Radio Resource Allocation for Indoor Secondary Access in TV White Space

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***Abstract*—This paper considers fair radio resource assignment for secondary users operating in TV white space by means of frequency hopping. The achieved throughput for different secondary users is used to measure the degree of fairness. The permissible transmission power for secondary users is set to protect the TV transmission from excessive interference. Hence, there are different limits on the secondary transmission power when operating in different idle TV channels because different adjacent channels generates different amounts of interference based on the TV receiver transfer function in the frequency domain. Moreover, different free TV channels experience different amounts of interference due to the non-linearities in the TV transmission. A model for power assignment in each of the free TV channels is developed based on the received TV signal, TV receiver characteristics and secondary user location. For the sake of fair resource allocation, frequency hopping is proposed herein, and its performance is evaluated. In this study, three different TV transmitters located in three different cities in Sweden, namely, Gävle, Stockholm and Linköping, are exploited where the interference from the TV transmission into the free channels is measured. For the secondary system, the deployment of indoor WiFi access points in an office environment is considered and simulated. The main finding is that frequency hopping can provide fair radio resource distribution in terms of the obtainable throughput. Moreover, it is shown that the denser the area is, the higher the achievable secondary throughput due to the higher attenuation of the interfering signals.**

Keywords–TV white space; Radio Resource Allocation; WiFi Access Points; Secondary Spectrum Access; Frequency Hopping; Throughput; TV Transmission Interference.

I. Introduction

This paper is an extended version of [1] and it reports more measurements analyses.

At the beginning of its appearance, designers of wireless communication systems designers were concerned about coverage to provide as wide as possible wireless access. Thereafter, capacity concern began to emerge where not only coverage is considered but also data rates as high as needed are pursued [2]. Previous studies realized that the capacity of wireless networks had doubled every two and a half years over a span of 104 years [2]. However, later studies have shown that this rate is currently higher, but for the sake of illustration, we can assume that this rate of wireless throughput increase currently holds, then, we have a one million-fold increase since 1965. This explosive growth is attributed to the reduced cell size and the availability of the spectrum with wider bandwidths [3]. In fact, both factors have their roots in spectrum-related aspects, as the former is feasible with the aid of spectrum reuse. Consequently, a fundamental question that arises is do we have sufficient and wide spectrum to go further with smaller cell sizes and provide higher data rates for the foreseeable future wireless access traffic demands? The answer to this question might be yes up to now but it will change to no at some point because we can not support infinite increase of this data traffic due to the existence of finite resources. Here, resources preliminary refer to the financial resources, infrastructure and electromagnetic radio spectrum. The concerns regarding the radio spectrum availability to adopt the growth in mobile data traffic has translated into a phenomenon known as spectrum scarcity [4].

Simultaneously with the emerging spectrum scarcity phenomenon, many experimental investigations have determined that the radio spectrum below 6 GHz is inefficiently utilized, where the duty cycles of some wireless systems reaches 1% or less [5]–[7]. Considering both facts of the need for more spectral resources and being inefficient in utilizing the current available spectrum forms a paradox. A framework that makes use of this paradox by accessing the spectrum opportunistically called cognitive radio (CR) was first proposed at [8]. CR enables flexible access to the radio spectrum, which can significantly enhance spectrum utilization efficiency [9]–[11]. Therefore, the ultimate objective of CR is to mitigate the spectrum scarcity 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 dynamically as long as they do not cause unacceptable interference to the communication by the legacy spectrum licensees known as primary users (PUs) in CR and DSA terminologies [12], [13]. The temporarily unused portions of the spectrum are called spectrum white spaces (WS), spectrum holes or spectrum opportunities. Throughout this paper,the term WS will be used, which may exist in time, frequency, and space domains. To find a WS, one of three approaches can be used, namely, spectrum sensing, beacon signal and geo-location database [14]. Both spectrum sensing and beacon signals are beyond the scope of this paper.

Using a geo-location database for accessing spectrum holes was proposed in [15] and has subsequently been extensively used in literature. With a geo-location database approach, the SU needs to reports its location into a database, which then informs the SU about the available spectrum to use with the associated constrains. A geo-location database is potentially beneficial when the activity pattern of the PU is highly predictable or slowly varying (quasi-static) over time. Such systems include the terrestrial TV transmission and the radar systems [16]. With a TV transmitter as a PU, the free of use channels are called TV white space (TVWS).

In the case of terrestrial TV broadcasting, to avoid exces-

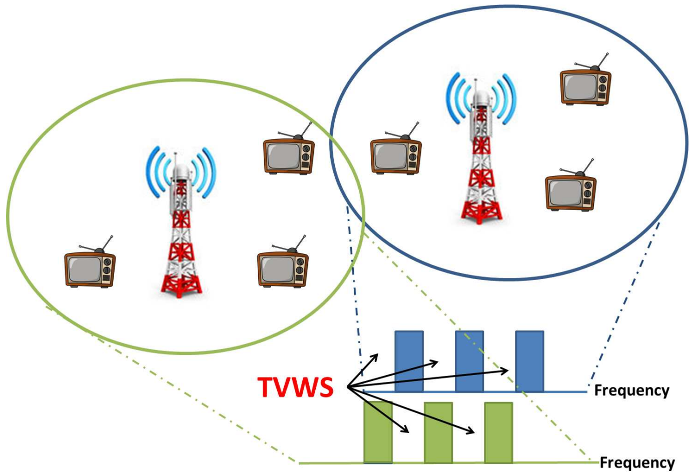

Figure 1. TVWS concept. The free channels located to the right are available for lo- power secondary access at the left location and vice versa.

sive interference into the TV transmission, SUs cannot use the same channel. However, interference caused by SUs is not only limited to co-channel interference. In particular, in short-range scenarios, adjacent channel interference is an equally severe problem. In [17], indoor home scenarios with cable, rooftop antenna and set-top antenna reception of TV signals were 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 a performance measure. Consequently, the transmission capacity depends on which of the free channels are assigned for a specific SU. Free channels that are exposed to interference from either local or neighboring TV masts will have lower throughput. One approach 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 [18] and [19]. In [18], the potentials and performance of WiFi-like network deployments in TVWS are studied. In [19], the attainable throughput of WiFi systems deployed in TVWS is studied in comparison to the current deployment approach in the ISM band.

In contrast to the related work in the literature, the distinct contributions of this paper are as follows:

- TV reception protection, TV transmission interference into free channels and the secondary to secondary interference are all considered to provide a full picture for a secondary access scenario.
- A combination of measured data together with simulations are used to obtain a realistic representative environment.
- Frequency hopping is adopted as a technique to fairly distribute the available free channels among the secondary users.
- The interference from the TV transmission into the free channels is empirically evaluated. This interference is because of the non-linearities in the TV transmitter chain in forms of spectrum leakage and intermodulation products.
- The performance of secondary operation in TVWS is evaluated in three different representative locations in Sweden.

The reminder of this paper is structured as follows. Section II introduces the system model, including the TV broadcasting transmission, the sharing model, SU power assignment and the propagation model. In Section III, the motivation for the frequency hopping framework is presented and discussed. The methodology for obtaining the parameters and for the performance evaluation is presented in Section IV. Section V shows the numerical results and interpretations. Finally, Section VI concludes the paper.

II. System Model

This section addresses aspects related to the system model and is further divided into three subsections. The first subsection overviews the concept of WiFi-like secondary operations in TVWS. The proceeding subsection explains how the maximum allowed transmission power of the APs is executed. Finally, the last subsection shows the model used to determine the received downlink power at the SUs terminals.

A. WiFi Secondary Access to the Terrestrial TV Band

The UHF terrestrial TV broadcasting band lies between $470-862$ MHz and is divided into 49 of channels 8 MHz each. 7.6 MHz is used for TV signals within each channel, while 0.4 MHz is deducted and evenly distributed as two guard bands at each side of the channel. The 49 channels are indexed as j, where

$$21 \leq j \leq 49. \tag{1}$$

Each channel j location in the frequency domain is determined as

$$j : 470 + 8 \times (j-1) \leq 470 + 8 \times j. \tag{2}$$

A single TV transmitter serves a coverage area with a radius of $30-50$ km using a transmission power of $40-50$ dBW. Due to the high power of the TV transmitter and high TV masts, neighboring TV transmitters use different broadcasting channels (typically less than 10 channels). Consequently, in each geo-location, a number of TV channels (generally more than 40 channels) exist that are unoccupied and potentially usable for low-power short-range secondary operation. These unoccupied TV channels are called TVWS. Figure 1 presents a conceptual demonstration of TVWS.

According to [20], WiFi-like short-range indoor wireless systems are the ’sweet point’ for secondary operations in TVWS for techno-economical considerations. Therefore, the deployment of WiFi access points (APs) is considered in the studies conducted in this paper. It is assumed here that among the unoccupied TV channels, a specific number of channels M is available for the deployed APs. With secondary indoor operation in TVWS, both secondary and TV reception experience interference from TV and secondary transmissions respectively. Figure 2 illustrates the entire system model including mutually interfering signals and geo-location database accessibility. Hereafter, WiFi APs are deployed following the layout shown in Figure 3, where all APs are attached to the

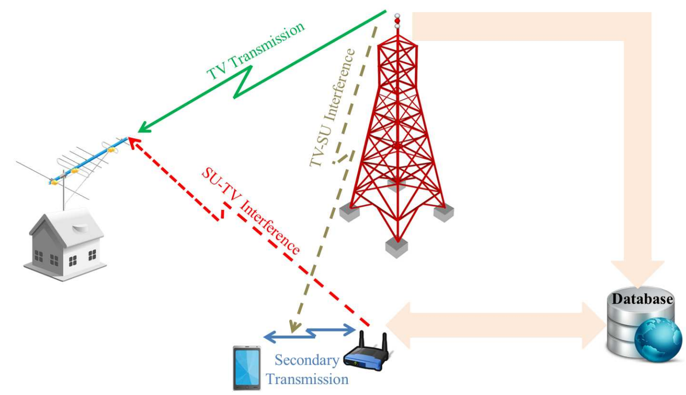

Figure 2. TVWS spectrum sharing using the geo-location database-based spectrum opportunities model. The geo-location database is populated by the TV transmitter either directly or by other entities such as spectrum sensing device or network. SUs access the database to inspect the available radio channels and their associated parameters. SUs also have to report their existence to the database to update different transmission parameters.

building's ceiling and equally spaced. Each SU terminal is linked to the closest AP. Users are uniformally distributed throughout the entire building and within each floor.

B. *Permissible Transmission Power of APs*

The permissible transmission power model is based on the interference tolerance of adjacent channels of the TV receiver, which guarantees a certain minimum level of TV reception quality. In [21], interference of adjacent channels was experimentally evaluated. The aggregate interference coming from multiple SUs into channel L at specific location coordinates (x, y) is denoted as $I_{tot}(x, y)$, which is calculated as

$$I_{tot}(x, y) = \sum_{\substack{k \\ k \neq 0}} \sum_{j=1}^{N} I_{j,k+L}(x, y), \tag{3}$$

where (x, y) are evaluated with a reference $(0, 0)$ denoting the TV transmitter mast location, N is the total number of SUs, and $I_{j,k+L}(x, y)$ is the interference injected 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 to meet the TV reception requirements, we should satisfy

$$S_L(x, y) \geq \gamma + I_{tot}(x, y). \tag{4}$$

where all quantities in (4) are on the logarithmic scale, i.e., dB.

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

$$P^t_{k+L}(x, y) = S_L(x, y) - \gamma - \zeta(k) - \delta \tag{5}$$

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 power leaked from the adjacent channel k into that channel. $\zeta(k)$ is dependent on the selectivity curve of the TV receiver, which is determined as

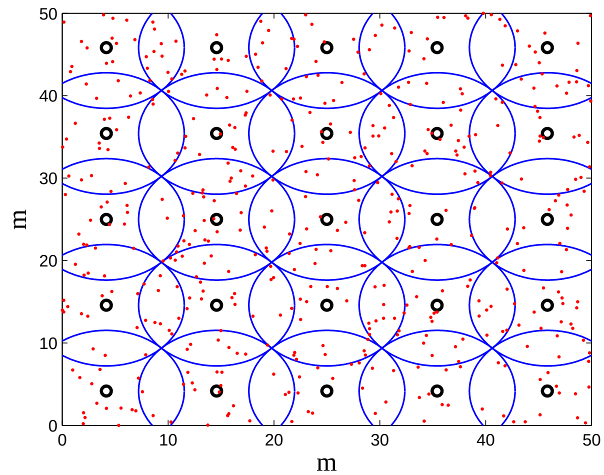

Figure 3. Deployment layout of APs. The APs are the small black rings. The blue circles represent the areas served by the APs to reflect the concept that each SU terminal is attached to its closest AP. The red dots are the users' terminals. Both the x and the y axes represent hypothetical Cartesian coordinates in units of meters.

$$\zeta(k) = \left(\int_{f_l^{k+L}}^{f_h^{k+L}} | H(f) |^2 \, dx \right)_{[dB]} - \left(\int_{f_l^{L}}^{f_h^{L}} | H(f) |^2 \, dx \right)_{[dB]}, \tag{6}$$

where f_l^i and f_h^i denote the upper and lower limits of the i^{th} TV channel, respectively, and $H(f)$ is the TV receiver's transfer function in the frequency domain. Both integration terms of 6 are on their logarithmic scale.

C. *Received Power at SU Terminals*

To obtain the received power at each SU terminal, a propagation model is required. In [22], a propagation model based on combining the COST 231 [23] model and ITU-R P.1238 [24] is developed. The model calculates the path loss between the SU transmitter and receiver as

$$PL(d, f) = PL_{FS} + \alpha d + n_w L_w + n_f L_f + A, \tag{7}$$

where $PL(d, f)$ is the path loss when the transmitter operates at a frequency of 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 account 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 modeled as a log-normally distributed random variable with a mean $(P^t_{k+L}(x, y) - PL(d, f))$ and standard deviation σ.

TABLE I. Propagation Model and System Parameters

Parameter		*value*
γ		25 dB [25]
$\zeta(k)$	$k=1$	-33 dB [21]
	$k=2$	-43 dB [21]
	$k=3$	-48 dB [21]
	$k\geq 4$	-50 dB [21]
δ		10 dB
α		0.17 dB/m [22]
A		1.4 dB [22]
n_w		0.231 wall/m [26]
L_w		5.9 dB [22]
L_f		14.0 dB [22]
σ		6.0 dB [24]
η		-174 dBm/Hz

III. Fair Radio Resources Distribution

In this section, the motivation for having a fair radio resource allocation mechanism in TVWS is shown, which is essentially the heterogeneity of the free TV channels. Moreover, frequency hopping as an enabler for such fairness is explained.

A. Heterogeneous Free Channels

Applying (5) to determine the maximum permissible AP transmission power at a specific location provides different values for different channels due to the following reasons. First - and most importantly - 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. Second, different used TV channels use different transmission powers, which provides different values of $S_L(x,y)$.

Not only is the AP transmission power different for different channels, but the TV transmission interference into different unoccupied channels also 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 originates from TV transmitter non-linearities in the form of spectral leakage and intermodulation products. Spectral leakage essentially affects the first adjacent channels while intermodulation products are found in different channels. Moreover, channels used by neighboring TV transmitters can also generates interference. Although TV transmission interference is more severe in outdoor operations, our measurements results presented in Section V show that the PU indoor interference into free TV channels is not negligible and considerably affects the performance of the SUs.

Having different permissible AP transmission power with different primary TV transmission interferences at different channels would result in having a wide range of throughput achieved when using different channels. The following subsection proposes frequency hopping as a solution to provide a fair distribution of the available channels among the APs.

B. Frequency Hopping

Frequency hopping is proposed in this paper to distribute the available heterogeneous free TV channels in a fair manner among the APs. By frequency hopping, it is meant that the APs hop between the available channels in a random uncentralized manner. Through the use of frequency hopping, it is ensured that no APs will be holding all the time on the channels with a high SINR and none will be forced to use the low SINR channels during the entire time of operation. Therefore, by means of frequency hopping, all APs will eventually achieve similar long-term throughput. The achievable downlink throughput when transmitting on channel $k+L$ with the maximum permissible power is denoted as C_{k+L} and calculated as

TABLE II. Equipments and measurements parameters

Equipment/Parameters	*Type/Value*
Antenna	R&S HE200 (RF Module 2)
Spectrum Analyzer	Anritsu MT8221B BTSMaster
Centre Frequency	666 MHz
Span	400 MHz
Resolution Bandwidth (RBW)	400 KHz
Preamplifier	On
Input Attenuation	0 dB
Detector	RMS
Sweeptime (SWT)	840 ms

$$C_{k+L} = \log_2\left(1+\frac{P^r_{k+L}(x,y)}{I^{SS}_{k+L}+I^{TV}_{k+L}+\eta}\right), \tag{8}$$

where I^{SS}_{k+L} is the interference from other APs occupying the same channel $k+L$, I^{TV}_{k+L} is the interference from the TV transmission into channel $k+L$ and η is the background noise.

Note that the throughput obtained using (8) and throughout the reminder 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 that has an index i and hops among the M available channels with equal probabilities. Denote the channel used by the serving AP as $\acute{m}$ at each hop. Thus, the average downlink throughput, C_{hop}, for each SU is calculated as

$$C_{hop} = \frac{1}{M}\sum_{m=1}^{M}\log_2\left(1+\frac{P^r_{k+L}(x,y)}{\sum\limits_{\substack{j=0\\ j\neq i}}^{N}\left(\beta_m P^r_{j,m}(x,y)\right)+I^{TV}_m+\eta}\right), \tag{9}$$

where

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

Without loss of generality, one can neglect the interference of adjacent channels among the APs because the use case is a low-power short-range WiFi-like system.

IV. Methodology

The methodology for evaluating the proposed frequency hopping framework is explained in this section. A representative case study is considered in which data based on measurements and simulations are obtained. Moreover, a simulation of deployed APs performing frequency hopping in TVWS is performed based on the findings of the representative cases.

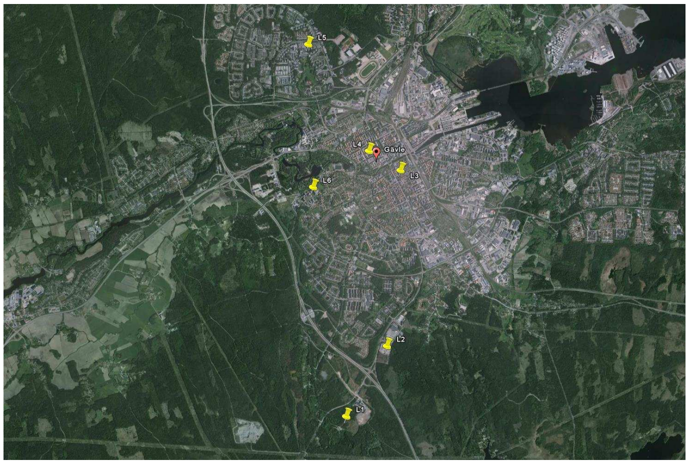

Figure 4. Measurements locations in Gävle. Measurements locations are the yellow markers

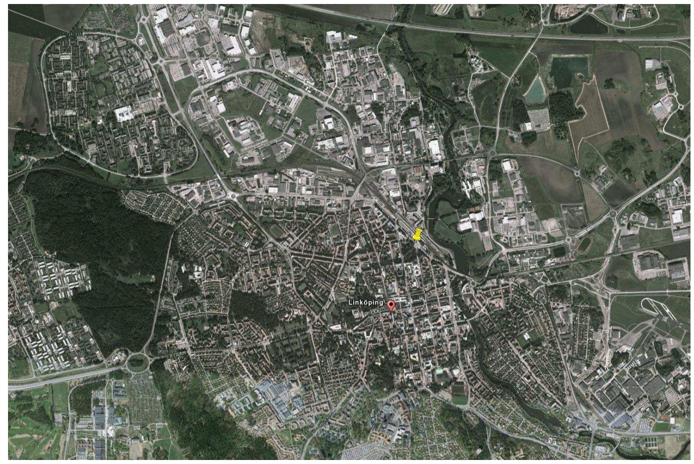

Figure 7. Measurements locations in Linköping. Measurements locations are the yellow markers.

Figure 5. Measurements locations in Stockholm. Measurements locations are the yellow markers

Figure 8. Measurements setup

A. Obtaining TV Received Signal Power

SPLAT (RF signal propagation, loss, and terrain analysis tool) [27] is a simulation tool that is used to obtain the received signal power at each point inside the area under investigation. The input data to SPLAT are the transmitter properties (e.g., transmission power, mast height, and so forth) which were obtained from the Post and Transport Agency (PTS), the Swedish communication regulator. SPLAT uses the Longley-Rrice propagation model [27] and terrain data that are available online at [27]. The simulation results for channel 24 in the surroundings of the Gävle area are shown as an example in Figure 11.

B. Measurements for Obtaining TV Interference into Free Channels

The TV transmission interference into free channels is not covered by the simulation model; rather, an empirical model for this interference is developed. Measurements are performed in three areas served by three different TV transmitters in Sweden, namely in the cities of Gävle, Stockholm and Linköping. In Gävle, the measurements were extensive and performed in 6 different locations, marked as L1-L6. The measurements in Stockholm and Linköping are complementary and performed for comparisons and to consider areas with different characteristics. Table III shows the GPS coordinates and descriptions of the measurements locations. Google Maps images for the measurements locations are also presented in Figures 4, 5, and 7.

The measurements are performed using a set up that consists of an antenna, a spectrum analyzer and a PC. The antenna and the spectrum analyzer are used to capture the signal in the entire TV band, which is then recorded using the PC for further analysis. The PC also controls the spectrum analyzer. Figure 8 presents a field photo of the measurements setup. Moreover, the equipments and other parameters are provided in Table I.

V. Results

The results can be divided into three parts, namely, fetching the interference from the TV transmission into the free channels, obtaining the model parameters part and evaluation

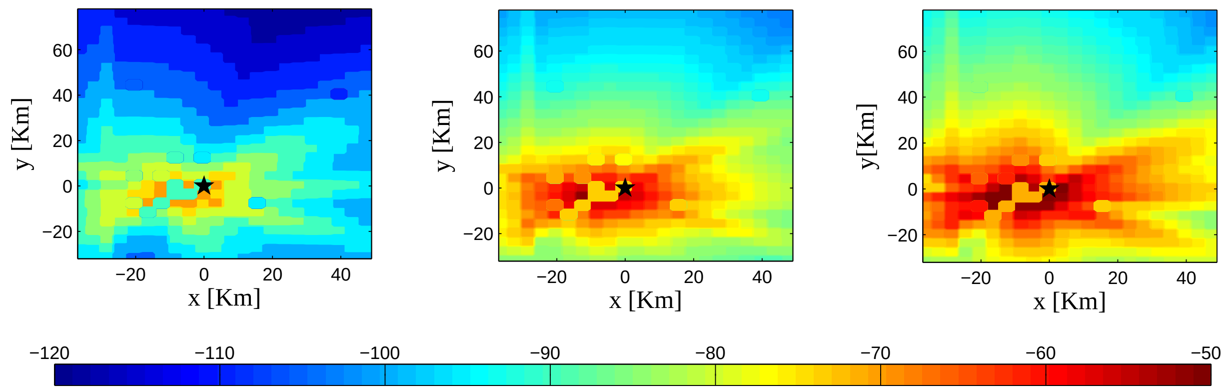

Figure 6. Maximum allowed transmission power density [dBm/Hz] for a SU in channels 25, 48, and 35 (from left to right). All the color-coded values correspond to the Gävle area.

TABLE III. Measurements Locations

Measurements Location		*Description*	*GPS coordinates*	*Active TV channels*
Gävle	L1	Next to the TV transmitter antenna	60.6400 N, 17.1322 E	24, 27, 30, 32, 46, 50
	L2	In a supermarket	60.6417 N, 17.1428 E	
	L3	In the city center	60.6734 N, 17.1395 E	
	L4	In a school	60.6689 N, 17.1514 E	
	L5	In an apartment	60.6904 N, 17.1198 E	
	L6	At University of Gävle	60.6692 N, 17.1210 E	
Stockholm		Office complex (ELectrum)	59.4053 N, 17.9489 E	21, 27, 31, 39, 40, 42, 53
Linköing		Central train station	58.4166 N, 15.6250 E	23, 36, 39, 42, 50, 53, 55, 56

of the deployed APs part. The AP evaluation is based on the achieved throughput.

A. Interference from TV Transmission into Free Channels

The interference from the TV transmission is caused by the non-linearities introduced by the TV transmitter power amplifier. These non-linearities are divided into spectrum leakage and intermodulation products. Figure 9 is a qualitative illustration of the measured leaked power at location L2 in Gävle as an example. In Figure 10, the intermodulation products are shown. For later analysis the quantitative findings of both the spectrum leakage and the intermodulation products are used.

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.

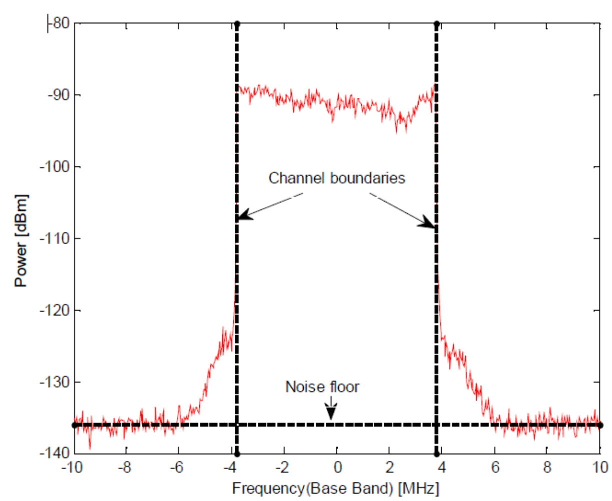

Figure 9. Measured spectrum of channel 30 at location L2 in Gävle. The leaked power from channel 30 into its adjacent channels is observed.

B. Obtaining Model Parameters

As described in Subsection IV, the received TV signal power and the TV interference into free channels are needed. The received TV signal power is obtained by SPLAT, as shown in Figure 11 as an example of one channel.

Using the received TV signal power at all points in the study area, the maximum permissible transmission power is calculated using (5). Figure 6 shows this permissible transmission power density for channels 25, 48, and 35 in the Gävle area. These three channels have been chosen as representatives for the 1^{st}, 2^{nd} and 3^{rd} adjacent channels, respectively. The figure shows how the permissible transmission power for SU differs in different channels and different locations. For example, SUs can transmitting in channel 35 with an approximately 20 dBm/Hz higher power density compared to transmit in

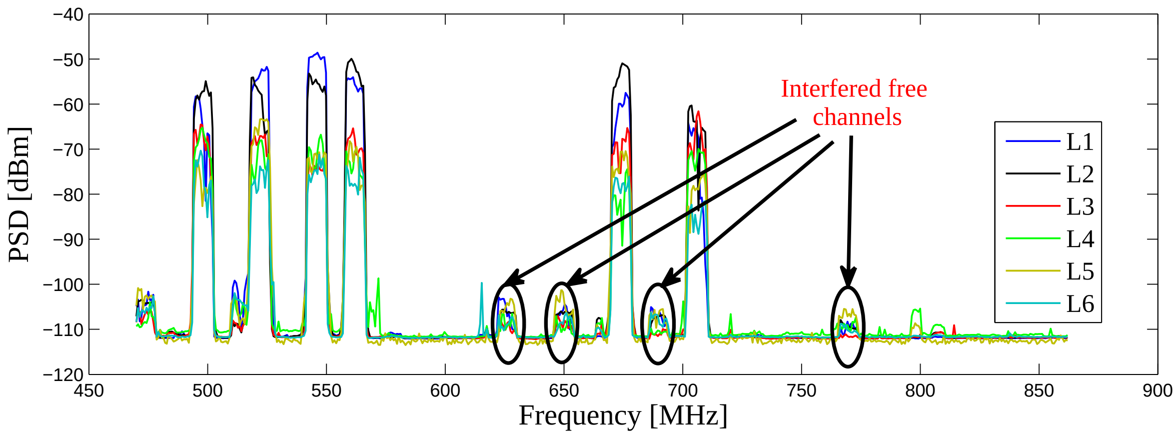

Figure 10. Spectrum occupancy for the entire TV band in the measurements locations in Gävle, L1-L6.

Figure 11. SPLAT results for the received signal power for channel 24 [dBm] in the Gävle area as a function of the TV receiver location.

channel 25.

C. 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 three different TVWS channels without hopping. AP1 uses channel 47, AP2 transmits on channel 34, and AP3 operates on channel 36. These three channels are selected to have three different classes of the provided throughput. Figure 12 shows the cumulative distribution function (CDF) of the throughput on each channel when each AP holds on its channel. As shown in this figure, user 1 served by AP1 obtains the lowest throughput all the time with an average of 2.6 bits/sec/Hz, while user 3 served by AP3 achieves the highest throughput with an average of 6.4 bits/sec/Hz. Applying frequency hopping among the three channels for all APs would then make the three users achieve the same throughput with an average of 5.8 bits/sec/Hz. Therefore, the three available channels are shared among the three APs in a fair manner.

As another case, Figure 16 shows the achievable throughput per square meter in Stockholm when using different numbers of APs for different floor areas. All the findings shown in Figure 16 consider a hopping set of 3 channels, which are channels 24, 36, and 48 chosen randomly.

Now, suppose that frequency hopping is applied among a certain set of channels, called a hopping set; then the achieved throughput depends on the permissible transmission power and the TV interference on this hopping set. As an example, consider the following three cases. In Case 1, the hopping set is three interfered channels with low permissible transmission power; for this case, use channels $44, 45,$ and 47. Case 2 uses better channels than Case 1, namely channels $25, 34$ and 35. the case 3 hopping set is the best, where chan-

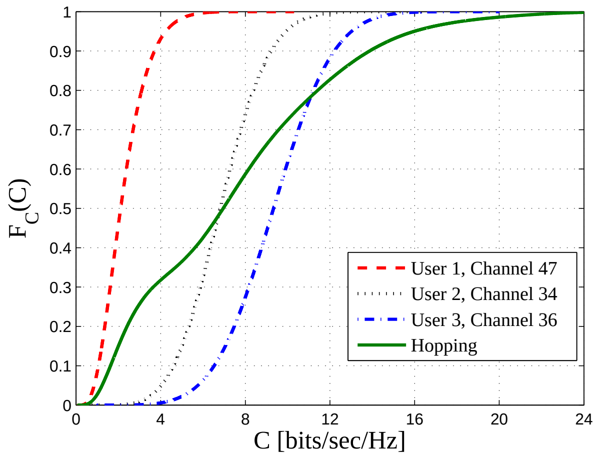

Figure 12. Achieved throughput CDF when using three different channels individually and when hopping is applied.

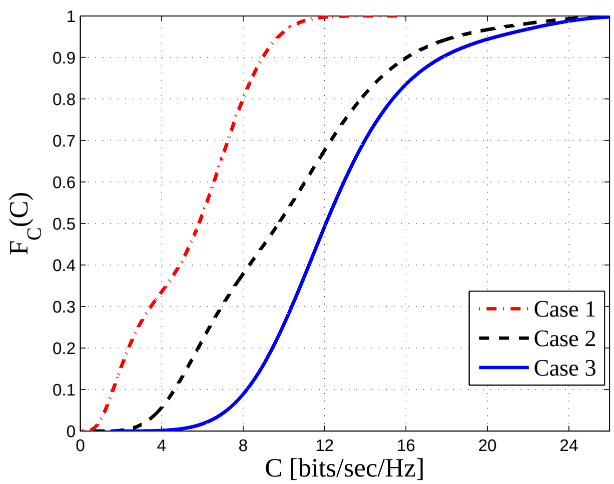

Figure 13. Achieved throughput CDF for three different cases when 3 channels are used by the APs with frequency hopping.

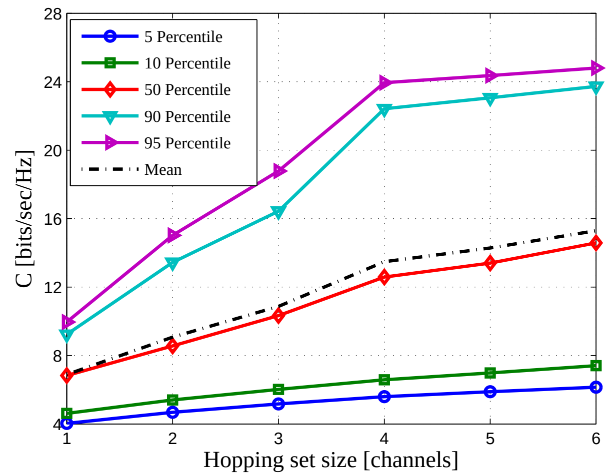

Figure 14. The 5, 10, 50, 90 and 95 percentile for the achieved throughput when using different sizes of hopping sets.

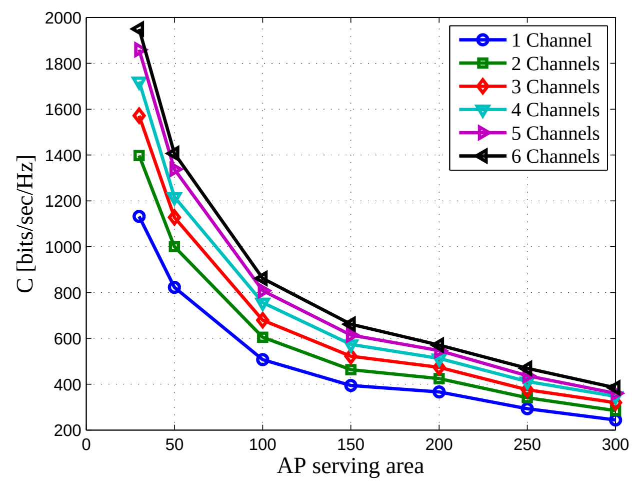

Figure 15. Overall throughput achieved in the building located in Gävle, L4 using different AP serving areas (i.e., different numbers of APs).

nels $35, 36,$ and 51 are used. As Figure 13 depicts, hopping among the case 1 set provides the lowest throughput, while using the channels in case 3 as a hopping set provides the highest throughput. the throughput in case 2 is in between that of cases 1 and 3. Quantitatively, the case 1 set provides approximately 50% of the throughput that the case 3 set achieves.

An important factor for the achieved throughput is the size of the hopping set (i.e., the number of channels). In this regard, a simulation is conducted in which the set size is changed. The hopping set is chosen such that the average channel quality is preserved when comparing different set sizes. Figure 14 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 the 50 percentile, when increasing the hopping size beyond 4 channels, the linear increase stops and the gain in the throughput tends to saturate. This result is due to the fact that APs using the same channel are more likely to be further separated when higher hopping sets are used.

Together with the hopping set, the AP serving area, which determines the number of APs in the building, determines the achieved throughput in the entire building. Figure 15 shows how the total throughput provided by the WiFi-like system is affected by changes in the AP serving area and the hopping set. Figure 15 shows that increasing the AP serving area decreases the provided throughput for the entire building because there are less resources to handle the traffic. However, increasing the AP serving area increases the distances between the APs using the same channel while hopping, which in turn decreases the interference among the APs. Therefore, the decrease in the throughput does not occur linearly with the increase in the AP serving area. It is important to study the throughput map in the building. Figure 17 presents a color-coded map of the throughput in one of the building floors with the APs locations. The figure is generated considering a deployment of 25 APs. In general, it is observed from the figure that the closer to the

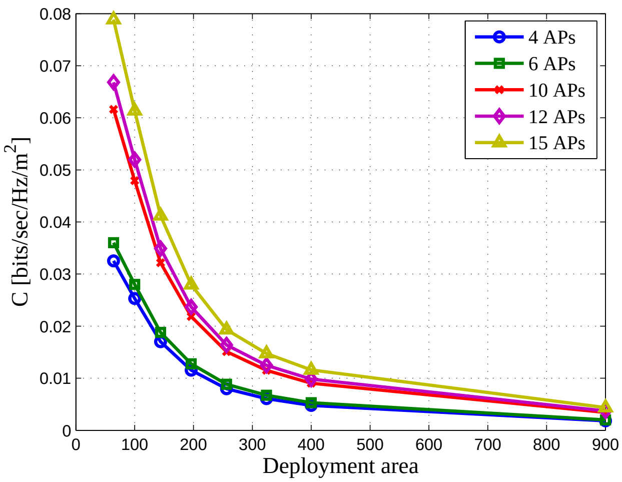

Figure 16. Achievable capacity density in the simulated building located in Stockholm in the measurements location using different numbers of APs and different floor areas.

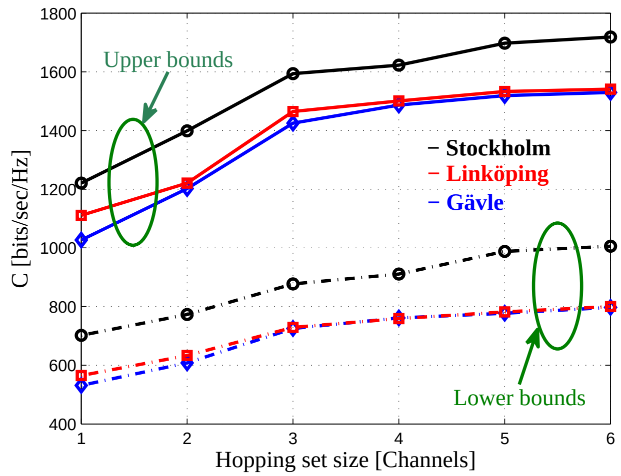

Figure 18. Throughput's upper and lower bounds in the measurements locations in Gävle, Stockholm and Linköing.

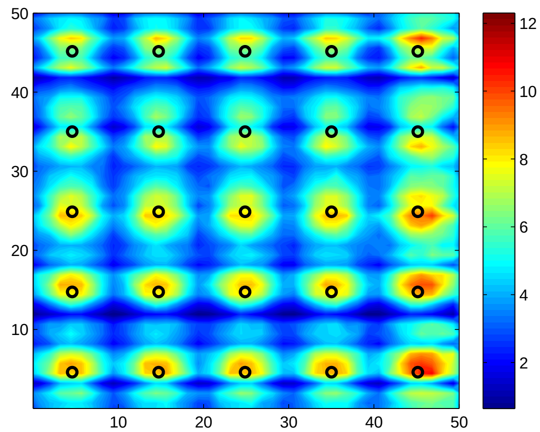

Figure 17. Average throughput at different points in one of the building's floors located in Gävle. The black rings are the deployed APs.

AP that the user is, the higher the throughput that they receive. This result is not only because of the higher received power from the AP but also because of being further from the other APs that use the same channel and hence, less interference is experienced. Moreover, the APs located closer to the edges of the building supply higher throughput because other interfering APs are located at one side and therefore have longer distances to APs located at the edges. On the other hand, the APs in the middle receive interference from all directions with lower distances from the interferes, which decreases their provided throughput.

For comparison, Figure 18 shows the upper and lower bounds for the entire building throughput for the simulated office building located in Gävle, Stockholm and Linköing. The bounds are considered when the hopping set is composed of 3 channels. For the upper bounds, the best 3 channels in each location are used for the hopping set, while the worst 3 channels are used to reach the lower throughputs' bounds. As shown in the figure, in the Stockholm area, higher throughputs are attainable in both sides due to the existence of higher buildings and more objects that attenuate more of the interfering signals. An important observation here is that the TV signal in Stockholm is still high compared to that in Gävle and Linköing, which enables high secondary transmission power. This high received TV signal is observed despite the high building and existence of attenuating objects, which is due to some consideration in the system design of the TV mast height and the transmission power. Comparing Gävle and Linköing, it is observed that the performance is nearly identical with slightly higher performance in Linköing. Note that these results are for the measurements locations which are specific cases. However, the general tendency can be extrapolated.

VI. Conclusion

Throughout this paper, the performance of a WiFi-like secondary network deployed in an office environment has been studied. Three different locations in three different cities, namely Gävle, Stockholm and Linköing, all located in Sweden, are considered for the studies within this paper. The secondary WiFi-like network operates in a TVWS using the 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 using 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. The results have shown that different TV channels experience a large variety in their provided throughput. Therefore, frequency hopping is applied for fair resource distribution among the access points. Moreover, an investigation on the impacts of the size of the hopping set and the number of deployed APs has also been conducted.

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