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TV WHITE SPACE NETWORK INTERFERENCE MEASUREMENTS AND APPLICATION PILOT TRIALS

Final report from field measurement campaigns and application pilot trials in WISE projects during 2011-2014

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Abstract

This report describes TV white space network measurements and trials conducted in Finnish WISE projects during 2011-2014. A TV White Space test network environment was developed and built in Turku, Finland, to aid in standardization and to demonstrate technical capabilities of TV white space networks. The test network environment was the first in Europe having a geolocation database to control the frequency use. This report introduces interference measurements conducted to aid in the standardization work in CEPT/ECC SE43 group. These measurements and the work in the SE43 group served as base information in the creation of an ETSI harmonised standard for TV white space devices, ETSI EN 301 598. The report also presents two application pilot trials conducted to demonstrate the technical feasibility of TV white space networks: a long-term video surveillance trial in Turku and Helsinki area public transport ticket sales and transit information screens trial.

Keywords

Application pilot trial, CEPT/ECC SE43, Digital Terrestrial Television, Geolocation database, Interference measurement, Reference geometry, PMSE, Radio Environment Mapping, Test network environment, TV white space

Contents

1 Introduction

This report describes TV white space (TVWS) network measurements and trials conducted in WISE and WISE2 projects in Finland during 2011-2014. The TV white space test network environment was developed and built to aid in the standardization work, and to demonstrate technological capabilities of TVWS to industry. A project consortium including universities, geolocation database provider, regulator, digital terrestrial television (DTT) broadcaster and user equipment manufacturer began its work in WISE project [1] in 2011. The objective of the project was to construct a testbed to study the use of cognitive radios utilizing white spaces of the UHF broadcasting band (470-790 MHz), follow closely the topics in CEPT/ECC SE43 and contribute the results obtained in the project within SE43. The first phase of WISE project (2011-2013) focused on the interference measurements to protect the incumbents (Digital terrestrial TV and PMSE users) within the DTT band, while the second phase (WISE2, 2013-2014) focused on the application pilot trials.

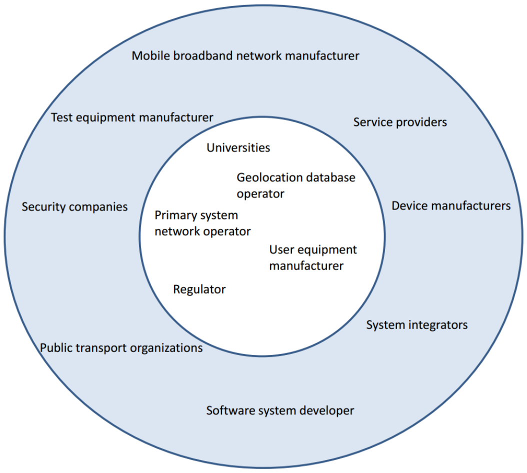


Figure 1: Original WISE consortium in the middle and extended consortium of WISE2 at the outer circle

The WISE project partners in the first phase were University of Turku, Turku University of Applied Sciences, Aalto University, Nokia, Digita, Fairspectrum, and

Finnish Communications Regulatory Authority (FICORA). Additional industrial partners were introduced in the second phase: Nokia Siemens Networks, Elektrobit, Teleste, Suomen Turvakamera Oy, Satel, Helsingin Seudun Liikenne, City of Jyväskylä (Local traffic), Viola Systems, Insta DefSec and QEM Software. Figure 1 illustrates the consortium partners in both the first (inner circle) and the second phase (both circles).

The first chapter gives a brief introduction to the conducted TVWS trials and the European level standardisation work, which was the main reason to build a test network environment for TVWS. The second chapter presents the TVWS test network environment, related radio license, geolocation database and its radio environment mapping techniques, and the device emission measurements conducted for the white space devices (WSD) used in the application pilot trials. The third chapter describes interference measurements conducted to study the protection of incumbents in scenarios under consideration in CEPT/ECC SE43 project team. The fourth chapter describes a video surveillance application pilot trial and the application pilot trials conducted with a public transport authority. Finally, the concluding remarks are given.

1.1 Technical work in CEPT/ECC SE43 group

Following a request from the Electronic Communications Committee (ECC), European Conference of Postal and Telecommunications Administrations (CEPT) Working Group Spectrum Engineering (WG SE) established a new project team, Spectrum Engineering 43 (SE43), at its 53rd meeting in May 2009. SE43 began its work with “Technical and operational requirements for the possible operation of cognitive radio systems in the “White Space” of the frequency band 470-790 MHz” [2]. SE43 met for the first time in June 2009, and completed the work at its 16th meeting in December 2012. All stakeholders were involved in the SE43 work: administrations, industry, operators, Programme Making and Special Events (PMSE) representatives, and broadcasters.

SE43 was mandated to:

- Define technical and operational requirements for the operation of cognitive radio systems in the white spaces of the UHF broadcasting band (470-790 MHz) to ensure the protection of incumbent radio services/systems and investigate the consequential amount of spectrum potentially available as “white space”.
- Provide, if required, technical assistance on further issues related to white spaces and cognitive radio systems that ECC may identify in the future.
- Liaise directly with relevant groups within ECC and European Telecommunications Standards Institute (ETSI) as necessary [3].

The outcome of the first phase of the work was ECC report 159 (Technical and operational requirements for the possible operation of cognitive radio systems in the ‘white spaces’ of the frequency band 470-790 MHz) [4], which was released in January 2011. The report still had a number of technical and regulatory issues requiring further consideration, but it was decided that instead of updating it, two complementary reports would be released. The interference measurements conducted in this report addressed the issues mentioned in ECC report 159, and contributed to the second phase of SE43 work, which resulted in two complementary reports: ECC report 185 (Complementary Report to ECC Report 159 Further definition of technical and operational requirements for the operation of white space devices in the band 470-790 MHz) [5] and ECC Report 186 (Technical and operational requirements for the operation of white space devices under geo-location approach) [6], which were released in January 2013.

The reports produced in SE43, and ECC reports in general, are studies in support of a harmonisation measure and have no direct regulatory power. Their importance is nevertheless immense, as they are used to aid in the European regulation and standardisation. The European Telecommunications Standards Institute (ETSI) is the official European standards organization which works under mandates from the European Commission to prepare harmonised standards under the provisions of Radio and Telecommunication Terminal Equipment (R&TTE) Directive [7]. ETSI BRAN (Broadband Radio Access Networks) has used the reports produced by SE43 as the basis of its "Harmonised European Standard EN 301 598: White Space Devices (WSD); Wireless Access Systems operating in the 470 MHz to 790 MHz TV broadcast band; Harmonised Standard covering the essential requirements of article 3.2 of the R&TTE Directive" [8]. This harmonised standard includes RF requirements to prevent harmful interference from WSDs by ensuring that the wanted radiated power and unwanted radiated power do not exceed specific limits, which have been set by using the results of the studies in SE43. The first phase of WISE project contributed to the creation of this standard, while in the second phase of the project the standard was used to measure if the WSDs used in the application pilot trials comply with the harmonised standard (see section 2.3). In June 2016, R&TTE was replaced by Radio Equipment Directive (RED) [9], and the harmonised standards are currently being revised to meet the updated requirements of RED.

2 WISE - White Space Test Environment for Broadcast Frequencies

Turku TV white space test environment was set up in WISE project [1] to develop and validate technical solutions, accelerate commercial utilization of white spaces, and to support the contributions to the regulation and standardisation work in CEPT/ECC SE43 group. The test network and radio laboratory are located in Turku, Finland. TV White space equipment has also been installed and trialled in different locations in Helsinki for use-case piloting.

The TVWS test network environment consists of the following components:

- A commercial level DVB-T terrestrial TV broadcast test network with three transmitters. The test network makes it possible to study the co-channel and adjacent channel interference of cognitive radios to real TV broadcasts.
- A complementary simulation environment developed by University of Turku and Aalto University.
- A full cognitive radio license for the TVWS frequency range 470 MHz - 790 MHz.
- Fairspectrum geolocation database.
- The Turku University of Applied Sciences radio laboratory, which is equipped with e.g. white space radios, spectrum analysis and spectrum measurement equipment.

FICORA has issued a test radio license for cognitive radio devices in the TV White Space frequencies for Turku University of Applied Sciences. The license covers the 470-790 MHz frequency range and a 40 km x 40 km area surrounding Turku, Finland. This area is illustrated with a rectangle in Figure 2. Nearly 300 000 people live in the radio license area. The license is the first in Europe having a geolocation database in control of the frequency use [10].

Radio license conditions are the following:

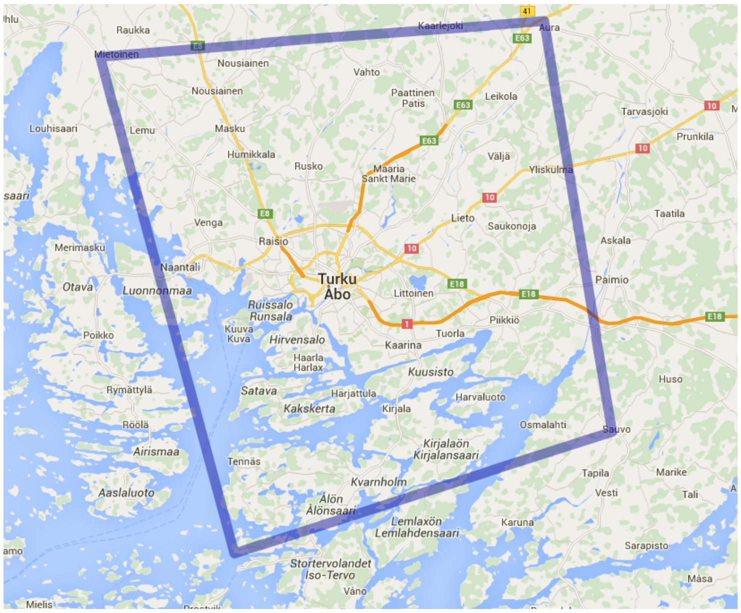


Figure 2: Radio license area

- Area: Turku region, 40 km x 40 km range (Figure 2).
- Max +44 dBm EIRP for fixed station / base station.
- Max +30 dBm EIRP for mobile station / terminal.
- Maximum transmitter power: +31 dBm.
- Antenna gain 0-14 dBi (omni or directional antenna).
- Antenna height: Max 40 m above sea level.
- Polarization: vertical.
- Channel width: 6 MHz or 8 MHz.
- Number of transmitters: 1 Neul base station and terminal, 1 Carlson Wireless base station and 5 terminals.
- Transmission frequencies and power of the white space devices are controlled by a geolocation database. The database makes the decisions based on the location of the TVWS radio transmitters and information on the primary users to be protected.

Fairspectrum provides the geolocation database for the TVWS test network according to the FICORA license rules. The TV White Space radios of the test network are from US manufacturer Carlson Wireless. One base station and five terminals are at our disposal. They operate in 470-786 MHz frequency bands, and both US 6 MHz and ETSI 8 MHz channel spacing can be used [11]. A prototype base station and terminal from UK-based Neul are also at our disposal.

The test network environment offers full control and flexibility in defining transmission parameters of the DVB-T network. Support for finding test locations and routes, estimating white space availability, and other relevant information is available through simulations, calculations and signal level field measurements. Computer simulations can be used to verify and interpolate measurement results.

The test environment enables a wide range of testing possibilities in diverse environments, such as:

- Service piloting.
- Interference management, protection ratios and co-existence.
- Algorithm development and optimization.

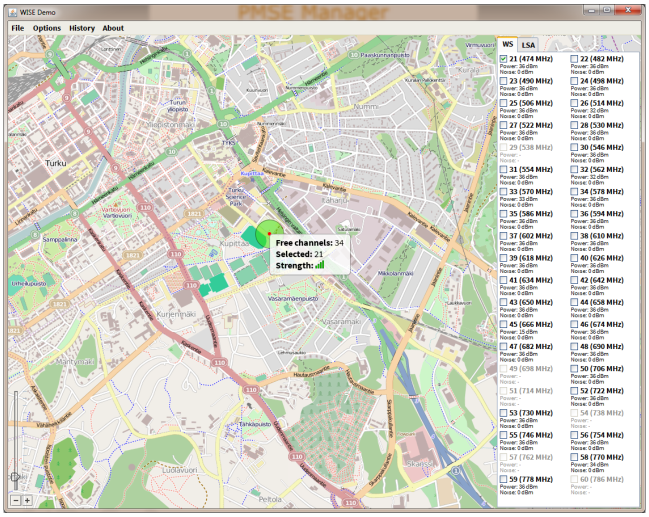
2.1 Geolocation and PMSE databases

The radio license requires that the incumbent users of the UHF TV band need to be protected from any harmful interference. A geolocation database is used to provide protection for DTT and PMSE incumbents operating in the band from interfering white space devices. In practice, the geolocation database contains coverage maps of the incumbent DTT networks. These coverage maps are used to calculate maximum allowed transmission powers for interference-free operation of the WSDs at their current geographical locations.

The incumbent PMSE users operating in the UHF TV band are wireless microphones. Turku University of Applied Sciences has developed a wireless microphone database to collect their operating parameters and locations to allow their protection. This database provides the data to the geolocation database, which is then able to calculate the needed protection for both DTT and PMSE users. The protection zones are defined as geographical areas, which are then converted to polygons. Geolocation database utilizes these polygons in the calculation of available channels and their associated power levels for different geographical locations. Geometrical computation makes the geolocation database efficient, fast, and easily customizable for various environments, regulations, and rules.

Before it can begin to transmit on TVWS frequencies, a WSD needs to connect to a geolocation database, and request available channels and their power levels by sending its capabilities (antenna height, operational location, device type and device emission class) and transmission parameters. The geolocation database calculates WSD's radio coverage area and analyzes the DTT and PMSE transmissions within that coverage area, and finally provides the WSD with a channel to operate in and the maximum allowed power level in that channel.

The geolocation database can also be accessed using the web interface or a mobile client software, which is illustrated in Figure 3. Both allow the user to select a location from a map, and to see the location's channel availability information



Free channels: 34
Selected: 21
Strength:

☑ 21 (474 MHz)
Power: 36 dBm
Noise: 0 dBm
☐ 22 (482 MHz)
Power: 36 dBm
Noise: 0 dBm
☐ 23 (490 MHz)
Power: 36 dBm
Noise: 0 dBm
☐ 24 (498 MHz)
Power: 36 dBm
Noise: 0 dBm
☐ 25 (506 MHz)
Power: 36 dBm
Noise: 0 dBm
☐ 26 (514 MHz)
Power: 32 dBm
Noise: 0 dBm
☐ 27 (522 MHz)
Power: 36 dBm
Noise: 0 dBm
☐ 28 (530 MHz)
Power: 36 dBm
Noise: 0 dBm
☐ 29 (538 MHz)
Power: -
Noise: -
☐ 30 (546 MHz)
Power: 36 dBm
Noise: 0 dBm
☐ 31 (554 MHz)
Power: 36 dBm
Noise: 0 dBm
☐ 32 (562 MHz)
Power: 32 dBm
Noise: 0 dBm
☐ 33 (570 MHz)
Power: 33 dBm
Noise: 0 dBm
☐ 34 (578 MHz)
Power: 36 dBm
Noise: 0 dBm
☐ 35 (586 MHz)
Power: 36 dBm
Noise: 0 dBm
☐ 36 (594 MHz)
Power: 36 dBm
Noise: 0 dBm
☐ 37 (602 MHz)
Power: 36 dBm
Noise: 0 dBm
☐ 38 (610 MHz)
Power: 36 dBm
Noise: 0 dBm
☐ 39 (618 MHz)
Power: 36 dBm
Noise: 0 dBm
☐ 40 (626 MHz)
Power: 36 dBm
Noise: 0 dBm
☐ 41 (634 MHz)
Power: 36 dBm
Noise: 0 dBm
☐ 42 (642 MHz)
Power: 36 dBm
Noise: 0 dBm
☐ 43 (650 MHz)
Power: 36 dBm
Noise: 0 dBm
☐ 44 (658 MHz)
Power: 36 dBm
Noise: 0 dBm
☐ 45 (666 MHz)
Power: 15 dBm
Noise: 0 dBm
☐ 46 (674 MHz)
Power: 36 dBm
Noise: 0 dBm
☐ 47 (682 MHz)
Power: 36 dBm
Noise: 0 dBm
☐ 48 (690 MHz)
Power: 36 dBm
Noise: 0 dBm
☐ 49 (698 MHz)
Power: -
Noise: -
☐ 50 (706 MHz)
Power: 36 dBm
Noise: 0 dBm
☐ 51 (714 MHz)
Power: -
Noise: -
☐ 52 (722 MHz)
Power: 36 dBm
Noise: 0 dBm
☐ 53 (730 MHz)
Power: 36 dBm
Noise: 0 dBm
☐ 54 (738 MHz)
Power: -
Noise: -
☐ 55 (746 MHz)
Power: 36 dBm
Noise: 0 dBm
☐ 56 (754 MHz)
Power: 36 dBm
Noise: 0 dBm
☐ 57 (762 MHz)
Power: -
Noise: -
☐ 58 (770 MHz)
Power: 34 dBm
Noise: 0 dBm
☐ 59 (778 MHz)
Power: 36 dBm
Noise: 0 dBm
☐ 60 (786 MHz)
Power: -
Noise: -

Figure 3: Geolocation database client software

calculated by the geolocation database. The channel information shows the availability and the maximum transmission power for WSD devices in each TV channel. Channels listed with grey colour are not available for WSD usage. Web and mobile clients use Protocol to Access White-Space Databases (PAWS) [12] to communicate with the geolocation database.

PMSE Incumbent Manager was developed as a cloud-based web service, where the users can add their PMSE devices to the PMSE database. The PMSE Incumbent Manager allows the users to add their wireless microphones by setting their location on a map and selecting a channel from the list of available channels. Time, location and frequency of a wireless microphone are needed by the PMSE database to enable the calculation of their protection. The user first selects the location of the wireless microphone on a map, after which the PMSE Incumbent Manager requests the channel and use time information. This information is then communicated to the geolocation database.

2.2 Radio environment mapping algorithms for the geolocation database

The key factor in TVWS operation is to calculate accurate maximum allowable power limits for WSDs. Accurate limits guarantee that the interference to the primary network remains within acceptable limits, while it also maximizes the throughput of the TVWS system. Too strict power levels limit the TVWS throughput, while too lenient limits cause harmful interference to the incumbents.

Radio environment mapping (REM) presents a more accurate alternative for signal level calculations than propagation modeling. Here we introduce hybrids of

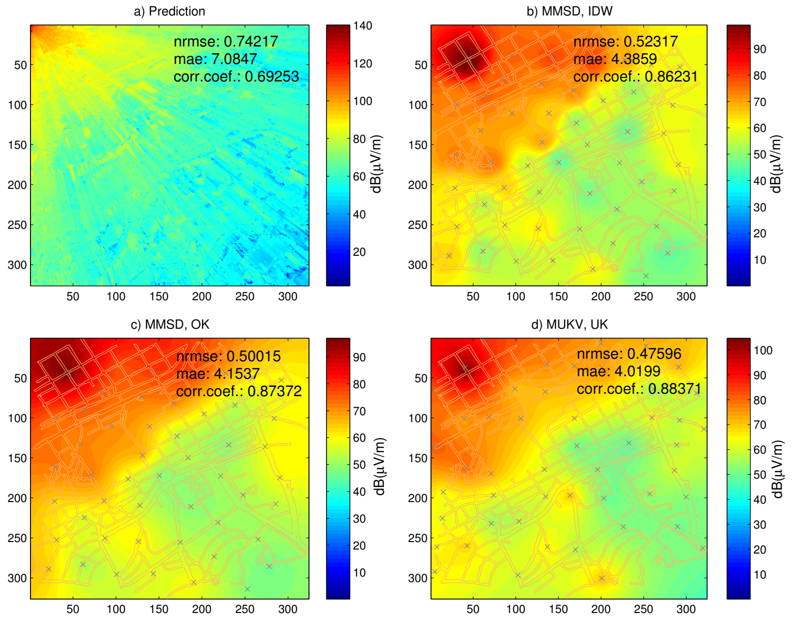


Figure 4: Estimated field strength values for Turku DTT test network area with the methods used in [13]. a) presents a prediction based on a propagation model. In b) and c), the field strength is estimated by interpolating the samples obtained from locations chosen with MMSD by using IDW and OK methods. The sampling locations in d) are selected by minimizing the MUKV, and the field strengths are estimated with UK interpolation. Grey crosses indicate the locations where the field measurements have been performed.

measurement campaigns and computer simulations, which have been used to validate the signal levels of DTT network in the geolocation database, and thus also the validity of the incumbent protection provided by the geolocation database.

In the creation of a radio environment map, measurements are conducted at some locations, and interpolation techniques are used to estimate values at locations which have not been measured. A sampling scheme makes decisions on where the samples are obtained from, i.e. the measurement locations. Since field measurements are resource-consuming, it is important to design a sampling scheme which allows an optimal estimation(interpolation) of the radio environment with a given number of measurement locations.

To overcome the limitations arising from using only radio propagation models or suboptimal field measurement locations, we have proposed a geostatistical modeling procedure for estimating the radio environment in [13]. An optimal sampling scheme was designed by using spatial simulated annealing (SSA) to minimize the mean universal kriging variance (MUKV) needed in the Universal kriging (UK) interpolation.

Figure 4 shows an estimation based on a propagation prediction model in a), and in b) and c) the estimation is performed by interpolating the minimum mean shortest distance (MMSD) scheme using inverse distance weighted interpolation (IDW) and ordinary kriging (OK) methods. These are earlier calculation and interpolation methods, to which the novel contribution in d) is compared. In d) the sampling locations are found by minimizing the MUKV with SSA, and the field strength estimates for unsampled locations are determined by UK.

Field measurements have been performed in locations indicated by gray crosses. SSA algorithm was able to find the optimal measurement locations in 200 iterations. The measurement locations are strictly limited to the street network within the test area, and the modeling procedure was verified with an extensive measurement campaign performed in an operational DTT test network in Turku. Pixel size of 6 m x 6 m was used for this 2010 m x 2085 m area of the test network.

The proposed method of [13] presented in d) of Figure 4 was the most accurate according to the used metrics: mean absolute error (MAE), normalized root mean square error (NRMSE) and Pearson correlation coefficient. It significantly improved the precision of local field strength estimates compared to using only propagation model (a), or by interpolating the field measurement values sampled on a regular grid (b and c).

In [14], we have designed an efficient technique for improving the REM estimation in scenarios where relatively small numbers of measurement samples are available. The proposed multivariate kriging method utilizes correlated secondary information obtained from a terrain based propagation prediction model [15] to complement the measurement data. Considerable improvement in prediction accuracy is achieved compared to univariate interpolation methods.

The proposed techniques can be utilized in designing sensing networks, or in measurement campaigns for REM. The radio environment maps can be used in the TV white space geolocation databases to calculate accurate protection levels for the DTT networks. The accurate signal level estimations also help in search of locations with specific signal level within the test network, such as in the outdoor reference geometry measurements of section 3.1.1.

2.3 Device emission class measurements

Prior to performing trials in the TVWS test network, the unwanted emissions levels of a WSD need to be verified. ETSI EN 301 598 harmonised standard for white space devices [8] is used for this purpose. This standard is based on the SE43 work, as described in section 1.1. The standard defines 5 different device emission classes for WSDs. This class is an important parameter in the geolocation database, and it is used in the calculation of allowed transmitter power level for the WSDs. A correct classification is essential to avoid harmful interference to incumbents of the UHF TV band.

Turku University of Applied Sciences (TUAS) Radio laboratory has a measurement system to conduct unwanted emission measurements to define and verify the device emission class according to the ETSI EN 301 598 [8]. The WSD adjacent channel leakage ratios (ACLRs) are measured within the 470 to 790 MHz TVWS operational band, and the emissions outside the band are measured from 30 MHz to 4 GHz. Table 1 of [8] presents the requirements for Adjacent Channel Leakage Ratio (ACLR) for different emission classes, and table 2 of [8] the requirements for transmitter unwanted emission limits outside the 470 to 790 MHz band.

The measurement requirements for prescan sweeps are: resolution bandwidth of 100 kHz in 30-1000MHz and 1 MHz in 1-4 GHz frequency bands, peak detection, and trace mode max hold. Emissions which are above the limits in the pre-scan shall be individually measured in a frequency band wide enough to capture each identified emission using continuous sweep, root mean square (RMS) detector and max hold trace mode.

The better the classification of the device under test (DUT) is, the less out of band (OOB) emissions there are and the more power can be granted by the geolocation database for WSD operation. Class 1 is the highest class with lowest unwanted emissions, while class 5 is the lowest classification for a WSD. The performance of the DUT is usually not constant in different channels. For example, a DUT can pass class 1 criteria on most of the channels, but on some channels it only passes class 4 criteria. The worst measurement result defines the classification of the DUT, so in this case the DUT would pass only as class 4 device even though it performs better in most of the channels.

3 Measurements contributed to CEPT/ECC SE43

This chapter describes the measurements conducted in the WISE project to investigate the technical and regulatory issues defined to need more consideration in ECC report 159. The DTT-WSD protection ratio measurements of section 3.1 have been contributed to CEPT/ECC SE43 in [16, 17, 18, 19] and the PMSE measurements of section 3.2 in [20, 21]

3.1 Protection ratio measurements in reference geometries defined in ECC report 159

The existing primary, licensed users in the radio spectrum are also known as incumbents. Their transmissions need to be protected from harmful interference from secondary users, such as white space devices. Various methodologies have been used to develop protection criteria for the incumbents in the UHF TV band, including calculations with parameters from ECC, International Telecommunication Union Radiocommunication sector (ITU-R) and ETSI deliverables. During the last few years, several measurement campaigns regarding the use of WSDs in TV frequencies have been conducted, but these efforts have not been able to clearly give safe operational rules for WSDs. This has resulted in a number of different recommendations for the technical and operational requirements that should be applied to WSDs operating in the frequency band 470-790 MHz in order to protect the incumbent DTT transmissions and PMSE wireless microphones within the band.

Technical work to define European-wide protection ratio proposals was started in CEPT/ECC project team SE43. The issue is discussed in ECC report 159 [4], and a proposed solution is to use reference geometries in the calculation of coupling loss between the devices. Several different reference geometries are proposed to simulate different DTT reception scenarios. The path losses in the reference geometries of the ECC report 159 are calculated as free space losses with certain assumptions on the used antennas. Two cases must be distinguished when considering the interference caused by a WSD to DTT reception. In the first case the WSD and the victim DTT receiver are separated by a relatively large distance and interference is primarily of co-channel type. The DTT receiver location can be estimated as the nearest possible pixel of the DTT service area in question, and the coupling loss between the WSD and DTT receiver can be calculated based on their distance and a suitable propagation model. In the second case the WSD and the victim DTT receiver are within the same pixel. In this case the interference is typically of adjacent channel type, as co-channel operation is not possible within the DTT service area. Calculating the coupling loss in this case is problematic as nothing is known about the geometry between the WSD and the DTT receiver, only that they may exist within the same pixel and thus their distance is constrained by the pixel dimensions.

An indoor and an outdoor reference geometry representing worst-case scenarios for DTT reception were created to enable the measurement and studies of adjacent-channel operation in such problematic cases. The reference geometries were presented in ECC report 159, and were naturally chosen as the scenarios for the field measurement studies of protection ratios between WSDs and DTT.

In [22] protection ratio (PR) is defined as the minimum value of the signal-to-interference ratio required to obtain a specific reception at the receiver input. Formally, this ratio is defined as

$$PR(f_{pri}, f_{wsd}) = \frac{P_{pri}(f_{pri})}{P_{wsd,max}(f_{wsd})} \tag{3.1}$$

that is, the ratio of the received TV signal power centered at frequency f_{pri} to the maximum allowable power transmitted by the WSD at center frequency f_{wsd}. In these measurements, the maximum WSD transmit power is determined as the limit where error-free TV reception is still possible according to a subjective criterion corresponding approximately to ESR5 criterion [23].

The presented measurement campaigns can be considered as the first practical testing of the proposed theoretical reference geometry WSD scenarios, but also as a source of realistic numerical estimates for the minimum protection ratios between WSD transmitters and TV receivers; as such, the given data can be used for example in further WSD system development, simulation, and performance evaluation. The results have been contributed to the SE43 group meetings in [16, 17, 18, 19] and published in 7th International Conference on Cognitive Radio Oriented Wireless Networks (CROWNCOM 2012, Stockholm, Sweden, June 18–20, 2012) [24].

3.1.1 Field measurements in outdoor reference geometry

The outdoor reference geometry defined in ECC report 159 and used in the field measurements is for rooftop antenna DTT reception at 10 m height with a portable WSD at 1.5 m height and 22 m away from the DTT reception antenna. An omnidirectional antenna is assumed for the WSD, so that a polarization discrimination of 3 dB is possible, but in the measurements a directional antenna with horizontal polarization for the WSD was also used to increase the available WSD equivalent isotropically radiated power (EIRP). The DTT antenna specified in the reference geometry has a gain of +9.15 dBi, which is assumed to drop by 0.45 dB to the direction of the WSD 22 m away. The antenna is described in ITU-R BT 1368 [25]. This geometry aims to represent a worst-case scenario: if the WSD is situated closer, the

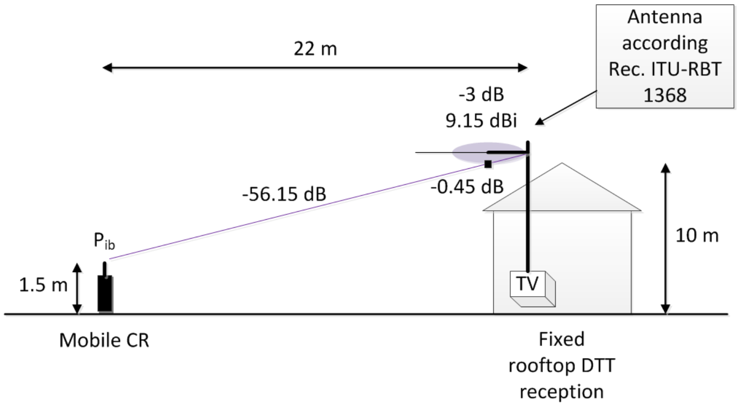


Figure 5: Outdoor reference geometry.

antenna gain will drop, and if the WSD is further away the free space loss will increase, decreasing the interfering signal power at the DTT receiver. The considered outdoor reference geometry is illustrated in Figure 5.

Figure 6: TVWS radio antenna at 1,5m above ground level (on the right) and 10m DTT reception antenna (on the left) in an outdoor reference geometry measurement.

The outdoor measurements study the maximum possible WSD power in the corresponding reference geometry before the received picture fails. The measurements were done at three different DTT signal levels. The first was at an input level of -80 dBm, 3 dB from the sensitivity limit of the receiver, corresponding to the situation where the DTT receiver is located at the edge of the service area. The second was with an input level of -70 dBm and the third with -62 dBm input level at the receiver. The locations of the measurements were selected so that a suitable signal level was achieved with a Yagi antenna at a height of 10 m. One field measurement location and measurement antenna setup is shown in Figure 6.

Interference measurements were performed with the WSD operating on the co-channel N and on adjacent channels $N-1$, $N-2$, $N-3$ $N-4$ and $N+9$. The WSD transmission power was increased until errors were detected in the picture and then decreased by 1 dB steps until no errors were visible during an observation period of several tens of seconds, corresponding roughly to the ESR5 criterion [23]. Then the power fed to the WSD transmission antenna was measured in the co-channel case. In the adjacent channel cases, the received WSD interference power at the DTT receiver input was also measured and used to calculate the corresponding protection ratio. It should be noted that with the WSD operating on the adjacent channel $N+9$ in the scenario with DTT signal strength -62 dBm, the WSD transmission power was insufficient to produce errors in the DTT reception, and the true protection ratio is higher than given here. This case is marked with bold text in Table 1, which shows a summary of the maximum WSD power levels for different frequencies and DTT input levels. The corresponding Field Strength (FS) at the DVB-T reception site is also shown, as well as the protection ratio calculated with formula 3.1. The ACLR values for each measurement and the laboratory measurements of the DTT receivers can be found in [17].

Table 1: Outdoor protection ratios with 64-QAM DVB-T

Frequency (MHz) / (Channel)	DVB-T level -80 dBm			DVB-T level -70 dBm			DVB-T level -62 dBm		
	WSD		PR	WSD		PR	WSD		PR
	EIRP (dBm)	FS (dbμV/m)	(dB)	EIRP (dBm)	FS (dbμV/m)	(dB)	EIRP (dBm)	FS (dbμV/m)	(dB)
578 / (N-4)	18.9	94.0	48.4	32.5	107.6	51.9	36.4	111.5	49.0
586 / (N-3)	18.3	93.4	47.5	21.5	96.6	40.6	23.0	98.1	35.4
594 / (N-2)	15.2	90.2	44.1	18.7	93.7	38.4	20.5	95.5	33.2
602 / (N-1)	1.7	77.0	31.4	13.3	88.6	33.2	12.8	88.1	25.9
610 / (N)	-50.0	24.7	-19.7	-36.5	38.2	-16.2	-30.0	44.7	-17.7
682 / (N+9)	20.9	95.6	51.1	33.8	108.5	53.7	38.5	113.2	**48.4**

3.1.2 Field measurements in indoor reference geometry

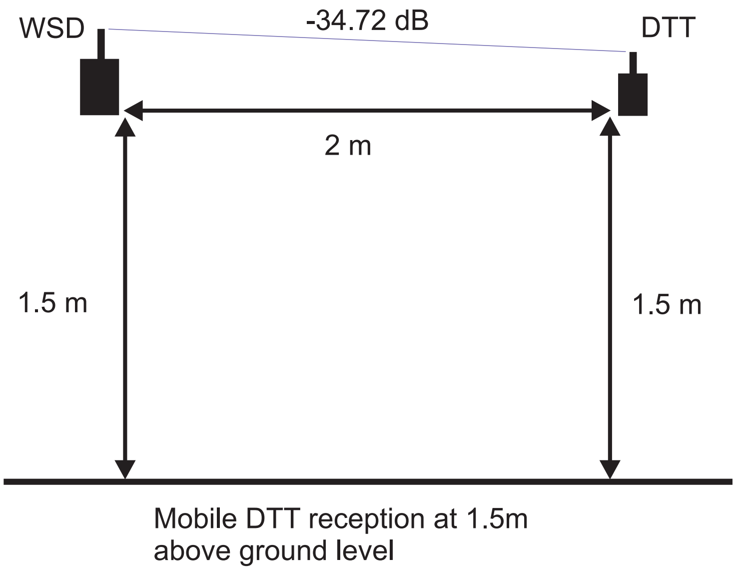


Figure 7: Indoor reference geometry.

The portable indoor reference geometry defined in ECC report 159 and used in these measurements is shown in Figure 7. Both the DTT reception antenna and the WSD transmitter are at a height of 1.5 m and 2 m away from each other. Omnidirectional antennas are assumed for both the WSD and DTT with no polarization discrimination. This was achieved in the measurements by using two similar omnidirectional antennas with a nominal gain of 2 dBi.

All indoor measurements were performed in an old school building constructed mainly of brick and concrete, whose windows are without any metallised shielding. The building, measurement locations, and transmitter direction are illustrated in Figure 8. It should be noted that DTT transmissions penetrate this type of building better than a modern office building. The following rooms were used for the measurements:

- ”Muotoilutila” (Muo): a small rooftop space used for project works.
- L229: class room in L-wing, second floor
- C20: class room in C-wing, second floor
- L321: class room in L-wing, third floor

The ”Muotoilutila” is a small room on top of the C-wing and has a window towards the transmitter. All other rooms have windows perpendicular to the transmitter direction, so no direct signal was received in these cases.

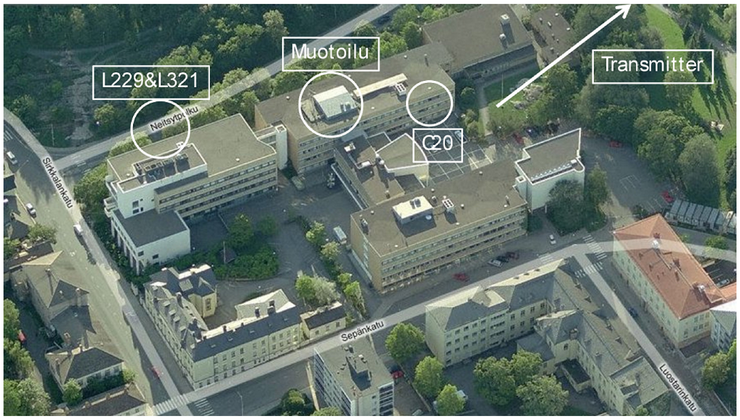


Figure 8: Indoor measurement premises.

The rooms where the measurements were performed have a different geometries and thus different reflections from the surroundings. Therefore the coupling losses also differ between the rooms, even though the distance between the WSD and DTT is constant. The coupling losses were measured in each room in the 2 m reference geometry. A comparison between these and a calculated free-space loss (FSL) is shown in Figure 9. Even though the number of measurements is not large enough to give statistically reliable results, a clear trend in the measurements is that the coupling loss is higher than the FSL.

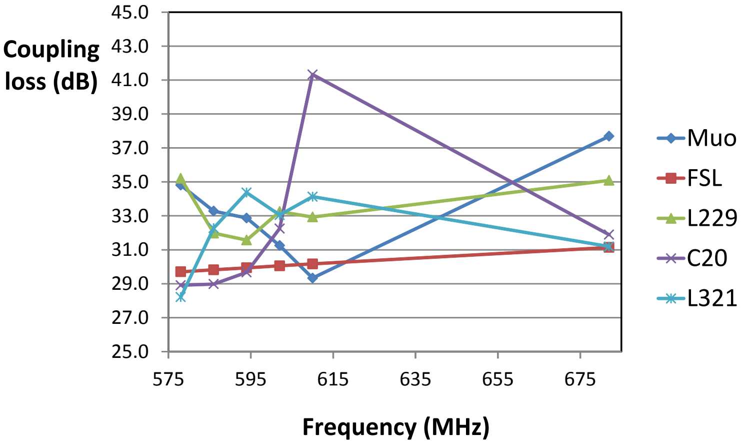


Figure 9: Free-space loss and coupling losses in different rooms.

The indoor measurements studied again the maximum possible WSD power in the reference geometry before the DTT reception failed. Most of the measurements were done close to the sensitivity limit of the DTT receiver, corresponding to the situation where the DTT receiver is located at the edge of the service area or in otherwise difficult indoor conditions. The protection ratios were calculated from the measured WSD and DTT powers at the DTT receiver input. Results are shown in Table 2. In one measurement, L 229 2m/N-4, the available WSD power was not high enough to cause any errors, and thus the calculated protection ratio is likely to be lower than the real value would be. This case is marked with bold text in Table 2. The protection ratio values are rather consistent. The greatest spread is in the values at N-1 (602 MHz). On average, the co-channel protection ratio is between -20 and -25 dB, protection ratio on channel N-1 is between 25 and 35 dB, on N-2 between 39 and 42 dB, and on N-3 and N-4 between 40 and 45 dB. The variations are at least partly due to different channel conditions at different locations. The laboratory measurements performed to calibrate the measurement setup are explained in [18].

Table 2: Indoor protection ratios with 256-QAM DVB-T2

Frequency (MHz) / (Channel)	Protection ratio with 32k 256-QAM 3/5 in room				
	Muo 2m	L229 2m	C20 2m	L321 2m	Average
578 / (N-4)	43.0	**40.1**	43.9	44.5	42.9
586 / (N-3)	41.9	42.5	42.9	40.1	41.9
594 / (N-2)	39.5	40.8	40.9	38.9	40.0
602 / (N-1)	25.6	28.6	35.0	30.7	30.0
610 / (N)	-23.5	-23.6	-22.8	-23.8	-23.4

3.2 PMSE wireless microphone measurements

PMSE is a term, which covers equipment that supports broadcasting, news gathering, theatrical productions, sport events and such. The PMSE operating on the TV White Space frequencies are wireless microphones. Geolocation databases are currently considered to be the primary method of protecting PMSE users as sensing techniques are currently not sufficient to provide reliable protection for PMSE, and the range of potential deployment scenarios causes large variability in the sensing thresholds. In the following we outline a measurement campaign conducted to evaluate interference between WSD and PMSE devices in a real use scenario.

Two theatres in Helsinki were used for the measurement campaign. Helsinki City Theatre, located in Kallio, is the biggest theatre in Helsinki. The main building was built in the 1960's and is a traditional concrete and steel construction. It has two stages, a big stage with 947 seats and a smaller stage with 400 seats. The Arena Theatre is a smaller 515-seat theatre nearby. Arena is located in a larger brick building built in 1923. Illustrations of both theatres are available in the full measurement report [20].

Two sets of analogue microphones were used in the measurements, altogether four microphones and two receivers. The purpose was to use microphones in real operating conditions, and therefore the receivers were placed at realistic places in the theatres. At the main stage, the receiver was placed in the middle of a balcony above the audience. In the Arena theatre, the receivers were placed on the balcony as well, and close to the existing antenna installations in the theatre. In both arenas, the microphone to receiver link in the measurements was somewhat more demanding than with the existing installations. The microphone receivers were using small whip antennas attached directly to the receivers.

During the measurements we found out that there is a large difference in the results depending on how the microphones are used. The worst case, but also most realistic, was the belt pack microphone attached to a person moving around the stage. The loss due to the bodies of the actors and the movement is at its highest in this scenario. Therefore the most realistic scenarios were the ones where the microphones were attached to people moving around the stage and simulating real actors, sometimes even going behind the stage.

Interference to the PMSE equipment was caused by a simulated WSD operating on the co- or adjacent channel. The measurements were performed with the WSD in several locations inside and outside the building. Figure 10 illustrates the locations of the microphones and PMSE receivers, and the WSD locations (yellow circles) inside the Helsinki City Theatre. Subjective evaluation was used to determine when the WSD was causing audible interference.

The measurements clearly show that a WSD operating co-channel with the PMSE causes interference on very low power levels (-15 dBm ... +5 dBm) when the WSD is in the vicinity of the PMSE equipment. Thus, the co-channel operation of PMSE equipment and WSDs is not possible in the vicinity of PMSE receivers. The protection ratios on the adjacent channel were approximately +30dBm and on the next adjacent channels +40 dBm or more. These values would allow adjacent channel operation with reasonable power levels for the WSDs located close to PMSE equip-

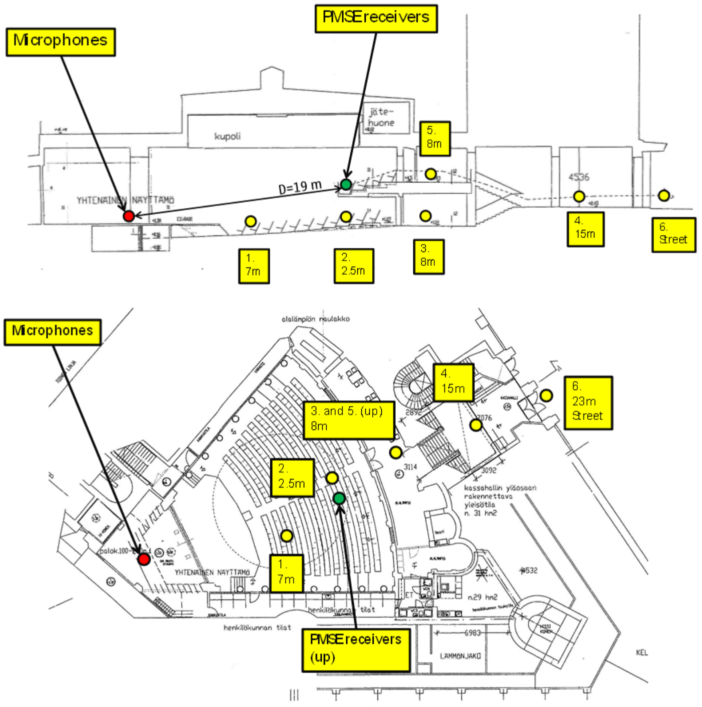


Figure 10: Locations of the PMSE equipment and WSD transmitters measured at Helsinki City Theatre. Figure adopted from [20].

ment. In the measurements conducted at Helsinki City Theatre it was not possible to cause co-channel interference at a distance of 560 m with the maximum transmit power of approximately 10 W.

The results of the measurement campaign were presented in 12th SE43 meeting in Cambridge, UK, in December 2011 [20, 21]. The key findings were included in ECC report 185 [5] and the full measurement report added as an annex to the report.

4 Application pilot trials

This chapter presents two TVWS application pilot trials conducted during the second phase of WISE project in 2013-2014. The first presented application pilot trial was a long-term video surveillance trial in the Turku TVWS test network environment. The second was an application pilot trial with the public transport authority in Helsinki, where the TVWS devices were tested to provide connectivity for their ticket sales and information screen systems. The application pilot trials are covered in more detail in these Bachelor's theses made at Turku University of Applied sciences: the video surveillance trial in [26, 27] and the public transport trial in [28]. The theses are in Finnish.

4.1 Video surveillance trial

The video surveillance application pilot trials were conducted utilizing the TUAS radio laboratory commercial TVWS cognitive radio systems from Carlson[11], cognitive radio license from FICORA and the Fairspectrum geolocation database. The data transmitted over the TVWS radio link was video signal from surveillance cameras.

Carlson TVWS radio system performance measurements were first conducted to verify the performance data provided by the manufacturer. This data was used in the system deployment design and field trial planning. Carlson system supports 16Mbps data rate, but it has asymmetric uplink/downlink speeds (30/70%). This is because the system is designed to provide rural broadband service, where more capacity is typically needed in the downlink direction. In video surveillance application this is not an optimal ratio, as the video cameras are installed in the terminal sites and the video content delivery needs higher bit rates in the uplink than the camera control data in the downlink direction does. Thus, the asymmetry should be the other way around to provide optimal performance for the video surveillance application. The data rate in both directions depends on the used modulation and error correction coding. The system supports 16-QAM, QPSK and BPSK modulation with several different code rates. Maximum bitrates measured in the laboratory tests were 10 Mbps for downlink and 6 Mbps for uplink with 16QAM modulation and ¾ code rates.

Experimental research and several field measurement campaigns were conducted to investigate the interference between DTT receivers and Carlson TVWS radio systems (i.e. white space devices). Interference from the adjacent ($N+1$ and $N-1$)

and alternate channels ($N+/-2,3,4,\ldots$) was measured using commercial DTT signals from the local broadcasting stations, and also from more distant DTT broadcasting stations.

In the first interference measurement campaign, the TVWS radio terminal antenna was mounted in the same mast with the DTT reception antenna, and separate antennas with distances of 2 to 5 meters were also used. Field strengths from the remote DTT transmitters were measured to study the effects to the TVWS radio base station uplink co-channel reception. The protection ratios between the TVWS radio and the DTT signal in the adjacent channel are in order of 20-50 dB for commercial TVs and set-top boxes (STBs). The measurement data and results of this campaign were used in the verification and further development of the geolocation database.

4.1.1 TVWS video surveillance system setup

The video surveillance application was designed and implemented with Carlson TVWS radio system and two commercial standard definition (SD) and high definition (HD) video cameras. Base station and the terminals were installed within the Turku TVWS test network license area. The base station was located at a rooftop of ICT-city building and the camera sites were at Sepänkatu with a distance of 1.6 km and at Lemminkäisenkatu with a distance of 200 meters. The cameras and their related equipment in the sites were on installed on rooftops at 15-20 meters AGL and the base station antenna on a rooftop at a height of 30 meters AGL. Base station antenna is omnidirectional, and the terminal antennas are log-periodic directional antennas. The TVWS radio system terminal access is based on time division multiplexing(TDM), where the terminals share the payload time slots depending on the data rate required for the service. Hence, the two cameras share the time slots between the short control transmissions of the base station. The locations of the terminals and the base station are illustrated in Figure 11.

Video camera and TVWS radio settings were the following:

- Site1/200m link. Camera: resolution 1920x1080 at 25 frames per second (fps). Terminal: modulation 16-QAM with a code rate of ¾.
- Site 2/1.6 km link. Camera: resolution 1280x720 at 25 fps. Terminal: modulation QPSK with a code rate of ¾.

Measured SNR in the Site 1 link was 27 dB, which supports the use of high modulations. Site 1 camera was pointed towards a motorway with almost constant traffic and movement in the picture. Video setting Variable Bit Rate (VBR) gave better quality than Constant Bit Rate (CBR). Bitrate of 3 Mbps was sufficient for smooth video.

On Site 2, the measured SNR was 15-20 dB. Site 2 antenna was pointing over the roofs of nearby buildings, resulting in stationary picture content and minor movements. CBR setting and 2 Mbps were provided sufficient picture quality in this environment.

The maximum uplink bitrates in the sites were the mentioned 3 Mbps and 2 Mbps, as only 30% of the bandwidth was used for uplink due to the asymmetry in

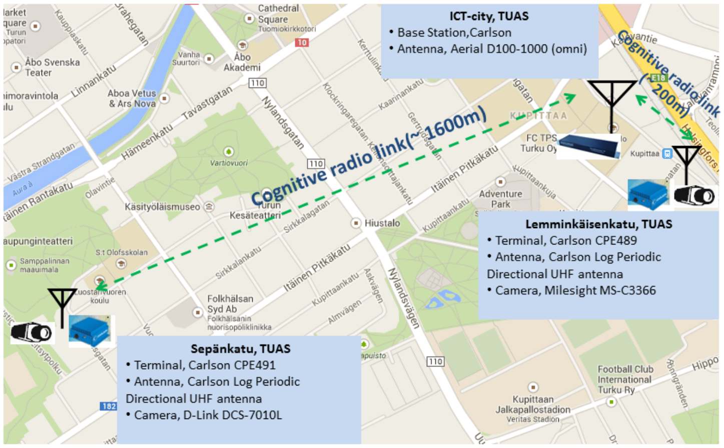


Figure 11: Transmitter and base station locations of the TV white space wireless video surveillance system.

the time-division multiplexing of the TVWS radio system. HD video surveillance application can be implemented with Carlson TVWS cognitive radio system, but the 70%/30% downlink/uplink ratio is far from optimal. 10%/90% ratio could support 12-13 Mbps capacity for cameras. Depending on the video parameters and bitrates, this could allow installation of 5-6 cameras and terminals to be used with one base station.

4.1.2 Long term measurements for the TVWS video surveillance system

Long term field measurements were conducted to investigate the reliability of the TVWS cognitive radio link and the service quality in real-time video surveillance. The TVWS radio system is connected to the geolocation database through Internet. The database controls the TVWS radio system and can evacuate the TVWS radio transmissions if the primary user needs the frequency resources which are utilized by the TVWS radio. TVWS radio channel SNR could be seriously decreased by remote DTT transmissions, which can propagate over long distances in certain weather and atmospherical conditions. Man-made noise can also cause similar effects.

The TVWS radio system downlink and uplink traffic information is stored by the system control manager software. The variation between the day and night times can be clearly noticed in the traffic. The data rate during the night time is very low,

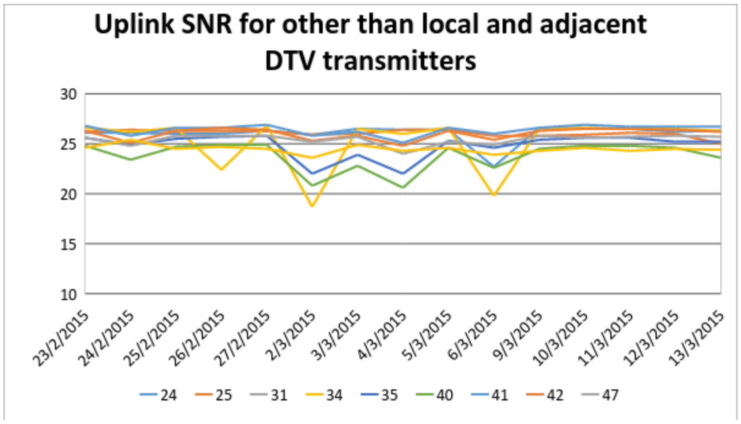


Figure 12: Uplink SNR (dB) for allowed UHF TV channels.

as it is very dark outside and the camera is directed towards a dark horizon. The downlink traffic is always very low, but the variation between day and night is also present in this direction. When the video monitoring software is set to recording mode, it tries to minimize the amount of stored data and the variation between day and night is present. If the recording mode is not in use, the data rate is constant throughout the whole day.

Uplink SNR for all the allowed channels for TVWS operation in the UHF band was measured and recorded between 23.2.2015 and 13.3.2015. Figure 12 illustrates that a decrement in the channel SNR can be seen in three of those channels. The highest decrement is 7 dBs in channel 31, but channels 34 and 35 have also decreased 2-5 dBs during three consecutive days. The base station antenna is omnidirectional and located higher AGL than the directional antennas of the terminals. This causes higher received DTT signal levels at the base station antenna, which result in a stronger decrease in the signal quality in the uplink direction from the terminals.

4.2 Public transport application pilot trial

The purpose of the public transport application pilot trial was to create radio links in white space frequencies in real operating conditions with real use cases. Helsinki Regional Transport Authority (in Finnish: Helsingin seudun liikenne (HSL)) is responsible for planning and procuring the public transportation in greater Helsinki area with its 1.1 million inhabitants. The public transportation in the area includes bus, tram, metro, ferry and commuter train services.

HSL uses many different types of services using wireless communications, from which two use cases were chosen as the pilot trials to investigate the eligibility of TVWS radio links in them: ticket sales and real time transit information screens. Currently both of the systems are implemented with 3G mobile broadband connections. The goal was to study if a TVWS system could replace these 3G communication systems. The main difference between the use cases is that ticket sales uses two-way communications, while the transit information screens only receive the information updates and do not communicate back anything.

The higher the base station antenna mast of the TVWS system is, the higher the DTT channel signal levels will be at the antenna. These high DTT signal levels present a huge challenge for the low-power TVWS terminal uplink connectivity to the base station. However, this problem only exists in the ticket sales application, where two-way communications are used. The transit information screen application allows use of higher antenna installations for the TVWS base stations as no information is transmitted back to the base station from the TVWS terminals.

FICORA issued a test license for the application pilot trial for the central Helsinki area. The license was valid only during the measurement days and only for the Carlson TVWS cognitive radios[11], which were to be controlled by the geolocation database.

The properties of the equipment HSL used in their applications were tested in laboratory environment before the field measurements. The TWVS radios were used as their communication method to investigate the connection requirements for each application. The ticket sales required a faster connection, which required the use of 16-QAM modulation with our TVWS radio. The information screens require very low data rates, and thus the necessary throughput could be achieved with BPSK modulation. With the knowledge obtained on the required modulations and their sensitivity levels, propagation models were then used to create initial estimations on the possible link distances that could be achieved with the TVWS radios in both of the application pilots.

4.2.1 Ticket sales trial

The base station antenna was installed on a rooftop at a height of 45 meters above ground level in the ticket sales application. The terminal was used in the measurement locations with an antenna installed to a 4-meter tripod. To achieve comparable results between different locations, channel 41 (634 MHz) was used for all of the measurements. Transmission powers of 23.2 dBm for downlink and 20.7 dBm for uplink were used. The interference level at the base station antenna was already high enough to cause interference for the uplink transmissions, as could be expected with the combination of strong DTT signals and the antenna on a high rooftop. This resulted in very short link distances for the ticket sales application, which needed two-way communications with low latency.

The ticket sales application became extremely slow if modulations of lower order than 16-QAM were used, making them practically unusable. 16-QAM uplink needed line of sight to operate in the urban environments of Helsinki. The information screens that only require communications in downlink direction and could be operated with lower order modulations were also measured and tested in the locations with more success. Still, the used TVWS radios can not be recommended for this application in an urban environment. The longest achieved radio link distance was only 1166 meters.

4.2.2 Transit information screen trial

Another measurement campaign focusing on the transit information screens was conducted to further analyse the propagation characteristics of UHF TV frequencies in city environment. With the transit information screens, the base station antenna height was not as problematic anymore as no uplink connectivity was required. The base station antenna was installed to a TV tower with an antenna height of 99.1 m above ground level (128.3 m above sea level). The base station antenna installation is shown in Figure 13.

Figure 13: Base station antenna in Pasila TV tower.

The base station had a vertically polarized panel antenna (Rymsa AT15-250) with a 26 degree main lobe directed to south (169 °). An antenna installed at this height picks up distant DTT transmissions at very high power levels. As can be seen from Figure 14, the measured DTT signal levels from the antenna are so high that they make the uplink connectivity towards the base station very difficult. Vacant channel 24 (498 MHz) was used for all of the measurements conducted with this antenna installation.

The transit information screens where the measurements were conducted are installed to tram stops, which allowed us to build a portable measurement setup and use the trams to move between the measurement locations. The tram stops for the measurements were chosen mainly within the main lobe of the base station antenna. In addition, two places in Pikku-Musta and Iso Mustasaari islands were measured, as well as the signal level on the ferry from the mainland to these islands. Figure 15 shows an overview of the measurement results on a map. All of the locations with green signal levels (higher than -70 dBm) in central Helsinki were measured in places with a lot of open space or at higher elevations, e.g. hills. Even in the islands, 7km away from the base station, the signal levels were significantly better than in the city centre 3-5 km from the base station. The islands had a lot of open space and line-of-sight conditions towards the base station antenna, while central Helsinki is full of tall buildings and thus non-line-of-sight conditions. The locations close to the

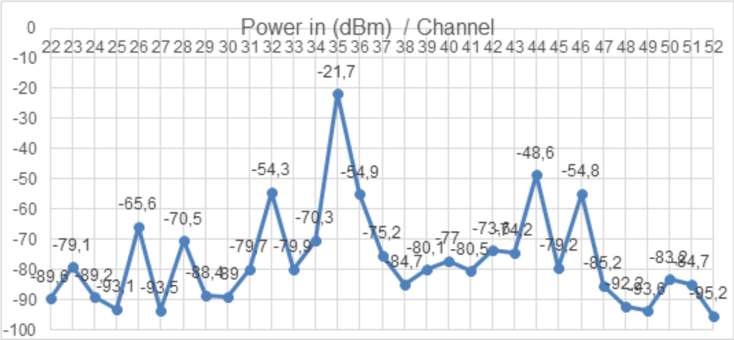


Figure 14: Channel powers in Pasila TV tower (Antenna gain 12 dBi, vertical polarization).

open space of Töölönlahti bay and up on the higher elevations of the Observatory hills were the only locations with consistent signal levels and operating conditions in central Helsinki.

Thus, the environment proved to be too challenging for the used TVWS radios. However, in the islands even the uplink worked well. The TVWS radios used in the measurements are not built for urban environments, which could be seen from the measurement results. In the rural-like conditions of the islands they performed well. Point-to-point operation with line-of-sight provides good connection with these radios in rural conditions, but they can not be recommended for non-line-of-sight operating conditions in urban environments required by these application pilots.

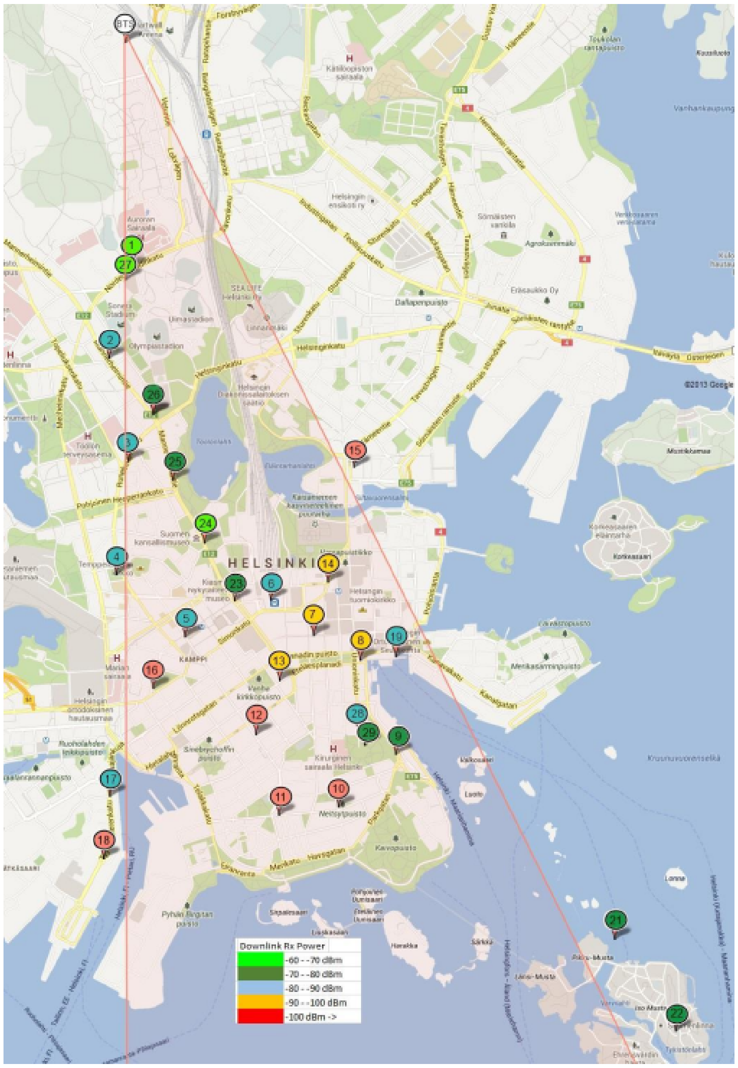


Figure 15: Pasila TV tower signal levels at measurement locations.

5 Conclusions

This report has presented a TV white space test network environment built in Turku, Finland, and its related geolocation database. The interference measurements conducted in the test network environment contributed to the standardization work in CEPT/ECC SE43 project team, whose results and reports have been used to create an ETSI harmonised standard for TV white space devices. The geolocation database and its interference protection algorithms have been developed and validated concurrently with the realistic protection ratio information obtained from the interference measurements in field conditions.

The technological capabilities of TV white space cognitive radios have been demonstrated to the industry through different application pilot trials. The penetration and range in the TVWS frequencies are extremely good, but the equipment used in the application pilot trials was more suitable for fixed or rural installations than for mobile use or urban environment. However, with accurately defined use cases and appropriate equipment, the demonstrations have shown that commercial deployments of TVWS radios are possible from the technological viewpoint. The regulatory insecurity within the TVWS frequency band, and particularly the introduction of 700 MHz and 800 MHz bands – formerly used for TV transmissions – for wireless broadband in Europe have created an unstable environment for investments in TVWS networks. From technological and regulatory viewpoints there are no obstacles for the European national administrations to build TVWS networks. In the UK such networks are already operational, but it is yet to be seen what will happen regarding TVWS network deployments in Finland.

Even if TVWS networks will not be deployed in Finland, the research conducted in the field of TVWS has been and will be beneficial for the development of future 5G wireless networks, as spectrum sharing and incumbent protection will play a huge role in the networks operating on frequencies below 6 GHz.

WISE project was part of Tekes' Trial Environment for Cognitive Radio and Network programme (2011-2015). Currently the Turku test network is used to study licensed shared use of UHF band in the Future of UHF project [29], which belongs to Tekes' 5thGear programme [30] and into 5G test network Finland ecosystem [31].

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