Experimental Verification of Indoor TV White Space Opportunity Prediction Model

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Abstract—**Recent work has demonstrated that the underutilized spectrum in the Digital Television Bands, commonly referred to as TV White Space (TVWS), is a prime candidate for opportunistic spectrum access (OSA). However, a systematic assessment of the availability of this spectrum for secondary transmission was, until very recently, lacking [5] [6]. In [6] a TVWS opportunity prediction model to estimate indoor secondary usage probability was proposed. In this paper we aim at verifying this model by means of measurement campaigns in both laboratory and real indoor environments. The match between the predictions from the simulation models in [6] and measurement results suggest that the model provides a realistic evaluation of the opportunities in TVWS for low power indoor secondary usage.**

Key Words: White Space, Digital Television Broadcasting, Opportunistic Spectrum Access.

I. Introduction

The constantly increasing need for new wireless services and applications has put the problem of spectrum scarcity in the spotlight. A potential opportunity is the spectrum freed up due to the switchover from analog to digital terrestrial TV, known as the Digital Dividend. However, also it has been suggested that temporally or spatially unused spectrum portions in TV bands, so called spectrum holes or white spaces could be used for other services. The suggestion is that frequencies assigned to the primary users (i.e. TV broadcasters), that are not being utilized in a particular time and specific geographic location, could be temporarily used by secondary users [1] [2].

The debate about allowing the operation of unlicensed access to temporarily vacant channels between occupied DTV channels is still ongoing [1]. Television broadcasters state that operations in the spectrum holes or white space will result in harmful interference to the DTV receivers due to their particular filter characteristics. Industrial and academic studies on the TV White Space claim that unlicensed devices operating (so called White Space Devices, WSDs) in the white space will not affect the quality in the reception of the DTV signal if Co-channel interference is avoided. In such an opportunistic spectrum access (OSA) approach, White Space Devices will periodically sense the spectrum in order to detect the presence of DTV signals and adapt their transmissions to avoid mutual interference.

Previous work on the feasibility of White Space Device (WSDs) operation in different scenarios has given quite diverse results [3] [4].Of critical importance to avoid harmful interference from WSDs are the spectrum sensing techniques, the separation distance between WSD and DTV receiver, the power levels and modulation techniques used by WSDs. Further, some theoretical studies have been done to quantify the real spectrum opportunities in the TV white space [5] [6].

Previous experiments in [7] and [8] have analyzed the interference generated by a DTV or NTSC signal into DTV reception. The interference generated by outdoor WRAN BS into DTV reception was studied in [9], that experiment was limited to the case of a single interferer with high transmit power. Measurements to quantify the interference effects of 3G and WiMAX signals on typical DVB-T receivers were conducted in [10]. The outdoor scenario with two different types of TV receiving antenna, outdoor and indoor antenna, was considered. Generally, these experiments aimed at specifying recommended thresholds or protection level required to guarantee the quality of DVB-T reception. However, the scenario where low power indoor WSDs are transmitting in the close proximity of the TV receiver has to our knowledge not been analyzed in any of the previous experiments.

As the WSDs become very close to the TV receivers in short-range indoor scenarios, it was demonstrated in [6] that not only the co-channel interference is a problem. Due to the limited Adjacent Channel Interference (ACI) rejection capabilities of simple TV-receivers, also the interference on near-by channels has to be considered. When determining spectrum reuse opportunities for WSDs. The interference models used in [6] are partially well-known but also some new assumptions are made, that need experimental verification. The purpose of this work is to verify the assumptions and interference model proposed in [6] by assessing the impact on TVs reception quality when low power WSD interference is operating in different channels in a real indoor environment.

The rest of the paper is organized as follows: section II gives a short introduction of our interference model proposed in [6];in section III, we briefly explain our objectives and approach; section IV explains our measurement setup; section V presents our results from both simulation and measurement as well as our interpretation of the results. Finally, we conclude this work in section VI.

II. Interference Modelling

Three different indoor scenarios are considered in this paper (See Figure 1). In all scenarios, the primary user is the Digital TV receiving broadcasting signal from either

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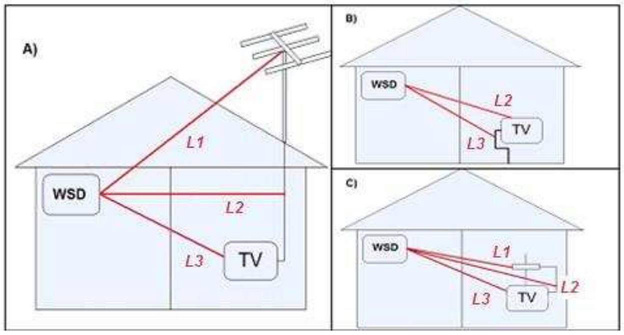

Fig. 1. Indoor Scenarios: Rooftop Antenna (A), Cable Antenna (B) and Set-top Antenna (C) Radiation into the receiver antenna (L_1), the cable (L_2) and the receiver (L_3)

antenna or cable. The secondary user or White Space Device (WSD) is a Wi-Fi like low power local broadband access point operating in both spectral and spatial proximity of TV transmission, with the same bandwidth as a Digital TV channel, i.e. 8MHz (Table I).

The proposed interference model in [6] assumes the interference reaches the DTV receiver over three different paths: through the antenna (path L_1), through the coaxial TV cable (path L_2), direct radiation into the TV-receiver (path L_3).The combined interference power for the three paths was evaluated. (See Figure 1).

The desired received power (P_D) at the TV receiving antenna for channel N will be calculated as follows:

$$P_D = \frac{E^2 c^2}{4 Z_0 f^2} G_{TV}(\theta_D) \tag{1}$$

where E is the field strength at the TV receiving antenna, c is the light speed; Z_0 is the free space impedance, f is the operating frequency and G_{TV} is the gain of the TV antenna. We assume the incoming TV signal is received in the main lobe of the TV antenna ($\theta_D = 0^o$). The total undesired received power (P_U) will be the sum of the interference powers from the WSD transmission (could be operating in a different channel $N+k$,$k = -3, -2, ..0, ..20$) at the receiver input from each interference path (L_1, L_2 and L_3):

$$P_U = \sum_{i=1}^{3} P_{U_i} = P_{WSD} G_{WSD} \left(\frac{G_1}{Lb_1} + \frac{G_2}{Lb_2} + \frac{G_3}{Lb_3}\right) \tag{2}$$

where P_{WSD} is the transmit power of the WSD, G_{WSD} is the antenna gain of the WSD in the direction of the TV receiving antenna; G_1 is the gain of the TV receiving antenna which depends on the incidence angle of the received signal from the WSD which is equivalent to $G_{TV}(\theta_U)$ (path L_1); G_2 is the TV cable attenuation (path L_2) and G_3 is the TV receiver attenuation (path L_3). The path loss, Lb, in each interference path is calculated based on an extension of the Keenan Motley (KM) model [12]. A pessimistic assumption was that the WSD antenna was always pointing towards the TV receiving antenna. The radiation into the receiver antenna constitutes the main component in the interference model. The direct radiation (EMC effects) into the receiver or interference in path L_3 is assumed to be negligible due to its presumed isolation characteristics. Thus, the total undesired received power (P_U) can be expressed as follows:

$$P_U = P_{WSD} G_{WSD} \left(\frac{G_{TV}(\theta_U)}{Lb_1} + \frac{G_2}{Lb_2}\right) \tag{3}$$

Finally, the Desired to Undesired (D/U) power ratio on channel $N + K$ was calculated as the ratio between P_D, the desired received power (Equation 1) and P_U, the undesired received power (Equation 3) at the TV receiving antenna.

$$\frac{D}{U} = \frac{P_D}{PU} \tag{4}$$

A channel is considered as free or available for WSD transmissions when the D/U ratio does not fall below the required D/U limit of the TV receiver.

TABLE I
MEASUREMENT PARAMETERS

WSD Signal Bandwidth (W):	8 MHz
WSD Wireless Interface:	OFDM
WSD Modulation Scheme:	QPSK
WSD Maximum output power:	10dBm
WSD Duplex Scheme:	TDD
WSD Maximum Antenna Gain:	16 dBi
TV set-top antenna 1: panel (Low Directivity)	4dBi (Main Lobe Gain) 0dB (Back Lobe Gain)
TV set-top antenna 2: Yagi (High Directivity)	8dBi (Main Lobe Gain) -10dB (Back Lobe Gain)
TV Rooftop antenna gain:	6 dBi
TV signal:	-55dBm (Strong Signal) -75dBm (Weak Signal)

III. EXPERIMENTAL METHODOLOGY

We aim to verify the assumptions and parameter settings in the interference model proposed in [6] by measurement comparing with the simulation results. Based on this knowledge we could further analyze the real opportunity for secondary transmission in TVWS. We will address the following questions:

- Is it enough to account the D/U ratio (Desired to Undesired received power ratio) of neighboring 10 channels? Is the D/U ratio valid as a good reference for estimation of white space opportunities?

- Is the direct radiation in the TV receiver significant? If yes, when is that radiation important? How far should be placed the WSD to make it irrelevant?

- Are the results obtained in [6] comparable to results obtained from experiments carried out in real environments?

Our experiments are composed of three main measurements:

1. Calibration– the first measurement will determine the adjacent channel rejection or D/U ratio of our DTV receiver under both strong TV signal level and weak TV signal level conditions And the results will be used as references for the following measurements and simulations;

2. Verification of the direct radiation impact– the second

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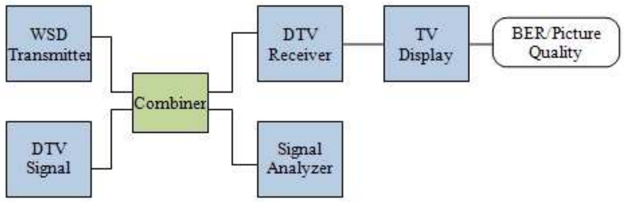

Fig. 2. Setup for Measurement 1

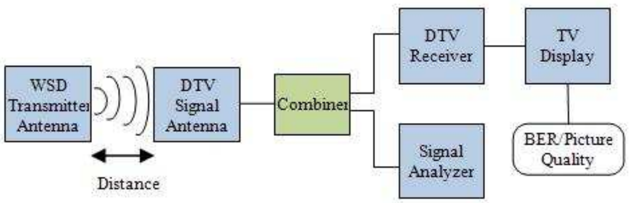

Fig. 3. Setup for Measurement 2

measurement aims at detecting the possible effect of the direct radiation into the DTV receiver generated by the WSD, and thus confirm or falsify the assumption in [6] that the interference from L_3 is negligible;

3. Validation of the prediction model– the last measurement is conducted in real environment (two different apartments). The measurement results are collected and compared with the simulation results based on the predication model proposed in [6].

IV. Experimental Setup

The first measurement has calibration purposes, since we aimed at determining the D/U ratio for acceptable TV reception in the different channel of the TV receivers. Given a fixed DTV signal in channel N, we increase the WSD interfering power in channel $N+K$ until the visible deterioration occurs on the TV display. Then the power ratio between the interference and TV signal is the D/U limit on $N+K$ channel. We repeat the experiment with different TV signal levels. The setup used for the first measurement is shown in Figure 2.

The second measurement is carried out in a laboratory environment with high isolation to any external signals. The DTV signal input is connected to the DTV receiver via high quality cables. In this way we isolated the effect of direct radiation into receiver. The WSD interfering antenna is transmitting at maximum output power (20-23dBm EIRP) with varying distance from the TV receiver. Thus, measurement results provide a lower bound approximation.

The third measurement is performed in the two different apartments using setup shown in Figure 3. The WSD antenna is placed randomly in the apartments. In order to create the worst case, the WSD antenna is always directed to the TV receiving antenna (see Table I) and transmitting at the maximum output power. At each location, the WSD operating channel varies along the whole UHF band. If the TV display glitches, then that channel is marked as unavailable for WSD transmission.

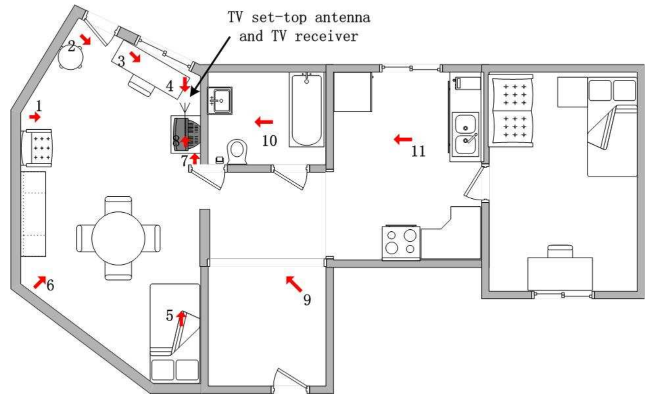

Fig. 4. Floor plan for Apartment 2 (city center) with red arrows indicating location and direction of the WSD transmitter

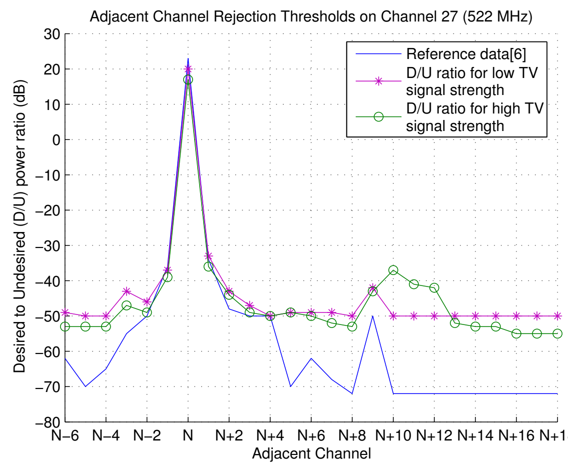

Fig. 5. Adjacent Channel Rejection Thresholds on Channel 27 (522 MHz) ratio

Apartment 1 is located in a suburban area with weak TV signal strength and Apartment 2 in the city center with strong TV signal strength. Both apartments have an average area of $70m^2$. The floor plan of Apartment 2 is illustrated in Figure 4. We use R&SFSQ 26 as a signal Analyzer and R&SMV 200A to generate WSD interference signal, parameters are shown in Table I.

V. Experiment Results

A. Calibration

From the measurements, we can verify the performance variations for different TV signal strengths. An observation that had also been confirmed in previous studies is the anomalies in adjacent channel $N+9$, which is less noticeable when a receiver with bad performance is tested. In addition, intermodulation effects [9] are observed in channels $N+11$, $N+12$ and $N+13$ for a strong TV signal level. From Figure 5, we can also observe that the receiver used in our measurement campaign can be categorized as a receiver with bad performance, since theD/U thresholds are above the reference level for a regular receiver [7].

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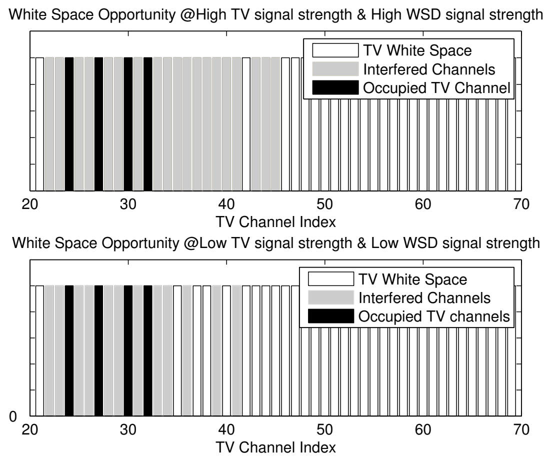

Fig. 6. Illustration of White Space Opportunities in the city of Gävle for different TV signal levels

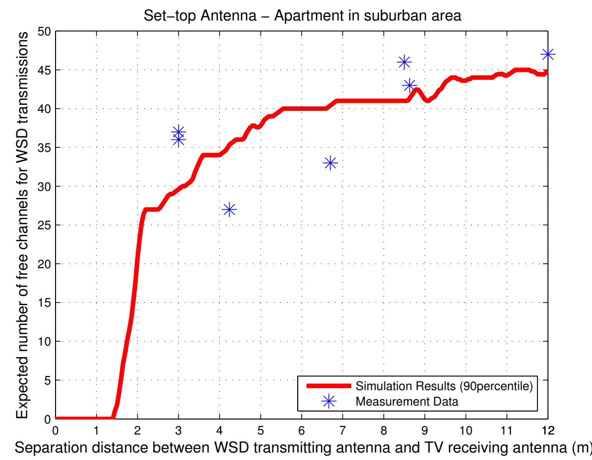

Fig. 7. Expected Number of available channels for WSD transmissions (low directivity set-top antenna)

Given the D/U characteristic of TV receivers, we could estimate the TV White Space Opportunities. Figure 6 illustrates the possible opportunities for a typical indoor scenario in an apartment in the City of Gävle, where WSD is operating in the proximity of TV with set-top antenna. There are four channels occupied by the TV broadcasting, so in theory all the other 45 channels could potentially be used for WSD transmission. However, due to the Adjacent Channel Interference, only 70% of the potential free channels can actually be used when we have low interfering power and low TV signal strength. This percentage is further reduced to 55% if strong signals cause intermodulation effect to the TV receiver.

B. Verification of the direct radiation impact on TV receiver

This experiment was carried out in a lab environment where the isolation is high and external signals are eliminated. The transmitting WSD antenna was moved around in the very close proximity of the DTV receiver, with separation distance in the range of zero to two meters. However, we were not able to notice any distortion on the TV display at any separation distance, even when the TV input signal was attenuated to a very low level and WSD transmitting at maximum EIRP. The assumption of neglecting direct radiation from the WSD into the receiver (path L_3) could thus be verified. In addition, noticeable interference through the cable feeder (path L_2) was not observed in any case.

C. Validation of simulation results

We counted the number of available channels for WSD transmission with different type of TV signal receiving setups. (Rooftop, Cable, Set-top) in both apartments. The results indicates severe co-channel interference for all configurations, thus co-channel transmission should be avoided. But we also noticed there are no harmful adjacent channel interference for cable and rooftop antenna scenarios, due to the high isolation of the cable and high pathloss between WSD antenna and TV rooftop antenna. For the case of set-top antenna, WSD

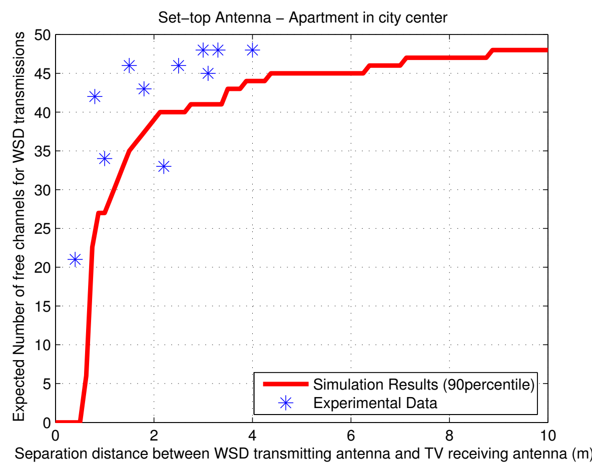

Fig. 8. Expected Number of available channels for WSD transmissions (high directivity set-top antenna)

transmissions could cause harmful interference to TV signal not only when the WSD is transmitting in the first adjacent channels ($N+1$ and $N-1$), but also when the transmitting channel of WSD is far away in frequency from the channel used by the TV broadcasting (channel N).

From Figure 7, we notice that for Set-top antenna, adjacent channel interference causes distortions to TV signal, especially for short separation distances. In comparison, with a high directivity TV set-top antenna and higher TV signal strength (Figure 8), the number of available channels for WSD increases even at shorter separation distance. Previous studies [6] have analyzed the effect of the WSD transmit power on the the number of available channels, their results demostrated that decreasing the WSD transmit power can actually increase the number of available channels for set-top antenna, however adjacent channel interference is still an important issue even for very low WSD transmit power.

As for the allocation of the available channels, we define

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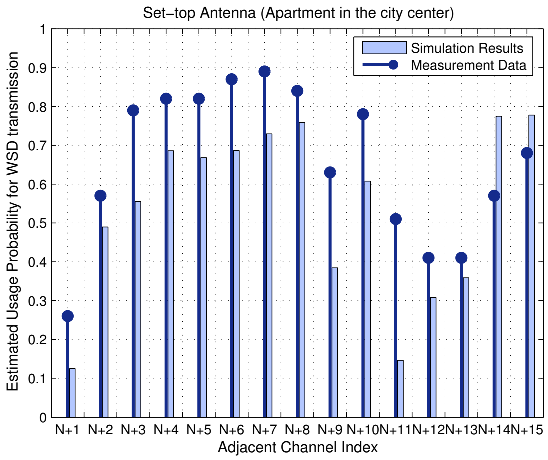

Fig. 9. Estimated Usage Probability for WSD transmission in each adjacent channel

the Expected Usage Probability of each adjacent channel as the probability that the WSD transmission on one adjacent channel will not cause severe interference to the TV reception in set-top antenna scenarios, regardless of the placement of WSD or TV receivers. We estimate this probability with the ratio between the number of experiments with successful reception and the total number of experiments, where the WSD transmitter is uniformly placed along the wall of the apartment. From Figure 9, it can be seen that the WSD transmissions on $N+1$, $N+2$ and $N+9$ will be most likely to affect the TV reception in both simulation and measurement. In addition, the possible intermodulation between WSD signal and strong TV signals in other broadcasting channels would also lower the Usage Probability in channel $N+11, N+12$ and $N+13$. (Channels with index larger than $N+15$ is not shown, since usage probability remains above 90%). In all the figures above, the measurement results match the numbers we obtained from simulation, which was adjusted according to the real environment and the characteristic of the particular receiver. The simulation results are more pessimistic due to the worst-case assumptions in our prediction model, but they can be used as lower-bound reference.

VI. Conclusions

In this paper we have evaluated a prediction model for assessing the TV white space availability through a series of measurements in both laboratory and real environments. In general, we have demonstrated that the assumptions and parameter settings of the model proposed in [6] are reasonable and the overall performance predicated by the model matches to our measurement results.

In particular we have confirmed that the direct radiation from WSDs into cables and the TV receiver set-top box can be neglected. For cable-TV or roof top antenna reception, adjacent channel interference was not severe and it is possible to use WLAN-like low power indoor WSD in almost any vacant TV channel without any noticeable effects on the TV reception quality. However, when an indoor, set-top antenna is used for TV reception, our measurements have verified that the number of available channels for WSD is significantly reduced, due to adjacent channel interference. Strong ACI causes intermodulation products between the signals from the WSD and other TV broadcasting channels. To achieve acceptable results for WSD, lower power than typical Wi-Fi devices or careful placement has to be employed.

Further work includes studies of a more realistic scenario with multiple WSDs simultaneously operating in different frequency channels in TVWS. Also the cumulative effect of multiple WSD interference to the TV receiver performance is of interest to provide a more comprehensive assessment of the opportunities in TVWS.

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