured that no APs will be holding all the time on the channels with high SINR and none will be forced to use the low SINR channels during the whole time of operation. Hereafter, achievable AP throughput will be used to evaluate the performance. Achievable downlink throughput when transmitting on channel $k+L$ with the maximum permissible power is denoted as C_{k+L} and calculated as

$$C_{k+L} = \log_2 \left(1 + \frac{P^r_{k+L}(x,y)}{I^{SS}_{k+L} + I^{TV}_{k+L} + \eta} \right), \tag{5}$$

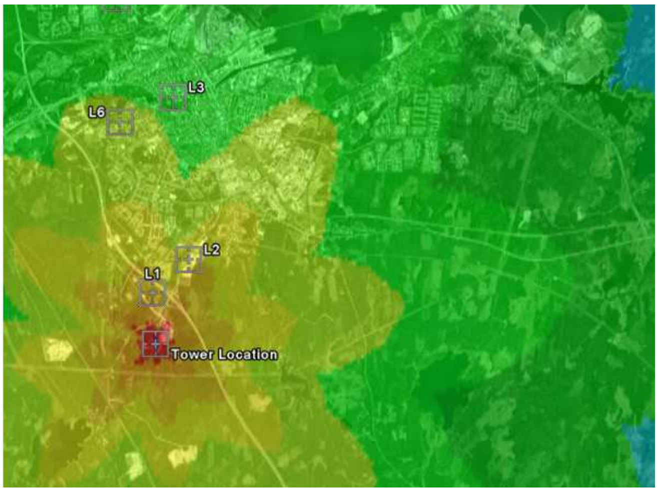

Figure 1. SPLAT! results for the received signal power for channel 24 [dBm] as a function of the TV receiver location.

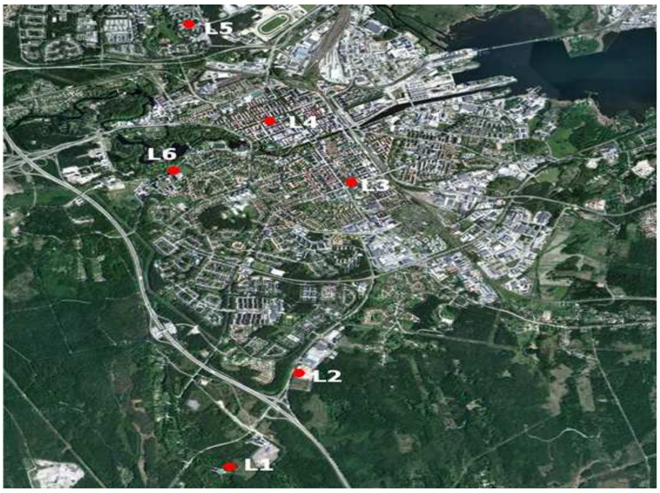

Figure 2. Measurements locations.

where I_{k+L}^{SS} is the interference from other APs occupying the same channel $k+L$, I_{k+L}^{TV} is the interference form the TV transmission into channel $k+L$ and η is the background noise. Note that the throughput obtained by (5) and throughout the rest of this paper is *per Hertz capacity* and given in [bits/sec/Hz]. For simplicity, the M available TV channels are locally re-indexed by the indices $1 \leq m \leq M$. Suppose that the SU terminal is served by its nearest AP which has an index i and hops among the M available channels with equal probabilities. Denote the used channel by the serving AP as $\acute{m}$ at each hop. Thus, the average downlink throughput, C_{hop}, for each SU is calculated as

$$C_{hop} = \frac{1}{M} \sum_{m=1}^{M} \log_2 \left(1 + \frac{P_{k+L}^{r}(x,y)}{\sum\limits_{\substack{j=0 \\ j \neq i}}^{N} \left(\beta_m P_{j,m}^{r}(x,y) \right) + I_m^{TV} + \eta} \right) \tag{6}$$

where

$$\beta_m = \begin{cases} 1 & \acute{m} = m \\ 0 & \text{Otherwise}, \end{cases}$$

Note that since the deployed system is low power short range Wi-Fi like, then the adjacent channels interference among the APs is neglectable.

IV. Methodology

The methodology of evaluating the proposed frequency hopping framework is explained in this section.

A. Study Case

A representative study case is considered where data based on measurements an simulations is obtained. Moreover, a simulation of deployed APs performing frequency hopping in TVWS is carried out based on the findings of the representative case.

The area covered by a TV transmission mast located in a city called Gävle in Sweden is considered for the studies in this paper. The TV mast is located at the GPS coordinates: $60^0\ 38'\ 0.39"$ N, $17^0\ 8"\ 13.92"$ E. Six TV channels in UHF are used in Gävle, those are channels 24, 27, 30, 32, 46 and 50.

B. Obtaining TV Received Signal Power

SPLAT (RF Signal Propagation, Loss, And Terrain analysis tool) [11] is simulation tool used to obtain the received signal power at each point inside the area under investigation. The input data to SPLAT is the transmitter properties (e.g., transmission power, mast height, etc) which were obtained from Post and Transport Agency (PTS), the Swedish communication regulator. SPLAT uses Longley-Rrice propagation model [11] and terrain data which is available online [11]. The simulation results for channel 24 are shown as a sample in Figure 1.

C. Obtaining TV Interference into Free Channels

The TV transmission interference into free channels is not covered by the simulation model; instead, an empirical model for this interference is developed. Measurements are done at 6 different locations in Gävle, marked as L1-L6. The map in Figure 2 shows the measurements locations. Measurements are performed employing a set up consists of an antenna, a spectrum analyzer and a PC. The antenna and the spectrum analyzer are used to capture the signal in the whole TV band, which is then recorded using the PC for further analysis and use. The PC also controls the spectrum analyzer.

D. Simulations

The scenario considered in this paper is a number of APs deployed in an office environment. A building having 3 floors 50 m $\times$ 50 m each located in the city center is assumed (i.e., data correspond to the measurement location L2). The APs are installed in the ceiling of each floor and equally share a uniformally distributed traffic in the building. Hence, all APs have the same circular shape serving area. Below Table I shows the used simulation parameters for permissible AP transmission power calculations and propagation model parameters.

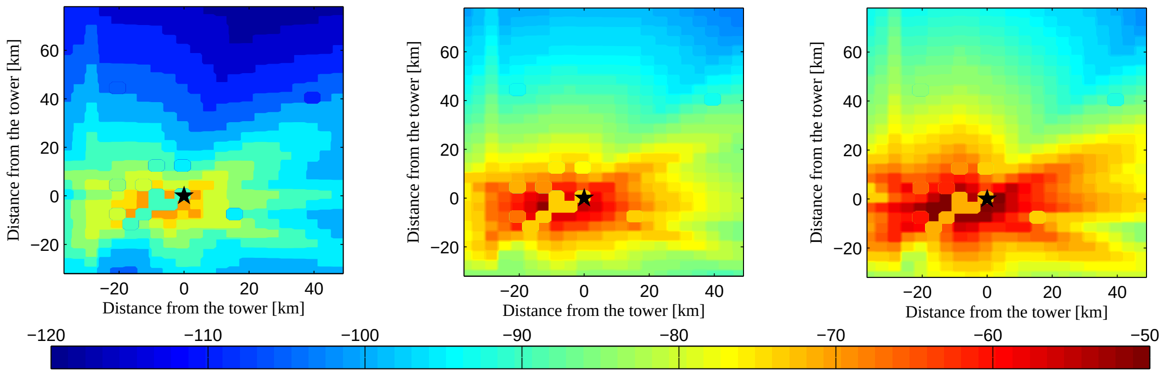

Figure 3. Maximum allowed transmission power density [dBm/Hz] for a SU in channels 25, 48 and 35 respectively (from left to right).

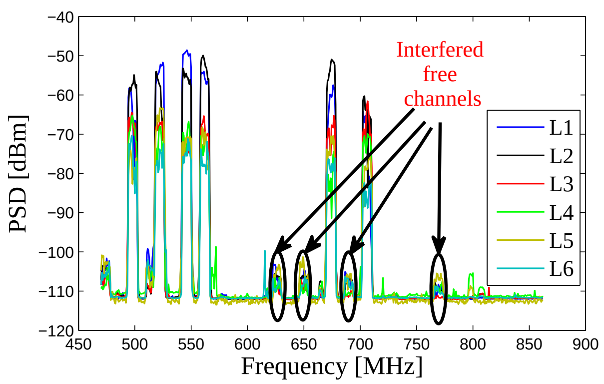

Figure 4. Spectrum occupancy for the whole TV band in the measurements locations.

TABLE I. SIMULATION PARAMETERS

Parameter		value
γ		25 dB [12]
$\zeta(k)$	$k = 1$	-33 dB [7]
	$k = 1$	-43 dB [7]
	$k = 3$	-48 dB [7]
	$k \geq 4$	-50 dB [7]
δ		10 dB
α		0.17 dB/m [8]
A		1.4 dB [8]
n_w		0.231 wall/m [13]
L_w		5.9 dB [8]
L_f		14.0 dB [8]
σ		6.0 dB [10]
η		-174 dBm/Hz

V. RESULTS

The results can be divided into two parts, namely, obtaining the model parameters part and the deployed APs evaluation part. The AP evaluation is based on the achieved throughput.

A. Obtaining Model Parameters

As described in Subsection IV, the received TV signal power and the TV interference into free channels are need. The received TV signal power is obtained by SPLAT as shown in Figure 1 as a sample of one channel.

By having the received TV signal power at all points in the study area, the maximum permissible transmission power is calculated using (3). Figure 3 shows this permissible transmission power density for channels 25, 48 and 35 respectively. These three channels have been chosen as representatives for 1^{st}, 2^{nd} and 3^{rd} adjacent channel respectively. The figure shows how the permissible transmission power for SU differs in different channels and different locations. For example, SUs can transmit in channel 35 with around 20 dBm/Hz higher power density compared to transmit in channel 25.

For the TV transmission interference into free channels, the measurements results shown in Figure 4 determine the interfered channels in the measurements locations. This interference influence is quantitatively evaluated. To reflect the extent of the variety of the free TV channels, let us define $\gamma_0(k+L)$ as the ratio between the permissible SU transmission in channel $k+L$ and the TV interference into the same channel. In many channels the value of γ_0 approaches ∞ as the best case while as the worst case in the measurements locations, the value of $\gamma(47)$ is equivalent to 26 dB in location L5.

B. APs Throughput

At first, to show the creditability of using the frequency hopping scheme, the achieved throughput without and with hopping is studied. Assume an AP serving area of 100 m^2 and three APs using different three TVWS channels without hopping. AP 1 uses channel 47, AP 2 transmits on channel 34 and AP 3 operates on channel 36. These three channels are picked to have three different classes of the provided throughput. Figure 5 shows the cumulative distribution function (CDF) of the throughput on each channel when each AP holds on its channel. As seen from the figure, user 1 served by AP 1 gets the lowest throughput all the time with an average of 2.6 bits/sec/Hz while user 3 served by AP 3 is achieving the highest throughput with an average of 6.4 bits/sec/Hz. Applying frequency hopping among the three channels for all

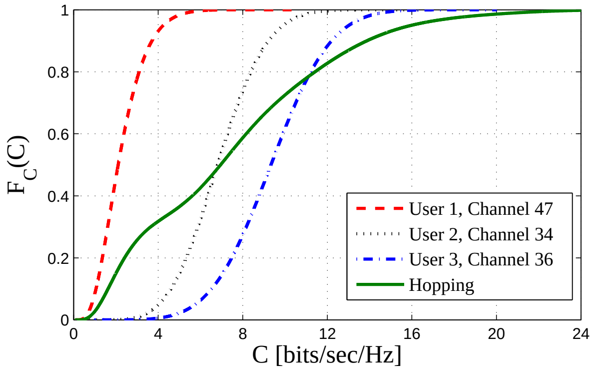

Figure 5. Achieved throughput CDF when using three different channels individually and when hopping is applied.

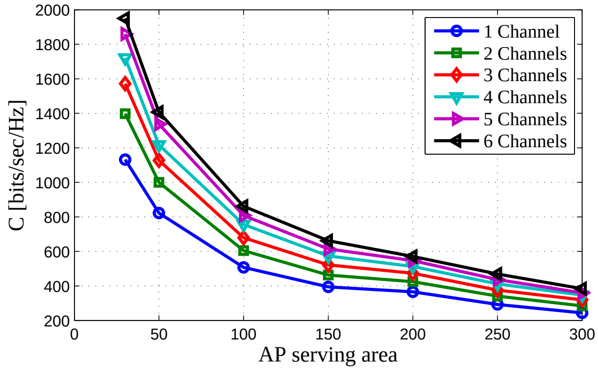

Figure 8. Overall throughput achieved in the building using different AP serving area (i.e., different number of APs).

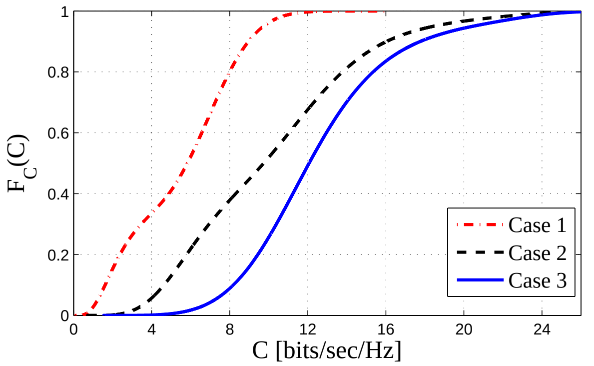

Figure 6. Achieved throughput CDF for three different cases when 3 channels used by the APs with frequency hopping.

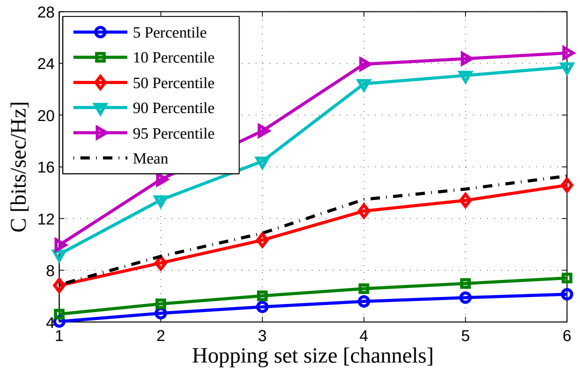

Figure 7. The 5, 10, 50, 90 and 95 percentile for the achieved throughput when using different sizes of hopping sets.

APs would then make the three users to achieve the same throughput with an average of 5.8 bits/sec/Hz. Therefore, the available three channels are shared among the three APs in a fair way.

Now, suppose that frequency hopping is applied among a certain set of channels, call it hopping set, then the achieved throughput depends on the permissible transmission power and the TV interference on this hopping set. As an example, consider three cases as follows. In Case 1, the hopping set is three interfered channels with low permissible transmission power, for that, use channels $44, 45$ and 47. Case 2 uses better channels than Case 1, those are channels $25, 34$ and 35. Case 3 hopping set is the best where channels $35, 36$ and 51 are used. As Figure 6 depicts, hopping among case 1 set provides the lowest throughput while using the channels in Case 3 as a hopping set gives the highest throughput and case 2 throughput is in between. Quantitatively, Case 1 set provides about 50% of the throughput that Case 3 set achieves.

An important factor on the achieved throughput is the size of the hopping set (i.e., the number of channels), in this regard a simulation where the set size is changed is carried out. The hopping set is chosen in a way that the average channel quality is preserved when comparing different sets sizes. Figure 7 shows that the achieved throughput changes almost linearly when increasing the hopping set from 1 to 4 channels in all regions of the CDF curve. However, for the mean and above 50 percentile, when increasing the hopping size beyond 4 channels, the linear increase stops and the gain in the throughput tends to saturate. This is due to the fact that APs using the same channel are most likely to be further separated when higher hopping sets are used.

Together with the hopping set, the AP serving area - which decides the number of APs in the building - determines the achieved throughput in the whole building. Figure 8 shows how the total throughput provided by the WiFi like system is affected by the change of the AP serving area and the hopping set. Figure 8 shows that increasing AP serving area decreases the provided throughput for the whole building as there are less resources to handle the traffic. However, increasing the AP serving area on the other hand increases the distances between the APs using the same channel while hopping, which in return decreases the interference among the APs. Therefore, the decrease in the throughput does not go linearly with the increase of the AP serving area. It is important to study the throughput map in the building. Figure 9 show a color-coded map of the throughput in one of the building's floor with the APs locations. The figure is generated considering a deployment of 25 AP. In general, it is observable from the figure that the closer to the AP the higher throughput the user gets. This is not only because of the higher received power from the AP but also because of being further from the other APs using the same channel and hence experiencing less interference.

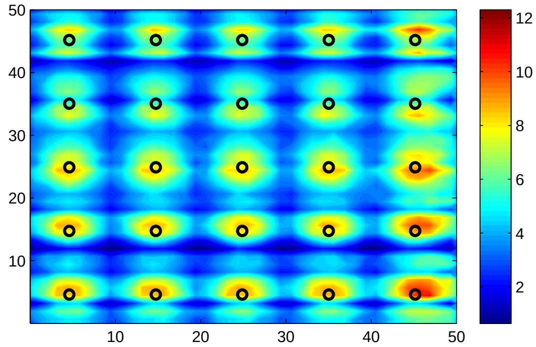

Figure 9. Average throughput at different points in one of the building's floors. The black rings are the deployed APs.

Moreover, the AP located closer to the edges of the building supplies higher throughput because other interfering APs are located in one side and therefore having longer distances to APs in the edges. On the other hand, the APs in the middle are receiving interference from all the directions with lower distances from the interferes, which decreases their provided throughput.

VI. CONCLUSION

In this paper, the performance of a Wi-Fi like secondary network deployed in an office environment has been studied. The secondary Wi-Fi like network operates in a TVWS using geo-location database spectrum opportunities framework. The main metric used in the performance evaluation is the achievable downlink throughput for the access points. This achievable throughput is determined by means of the permissible transmission power, which protects the TV reception, the interference among the access points and the TV transmission interference. All these parameters have been obtained using either measurements or simulations for a realistic scenario. Results have shown that different TV channels experience large variety in their provided throughput. Therefore, for fair resources distribution among the access points, frequency hopping is applied. Moreover, an investigation on the impacts of the size of the hopping set and the number of deployed APs have also been addressed.

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 ISBN: 978-1-61208-433-6