IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received August 4, 2017, accepted August 21, 2017, date of publication September 11, 2017, date of current version October 12, 2017.

Digital Object Identifier 10.1109/ACCESS.2017.2751138

Application of Radio Environment Maps for Dynamic Broadband Access in TV Bands in Urban Areas

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The work of A. Kliks and P. Kryszkiewicz was supported by the National Science Centre, Poland, through the SONATA Project under Grant DEC-2015/17/D/ST7/04078. The work of A. Umbert, J. Pérez-Romero, and F. Casadevall was supported by the Spanish Research Council and FEDER funds under RAMSES grant TEC2013-41698-R.

ABSTRACT Spectrum sharing based on the dedicated databases, particularly in the context of TV band, is widely considered as a promising tool for better spectrum utilization in the future wireless networks. Practical realization of this paradigm entails the need for the true protection of the incumbent system, and at the same time the guarantee of the quality of the services offered to the secondary users. In this respect, this paper discusses the results achieved in numerous measurement campaigns performed for last years in two European cities, i.e., Poznan, Poland, and Barcelona, Spain. Both indoor and outdoor measurements of the TV band have been compared with the main purpose of true identification of key practical considerations for spectrum sharing in the TV white spaces. As such, this paper constitutes a concise summary of various analyses and provides pragmatic guidelines for deployment of radio-environment maps (REM)-based systems. Based on the conducted measurements and achieved results, the set of practical conclusions for REMs has been deduced, and the prospective procedure of deployment of such a network has been proposed.

INDEX TERMS Spectrum sharing, radio environment maps, system coexistence, TV white spaces.

I. INTRODUCTION

The idea of simultaneous usage of the spectrum by the incumbents (known also as the Primary Users, PU) and the Secondary Users (SU) has attracted the research community for many years. This trend has been intensified by the key findings in the area of spectrum sharing, which was the invention of the cognitive radio technology, proposed for the first time by Mitola and Maguire [1]. The idea of introduction of some artificial intelligence to the whole wireless communication ecosystem has paved the way for the development of new paradigms for better spectrum utilization. It appeared as a good solution for the well known problem of highly underutilized spectrum resources (various measurements have shown that at certain time and location the spectrum is occupied even only at the level of 20% [2]–[8]). Various research activities associated with dedicated measurement campaigns have been conducted. In [9] the focus was on the extended spectral analysis of the UHF TV band, which has been conducted to achieve realistic values of selected figures of merit: occupancy threshold, sensing bandwidth, noise, and hidden-node margin. The authors of [10] concentrated on discussion of co-channel and adjacent channel interference and protection aspects with regards to the DVB-T2 and IEEE 802.22 WRAN systems. Other interesting results coming from measurements campaigns or field tests can be found in, e.g., [11]–[13]. In consequence, new spectrum sharing policies among various stakeholders have been proposed and discussed by various bodies, including academia, regulators, mobile network operators and others. The application of the cognitive radio idea has been particularly analyzed in the context of TV bands, where big portions of spectrum have been released due to the digital switch-off in many countries, e.g., [14]. Recently, however, various decisions have been made which envisage the flexible usage of certain frequency bands and application of so-called white space devices, e.g., [15]–[21]. At the same time, regulators such as Ofcom or Federal

Communications Commission (FCC) force the development and deployment of new wireless systems under various spectrum sharing strategies (e.g., Licensed Shared Access, or Citizen's Broadband Radio Service with Spectrum Access System) [22], [23].

In that context, the increasing traffic demand in wireless networks and problems of getting exclusive spectrum, will lead future wireless networks to face a severe shortage of spectrum, especially in urban areas. This problem can be particularly critical when considering the highly dense deployments of small cells envisaged for meeting the demands of future systems. Again, technological solutions that enable spectrum sharing, such as Cognitive Radio Networks (CRN), will bring the light to this spectrum scarcity problem. Two questions arise when thinking about deploying these solutions: *What bands can be considered to share?*, and *How to manage this spectrum sharing?* A popular answer to the first question is the television band due to the presence of several channels not used, called as TV white spaces (TVWS), and due to the nearby static channel assignment. Conversely, the answer to the second question is more complex and requires a deeper analysis and discussion on advanced, flexible spectrum management systems. However, it has appeared that the practical implementation of the pure cognitive radio concept with all phases of the cognitive cycle is very challenging. It is mainly due to the insufficient accuracy or efficiency of the spectrum sensing methods [7], [8]. Single node spectrum sensing seems to be not able to guarantee expected protection level of the incumbents, as the reliability of sensing procedures is not high enough to meet the requirements defined by various regulators. For example, in [24] and [25] FCC identified many criteria for white space devices, such as the detection threshold at the level of −114 dBm averaged of 6 MHz channel for Advanced Television Systems Committee (ATSC) signals.[1] Analogously, Electronic Communications Committee (ECC) discussed the detection thresholds at the level of around −120, or even −140 dBm [26]–[28].

One of the possible solutions to the problem of unreliability of the single-node spectrum sensing or the problem of hidden nodes is to apply either separately or jointly: (a) the cooperative sensing algorithms [7], [27], [29], [30] and (b) the so-called radio environment maps (REMs) [31]–[35]. The latter is a form of advanced database with some learning capabilities, abilities for enforcing optimized solutions and interactive decision making. A REM, originally introduced by the Virginia Tech team [36], is a database consulted by intelligent devices containing information on the radio environment. Thus a REM could be able to estimate the state of certain locations where no measurement data is available by using its cognitive engine. Particular attention shall be put on some EU-founded projects, i.e., FARAMIR,[2] ARAGORN[3] and COGEU,[4] where some technical considerations on such databases have been discussed.

The use of shared spectrum such as TVWS to extend the capacity in LTE and LTE-A networks has been found particularly relevant in different works [37]–[40] for small cell scenarios. However, there are actually still very few works that have addressed the problem of how to allocate TVWS spectrum in an optimized way. In this context, this paper raises practical considerations on the REM deployment and intends to support the theoretical activities by analyzing in particular the characteristics of the TVWS band (e.g. stability, etc.) so that a REM database can be built as a support for the deployment of small cells using TVWS. Moreover, the paper also addresses the design of the REM structure including the relevant parameters to be stored. The characterization is done based on measurements both in indoor and outdoor locations. A proper characterization of the indoor behaviour can be relevant for deploying local REMs that include detailed radio environmental information of a reduced area, e.g. at the level of a building and its surrounding buildings, usually corresponding to the coverage area of a few small cells. Instead, the characterization of outdoor locations will be relevant from the perspective of global REMs that encompass larger areas.

In a nutshell, a lot of work has been done in order to identify the best way how to utilize spectrum in a flexible way and how to make the devices more spectrum agile. At this stage it is apparent that REM can be considered a key technical enabler for the practical implementation of the cognitive radio concept. Besides, it has been identified that the abovementioned hierarchical structure composed by both local and global REMs is appropriate for a better management of local resources [34]. This hierarchical approach is particularly for the case where the secondary system will be deployed in a small geographical area. An exemplary case is the mass deployment of cognitive small cells outside building (e.g., along the streets on road infrastructure) for better broadband service delivery to mobile users. Another interesting case would be to utilize the licensed spectrum inside the building benefiting from the high wall attenuation. In other words, the spectrum being occupied outside the building will be treated as vacant inside the building due to the attenuation of the signal after passing the walls. One may foresee that application of local REM databases for these transmission schemes would increase the spectrum utilization and will provide new services to the users while protecting the PUs, e.g., TV broadcasters.

These two cases have motivated us to perform some long-term investigations on the possibilities of real deployment of secondary systems with associated REMs that will operate in TV band while protecting the Digital Video Broadcasting Terrestrial (DVB-T) receivers. Our goal was to verify various factors which may influence the practical deployment of such secondary system and to identify how these factors map on the design of the secondary system. In order to meet

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[1] please note that this value is below the thermal noise power observed within such band at the temperature of 20° C, what equals approximately −106 dBm

[2] www.ict-faramir.eu

[3] www.ict-aragorn.eu

[4] www.ict-cogeu.eu

these goals we have conducted various measurements (e.g., the received power of the DVB-T signal was measured), both inside the building as well as during some drive tests. We have tested the stability of the signal, the influence of moving objects (both humans and cars), as well as the signal changes in time. Moreover, in order to diversify the results, the experiments have been made in two European cities - Poznan in Poland, where the number of occupied TV channels (also denoted hereafter as multiplexes) is relatively low, and Barcelona in Spain, where the number of active multiplexes is high. Based on the achieved results we were able to draw some conclusions on the practical consideration associated with creation of the REM databases for secondary systems inside and outside buildings. Moreover, the measurements have been performed for a longer time, thus we were able to observe the influence of the change of the channel plan on the REM structure. Thus, the key novelties of the paper are the following:

- we present multiple measurements on the spectrum availability in TV band both in indoor and outdoor locations. The measurement results presented in this paper consolidate and harmonize the prior measurements performed by the authors of this paper and were partially published in [41]–[45];
- we create a direct mapping between the measurements and the REM database indicating which parameters have a substantial impact and which aspects seems to be negligible;
- we discuss various approaches on the creation of the digital coverage maps from the perspective of their practical application in real scenarios;
- we identify a set of practical guidelines for real deployments of REM-based secondary systems.

The paper is structured as follows. First we discuss the details of the measurement setups applied in Barcelona and in Poznan. In the next two chapters we provide in-depth analysis of numerous results obtained withing the conducted indoor- and outdoor-measurement campaigns, respectively. Based on that, in the following chapter we present the comprehensive analysis of the practical aspects of REMs, and finally, we propose a pragmatic procedure for prospective REM deployment, which concludes the paper.

II. MEASUREMENT SETUP

Let us now provide the description of the key parts of the considered experimental scenario.

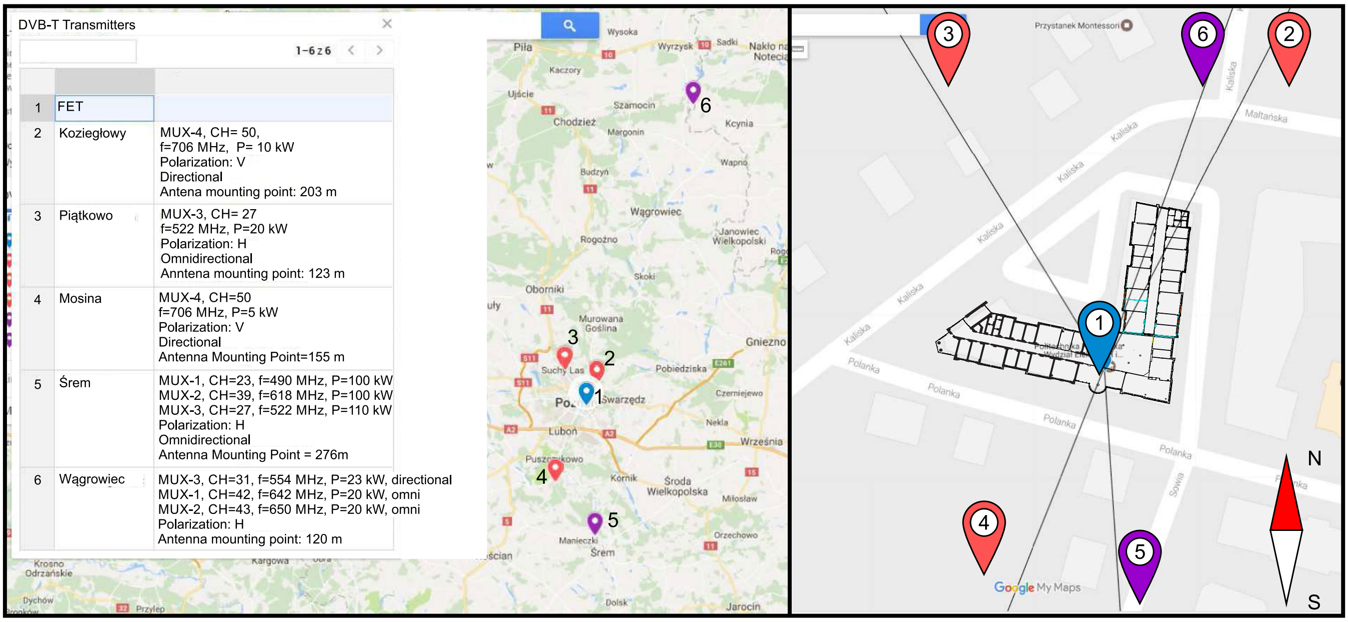
A. CHARACTERIZATION OF THE CITIES

As it was stated in the introductory part, in this paper we compare the results of the measurement campaigns performed in two European cities, namely Poznan in Poland, and Barcelona in Spain. As the latter is the excellent example of a big city, with a high number of inhabitants, Poznan is a representative of an eastern Europe city of mid-size. As for Barcelona, in the administrative boundaries of the city of more than 100 km^2 live around 1.7 million people, which results in the approximate density of more than 16000 persons per square kilometer in 2016. Moreover, the whole urban area counts around 5 million people. From the wireless communication point of view, these numbers mean high traffic requirements and the need for spectrum for delivering new services. On the other side, the city of Poznan has around 540000 inhabitants living on the area of 261 km^2 (resulting in the density of around 2076 persons per square kilometer); the whole agglomeration has around 1 million people. One may observe that in Poznan the average number of people per square kilometer is much smaller than in Barcelona, which results in less demanding requirements put on the wireless communication systems. From the perspective of the study, these two cities are good representatives of two completely different deployment scenarios, what increase the diversity of this analysis.

B. DEPLOYMENT OF DVB-T TRANSMITTERS IN THE CONSIDERED REGIONS

In order to effectively compare the achieved results one needs to be aware of the key parameters of the deployed DVB-T transmitters. In case of Poznan, the location for the measurements are at the premises of the Faculty of Electronics and Telecommunications of the Poznan University of Technology, PUT (exact coordinates are 52°24′1.58″ N, 16°57′21.06′ E). The measurements have been done in two phases; the first set of campaigns have been carried out in 2014, whereas some new results have been achieved in 2016. While the deployment of the TV towers did not change, the frequency plan of the TV channels is different. This is a highly beneficial situation as one may observe the influence of the change of frequency plan on the database creation. The location of the DVB-T transmitters as well as the important parameters are summarized in Fig. 1. The coloring of the pins used on the Google map has the following meaning - blue pin represents the location of the PUT premises, violet pins represent the DVB towers which did not change the transmit parameters, whereas the red pins correspond to the DVB-T towers for which the transmit setup has been modified during experiment time. The key changes are the following: first, the new transmitter has been mounted (location 3 at Piatkowo), second the change of the TV channel from 36 (594 MHz) to 50 (706 MHz) has been applied to stations (pins 2 and 4). Let us note that channel 36 is a scheme of single frequency network (SFN) and the signal comes from two transmitters distanced by 4.6 km and 19.2 km with transmit powers 10 kW and 5 kW, respectively (locations denoted by pins 3 and 5 at the map).

In the case of Barcelona, the location for the measurements are at building D4 at Campus Nord of the Universitat Politecnica de Catalunya UPC (exact coordinates are 41°23′20″ N, 2°6′43″ E). The measurements have been done in 2013, a total of 21 DVB-T channels were detected at the rooftop from one single DVB-T transmitter (named Torre de Collserola) located at 3.1 km. The location of the DVB-T transmitter as

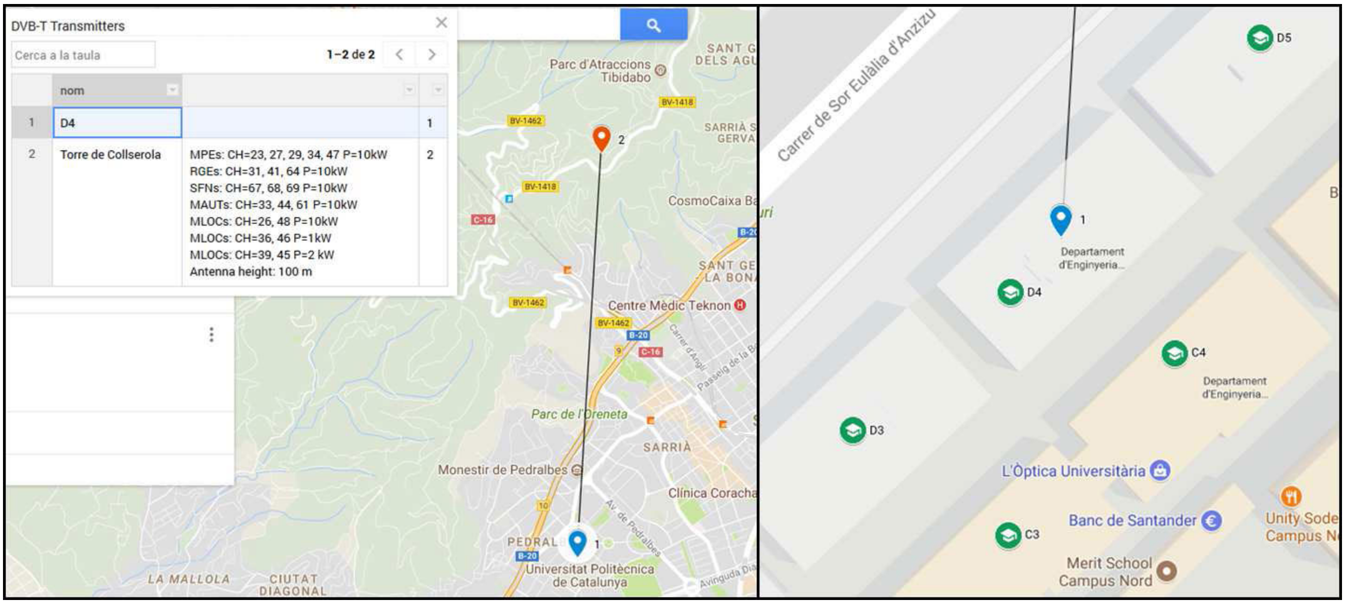


DVB-T Transmitters

1–6 z 6

1	FET	
2	Koziegłowy	MUX-4, CH= 50, f=706 MHz, P= 10 kW Polarization: V Directional Antena mounting point: 203 m
3	Piątkowo	MUX-3, CH= 27 f=522 MHz, P=20 kW Polarization: H Omnidirectional Anntena mounting point: 123 m
4	Mosina	MUX-4, CH=50 f=706 MHz, P=5 kW Polarization: V Directional Antenna Mounting Point=155 m
5	Śrem	MUX-1, CH=23, f=490 MHz, P=100 kW MUX-2, CH=39, f=618 MHz, P=100 kW MUX-3, CH=27, f=522 MHz, P=110 kW Polarization: H Omnidirectional Antenna Mounting Point = 276m
6	Wągrowiec	MUX-3, CH=31, f=554 MHz, P=23 kW, directional MUX-1, CH=42, f=642 MHz, P=20 kW, omni MUX-2, CH=43, f=650 MHz, P=20 kW, omni Polarization: H Antenna mounting point: 120 m

FIGURE 1. Location of DVB-T transmitters with regards to the PUT premises.



DVB-T Transmitters

Cerca a la taula

1–2 de 2

	nom		
1	D4		1
2	Torre de Collserola	MPEs: CH=23, 27, 29, 34, 47 P=10kW RGEs: CH=31, 41, 64 P=10kW SFNs: CH=67, 68, 69 P=10kW MAUTs: CH=33, 44, 61 P=10kW MLOCs: CH=26, 48 P=10kW MLOCs: CH=36, 46 P=1kW MLOCs: CH=39, 45 P=2 kW Antenna height: 100 m	2

FIGURE 2. Location of DVB tower and Barcelona measurement scenario.

well as the important parameters are summarized in Fig. 2, where blue pin represents the location of the UPC premise and red pin the DVB-T tower.

C. BUILDING PARAMETERS

As the location of the buildings is known, as well as the deployment of the TV towers, let us now discuss the key building parameters. In both cases, the indoor measurements have been performed in each room, as well as along the corridors of a typical university building (which can be treated as the example of the office building), where many rooms of similar size are present. Both buildings contain three tiers, i.e., the ground floor, as well as two upper levels. Additionally, premises of UPC have some underground levels. The buildings are quite new - the one at Spain is from 1990, whereas the premises of the PUT have been constructed in 2006. In both cases the outer (load-bearing) walls are made of bricks and concrete, whereas the rooms are spit by means of thinner partition walls. Clearly, each room has a big window and wood-base doors. The floorplans and photographs

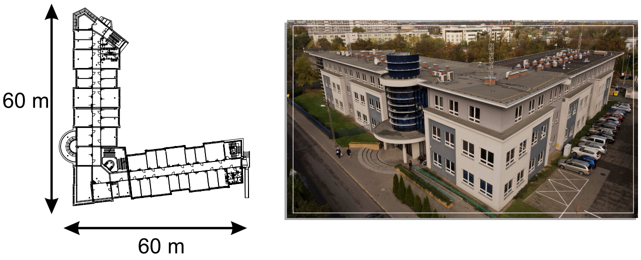


FIGURE 3. Floorplans and photos of the PUT premises.

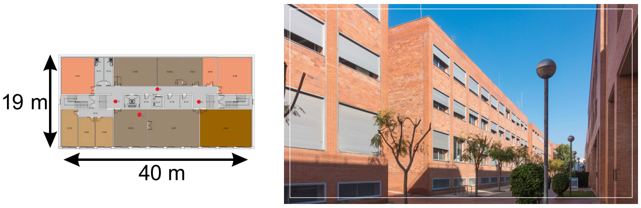


FIGURE 4. Floorplans and photos of the UPC premises.

for a selected tier in both universities are shown in Fig. 3 (for PUT), and in Fig. 4 (for UPC).

Barcelona measurement campaigns include indoor measurements, mainly in the building D4 of UPC Campus Nord, but also in surrounding buildings located at the same Campus. The building D4 consists of 3 floors and 1 basement floor, it has a rectangular shape with dimension 38.6 meters per 17.9 meters, an external structure made of concrete, large glass windows, and interior plaster or brick walls and wooden doors. The distribution of the different floors is similar and combines areas of offices, laboratories and classrooms. The UPC Campus Nord has a regular structure with buildings arranged in rows. D4 is located in the north part of the campus, and it is surrounded by buildings D3, D5, C3 and C4, as shown in Fig. 2. D4 building is closer to the transmitter than C3 and C4 buildings.

D. MEASUREMENT DEVICES - SETUP FOR INDOOR/OUTDOOR TESTS

In general, our goal was to measure the received power of the present DVB-T signals both indoors and outdoors. In both cities the DTV signal was measured by the passive omnidirectional antenna of type AOR DA753, covering the frequency range from 75 to 3000MHz, and then sent to the spectrum analyzer (R&S FSL6 in Poznan, and ANRITSU MS2721 at UPC). Collected samples have been finally stored on the portable computer via Matlab. In both setups the resolution and video bandwidth of the spectrum analyzers were the same and equal to RBW=30kHz and VBW=100kHz, respectively. Moreover, in order to mitigate the multipath effect in indoor campaigns, for each point the measurements have been spatially averaged over a small area, i.e., the antenna has been randomly moved within a square area of around 30 cm. The system setups are shown in Fig. 5.

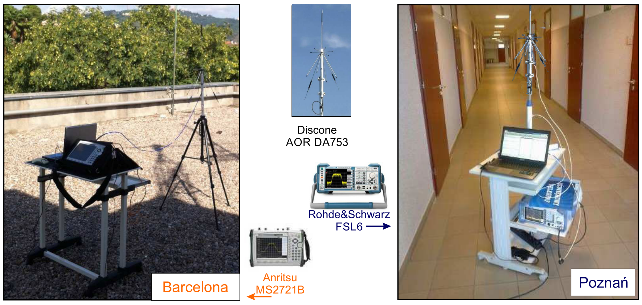


FIGURE 5. Measurement setup applied in Barcelona and Poznan.

E. MEASUREMENT DEVICES - SETUP FOR THE DRIVE TEST

There were also some drive tests performed in Poznan. For this scenario again the discone antenna AOR DA753 was used, which was connected to the R&S FLS6 spectrum analyzer. The later was previously equipped with a card allowing for powering it from direct current (DC) source, i.e. lighter socket. Once the data have been received by the FSL analyzer, they have been further delivered to the laptop that runs Matlab with Instrumental Control Toolbox installed. In order to track the position of a car, a GPS receiver was placed on the top of the car and connected to the computer via USB cable. The setup used for Poznan's drive tests is presented in Fig. 6.

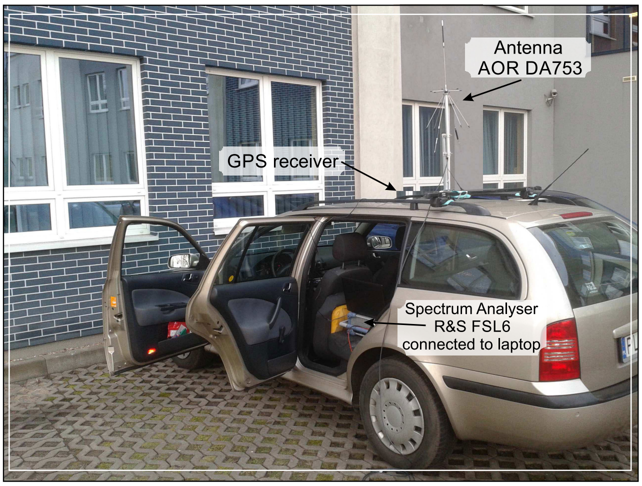


FIGURE 6. Car used for street measurements.

F. LOCATIONS OF MEASUREMENT POINTS - STATIC MEASUREMENTS

In order to assess the distribution of the received power of DVB-T signal in any potential point inside and around the building, a set of reference measurement points have been identified. In general, two main assumptions have been made: first, it was agreed that one measurement point was associated with an area of around 20 m^2; second, if there were smaller rooms, at least one measurement point was associated with every room in the building. The same locations have been

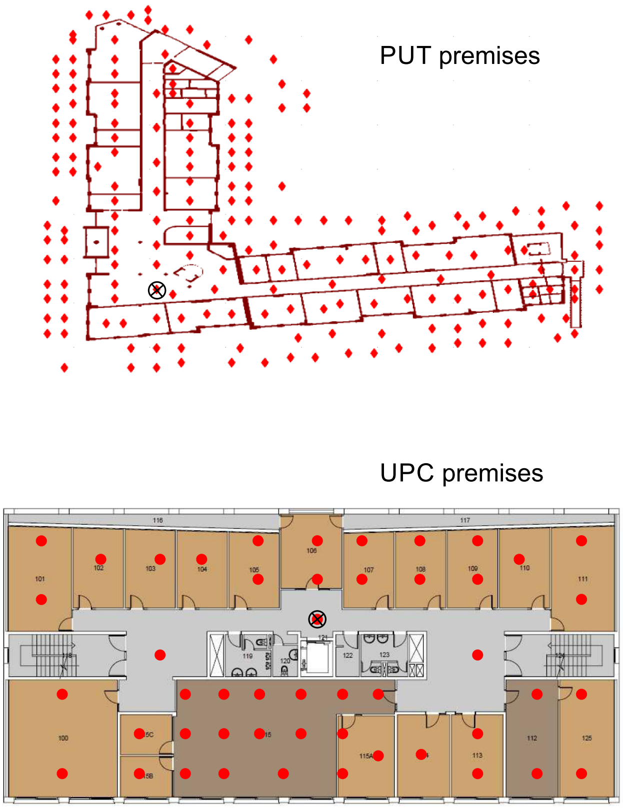


FIGURE 7. Measurement points identified for PUT and UPC.

selected on each floor of the building as far as it was possible (i.e., the differences in room locations between the levels influences sometimes the location of the measurement point), however the differences were negligible. The set of reference points for a certain level for both PUT and UPC are shown in Fig. 7.

G. LOCATIONS OF MEASUREMENT POINTS - DRIVE TESTS

Two drive-tests in normal traffic conditions during daytime have been conducted in Poznan in autumn 2013 and in late winter (February) 2014. Both routes started close to the premises of the PUT, and go via various areas in the city (i.e., of different type of architecture, such as high tenement houses, residential areas, ducts over river, sport areas etc.) as illustrated in Fig. 8, where the distances are also highlighted. The first route (denoted by yellow line) was around 25km long, whereas the second one (yellow line in the figure) was shorter - around 25 km. Recall that the measurements have been done in the typical daily traffic conditions, i.e. depending on that traffic and on the switch-on- turn-on phases of the lamps at the crossroads, in some places the number of collected samples will be e.g. higher than in other places due to the travel speed. Moreover, one may observe the approximate location of the DVB-T towers. Finally, let us notice three specific places A, B and C, which have been marked in Fig. 8. In these places, the car used in the measurements

FIGURE 8. Drive tests in Poznan - routes and location of long-stay places A, B and C.

stayed intentionally for longer time (approximately around 15 mins, 30 mins, and 10 mins, respectivly), i.e., it was stopped allowing for stable power measurements in one specific point as a function on time.

III. INDOOR MEASUREMENTS - DISCUSSION ON RESULTS

Applying the setup defined in the previous Section, several measurement campaigns have been conducted to verify the real influence of various phenomena on the received signal power, such as its stability over time or impact of humans moving inside the building. The results are discussed in this section.

TABLE 1. Average received power on the selected TV channels: 26th at UPC, and 27th at PUT.

Level	UPC	PUT
Rooftop	-44.41 dBm	-43.57 dBm
2nd floor	-62.06 dBm	-68.17 dBm
1st floor	-56.61 dBm	-72.28 dBm
Ground floor	-64.38 dBm	-77.30 dBm
Underground	-70.99 dBm	-

A. AVERAGE RECEIVED POWER

In the first step we have compared how the average power of the received signal varies across the floors of the building (see more details in [45]). In Table 1 we have compared the averaged power within the 8-MHz wide TV channel in arbitrarily selected location on each floor of the building (including roof). The selected point of the first floor is marked in Fig. 7 with the black *X*. In the other floors, a point in a similar location as the one shown in Fig. 7 is selected. Let us notice that in case of PUT the values for 27th TV channel are presented, whereas for UPC the channel number 26 was chosen. One may observe the significant signal degradation in the lower building floors. In general we may conclude that around 5-10 dB difference is observed between any two adjacent floors.

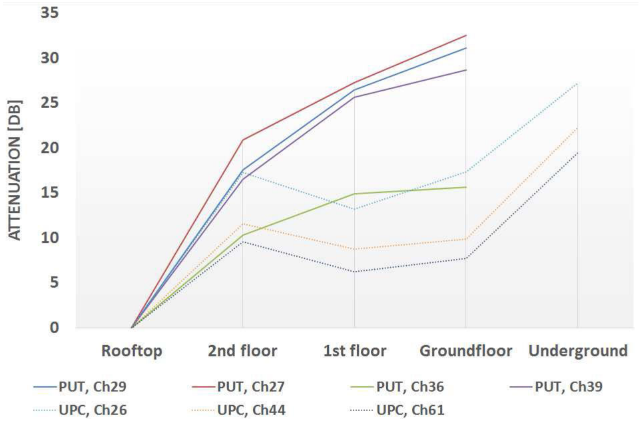


FIGURE 9. Average attenuation observed between floors at PUT and UPC with the reference to the signal power at the rooftop.

Now, let us compare the impact of each floor on the received signal power. The goal was to calculate the average (over time and location) attenuation observed on each building level with regards to the signal power at the rooftop, i.e., the value observed at the rooftop were treated as the reference to the values observed on each level. Obtained results are shown in Fig. 9. Please note that in case of PUT, the three level building was considered, whereas at UPC four floors have been taken into account. The following conclusions can be drawn, first, there is a direct relation between the received signal power and the vertical profile of the building; second, one may observe the impact of the building construction on the received signal power, in particular at UPC the signal strength on the first floor is slightly higher (signal is less attenuated) than on the second floor. Please note that in this case the DVB-T transmitter is located at only 3.1 km from the UPC premises (with almost line-of-sight conditions for all the floors except the underground). It means that the main attenuation comes from the wall penetration losses, which are similar for all the floors. More details can be found in [45].

In Fig.10 we plot the power spectral density of channel 26 at D4 rooftop and in several points located in the first floor. It is observed that, for the points in the first floor, the signal in an TV channel suffers from some distortion (i.e. not all the frequencies are equally attenuated) due to multi-path effects.

In Table 2 the average attenuation from D4 roof to the different floors is shown. For the case of 2nd floor where the signal passes through only one floor, the television signal suffers around 15.77 dB attenuation, whereas for the 1st floor where the signal passes through two floors, there is an attenuation of 19.55 dB and finally passing over 3 floors (groundfloor) there are about 21.32 dB loss.

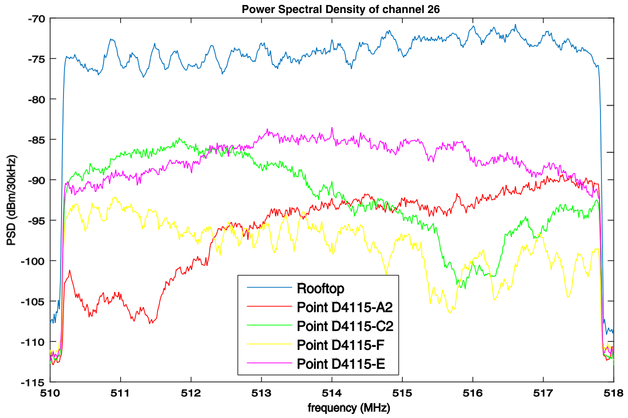


FIGURE 10. Power Spectral Density of channel 26 at D4 rooftop and in several points located in the first floor.

TABLE 2. Average attenuation from D4 roof.

to 2nd floor	to 1st floor	to ground floor
15.77 dB	19.55 dB	21.32 dB

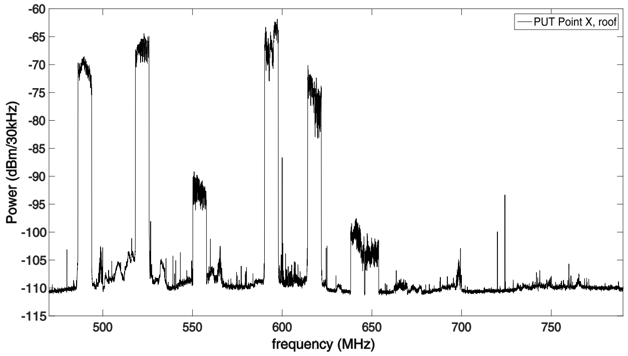


FIGURE 11. Power spectral density of the signal observed at the rooftop in the TV-Band frequency range - at PUT.

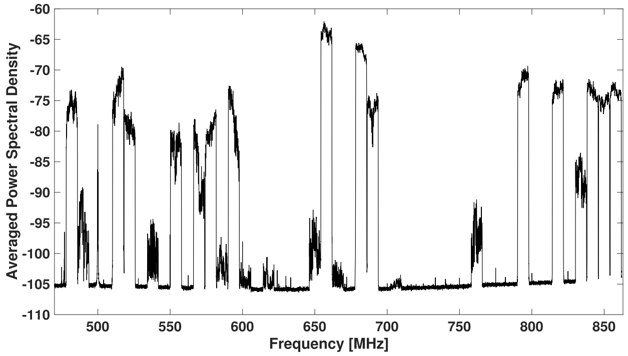


FIGURE 12. Power spectral density of the signal observed at the rooftop in the TV-Band frequency range - at UPC.

Moreover, we have measured the power spectral density (PSD) of the observed signals within the TV band. The comparison between the PSD plots at the rooftop at PUT and UPC is shown in Fig. 11 and in Fig. 12; please note that the values of power are measured using 30 kHz RBW filter. Taking into account that the minimum required level of the received signal which guarantees proper reception of the

DVB-T signal is of $48dB\mu V$ (please note that this value can be different depending on the country, in Poland for 64-QAM and $\frac{3}{4}$ Forward Error Correction the minimum value is $48dB\mu V$), what corresponds -59 dBm/8 MHz channel (equivalently -83.26 dBm over 30 KHz band), only some DVB-T multiplexes can be identified as useful and serviceable. The signals with the power less than -59 dBm are not useful in general, as the standard DVB-T receiver will not be able to achieve sufficient quality. Finally, one may observe that the amount of potentially vacant frequencies at PUT is much higher than at UPC.

B. STABILITY OVER TIME AND INFLUENCE OF THE HUMANS

Albeit the average received power in different locations of the building is a paramount factor, it does not illustrate the authentic demeanor of the signal since the averaging process of the received power smooths the temporal variations of this parameter. Therefore the stability of the received power over time has been selected as the second figure of merit that has to be verified in the REM creation. The second key factor is the influence of people inside the certain room on the received signal power.

In order to verify the stability of the observed power over time, the measurements of the received power have been performed in different day phases and repeated for different days of the week and for different durations. Fortunately, in every case the results were similar, thus in the following we focus on a specific case, where the signal was observed over 30 minutes.

Next, referring to the second factor, the quotidian utilization of the premises has to be considered, since there will be no need for new spectrum and new services if there will be no users inside. In fact, the new frequency resources will be highly needed when the rooms will be crowded, as significant traffic will need to be served. We have performed various measurements and below we summarize the results in various forms.

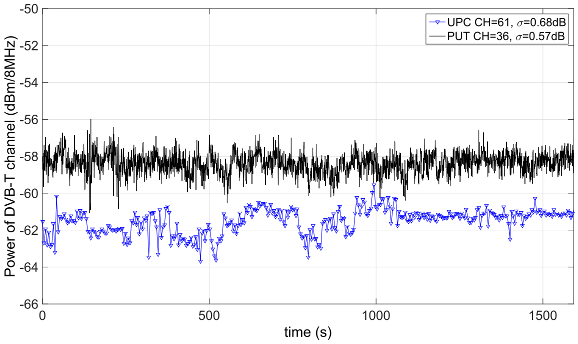


FIGURE 13. Power observed within two selected TV channels (36 at PUT and 61 at UPC) as a function of time where there are no people inside the room.

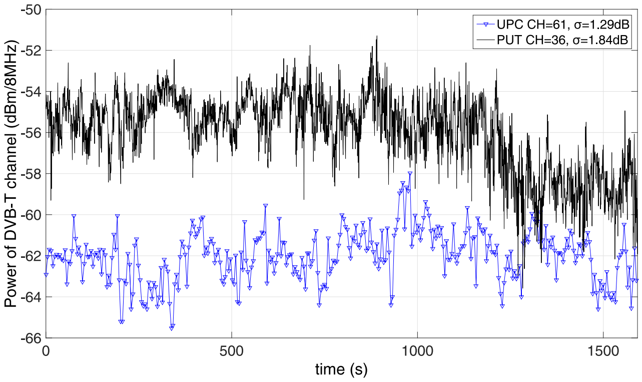


FIGURE 14. Power observed within two selected TV channels (36 at PUT and 61 at UPC) as a function of time where there are many people inside the room.

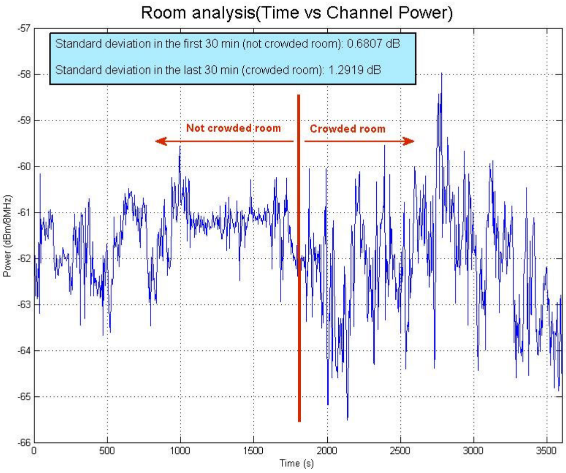


FIGURE 15. Fluctuations on the received power in time in almost empty and crowded office.

1) FIRST CASE

In the first case, the results for two arbitrarily selected TV channels (i.e., 36 at PUT and 61 at UPC) are shown in Fig. 13, for the case when the room is empty, and in Fig. 14, when there are many persons inside. Based on the comparison of these two figures we may conclude that observed power is quasi-stable - there is an increase of the power variance from around 0.57 dB to 1.84dB when the room is crowded, but still these values are relatively small [45]. One may thus conclude that the typical, quotidian usage of the office-like premises has only slight impact on the stability of the received power. Let us note that similar results have been observed regardless of the place of measurements, i.e. if the reception antenna was located on the corridor or inside the offices or class-rooms. However, one may observe that the mean received power in the crowded environment changes in time from around -55 dBm to -58 dBm in the case of measurement done at PUT, and 4-5 dB lower in the case of measurements done at UPC. This suggests that there may be some changes in the observed signal power as the function of time, however the change is maximally of some decibels.

2) SECOND CASE

As stated already, in order to be able to draw any reliable conclusions on the possible deployment of heterogeneous

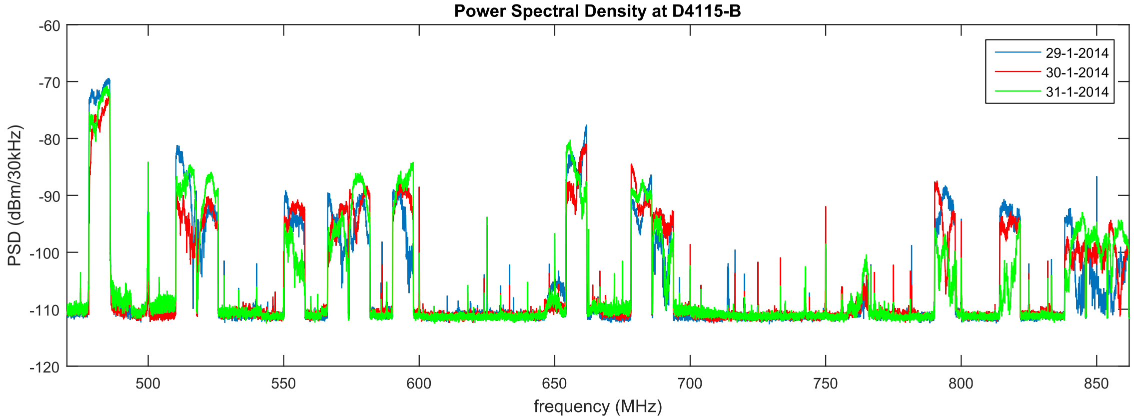


FIGURE 16. Power Spectral Density at point B located in the first floor of D4 building.

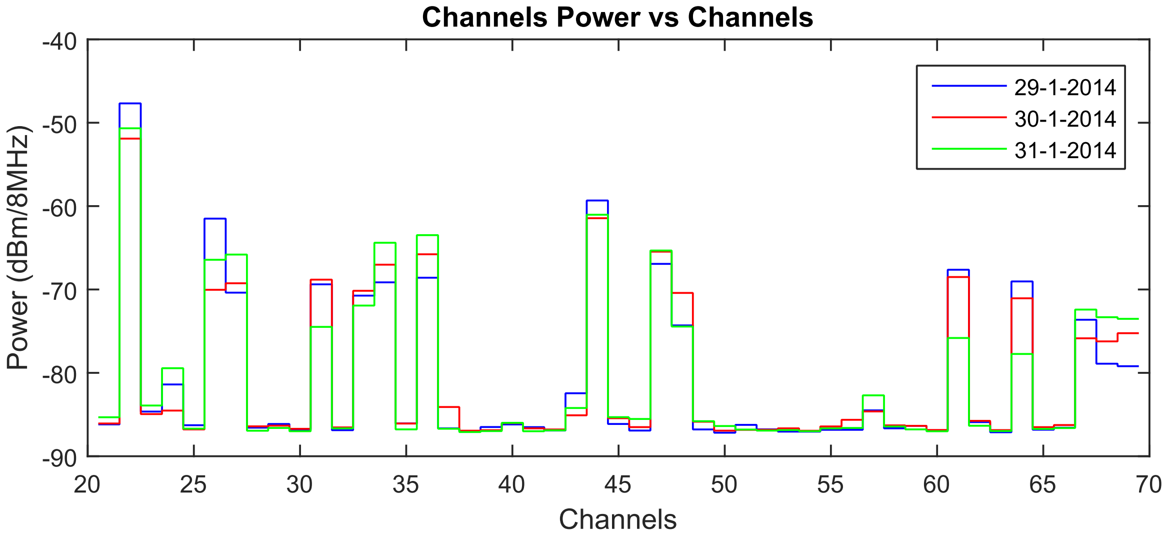


FIGURE 17. Power per channel at point B located in the first floor of D4 building.

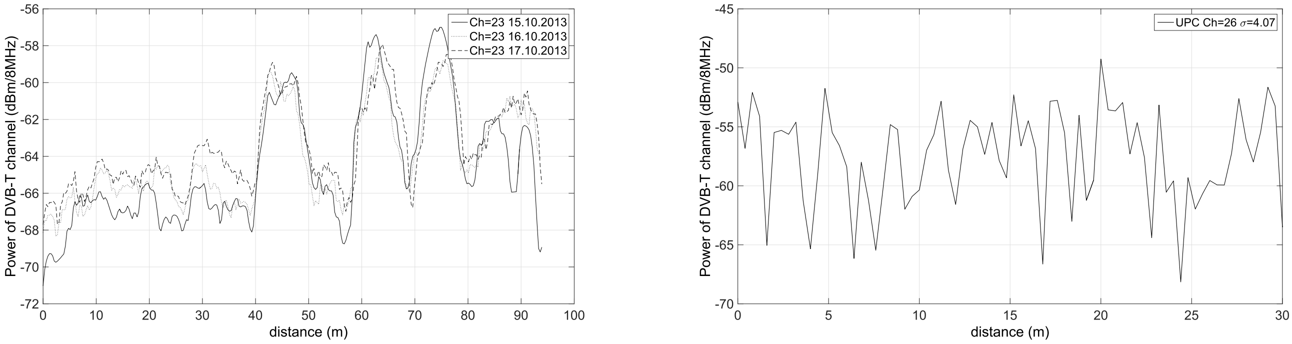
networks operating in TVWS, the radio environment maps have to take into account quotidian utilization of the premises (offices, class-rooms etc.). Therefore dedicated measurements have been performed in Barcelona in order to highlight the difference between crowded and empty offices. We have measured the power spectral density and the total power of received signal in channel 61 (i.e. between 790 and 798 MHz) into a laboratory located at the ground floor of D4 building, without and with students. For that we started measurements 30 minutes before the beginning of the class, and until the first 30 minutes of the class. We stored the continuous sweeps without averaging them. In Fig.15 the power of the channel for the whole hour is shown. The standard deviation in the first 30 minutes, when the laboratory was empty, is 0.68 dB, and the standard deviation in the last 30 minutes, when the laboratory was crowded, is 1.29 dB, these values bring us to the conclusion that the channel power is again quasi-stable in the sense, that the power variance takes quite limited values. In general however, such an observation means that the quotidian usage of the premises does not impact on the stability of the received power. Similar results have been observed regardless of the place of measurements, i.e. if the reception antenna was located on the corridor or inside the offices or class-rooms.

3) THIRD CASE

An exemplary plot in a given point located at first floor of D4 building in Barcelona is presented in Fig.16. We perform 50 measures of the whole TV band, in three consecutive days, at same point, and we average and plot the day result. In Fig.17 we calculate the channel power and we notice that there is a very little time variation of the received power. The high grade of stability of TV channels occupancy is a very relevant feature for the construction of the database, as it simplifies the need for updates.

C. DEPENDENCY ON TIME AND LOCATION

Previous results suggest that there is a relation between the observed signal power inside the building, time and - generally speaking - presence of humans. Thus, in the next step we decided to check how the signal varies in various locations inside the building in three consecutive days. Let us stress



(a)

(b)

FIGURE 18. Power observed within a given TV channels (no. 36 at PUT and no. 26 at UPC) as a function of location; in case of Poznan three consecutive days have been considered. (a) Measurements at PUT premises. (b) Measurements at UPC premises.

that it is the multipath effect that dominates the signal strength inside the building in a static scenario (i.e., when the DVB-T receiver does not move). Thus, it is important to see what can be the expected fading values due to the multipath propagation. In order to check this aspect, walk-tests have been done, in which the averaged power in the TV band has been measured every 30 cm (in case of Poznan) and every 40 cm (in case of Barcelona) along the corridor. The corresponding results are shown in Fig. 18a and Fig. 18b. In both cases the standard deviation of the signal power is at the level of around 4-5 dB. Moreover, one may observe that there is almost no difference in the observed signal power between the days. Unfortunately, the analysis of the figures 18a and 18b shows that there is relatively high variation of the received power as the function of the location inside the building. This observation suggests that there is a need to approximate the real values of the received power on each location inside the building (in other words, there is a need for a detailed coverage map, as discussed later) to better analyze this phenomenon.

1) IMPACT OF OTHER SURROUNDING BUILDINGS

We decided to analyze the variations of the PSD taking into account the location of the main transmitter, so that measurements are made at different points of a surrounding building, namely the C3 building in the North Campus of the UPC (see the map in Fig. 2). As indicated in the map, the D4 building has direct vision with the main transmitter while this is not the case for the C3 building. The results obtained for a point located in the lobby of the first floor of both buildings, for channel 26, are presented in Fig.19. It clearly shows that the channels were received with more power and the shape of the spectrum is better defined in D4, due to direct vision. Then, the indoor coverage changes dramatically depending on the position of the room from the main transmitter. Similar behavior has been obtained for the other occupied channels. So for future CR users an indoor scenario with more obstacles (i.e. buildings,...) to the TV transmitters would result to have TVWS which in turn would give greater benefits for the reuse of these channels.

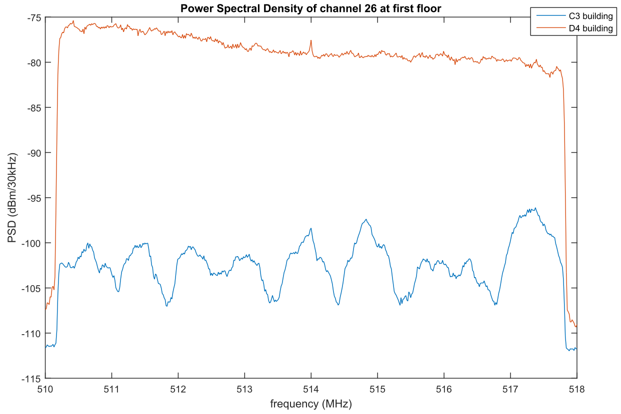


FIGURE 19. Power Spectral Density of channel 26 at C3 and D4 buildings in the first floor.

2) CLOSE-TO-BUILDING MEASUREMENT

In order to see the effect of the distance of the receiving antenna with respect to any building or obstacle and take this into account when deploying a REM just around the building, we perform measurements at points located at different spacings from the wall of building D4 in Barcelona. We measure all the way around D4 building. As an illustrative example, we will discuss the measures on the street that separates the C4 and D4 buildings. Separation of the two buildings is 13 meters, and we started measuring at 0.5 meters from D4 wall, and we took measurements every 2 meters, up to 12.5 meters from D4 that is 0.5 meters to C4. We repeated the experiment in 4 points equispaced along the nearly 40 meters of the buildings. In Fig. 20 the average of the received signal power as the function of the distance from building D4 is shown for channels 26, 44 and 61. We can observe that differences depending on the distance to the wall are not significant.

D. COVERAGE MAP

The digital map is built by estimating the received power in every point of the map based on the real power measurements performed at a set of discrete points. To address this

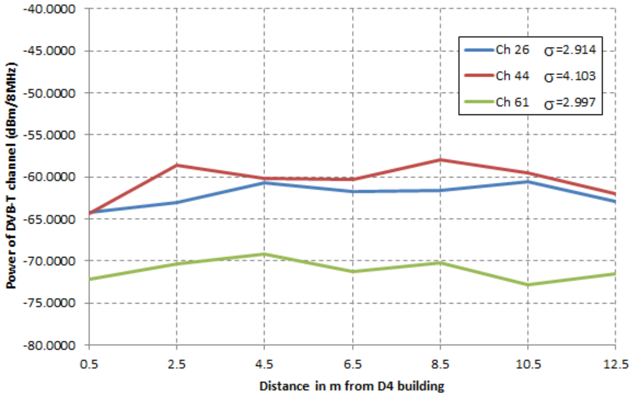


FIGURE 20. Received signal power as the function of the distance from building D4.

interpolation problem we have applied the well-known ordinary kriging algorithm (see, e.g., [46]).

1) APPLICATION OF THE ORDINARY KRIGING

In the classical kriging, the algorithm calculates the optimal weighting coefficients for the measured values while calculating the approximated value in the unknown location. In other words, it is needed to define the real impact (correlation) of the measured values obtained in the measurement campaign in known points on the certain location for which there was no measurement made. In general, the farther away the measurement point is from the interpolated one, the less its impact on the calculated value. This generic routine has to be modified in our case to reflect the true impact of inside and outside walls on the signal propagation. It is easy to observe that two points will be highly correlated if there is no obstacle between them (such as furniture or walls); thus, the points separated by the walls shall have smaller weighting coefficients (are less correlated) comparing to those points which are in direct visibility. Following [47] and [48] one may mimic the influence of the wall by virtually increasing the physical distance between two points if there is wall between them. The achieved coverage map is shown in Fig. 21; the map is obtained based on the measurements in PUT building. The red points correspond to the real measurements, while the color map represents the interpolated values.

2) INCLUSION OF WALLS

Now, let us compare the achieved results with the coverage maps achieved for the case where the walls are not considered in ordinary kriging algorithm. In order to better visualize the differences, we have reduced an analyzed area to the arbitrarily selected fragment of the building. The results are presented in Fig. 22 (where the walls are not considered) and in Fig. 23 (where the walls are included as described previously). One may observe that in the latter case the figure is slightly smoother, however this difference is rather negligible.

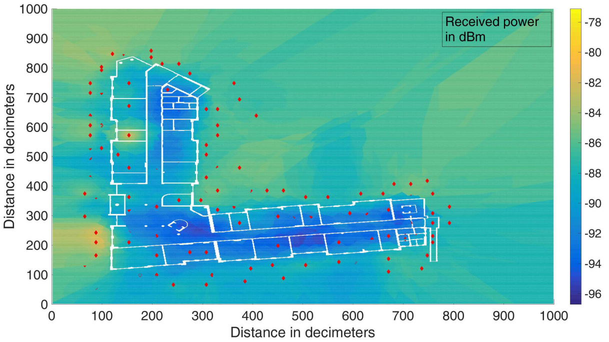


FIGURE 21. Achieved coverage map for groundfloor for the channel 23 at PUT; values expressed in dBm.

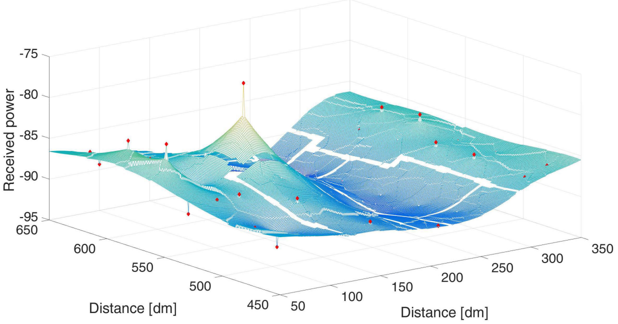


FIGURE 22. Achieved coverage map for the selected fragment of the building for the channel 23 at PUT; values expressed in dBm; the walls are not included in the ordinary kriging algorithm.

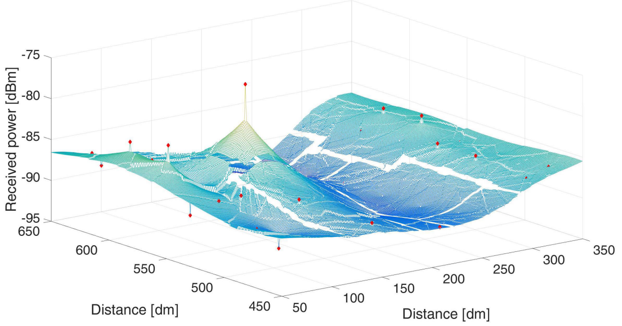


FIGURE 23. Achieved coverage map for the selected fragment of the building for the channel 23 at PUT; values expressed in dBm; the walls are included in the ordinary kriging algorithm.

3) INCLUSION OF THE LOCATION OF THE TV BASE STATION

Let us observe, however, that in the process of creation of the digital map for DVB-T signal utilizing the above mentioned kriging algorithm, one should consider the true location of the TV transmitter. The motivation for such an approach lays in the observation that the impact of walls which are parallel to the direction of arrival of the DVB-T signal is negligible compared to the walls which are perpendicular. The latter will for sure attenuate the signal, whereas the former will be rather transparent. This phenomenon is illustrated in Fig. 24. We have plotted the achieved mean square error value as

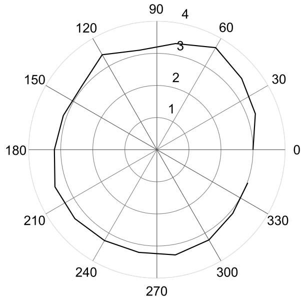


FIGURE 24. **Mean Square Error for the applied kriging algorithm as a function of the DVB-T radial location (in angles on polar plot).**

the function of the DVB-T radial location $\hat{\alpha}$ (selected as a parameter in the kriging algorithm) on a polar plot. As the true location of the DVB-T transmitter is fixed (and thus the true angle α is fixed as well), the interpretation of the figure is the following. If the modified kriging algorithm takes the value of the angle as $\hat{\alpha}, \hat{\alpha} \in \left\langle 0^\circ, 360^\circ \right)$, it will achieved the certain error shown on the polar plot. The smallest error should be achieved when $\hat{\alpha} = \alpha$. The error is understood as the difference between the measured values (in known points), and the interpolated values at these points while treating them as unknown. One may observe that the MSE value differs depending on the assumed angle.

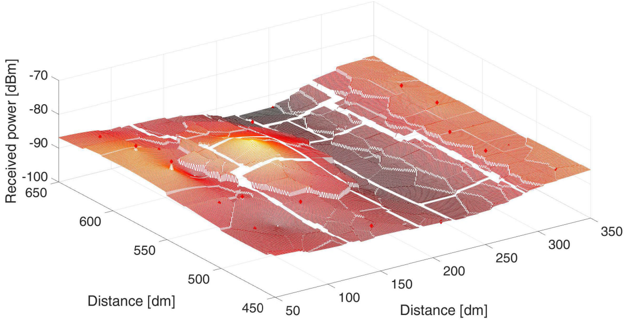


FIGURE 25. **Achieved coverage map for the selected fragment of the building for the channel 23 at PUT; values expressed in dBm; the walls and the location of the DVB-T transmitter are included in the ordinary kriging algorithm.**

This phenomena is particularly important in the situation when there is a presence of the dominating (most probably line-of-sight) path between the DVB-T transmitter and receiver, such as in the higher levels of the buildings. As the result of the inclusion of the influence of both internal and external wall as in [48], the digital coverage map shown in Fig. 25 has been obtained. It corresponds to a groundfloor in PUT premises. Please note, however, that the gain due to the incorporation of the DVB-T location in the kriging algorithm may be limited in the single-frequency networks, where a certain multiplex is transmitted in the same TV channel in the entire considered area (e.g., country). In such situation there may be no dominant path from which the signal is transmitted (especially at the edges of the area covered by the DVB-T transmitters), and on each location inside the building the received power will be a superposition of incoming signals. Such a particular situation is observed in Poznan, where a distant DVB-T transmitter is supported by the DVB-T transmitter placed in the outskirts of the city.

4) SPLIT ON INSIDE AND OUTSIDE PART

Finally, one may notice that proper consideration of the walls requires the accurate knowledge about the type of the materials from which the walls have been made, or at least it would require that the true attenuation of the walls (both internal and external) will be measured. This is however pragmatically not possible. Thus, the other approach that could be applied for creating the signal coverage map is to split the considered area into two parts - internal and external ones. In other words two separate coverage maps will be created: the one that covers the interior of the building, and the one that corresponds to the external part. The results achieved in this case are presented in Fig. 26

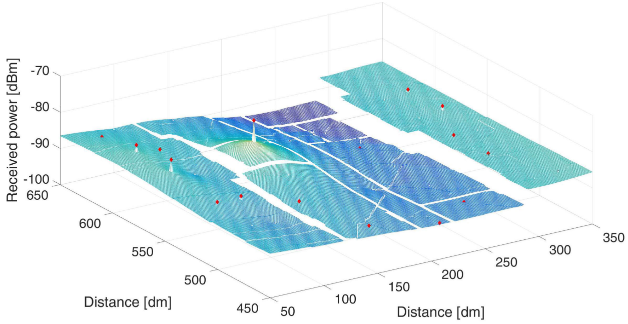


FIGURE 26. **Achieved coverage map for the selected fragment of the building for the channel 23 at PUT; values expressed in dBm; interior and exterior parts are separated.**

In addition to the visual analysis of the results for the different approaches shown in figures: 22, 23, 25, and 26, in the following a quantitative comparison is performed. For that purpose, we calculate the difference between the value measured in a reference point and the value obtained with the kriging algorithm if that reference point was treated a unknown. Mathematically the error $\hat{e}_i$ observed at the ith reference point will be defined as $\hat{e}_i = V_i - \hat{V}_i$, where V_i is the measured value and $\hat{V}_i$ is the value computed by means of kriging algorithm. In our experiment we have computed the error for each measurement point (at PUT premises), and calculated the mean absolute error in logarithmic scale. In Table 3 we present the achieved results.

Analysis of the four coverage maps and the values presented in Table 3 allow us to draw the conclusion that the differences between the four approaches are rather small, and negligible. The smallest mean error has been achieved for the approach when the interior and exterior parts have been separated, however the difference between this scheme and the one where the pure kriging algorithm is applied for the entire area is of only fractions of one dB. This observation is crucial from the perspective of practical deployment of REM

TABLE 3. **Averaged absolute error for considered versions of the kriging algorithm.**

Method	$\bar{e}$ [dB]	Variance [dB]	Max [dB]
Walls not included	1.5818	2.4734	11.6176
Walls included	1.5756	2.4665	11.7027
Walls and location of DVB-T transmitter included	1.6299	2.4444	11.6486
Interior and exterior parts separated	1.5183	2.3981	11.8588

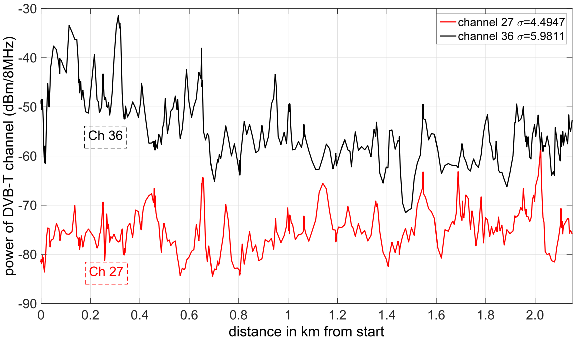


FIGURE 27. **Received signal power as the function of the distance from the route start - Route 1.**

based systems, where we need to create the coverage maps. One may assume that it will be impossible to measure the true attenuation of walls, thus if there is almost no difference, the simplest case should be applied. Thus we propose to select the pure ordinary kriging algorithm either for the entire considered area, or with the setup that the exterior and interior parts are split.

IV. OUTDOOR MEASUREMENTS - DISCUSSION ON RESULTS

In Sec. III we have discussed various aspects of the TV signal received indoors in the context of REM database application for service delivery inside and around offices. However, it is widely foreseen that deployment of REMs could improve the spectral efficiency also in the outdoor scenarios, especially along the streets and in the city centers (see more in [42], [44]). In such a scenario the local REM databases support the management of outdoor users in their close vicinity. However, again, the key issue will be to protect the DVB-T receiver, especially the handheld ones for which neither the location is known nor the usage of external antenna is possible. In order to check the parameters of the received DVB-T signal, we have conducted two drive tests in Poznan following the setup presented in the first section of this paper.

A. POWER AS FUNCTION OF DISTANCE/TIME

Let us now analyze the results - observed received power as function of distance and time - achieved for both routes described in the first section and presented in next four figures from Fig. 28 to Fig. 29.

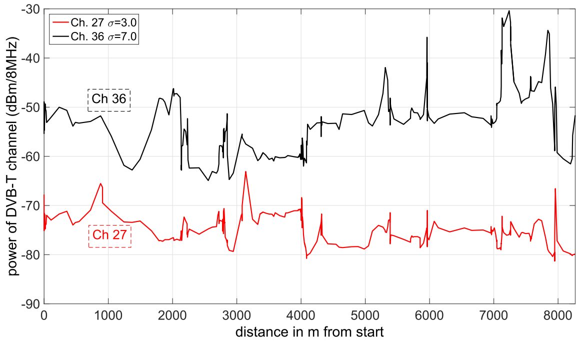


FIGURE 28. **Received signal power as the function of the distance from the route start - Route 2.**

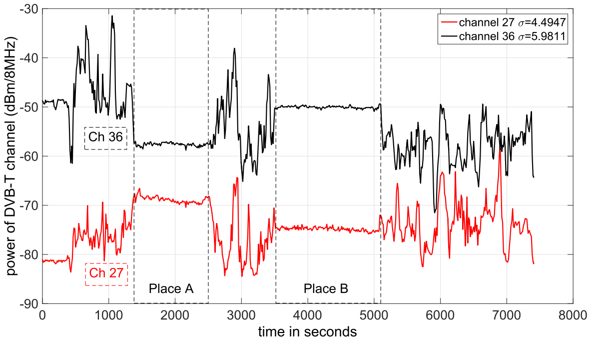


FIGURE 29. **Received signal power as the function of the time passed from the route start - Route 1.**

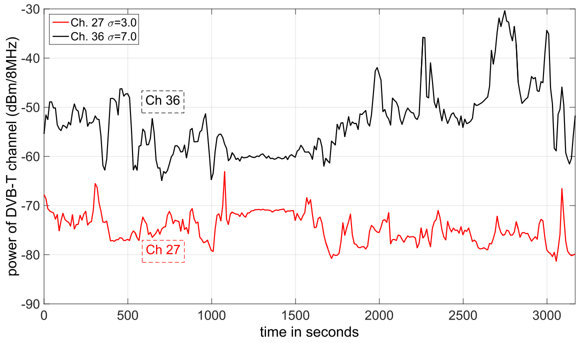


FIGURE 30. **Received signal power as the function of the time passed from the route start - Route 2.**

An immediate observation is that there is quite high variations of the received signal power depending on the current position. This is of course in line with our expectations, as the signal power strongly depends on the location - the impact of the path loss and the multipath propagation varies in different positions. In terms of numbers, the standard deviation of the received power in channel 36 was equal to around 6dB (Route 1) or 7dB (Route 2), while the variation of the received signal in the other channels was close to 4.5dB (Route 1), and 3 dB (Route 2). However, at a given location the variance is much smaller. In consequence, there should exist a practical possibility for deployment of low power White Space Base Stations that will operate in the TV White Spaces with the support of the local Radio Environment Map.

B. STABILITY OVER TIME INSIDE THE CITIES

As in the indoor case, the key aspect is the stability of the observed signal over time. In order to verify this phenomena we have selected two points (denoted as Place A and Place B in Fig. 8), where the observation of the signal took around quarter and half an hour, respectively, in a normal, quotidian street traffic (see more in [44]). The former point is located close to the park area and railway station (thus the traffic in that place will be rather limited), whereas the latter is exactly in the city center, close to two big streets, full of cars, buses and pedestrians. The results corresponding to this situation are highlighted in Fig. 29. One may notice that the variance of the observed signal power is rather negligible, thus the influence of moving objects around the measurement points will be small. It is worth noticing that similar results have been observed in both points.

V. REM DEPLOYMENT ANALYSIS

There are a wide range of issues to consider when building a REM. In the following we try to highlight the essential ones, starting from the definition, we discuss also its applicability and scope, the constitutive elements and the methods to create and maintain REMs.

A. REM DEFINITION

A REM is a knowledge database, constructed from spectrum measurements provided by different devices, used to dynamically store information related to the radio environment of wireless systems so that optimization in the use of spectrum resources can be achieved [49], [50]. Whereas a geolocation database has up-to-date information of incumbents, a REM is additionally fitted out with the ability to predict white spaces availability in its region, and notify the spectrum opportunity to the connecting radio devices [31].

B. REM APPLICABILITY AND SCOPE

A REM will be used for deployment of heterogeneous networks like overlapping small cells, access points of different kinds, etc. Information such as the available spectrum, the maximum allowed transmit power of the secondary devices, can be obtained by a query to the REM.

There are also other important aspects that need to be decided when considering REM as the support for spectrum sharing, such as the area that it covers, and the interaction between different REMs to share information. In [33] authors propose a multi-level hierarchy for REM implementation. Each level has a different spatial and temporal granularity.

There is no single definition for local and global REM.[5] In this respect, in this work we define them as follows. A local REM covers a hundred meters at most and it is mainly focused in indoor REM databases which include one or several buildings and its surroundings. In turn, a global REM covers few kilometres and is focused in outdoor REM databases which can include urban, suburban and rural areas, and it is linked to a network infrastructure.

C. REM CREATION

The creation of a reliable REM from scratch considering only measures would be highly challenging. Thus engineers have developed different techniques to estimate realistic information to build it.

The estimation techniques to construct a REM can be classified in two groups [31], [51]: transmitter location determination based methods, and spatial statistics based methods. The first group estimates the signal strength at each location from the transmitter parameters and applying propagation modeling, whereas the second group estimates the signal strength using the measured data and different spatial interpolation algorithms. The difficulty of having accurate enough indoor propagation models gives more importance to the construction of the REM from measurements and applying interpolation algorithms (and this is one of the reasons why we have applied them in our work). The analysis of the characteristics of the radio spectrum band are interesting to be able to decide the granularity of the measures, the need to update them and other aspects related to REM. One may assume that practically only sparse measurements will be possible.

D. REM USE AND MAINTENANCE

Many papers and projects have been issued to discuss the prospective content and structure of the REM databases for cognitive usage, such as [52] or in [35], where the in-depth discussion on the White Space Device Database is provided. The goal of this work, however, is not to repeat the discussion on the content in general and how exactly the particular entries of the records shall be calculated (i.e., we do not want to discuss the applicability of certain formulas for, e.g., proposed path-loss models or protection margins), but to identify the relationships between the potential parameters for inclusion in the database and the measurements conducted in real scenario (real functioning DVB-T networks) for a long operation time.

In our discussion we made the following assumptions. First, the primary goal of deployment of REMs is to deliver new services (even broadband, if possible) for indoor users (and possibly for outside users located close to the considered building) by utilizing vacant frequency resources in TV band. However, this can be done only in a case when the primary services (TV receivers) will not be distorted, thus the quality of service and experience of the licensed users have to be preserved. Second, we assume that there will be no standalone sensing-based devices, and all decision regarding the secondary systems will be stored and managed by the REM. Next, we try to assume a practical situation, where there will be a dedicated company responsible for database installation and maintenance. In practice, this entails the following limitation - such a company will be allowed to make some detailed

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[5] As an example, one may refer to the work done by the researchers at Virginia Tech who classified REMs in these two classes, defining a global REM as obtained from the network infrastructure and a local REM obtained by each radio from its own spectrum sensing [50].

measurements once the system is being installed and tested. It will not be granted or even practically possible to make detailed measurements frequently, as it disorganizes the work of the other users, it would require to obtain the grants for accessing the rooms, and is costly, as it requires hiring stuff to make these measurement campaigns. In that context, even one dedicated measurement campaign conducted by service staff per year seems to be too frequent, and the practical deployment should go to more autonomous and automatic solutions. In other words, once the first measurement campaign is done, a dedicated sensor network should be deployed to monitor the current status of the TV band utilization. Such a measurement can be done either continuously, or periodically, or can be initiated per request (e.g., by the TVWS base station).

VI. REM CREATION: PRACTICAL LESSONS LEARNED FROM THE MEASUREMENT CAMPAIGNS

Having these assumptions in mind and based on the results obtained during the previously discussed measurement campaigns, let us now discuss how the REM database should be created:

1) *Ownership Issues:* Various solutions can be found in [35] regarding the management and ownership of the white-space database. In particular, it is discussed if the databases should belong to private companies or to national regulator authority. In our case, we envisage that it will be the building manager (or a company that rents the part of the building) who decides to deliver REM-based services. If it will be guaranteed that the level of interference observed in the agreed area outside the building is not violated one may assume that the building manager will be the owner of the entire REM-based system.
2) *Short-Term Stability:* Based on the presented results (see, e.g., Fig. 13 and Fig. 14), one may conclude that the measured values of observed DVB-T signal power are quasi-constant in time. It means that various propagation conditions may temporarily influence the observed values of DVB-T signal power, but the averaged (in time) values are constant; *Conclusion*: there is no need for highly frequent monitoring of the DVB-T signals;
3) *Long-Term Stability:* The DVB-T broadcasters may modify the frequency plans (e.g., to shift the occupied channel from one to another), may deploy new transmitters (e.g., in single-frequency network type to strengthen the received signal in a certain area), or may modify the transmit parameters due to various reasons. Moreover, the digital map will change as the surrounding environment will change, e.g., when some new buildings are constructed in the vicinity. Although these changes will not be so frequent (i.e., these will not occur every day or week even), they can significantly influence the observed values of signal power. For example, the shift of one DVB-T multiplex to another TV channel modifies completely the calculated digital coverage maps; *Conclusion*: there is a need for periodic or pre-request update of the entire map to reflect the high level changes. However, in many cases these changes can be known in advance because they will respond to planned events (e.g., frequency changes in the channels are usually notified to users, the appearance of new buildings will also be planned, etc.). This facilitates the decision on when a new REM update is needed.

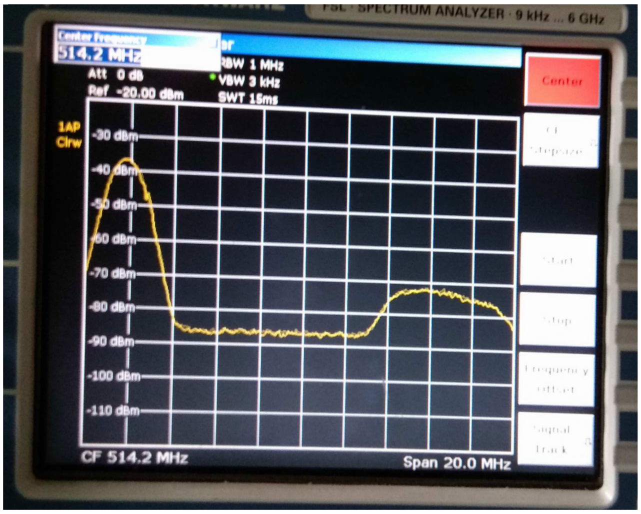


FIGURE 31. Spectrum observed during the white-space transmission.

4) *Influence of Humans:* This paper has shown in Sec. III-B that the impact of the people living and working inside the rooms of a building is rather small but it can be in the order of a few dBs. *Conclusion*: It would be reasonable to add a dedicated degradation margin to the digital map;
5) *Vertical Building Profile:* The measurements have clearly shown a direct relation between building floor level and the observed signal; the lower the floor, the smaller the signal (due to the propagation and penetration losses). It may be assumed that in the lower levels (especially for the levels where there is no line-of-sight between the DVB-T transmitter and the considered building) the signal strength is not high enough to allow acceptable quality of signal reception; in other words, the usage of external (rooftop possibly) antennas, or even cable-TV solutions, may be necessary, leaving the entire TV-band free for secondary transmissions (of course in the area covered by the cable-based DVB-T signal). One may consider that both of the considered buildings have only three levels above the ground. Other phenomena (than those discussed above) may arise if one would consider a skyscrapers or simply multi-storey and higher buildings. Clearly, the vertical building attenuation profile will depend on various factors, mainly of the type of surrounding architecture and the presence of line of sight propagation of the

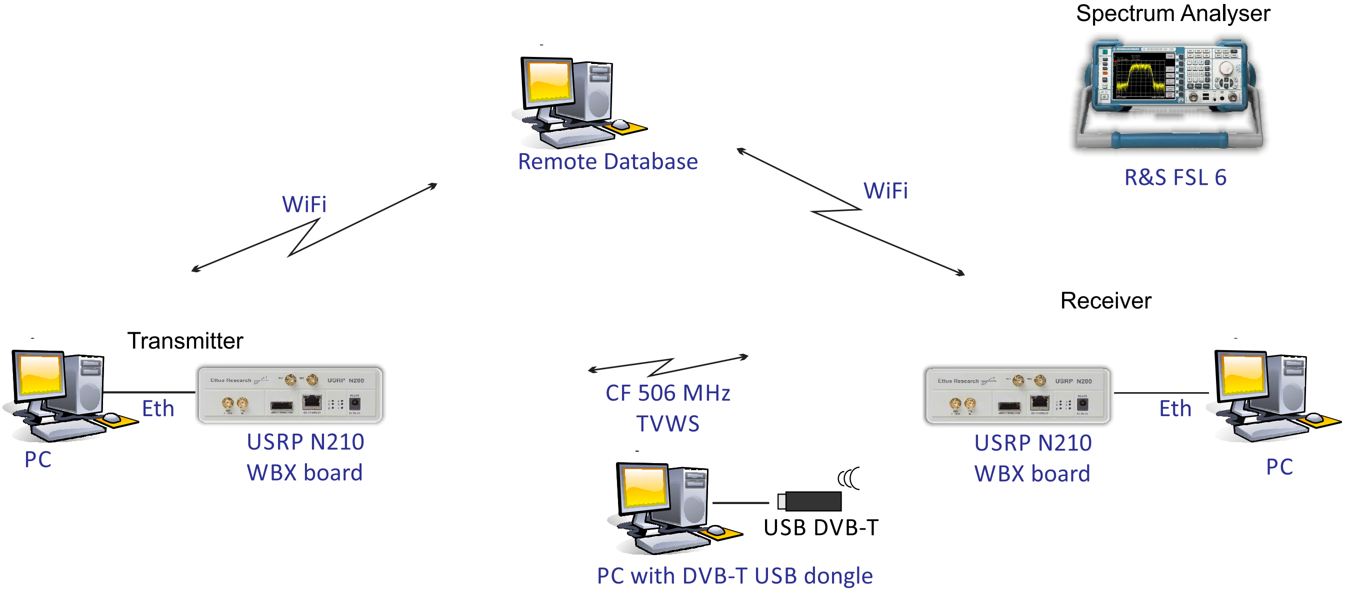
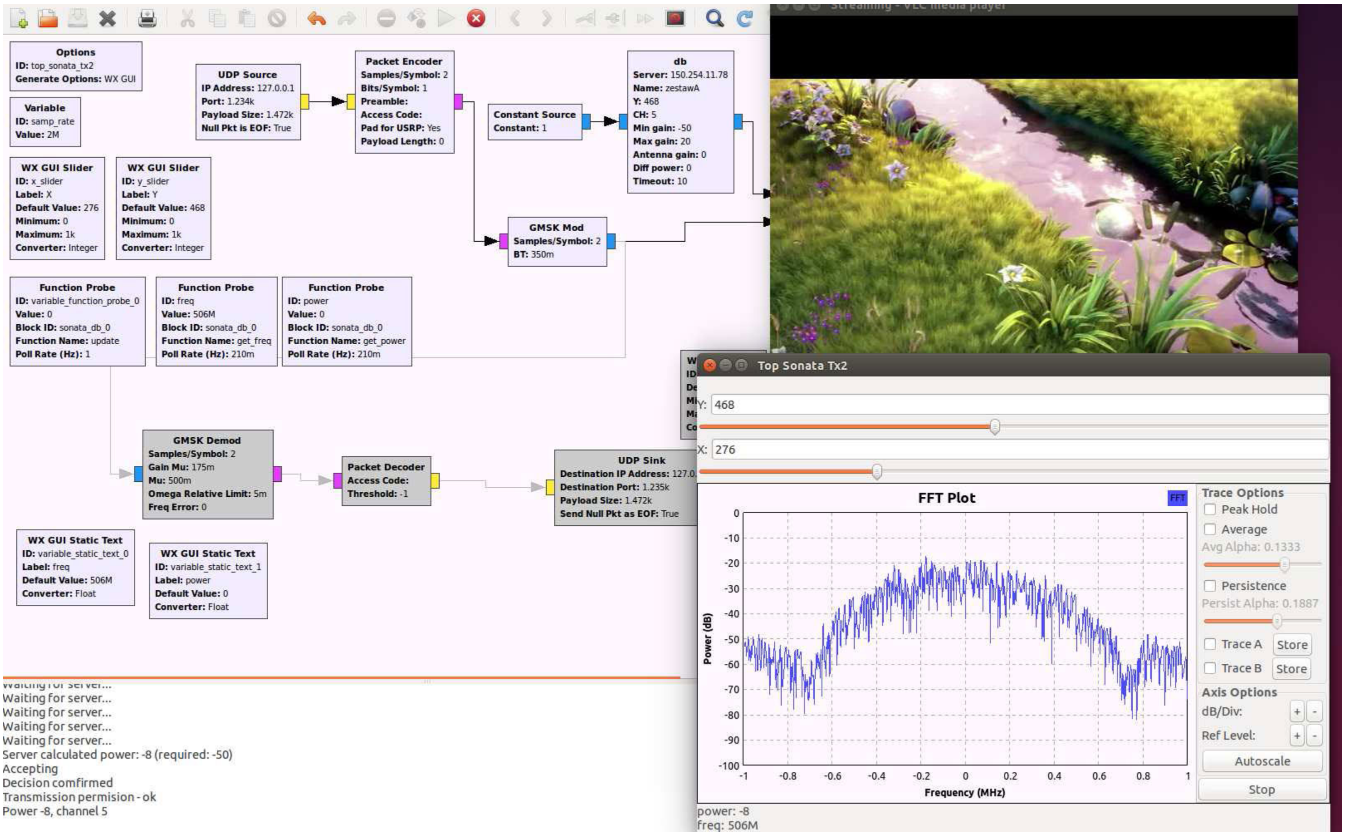


FIGURE 32. Setup of the experiment.



Options
ID: top_sonata_tx2
Generate Options: WX GUI

Variable
ID: samp_rate
Value: 2M

UDP Source
IP Address: 127.0.0.1
Port: 1.234k
Payload Size: 1.472k
Null Pkt is EOF: True

Packet Encoder
Samples/Symbol: 2
Bits/Symbol: 1
Preamble:
Access Code:
Pad for USRP: Yes
Payload Length: 0

Constant Source
Constant: 1

db
Server: 150.254.11.78
Name: zestawA
Y: 468
CH: 5
Min gain: -50
Max gain: 20
Antenna gain: 0
Diff power: 0
Timeout: 10

WX GUI Slider
ID: x_slider
Label: X
Default Value: 276
Minimum: 0
Maximum: 1k
Converter: Integer

WX GUI Slider
ID: y_slider
Label: Y
Default Value: 468
Minimum: 0
Maximum: 1k
Converter: Integer

GMSK Mod
Samples/Symbol: 2
BT: 350m

Function Probe
ID: variable_function_probe_0
Value: 0
Block ID: sonata_db_0
Function Name: update
Poll Rate (Hz): 1

Function Probe
ID: freq
Value: 506M
Block ID: sonata_db_0
Function Name: get_freq
Poll Rate (Hz): 210m

Function Probe
ID: power
Value: 0
Block ID: sonata_db_0
Function Name: get_power
Poll Rate (Hz): 210m

GMSK Demod
Samples/Symbol: 2
Gain Mu: 175m
Mu: 500m
Omega Relative Limit: 5m
Freq Error: 0

Packet Decoder
Access Code:
Threshold: -1

UDP Sink
Destination IP Address: 127.0.
Destination Port: 1.235k
Payload Size: 1.472k
Send Null Pkt as EOF: True

WX GUI Static Text
ID: variable_static_text_0
Label: freq
Default Value: 506M
Converter: Float

WX GUI Static Text
ID: variable_static_text_1
Label: power
Default Value: 0
Converter: Float

```
Waiting for server...
Waiting for server...
Waiting for server...
Waiting for server...
Server calculated power: -8 (required: -50)
Accepting
Decision comfirmed
Transmission permision - ok
Power -8, channel 5
```

Top Sonata Tx2

Y: 468

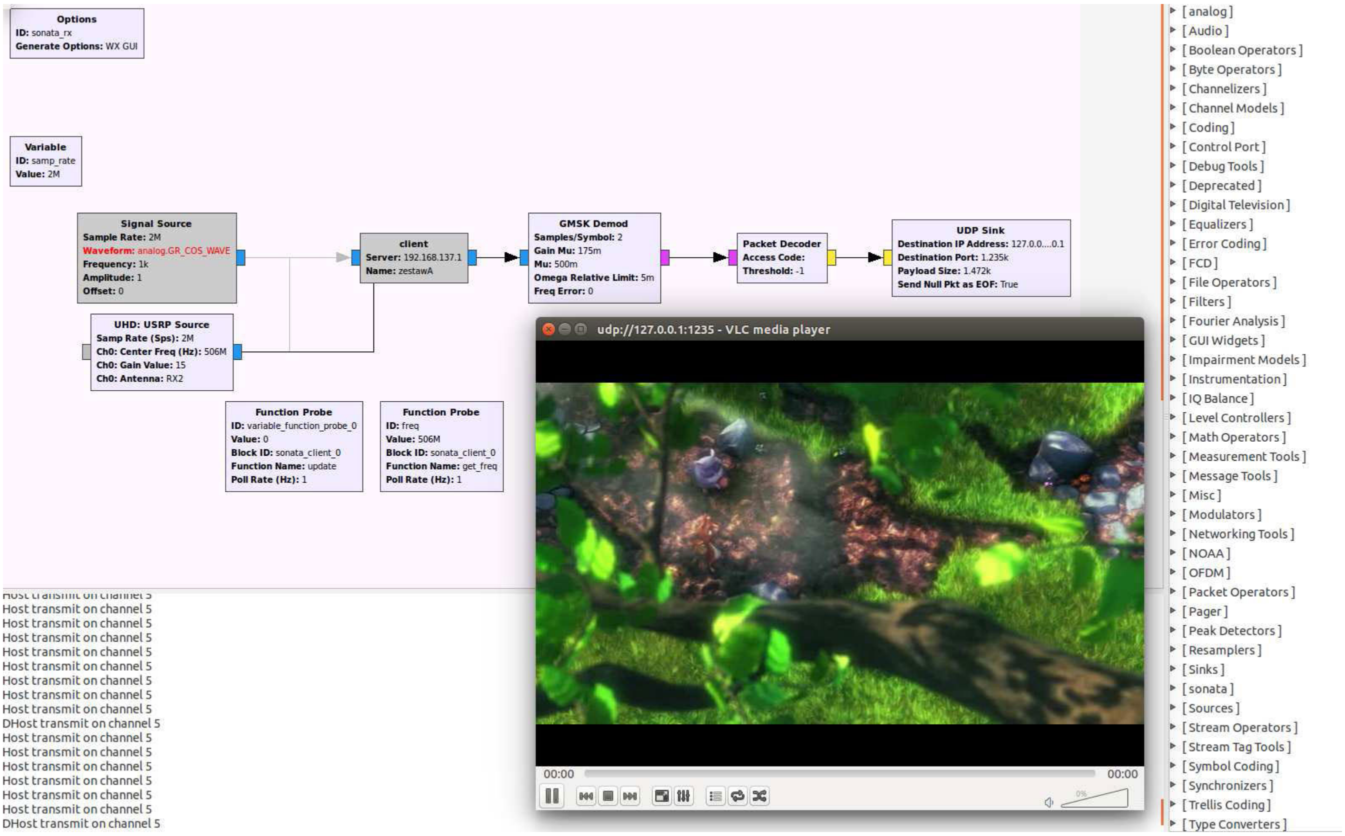
X: 276

power: -8
freq: 506M

FIGURE 33. Screenshot from PC realizing the transmitter functionality.

DVB-T signals; *Conclusion*: once the initial measurement campaign is done, it should be possible to estimate the penetration losses between the neighboring floors and to identify the floors where the entire TV-band could be used (i.e. those where the received DVB-T signal is below the sensitivity);

6) *Creation of the Digital Coverage Map:* The presence of detailed and accurate coverage map is in some sense



Options
ID: sonata_rx
Generate Options: WX GUI

Variable
ID: samp_rate
Value: 2M

Signal Source
Sample Rate: 2M
Waveform: analog.GR_COS_WAVE
Frequency: 1k
Amplitude: 1
Offset: 0

UHD: USRP Source
Samp Rate (Sps): 2M
Ch0: Center Freq (Hz): 506M
Ch0: Gain Value: 15
Ch0: Antenna: RX2

client
Server: 192.168.137.1
Name: zestawA

GMSK Demod
Samples/Symbol: 2
Gain Mu: 175m
Mu: 500m
Omega Relative Limit: 5m
Freq Error: 0

Packet Decoder
Access Code:
Threshold: -1

UDP Sink
Destination IP Address: 127.0.0....0.1
Destination Port: 1.235k
Payload Size: 1.472k
Send Null Pkt as EOF: True

Function Probe
ID: variable_function_probe_0
Value: 0
Block ID: sonata_client_0
Function Name: update
Poll Rate (Hz): 1

Function Probe
ID: freq
Value: 506M
Block ID: sonata_client_0
Function Name: get_freq
Poll Rate (Hz): 1

```
Host transmit on channel 5
Host transmit on channel 5
Host transmit on channel 5
Host transmit on channel 5
Host transmit on channel 5
Host transmit on channel 5
Host transmit on channel 5
Host transmit on channel 5
DHost transmit on channel 5
Host transmit on channel 5
Host transmit on channel 5
Host transmit on channel 5
Host transmit on channel 5
Host transmit on channel 5
Host transmit on channel 5
DHost transmit on channel 5
```

FIGURE 34. Screenshot from PC realizing the reception functionality.

crucial for proper functioning of the spectrum sharing systems - it is the basis for decision, if there is a space for any new transmitter working in the building. Based on that map the resource allocation algorithm can assess the amount of induced interference on each TV channel and in consequence protect the licensed users. In that context, there will be a great need to correctly model the influence of walls and obstacles inside the building - a good path loss model is needed. However, having the above mentioned assumptions on practicality of this study in mind, one can state that the modifications of the kriging algorithm discussed in this paper with regard to the accurate modeling of inside walls did not bring significant improvement in terms of the observed mean error. Moreover, the location of the DVB-T transmitter provides some improvement in terms of mean square error, but this gain is much harder to be obtained in single-frequency networks (i.e., where the same TV channels are delivered from different directions simultaneously). The other approach would be to increase the number of measurement points, but this is practically and pragmatically impossible. Probably it would be doable to have one or two points more inside each room if the office furnishing allows that. But still, such small number of measurement points will not be sufficient to reflect short-range changes of the DVB-T signal strength, thus one or two points per one small room (around 10 to 15 meter squared) would be enough to approximate the average field strength in that field. In fact, even if the first map is created based on a very detailed measurements, it would not be possible to update the map after each change in frequency plan at the same level of details. Thus, there is a great trade-off between the map accuracy and the practical possibilities of their creation and maintenance. Therefore, there is a need for some coarse solutions, where one could relax the requirement on map accuracy while keeping the protection level of licensed users unchanged.

Following this reasoning one may observe that it is then justified to split the map into indoor and outdoor part. The outside samples will have an impact only on other samples located outside, whereas the indoor part of the map will base on only the indoor measurement points. This is further justified in the context of multi-level buildings - the outdoor measurement will be done practically with the measurement device mounted some of meters above the ground. Thus, there is no reason to merge these measurements while creating the map on the higher floors. Next, as there have to be either periodic or per-request updates of the measurements, there will be a need for creation of, e.g., a dedicated sensor network or deployment of specialized sensing modules.

Based on the above analysis, there should be one sensor associated with one measurement point and this sensor will be activated only when there is a need for new measurements. *Conclusions*: First, there is a big trade-off between the map's accuracy and the practicality of its creation. The need for per-request or periodic update of the map entails the significant reduction of the density of measurement points (due to high costs) and in consequence makes the map coarse. This fact has to be taken into account while obtaining the decision for the new secondary transmission. Second, it is rational to have two separate maps, one for interior part and one for the closest surroundings of the building.

7) *Deployment of REM-Based Systems Outside Buildings:* Based on the presented results from drive tests it is reasonable to consider the deployment of low-range cognitive transmitters inside the cities, e.g., mounted on the building pediments, elevations, or along the streets. The tests show that there is rather slight impact of moving objects (cars, persons) on the observed signal power. Moreover, it seems feasible to deploy low-power transmitters also outside the building (i.e., the buildings for which the REM-based system has been already deployed inside). For example, the dedicated secondary transceiver can be mounted on the outside lounge where employes spend their breaks. *Conclusion*: Performed outside measurement campaigns prove that there is a space for deployment of secondary transceivers also outside buildings.
8) *Impact on the Neighboring Buildings:* It is quite often and typical in contemporary cities that the (office) buildings are close to each other. It would result in significant interference induced mutually between the same floors of adjacent buildings. This observation entails that there is a need for careful planning of the secondary system to avoid harmful interference induction to other buildings. Practically it will result in minimization of the transmit power in the rooms located close to other buildings. One may imagine the situation that if there will be REM-based systems in both buildings, these will exchange necessary steering information, as both of them will be connected to the IP network. Whenever this message exchange cannot be guaranteed, the worst case scenario has to be considered. *Conclusion*: The resource allocation algorithm has to consider the presence of neighboring buildings.
9) *Other Maps:* Clearly, the creation of coverage maps based on the measurements is just the first and necessary condition to think on practical deployment of REM-based systems. Once the coverage map is available, the other maps (such as interference map associated with each separate transceiver, which define the interference caused by this transceiver to other users) has to be calculated and updated every time, when the secondary users change their transmit parameters or location.

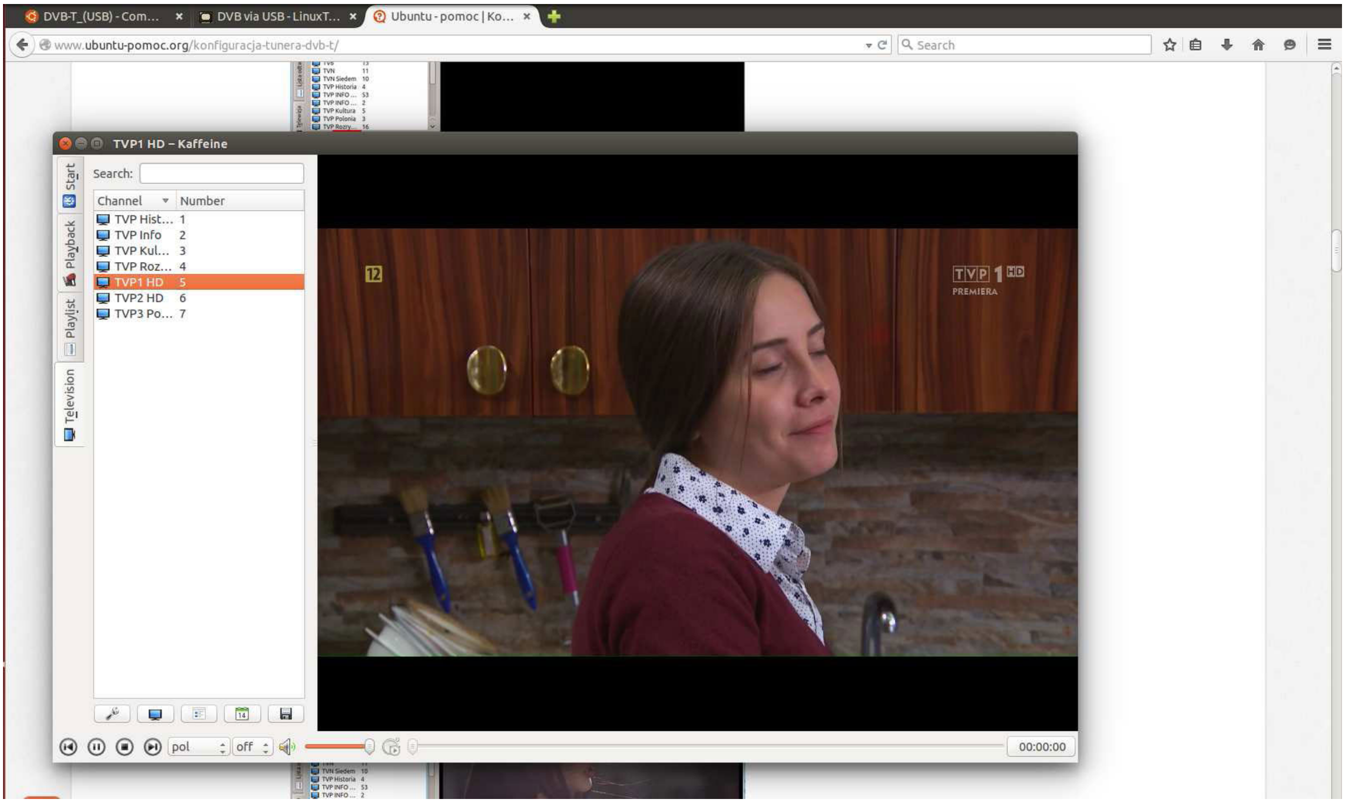
VII. PRACTICAL REM APPLICATION - RESULTS OF THE PERFORMED EXPERIMENT

In order to verify the correctness of the observations made so far, an experiment has been made in the premises of PUT. The main goal of this test was to establish a new white-space link between white-space transmitter and white-space receiver operating in TV band, while protecting the observed DVB-T signal. In order to guarantee the appropriate level of protection to the DVB-T signal, a dedicated database for indoor communications in TV white spaces has been created and stored on a remote server. The tables saved in the REM database have been built based on the performed detailed measurements at PUT. Advanced routines for remote server control, written in Matlab, have realized the functionality of the steering engine, so they were responsible for management of the database and for inferring about the allowed transmit parameters for the white space device. The key target of the conducted experiment was to allow secondary user's communication (at a given location inside the building) so that the observed DVB-T signal is not affected. Then, the algorithm must take into account various factors (such the level of interference induced by the white space transmitter...) for calculation of the allowed values of EIRP.

The white space link has been created by deploying two USRP N210 devices equipped with WBX daughter-boards, where one acted as transmitter and one as the receiver. USRP platforms have been steered from the PC side, managed by Ubuntu 14.04LTS operating system with GNU Radio environment running on it. As for transmitted source data we have selected the video streaming using VLC player that deliver the UDP data to the GNU Radio. The real data transmission was made by applying GMSK modulation and simple packed coding. The whole spectrum has been monitored in real time by means of the Rohde&Schwarz FSL6 spectrum analyzer.

The following scenario has been considered: the experiments has been conducted on the ground floor (so the strength of the DVB-T signal power was low) and intentionally we have selected for white-space transmission the frequency band close to one of the DVB-T channels. The center frequency was set to 506 MHz, whereas the closest DVB-T signal was on central frequency set to 522 MHz. The spectrum (stored in form of a photograph of the spectrum analyzer screen) observed during the experiment is shown in Fig. 31.

The conducted experiment consisted of the following steps: 1. The white-space transmitter send a transmission query to the remote database (in our case the WLAN link connection has been used for guaranteeing connection to the internet, as the classical Ethernet link was used for USRP-PC communication) providing an exact location in the building and expected transmit frequency. 2. Database processes the received request and calculates the allowed transmit power for a given location and central frequency. These values are provided to the white-space devices and are stored in the database (i.e., the database stores the information about the existing transmissions). If there are no possibilities for establishing new connection, the database return negative



Channel	Number
TVP Hist...	1
TVP Info	2
TVP Kul...	3
TVP Roz...	4
TVP1 HD	5
TVP2 HD	6
TVP3 Po...	7

FIGURE 35. Screenshot from PC being the DVB-T receiver.

message to the white space transmitter. 3. White-space receiver, expecting the data transmission at certain center frequency, checks periodically, if there is new transmit activity stored in the database. If this is a case, it tune itself to the parameters stored in the database and starts signal reception.

Fig. 32 illustrates the setup of the experiment. One may observe the presence of the white-space transmitter and receiver (consisting of a PC and connected USRP platform) which negotiates the transmit parameters via WLAN link with the remote database. Once the white-space link is established, the quality of the received DVB-T signal is observed on the PC equipped the DVB-T USB dongle. During the test the DVB-T receiver was set exactly between the white-space transmitter and receiver. In the figure, one may also observe the presence of the spectrum analyzer.

The following three figures present the screenshots from the three PCs utilized during the experiment: in Fig. 33 the structure of the transmitter implemented in GNU Radio is shown together with the transmitted video sequence; analogously, in Fig. 34 the structure of the receiver implemented in the GNU Radio is presented together with the received video signal[6]; finally, in Fig. 35 the TV reception in the PC with DVB-T USB dongle, influenced by the transmission in the adjacent TVWS, is shown. The results come from the tests, where the database has accepted the query from the white-space transmitter to use frequency 506 MHz, and instructed the transmitter that the allowed transmit power is −8.9 dBm. The value was so low due to the stringent restrictions put on the protection of the neighboring DVB-T signal. However, even for such a low value, the transmission was successful, i.e., the white space receiver detected and decoded successfully the transmitted video stream, and the quality of the observed DVB-T signal was not affected.

VIII. CONCLUDING REMARKS - A PRAGMATIC APPROACH FOR REM DEPLOYMENT

This paper has presented an analysis of different indoor and outdoor measurement campaigns of TV white spaces in two European cities, with the main target of identifying the practical aspects for the deployment of radio environment maps. The presented analysis has discussed several aspects, such as the stability over time, the influence of human behavior or the interpolation strategies to build the coverage map.

Taking into account all of the above aspects the whole design process of practical deployment of REM-based systems can be summarized as follows:

1) The measurement campaign has to be carried out in order to identify the real strength of the DVB-T signal on each floor and each room. The identified measurement points shall correspond to the locations where the monitoring modules will be deployed in the future for periodic or per-request update of the measurements.

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[6] Please note that the video images shown in Fig. 33 and in Fig. 34 are different, as we made the screen-shots in the real-time experiment, and it was not possible to capture exactly the same video frame at the transmitter and receiver side.

The density of the measurement points shall be (at least at the first stage of REM-based system deployment) as dense as possible - the more the points the more accurate the map and more careful dynamic spectrum assignments.

2) Based on the measurements, the coarse coverage maps should be created. Depending on the floor elevation (height above the ground) this map can consider outside part or can be limited only to interior fragment. This coverage map should contain information about the floorplans (in the entire building), i.e., the wall's position and type should be known.
3) Once the map has been created, the floors (or areas on the floor) where there is no technical possibility to receive and decode the DVB-T signal correctly should be identified. In these areas there will be limited requirements on interference induced to occupied TV-channels, as one may treat the whole spectrum as free (due to too weak signal power).
4) Once the coverage map for DVB-T signal is created, another map should be calculated, which will provide a detailed information, how much interference can be induced to a certain physical location in order to not disturb the legacy systems. Clearly, in the calculations one needs to add some margins, such as the margin resulting from the influence of humans or improper DVB-T signal measurement. If these margins will be at the level of 10 dB, still there is around 30 dB of interference that could be potentially induced without disturbing the legacy system.
5) In the next step the interference map has to be created and permanently updated as only any change in transmit parameters of any secondary user appears. The interference map has to consider such parameters the transmit masks by the secondary transmitters and the typical reception filter characteristics of the DVB-T receivers. In other words, if there will be a decision to allow to start the secondary transmission at the certain location with a given power, then this transmission will cause the presence of co-channel and adjacent-channel interference, both at the same floor and in the adjacent floors (above and below the current one). Moreover, the potential interference to neighboring buildings have to be considered.
6) The REM-based system shall update periodically or per-request the coverage map, and in consequence, modify all other maps.

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