QUASAR Deliverable D5.2

Methods and tools for estimating spectrum availability: case of single secondary user

Project Number:	INFSO-ICT-248303
Project Title:	Quantitative Assessment of Secondary Spectrum Access - QUASAR
Document Type:	PU

Document Number:	ICT-248303/QUASAR/WP5/D5.2/111231
Contractual Date of Delivery:	31.12.2011
Actual Date of Delivery:	31.12.2011
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Workpackage:	WP5
Estimated Person Months:	30 MM
Security:	PU[1]
Nature:	Report
Version:	1.0
Total Number of Pages:	90
File:	QUASAR_D5.2_111231

Abstract

This deliverable presents the results of spectrum availability assessment for selected scenarios of secondary spectrum access. The basic assessment framework provided in QUASAR deliverable D5.1 is adopted and refined to take into account the characteristics specific to the scenarios. Throughout this deliverable, it is assumed that there exists a single secondary user in the system. Four scenarios are investigated which consider macro cellular system, Wi-Fi hotspot, and indoor broadband access as the secondary use cases. Digital TV, radar, and aeronautical navigation systems are assumed to be the primary systems.

[1] Dissemination level codes: **PU** = Public
PP = Restricted to other programme participants (including the Commission Services)
RE = Restricted to a group specified by the consortium (including the Commission Services)
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Keywords List

Secondary spectrum access, spectrum availability, quantitative assessment, single secondary user, white spaces, digital TV broadcasting, radar, aeronautical navigation, macro cellular system, Wi-Fi-like system, indoor broadband

Executive Summary

The EU FP7 project QUASAR aims to provide quantitative assessment results for the availability of secondary spectrum access. The objectives of work package 5 in the QUASAR project are to develop methods and tools for the assessment of the secondary spectrum based on the inputs from other technical work packages and to provide tangible results about the spectrum availability.

This deliverable presents the results of spectrum availability assessment for selected scenarios of secondary spectrum access. The basic assessment framework provided in QUASAR deliverable D5.1 is adopted and refined to take into account the characteristics specific to the scenarios. As an intermediate step of the assessment work, it is assumed throughout this deliverable that there exists a single secondary user in the system. An extension of the assessment results to cases with multiple secondary users will be presented in the next QUASAR deliverable D5.3.

It is known that the quantitative assessment requires detailed secondary usage scenarios, i.e. primary system and spectrum, secondary system, access and sharing schemes, and geographical area. Four scenarios are investigated which consider macro cellular system, Wi-Fi hotspot, and indoor broadband access as the secondary use cases. Digital TV, radar, and aeronautical navigation systems are assumed to be the primary systems. The considered scenarios and the assessment results are summarized as follows:

Macro cellular use of TV white spaces

Possibility of macro cellular deployment in TV white spaces is examined. It is demonstrated that contiguous coverage is difficult to achieve in urban areas, where the spectrum demand is expected to be high. In some areas, TV white spaces can be utilized as a capacity booster. It is also shown that current secondary access methods considered by FCC and ECC are not suitable for cellular type of secondary use, which necessitates an improved scheme for permissible secondary power levels.

Wi-Fi-like use of TV white spaces

Wi-Fi-type hotspot service in TV white spaces is considered which covers not only indoor but also limited outdoor. Due to the favourable propagation characteristics of digital TV broadcasting spectrum, improvement in capacity and coverage can be obtained compared to 2.4 GHz ISM band. However, impact of multiple secondary users on secondary-primary and secondary-secondary interference needs more investigation.

Indoor broadband in radar spectrum

Air traffic control radars in 2.7-2.9 GHz are considered as primary systems, while low-power devices like LTE HeNBs act as secondary users for indoor broadband. The availability of radar spectrum depends on regulatory parameters about the primary user protection. However, the secondary access to adjacent channels looks feasible with the conservative parameters, bringing about a substantial opportunity in the radar band.

Indoor broadband in aeronautical spectrum

The distance measuring equipment (DME) system for aeronautical navigation in 960-1215 MHz is considered as primary system in the presence of secondary user of an indoor broadband system. Technical challenge comes from the uncertainty in propagation estimation. It is observed that co-channel access is challenging due to large separation requirement between the primary victim and the secondary interferer. Adjacent channel usage is found feasible in most of city areas. As with the radar spectrum, the adjacent channel access is expected to give a considerable opportunity for the low-power indoor devices.

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1 Introduction

The need for radio spectrum increases rapidly with the explosive growth of wireless services. Secondary use of already licensed, but under-utilized spectrum has been suggested as a possible solution to increase spectrum availability. Though it is generally believed that the secondary spectrum access has a potential to significantly increase the spectrum utilization, it is not yet clear how much spectrum is available for the secondary usage; the questions to answer are in which primary frequency band, for which secondary service, with which access and sharing scheme, and at which time and location. The EU FP7 project QUASAR [QUASAR] aims to provide quantitative assessment results for the availability of secondary spectrum.

The objectives of work package 5 (WP5) in the QUASAR project are to develop methods and tools for the assessment of the secondary spectrum based on the inputs from other technical WPs and to provide tangible results about the spectrum availability. In the previous deliverable D5.1, basic framework and methodology for the quantitative assessment have been proposed and some preliminary assessment results have been presented [D5.1].

1.1 Scope of D5.2

In this deliverable, refined assessment results are provided based on practical secondary access scenarios. Fine-tuned methods are also presented that are specific to each scenario while sharing the basic framework proposed in [D5.1] as a basis.

It should be emphasized that a single secondary user (SU) is assumed in the assessment throughout the D5.2. It is not a realistic assumption considering the business success of secondary access depends on scalability. However, the assumption makes the interaction between SU and primary user (PU) clearer, and thus helps develop the refined assessment methods. An extension of the assessment results to the cases with multiple SUs will be presented in the follow-on deliverable D5.3 [D5.3].

It is known from [D5.1] that the assessment requires detailed secondary usage scenarios, i.e. primary system and spectrum, secondary system, access and sharing scheme, and geographical area. In WP1, six use case scenarios have been proposed [EMC10][D5.1]. The scenarios comprise wide area broadband, indoor broadband, backhaul, and machine-to-machine secondary services. For the primary systems, digital TV, radar, and aeronautical navigation systems are included. Since mobile broadband services are expected to account for most of the traffic demand in a near future, the focus of this deliverable is devoted to the broadband-related scenarios. The scenarios are further revised to reflect the characteristics of primary and secondary systems. Consequently, the following four scenarios are chosen here for detailed analysis.

- *Macro cellular use of TV white spaces*,
- *Wi-Fi-like use of TV white spaces*,
- *Indoor broadband in radar spectrum*, and
- *Indoor broadband in aeronautical spectrum*.

The first two scenarios are about the secondary use of TV white spaces. They consider different secondary systems, macro cellular and Wi-Fi-like systems. The latter scenarios target radio spectrum primarily allocated to radar and aeronautical systems. Both scenarios assume femtocell-type indoor broadband as the secondary usage. Although these four scenarios share the same basic assessment framework, the detailed analysis methods differ in each scenario.

1.2 Organization of D5.2

The remainder of the deliverable has the following structure: Section 2 addresses the assessment of TV white spaces. An overview of TV white spaces is given and the basic assessment methodology for TV white spaces is reviewed. Then, the macro cellular and Wi-Fi-like systems are assessed as potential secondary systems in each subsection, respectively. In Section 3, secondary use of radar and aeronautical spectrum is investigated. Primary systems of interest are introduced, and then assessment results for secondary sharing with air traffic control radar in 2700-2900 MHz and distance measuring equipment in 960-1215 MHz are presented sequentially. Finally, conclusions are drawn in Section 4.

2 Secondary use of TV white spaces

2.1 Description of primary system

2.1.1 Introduction

Terrestrial digital television (DTT) bands offer an interesting opportunity for secondary use of spectrum. Transmitter locations and the channels they occupy are usually fixed. This information is publicly available and can be used when assessing the available spectrum for the secondary use.

QUASAR deliverable D5.1 [D5.1] described a general methodology for assessment of spectrum for the secondary usage. The deliverable also described similarities and differences regarding the regulatory situation of secondary usage in both USA and Europe. The presented results used a simplified model of the primary TV service to calculate TV coverage areas that needs to be protected from the secondary usage.

The current deliverable evolves and improves on the TV transmission model in [D5.1] for more accurate calculation of the primary TV coverage areas. At the same time a plethora of improved secondary system types which utilize the TV bands are introduced.

When assessing secondary use of television spectrum, the type and the level of interference the primary system can tolerate should first be carefully determined. In most situations, the DTT networks are interference limited, so self interference (co and adjacent channel) has to be taken into consideration.

In Europe, the bands 47-68 MHz, 174-230 MHz and 470-862 MHz are mainly used for TV distribution. In 2006 a large planning conference was held at ITU [RRC06], where all European countries in addition to some African and middle-eastern countries participated. The goal was to plan the future digital TV network that will replace the existing analogue network. One of the conference targets was to allow each participating country to have at least 7 available frequencies for DTT distribution in its own country. The conference also used 2 different ways of specifying a DTT channels coverage area, i.e. one named "allotment" and the other named "assignment". An allotment explicitly specifies the geographical coordinates of a DTT channels protected area/contour, while an assignment defines the planned broadcasting transmitters along with their parameters, so the protected area/coverage has to be calculated.

As a result of the so-called Digital Switch-Over (DSO) process, when spectrum-efficient digital television schemes replaced analogue TV broadcasting, large portions of frequency spectrum became vacant. This spectrum, also referred as the "Digital Dividend" has been subject to a debate around the world and will be up for auction as cleared spectrum, in order to be reallocated by regulators to other services. In large part of Europe the 790-862 MHz band have been reallocated from broadcasting to other services, which reduced the broadcasting part of the UHF band to 470-790 MHz. Furthermore, the sparse frequency planning with large interference margin of DTT-networks causes an existence of TV channels in a given geographic area that are not being used by DTT stations, because such stations would not be able to operate without causing interference to co-channel or adjacent channel stations. These unoccupied TV channels at different space and at any specific time are referred as TV “white space” (TVWS) and can be used by secondary devices, known as “white space devices” (WSDs).

2.1.2 Basic features of DTT system

This subsection contains description of the basic characteristics of the DTT system in general and specific entities, which are important for introducing secondary systems in TV bands. At the same time, it gives the necessary definition and terms used in the subsections that follow.

When a country's DTT network is specified using allotments, it is simple to calculate the available TVWS (one is either inside or outside of a protected area). However, in most cases, the DTT networks in Europe are specified according to the assignments paradigm, so the protected areas/contours have to be calculated. The contours can be calculated from a number of assumptions usually all giving different results. The propagation model used for these purposes in the European DTT planning conference in 2006 was from ITU Recommendation P.1546 [P1546]. This model is a point to area prediction model based on measurements data, which calculates the average field strength for an area at clutter height, when 1 kW transmitter power is used and when effective transmitting antenna heights are less than 3000 m. The model also has a number of correction factors that should be applied when either the transmitter height is lower than 10 m above clutter height or when the receiver height deviates from the clutter height. Since the field strength values are calculated for 50% coverage, a scaling factor of 9 dB is used for required field strength at 95% coverage (normally used requirement for roof placed receive antennas [TR190]).

In Europe DVB-T/T2 was selected as the terrestrial broadcasting system. DVB-T is based on OFDM technology and a typical parameter-set used for example in Finland and Sweden, is presented in Table 2-1.

Table 2-1: Typical DVB-T parameters [D3.1].

Parameter	**Value**
Channel bandwidth	8 MHz
FFT size	8192 (8k)
Number of subcarriers	6817
Modulation	64-QAM
Code rate	2/3
Carrier spacing	1116 Hz
Useful symbol duration	896 μs
Guard interval	1/8

The DVB signal is normally transmitted as a plane polarized wave in horizontally or vertically polarized state, and the receiver has its polarization oriented according to the wanted transmitter [BT419]. The plane of polarization is usually horizontal, but from the viewpoint of planning, there is much to be gained from allowing the possibility of also using vertical polarization.

The use of orthogonally polarized transmissions, together with appropriately polarized receiving antennas, offers significant advantages in terms of spectrum utilization. In the case of orthogonal polarization the combined discrimination provided by directivity and orthogonallity cannot be calculated by adding together the separate discrimination values. However, it has been found in practice that a combined discrimination value of 16 dB may be applied for all angles of azimuth in the terrestrial television bands I to V [BT419].

There is a lack of information concerning the use of circular or elliptical polarization in planning the television broadcasting services. However, some administrations permit the use of circular or elliptical polarization as an alternative to the more usual horizontal or vertical. For a given transmitter power, a circularly polarized transmitting antenna will result in a field strength lower by 3 dB in the horizontal or in the vertical plane than that provided using a linearly polarized transmitting antenna, thus effectively giving a reduced coverage area [BT419].

Another property of the DVB-T/T2 transmission, being based on OFDM, is the possibility to add signals from several nearby located transmitters (property known as signal combining). Selected guard period for the OFDM signal decides how close the transmitter has to be and when the constructive signal additions become co-channel interference. The usual notation is the following: T_u denotes the symbol duration time, T_g is the guard interval time and T_p is related to the existence of pilot carriers in DVB that are needed for coherent demodulation so the total loss of constructive signal components occurs beyond a relative delay of $T_p = T_u /3$. DVB-T with 8k carriers has a T_u value of 896 μs and possible T_g values of 1/4, 1/8, 1/16 or 1/32 of its T_u value, while DVB-T2 with 32k carriers has a T_u value of 3584 μs and possible T_g values of 1/8, 1/16, 1/32 or 1/128 of its T_u value. The part of the DTT network using the previously explained signal addition is called a single frequency network (SFN).

In a SFN, the receiver combines the different signal components coming from the different transmitters in the network. For the i_{th} signal component, the received signal power P_i may contribute to the useful part of the combined signal or the interfering part or to both depending on the relative signal delay. The ratio between the useful contribution, U and the interfering contribution I, of the i_{th} signal component is modelled by the weighting function $w_i(\Delta t_i)$ where Δt_i represents the relative time difference in the receiver between signals from reference transmitter and i_{th} transmitter in the SFN network.

$$U = \Sigma\, w_i(\Delta t_i)\cdot P_i. \qquad (2\text{-}1)$$

$$I = \Sigma\, (1 - w_i(\Delta t_i))\cdot P_i. \qquad (2\text{-}2)$$

For the weighting function, the following form has been proposed in [BH03]:

$$w_i = \begin{cases} 0 & \text{if } \Delta t_i \leq 0 \\ 1 & \text{if } 0 < \Delta t_i \leq T_g \\ \left(\dfrac{T_u - \Delta t_i + T_g}{T_u}\right)^2 & \text{if } T_g < \Delta t_i < T_p \ \left(= \dfrac{T_u}{3}\right) \\ 0 & \text{if } \Delta t_i \geq T_p \ \left(= \dfrac{T_u}{3}\right) \end{cases} \qquad (2\text{-}3)$$

When performing a study, one must select the reference transmitter (used as reference to calculate Δt_i). Basically there are two different criteria, strongest transmitter or closest transmitter. In some situations when several transmitters are combined in a SFN, a reference to the closest transmitter can give improved receiving conditions. This effect can be avoided if the simulation tool uses a 'sliding time window' instead of a fixed reference time (from reference transmitter) when calculating SFN gain.

DVB-T is designed to have a relatively good interference tolerance. One key feature is error correction coding. A kind of concatenated coding scheme is used for DVB-T systems. An outer code uses Reed-Solomon coding which is very robust against bursty errors, while an inner code uses convolutional coding which is good against random-type errors. In addition to this coding method, interleaving and energy dispersal are used to improve the received video quality. These error correction methods are needed, because bit errors in MPEG-2 video stream usually causes easily noticeable and irritating errors (e.g. pixelization, freezing, clipping sounds) in the received video stream. The acceptable bit error rate (BER) at the input of MPEG-2 demultiplexer is 10^{-11}, which means in practice one uncorrected error event per hour. This error level is called Quasi Error Free (QEF) level and it is achieved at the receiver when the BER after the inner (Viterbi) decoding is $2x10^{-4}$.

In practice, different TV receivers have different performance. DVB-T receivers have not been designed to work with high level of interference, since traditionally there have not been any interference sources except other television transmission. The highest interferer on some adjacent channel has usually been another TV-channel multiplex that is transmitted from the same source as the wanted received transmission. This means that the interference is only about as strong as the wanted signal. Organizations such as NorDig, DIGITALEUROPE/EICTA and Digital TV Group (DTG) provide requirements and specification to DVB-T receivers. The protection ratios against adjacent channel DVB-T/H interferer are shown in the following figure. There is a notable difference between these given protection ratios.

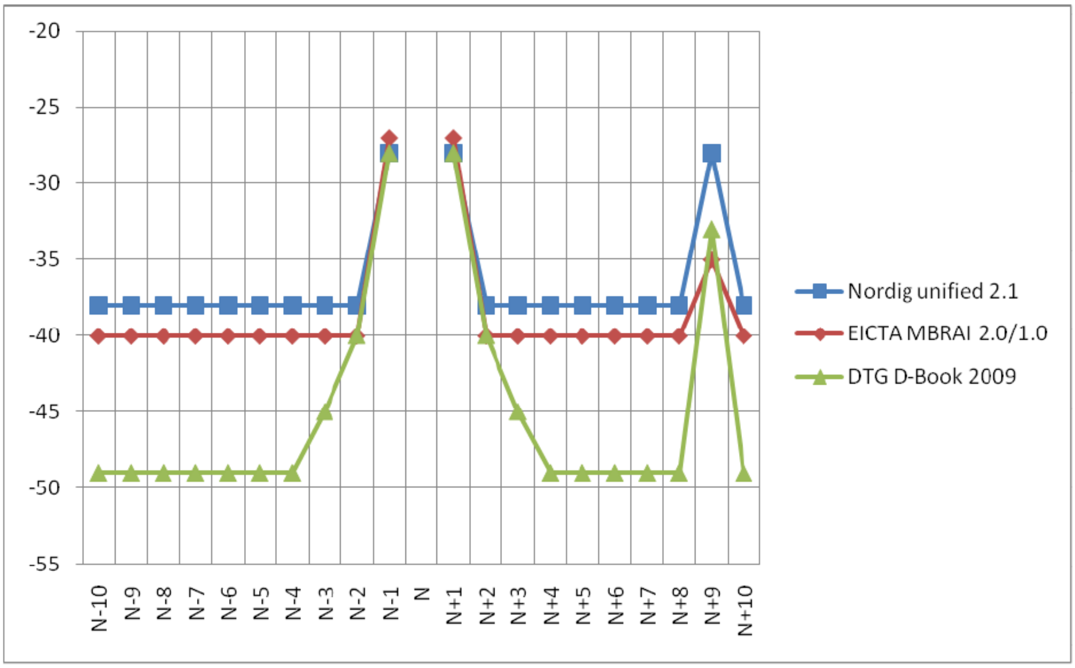


Figure 2-1: DVB-T receiver requirements for adjacent channel interference tolerance [D3.1].

Some TV receiver designs use 36 MHz as an Intermediate Frequency (IF). In this case, channel N+9 is the image channel, and therefore it has loose requirements. There has also been a proposal to include even more stringent requirements to the future version of network planning criteria in ITU-R BT.1368. New and more stringent requirements are needed for efficient use of TV-frequencies. Draft revision of ITU Recommendation BT.1368-9 [B1368], targeted for approval during 2012, has included an extended table for needed protections ratios (PR) between adjacent DVB channels to avoid interference. The values are based on DVB-T receiver measurements and are given for up to +/- 10 adjacent channels, selected to protect 90% of the receiver population. The receiver PR values can be converted into receiver ACS (Adjacent Channel Selectivity) values. The simplest way to convert PR to ACS is to assume that the receiver filter is the dominant contributor to the interference (assume ideal transmitter mask) and assume negligible thermal noise. With this assumption the ACS is the difference between co-channel PR (17-23 dB, depending on used channel model) and the adjacent channel PR (measured to be between -30 to -54 dB, depending on channel (frequency) difference between co and adjacent channels). A more correct calculation can be made by using the actual transmitter mask and given PR measurements conditions [EICTA]. For the situations were non-critical mask is used [EN744], beyond the second adjacent channel, the transmitter ACLR (Adjacent Channel Leakage Ratio) is sufficiently high to make the receiver ACS to dominate the interference contribution. The transmitter ACLR and the receiver ACS are then usually merged to an ACIR (Adjacent Channel Interference Ratio). Example values for the ACIR are presented in Table 2-2.

Table 2-2: Adjacent channel interference ratio.

Channel offset (both upper and lower)	ACIR value [dB]
1	49
2	61
3	53
4	74
5	74
6	75
7	77
8	77
9	64
10	84

The roof placed DTT antennas give the largest coverage area that needs to be protected from other services, e.g. white space devices. Most studies of DTT system assume the antenna type proposed by ITU recommendations for DTT planning purposes [BT419].

Finally, DVB-T transmitters are usually “easy” to detect, since they are relatively few, fixed, elevated, with high power and installed with the purpose of providing as good coverage as possible. This gives an opportunity to utilize spectrum sensors in an outdoor WS base station for the purpose of detecting whether a particular TV tower is broadcasting or not. However, for the cases when the secondary system has a connection to the Internet, a database solution seems to be a more attractive approach for detection of DVB-T transmitters.

2.1.3 Common assessment methodology of DTT coverage

The final subsection will present an example of the secondary assessment methodology of DTT network. The simulation target territory is Sweden and uses ~5600 DTT transmitters of which ~1400 are inside Sweden and the rest in neighboring countries needed for coordination. Location coverage of 95% is used when defining a DTT channels coverage area. Signal to noise + interference figures always include fading and polarization effects. Results for field strength values are noise limited, i.e. the field strength value is selected so sufficient signal to noise ratio is achieved. In Sweden only horizontals polarization is used, so polarization impact is very limited within the country (the limited impact is from a number of vertically polarized transmitters in neighboring countries giving some border effect).

Channel 23 is used as an example for estimating the influence of different assumptions over the protected DTT area for a single channel (i.e. area not available for white space usage). The country was represented by a fixed grid (termed pixels) with 2.5 arc minutes resolution for longitude and latitude separation between pixels. For each of the pixels the actual field strength is calculated, with (at DTT receiver) and without (in air) DTT receive antenna, at clutter height from each DTT transmitter, using the transmitter information from the ITU broadcasting database and propagation model P.1546. Figure 2-2a shows the protected coverage area if only the field strength in air ('noise limited') from the strongest transmitter at clutter height, is used as criteria. This is expected to be an overestimate of coverage area, due to the normally interference limited situation. In such case the coverage area will in many location shrink to small areas (Figure 2-2b). The unaffected areas have low interference and are therefore more noise limited while the affected areas have strong interferers (from co- or adjacent- channel transmitters). The normal reason for a co-channel strong interfering transmitter is that they belong to the same SFN network (not included in Figure 2-2a or 2-2b).

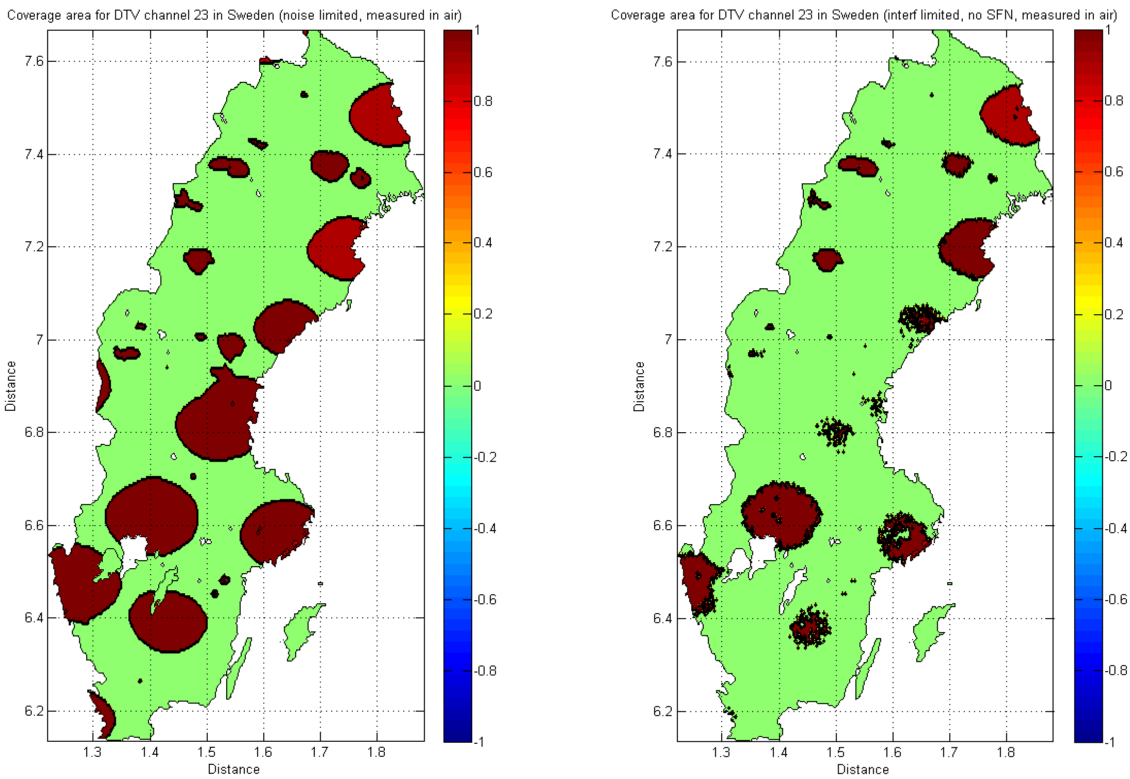


Figure 2-2a (left) and 2-2b (right): Coverage for CH 23 in two different situations (2-2a: noise limited and 2-2b: SINR limited).

Figures 2-2c and 2-2d uses the same criteria, but include SFN effects when calculating the signal strength. Comparing Figure 2-2c with Figure 2-2a shows a very small increase of coverage area, while the change between Figure 2-2b and Figure 2-2d is quite large illustrating the impact of SFN gain.

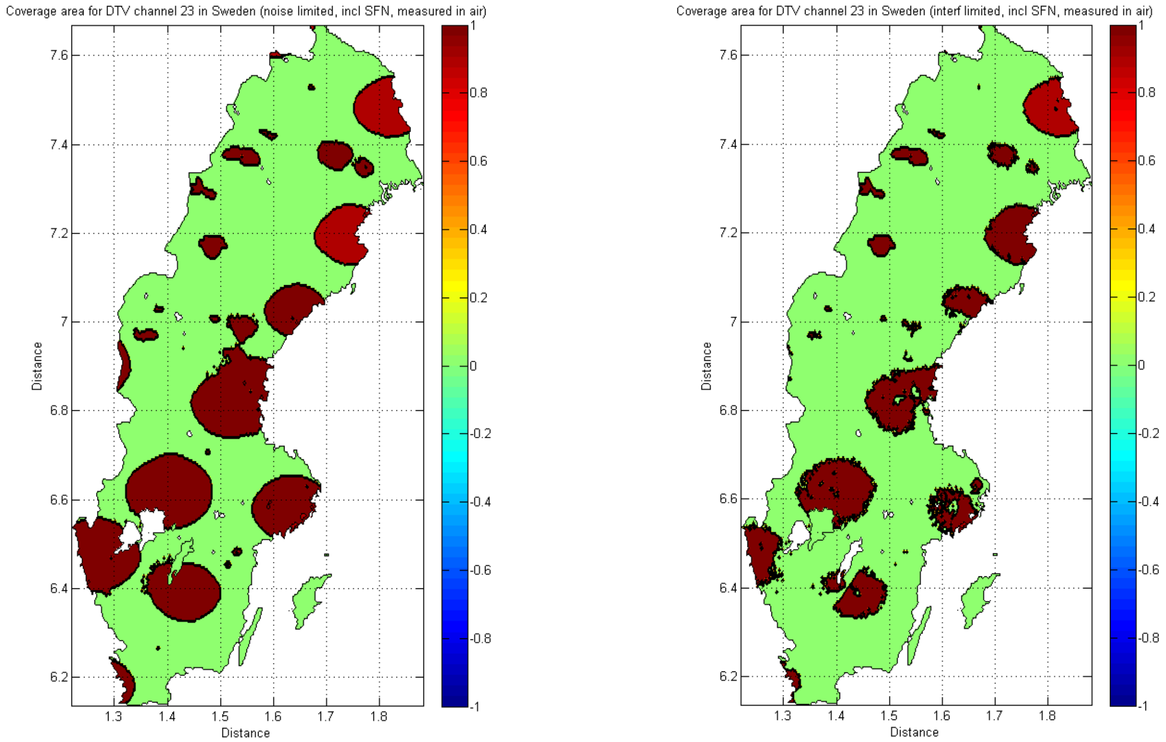


Figure 2-2c (left) and 2-2d (right): Coverage for channel 23 when adding SFN gain to Figure 2-2a and 2-2b, respectively.

Finally the impact of the directive antenna is added. The antenna direction can be selected in two different scenarios, one where each position uses only a single antenna pointing in the direction with the highest number of available DTT channels, while the other scenario uses multiple antennas, one per channel in every position, pointing in per channel optimum directions. For the single channel comparison all channels were used when determining the optimum direction for single antenna scenario and only channel 23 when determining optimum direction for multiple antennas scenario. Figures 2-2e and 2-2f show the coverage area for the single antenna (Figure 2-2e) and multiple antennas (Figure 2-2f). Criterion in both cases is SINR.

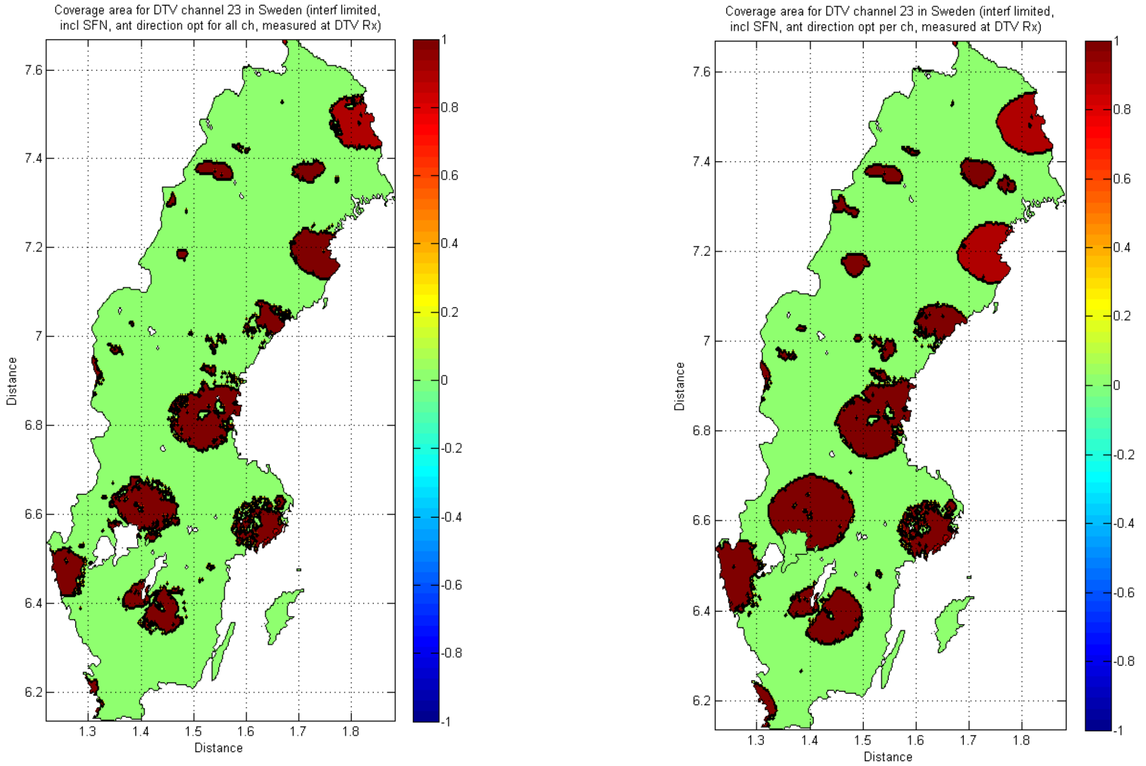


Figure 2-2e (left) and 2-2f (right): Coverage for CH 23 when also including the directive receive antenna for two different scenarios.

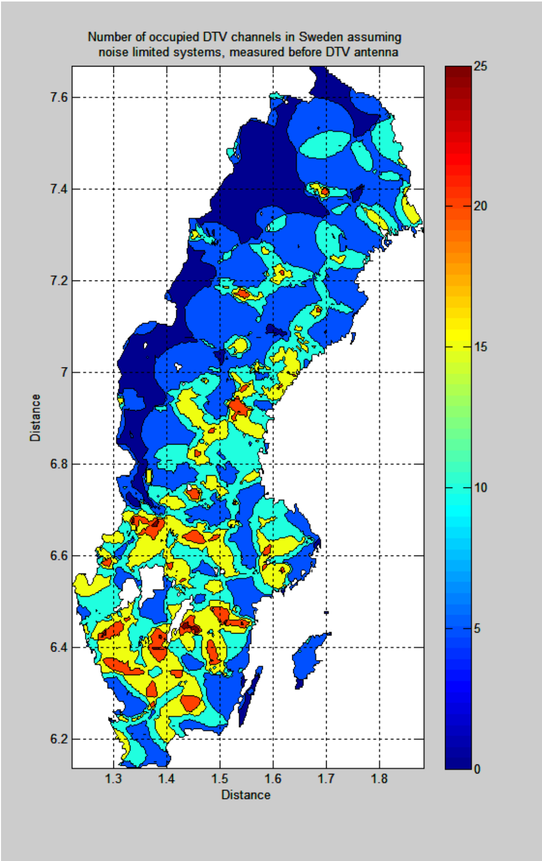
Figures 2-2e and 2-2f are the best estimates of the coverage area if comparing the used assumptions with the coverage area definition for an assignment. Table 2-3 shows calculated country coverage for Figures 2-2a-f.

Table 2-3: Relative country DTT coverage for channel 23 in Sweden.

Selected conditions according to figure	**Area coverage (% of country area)**
2-2a	26.98%
2-2b	11.68%
2-2c	27.35%
2-2d	16.99%
2-2e	14.59%
2-2f	21.76%

Obviously the occupied country area for DTT channel 23 varies between 11.7-27.3% depending on used assumption. According to the assignment definition the coverage area should be somewhere between 14.6-21.8%. Even though in most of the situations a single antenna is used for DTT reception, the DTT users can use more than one antenna or point the antenna in a different direction (different regions DTT channels)in order to increase the location probability.

Moving from one channel to all channels, one can count the number of occupied channels per pixel. Figures 2-2g and 2-2h show the number of occupied channels when using same conditions as in Figure 2-2a and 2-2b. In Figure 2-2g the number of occupied channels is between 0 and 25, while the interference limited situation in Figure 2-2h reduces the maximum number to ~15 channels.



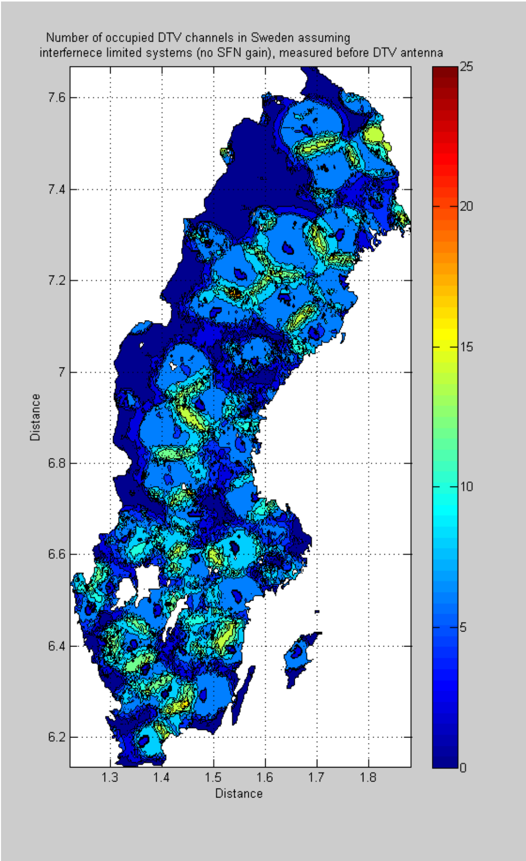


Figure 2-2g (left) and 2-2h (right): Number of occupied channels for the noise limited and the interference limited (including SFN) cases in air.

Figure 2-2i shows a CDF of the occupied channels. The median occupied channels are 9 for the field strength case coverage area and 7 for the interference limited case. The graph also contains the interference limited case when SFN is included. This graph shows an increase in numbers of occupied channels without increasing the median number compared to the case without SFN.

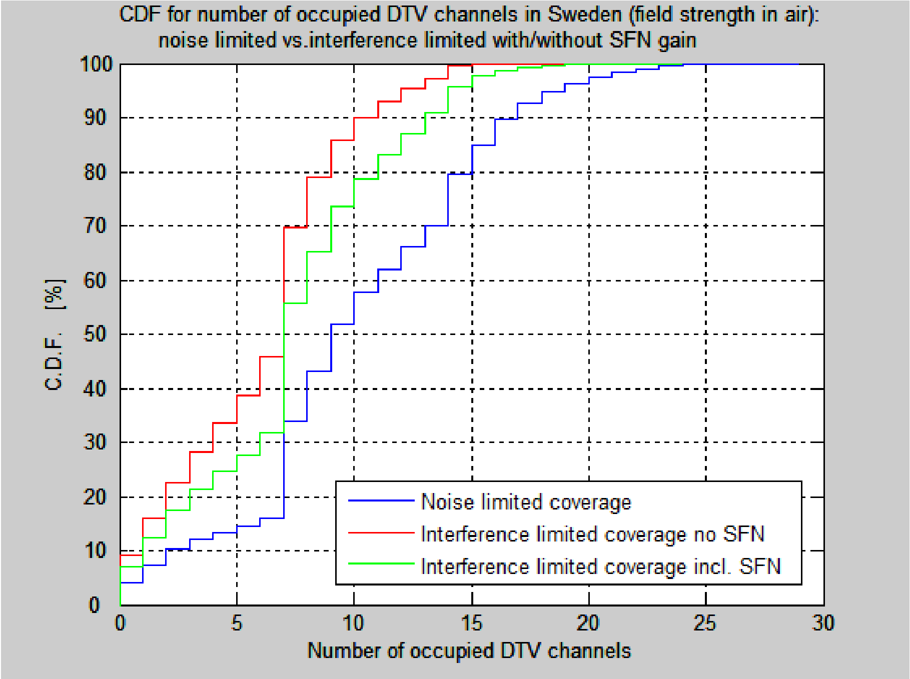


Figure 2-2i: Distribution of occupied channels for the noise limited and interference limited, with or without SFN, for signals calculated in air.

Figures 2-2j and 2-2k show the number of occupied channels when antenna impact is added. Receive antenna direction is selected towards strongest transmitter and results present the cases with a single antenna or multiple antennas per position. The single antenna case shows up to ~15 occupied channels, while the multiple antenna case up to 25 channels.

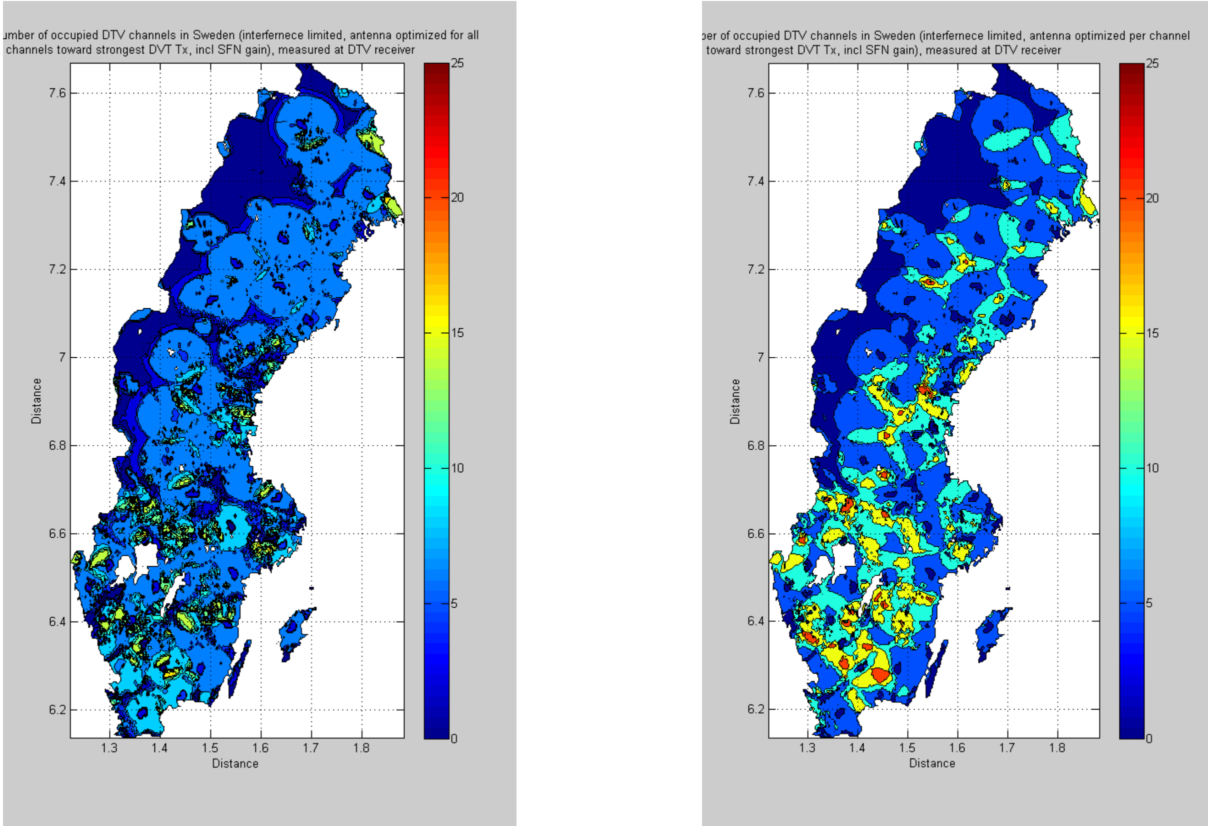


Figure 2-2j and 2-2k: Number of occupied channels for the two the interference limited (including SFN) antenna cases calculated at DTT receivers.

The number of occupied DTT channels for two used antenna cases can also be compared for each pixel and area where difference in numbers exists. Figure 2-3 identifies the areas where the usage of two antennas results in different number of occupied TV channels compared to the single antenna case. In particular, green areas are the areas with same number of occupied channels. For each pixel within green areas, the total number of occupied (used) TV channels by DTT system, is the same for both cases (single antenna case and multiple antenna case). The yellow/red areas represent the cases where the usage of multiple antennas results in higher number of used TV channels compared to the case with single antenna. And finally, the blue areas show the cases where the multiple antennas usage occupies lower number of channels compared to the single antenna case. As seen in the figure the difference in used channels per pixel for some areas is higher than 10 channels. The figure illustrates how different antenna assumptions have a large impact on the number of occupied DTT channels for some areas and thereby on the number of available channels for secondary usage, as well.

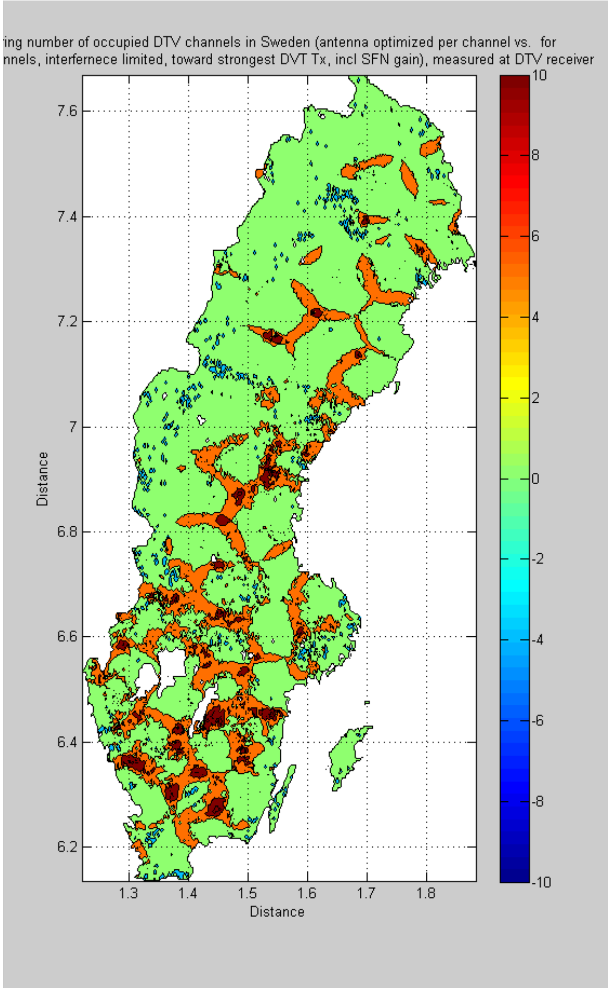
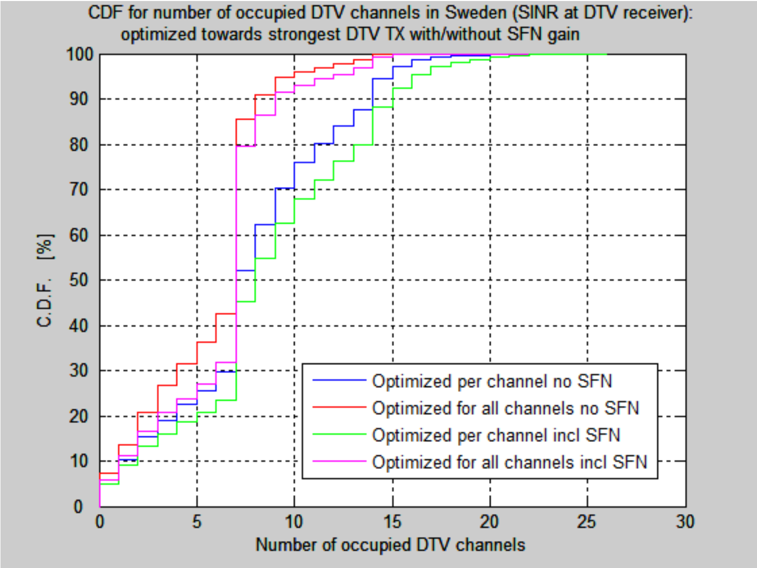
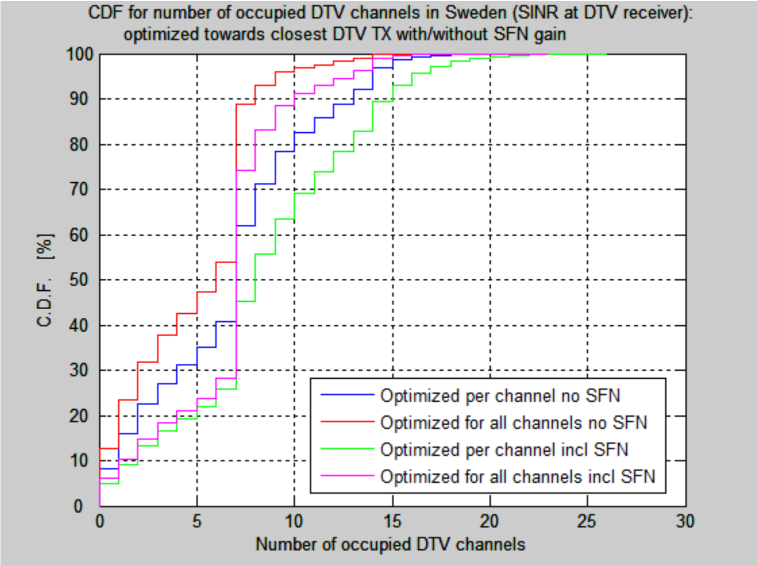


Figure 2-3: Difference in number of occupied channels per geographical area for the two antenna cases.

Figure 2-4a shows the number of occupied channel distribution of the cases in Figures 2-2j and 2k. The figure also includes the two cases without SFN. The multiple antenna case occupies up to eight more channels, but for the median value differs by one channel. For the single antenna case (the most common case in Sweden) a large part of the country has 7 occupied channels. This is in line with one of the used targets at the European DTT planning conference in 2006. As a comparison, also the number of occupied channel distribution is shown for the case where the reference transmitter is selected to be the closest instead of the strongest. The difference for the multiple antenna case is small while the single antenna case achieves a slightly better geographical coverage if 7 or more occupied channels are used as comparison.



(a)



(b)

Figure 2-4a and 2-4b: Distribution of occupied channels for the two antenna cases (2-4a: the strongest transmitter is selected as the reference, 2-4b: the closest transmitter is selected as the reference).

The difference in the number of occupied channels can also be expressed as difference in coverage area. The interference limited multiple antenna case is used as reference (the case closest to assignment definition allowing some freedom in selecting receiver antenna direction). The coverage area is calculated for each channel. This per channel value is set as reference and the relative coverage is then calculated for some of the other cases. The results are plotted as CDFs for all channels where the reference is one and the other scenarios have a higher or lower value.

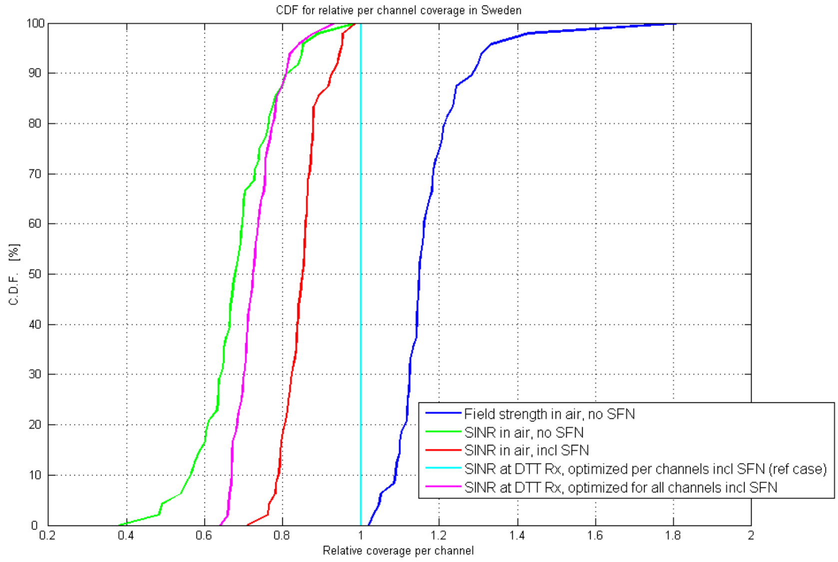


Figure 2-5: Relative area coverage for all channels using the interference limited multiple antenna case as the reference coverage.

As seen in Figure 2-5, the light blue curve illustrates the reference case where the SINR signal is measured at the DTT receiver including SFN and optimized per channel antenna. The dark blue shows coverage if only field strength is taken into consideration. The green curve shows interference limited (SINR) coverage in air without SFN and the red curve SINR coverage in air including SFN. The purple curve shows how the coverage would change for the reference curve if a single antenna direction is used for all channels instead of one per channel. The median relative coverage varies between 0.66 for the interference limited case in air, to 1.17 for the noise limited case in air. The median difference between the two antennas cases is ~17% less relative coverage for the single antenna case.

2.2 Macro cellular system as secondary user

Cellular secondary use of TVWS is an interesting approach that could enable completely new services, or it could be used for increasing the capacity of existing cellular systems. In this subsection three different methods are used to analyze macro cellular use of TVWS. In the first part, a detailed availability of spectrum chunks is analyzed focusing on Rhineland area, located in the western part of Germany. In the second part, standalone macro cellular LTE network operating on the TVWS and normal LTE network with TVWS offloading capability are investigated in Germany. In the third part, standalone macro cellular secondary system using FCC and ECC rules are analyzed in Finland.

2.2.1 Availability of spectrum chunks in TVWS

2.2.1.1 Simulation and modeling parameters

This study of spectrum availability was carried out applying the methodology developed in the project on two areas of different sizes to show area-specific effects and general characteristics of the TV whitespaces. To achieve highly accurate and relevant results, computationally complex propagation models were chosen, namely the ITM Longley-Rice terrain-based model [ITM82]. This allowed us to show the effects that obstructions have on the coverage of the TV system and give guidance for the understanding of the relevance of measurement-based spectrum cartography. For larger study areas such as an entire country, the projection of map data becomes highly relevant for the accuracy of the results. Focus was therefore put on finding discrete sample points in the study area with properties representative for the area surrounding them. A method for generating a grid projection with equal-sized “grid boxes” was derived to allow sample-based statistics generation. All other parameters were chosen according accepted standards of the DVB-T standardization community and similar to coverage analysis tools used by TV broadcasters. Options for primary system modeling were chosen to reflect best-case coverage, namely by using the reference geometry of a roof-mounted directional Yagi antenna and best-case preamplifier gains [EN744]. The study area and focus area were not only chosen due to their interesting geographical properties, but also due to the good availability of TV transmitter data. All simulation parameters are summarized in Table 2.4. The following analysis deals with issues relevant to the secondary deployment of a cellular system, namely (contiguous) channel availability, protection zone distance, achievable throughputs and distances to the protection zones.

Table 2-4: Modeling parameters of primary TV system in Germany.

Parameter name	**Value**
Propagation model	ITM Longley Rice, F(99,95)
Primary receiver antenna height	10 m (Fixed Roof-Mounted)
Receiver antenna gain	10 dB
Receiver Preamplifier gain	14 dB (e.g. Maximum UHF 15A)
Receiver Feeder Losses	7 dB
Thermal noise floor	-105.2 dBm (7.6 MHz channel)
Interference margin	3 dB
Channel model	Gaussian
Adjacent Channel Rejection Ratio	-40 dB
# adjacent channels	± 10
Minimum SINR	According to ETSI EN 300 744 [EN744]

2.2.1.2 TVWS capacity in the focus area of Rhineland, Germany

In a focused analysis to test the computational and modeling capacities of the QUASAR methodology, we used the Southern Rhineland area of Western Germany as a starting point [APM11]. The Southern Rhineland, located at the border of Germany, the Netherlands and Belgium, features some properties which are of interest to a whitespace exploitation study. Inherent cross-border issues can be expected to become visible in this focus area, intensified by the comprehensive usage of TV frequencies by the neighboring countries. Furthermore, the geography of this area is rather peculiar. The mountainous Eifel area in the South meets the so-called Cologne Bay area, resulting in a large variation in terrain profiles. Population density shows to be highly varying with the City of Cologne in the center (approx. 1 million citizens) and rural areas surrounding it. Important to the planning aspect of the primary network is the adjacent Ruhr area in the North, where the densest population of all Europe can be found.

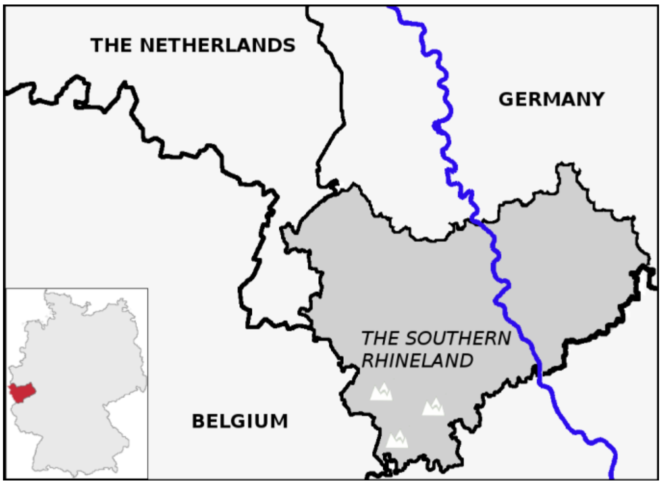


Figure 2-6: Location of the German focus area at the border to the Netherlands and Belgium.

2.2.1.3 *Channel availability*

In this subsection, a channel is deemed available if the allowed transmit power of SU is larger than noise floor. In Figure 2-7 we depict the spatial distribution of unused channels in the focus area. Most notably, the number significantly differs between the central and northern parts and the southern and eastern parts. We found this to result from the terrain irregularities and the population density distribution of the focus area. While the eastern and southern parts have a rough terrain, originating from the volcanic activity in this area in the Tertiary period of earth formation, the central parts are rather flat and allow for good propagation along large distances. A further effect that comes into play to this respect is the surrounding environment. The focus area shares borders with the Ruhr area, the most densely populated area in Central Europe. Here, most channels are used to provide coverage for regional and local TV stations and fewer resources remain available for secondary use. The focus area furthermore shares borders with two states of Germany’s federation. The TV network planning is under supervision of the individual states, hence network layouts are aiming at an universal coverage particularly within the state’s area and less coverage is observed at the borders in order to avoid inter-network interference.

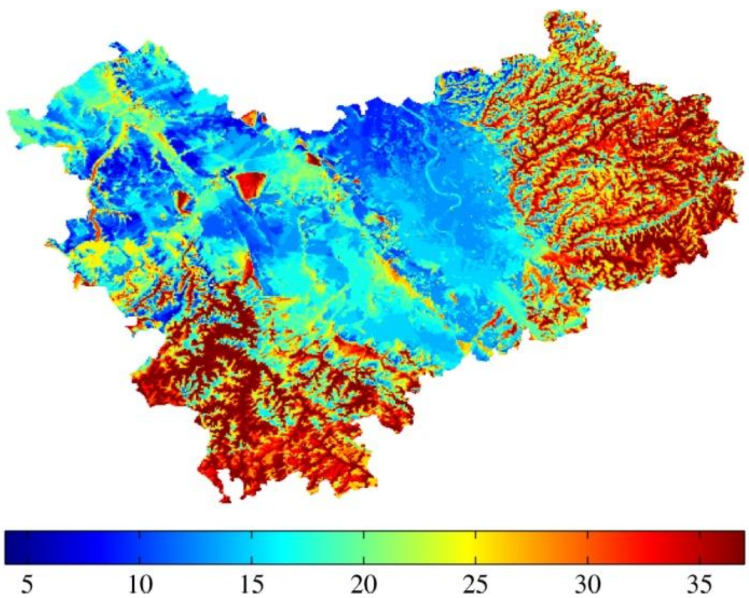


Figure 2-7: Spatial distribution of the number of available channels in the focus area assuming generic protection rules for out-of-country transmitters.

The TVWS is further limited in the western part of the focus area due to large installations in the neighboring Netherlands. The Dutch operator maintains a TV network in the Maastricht region consisting of 4 aligned transmitters each with small transmit powers to cover a spike-shaped area. The regulatory implementation of handling out-of-country channel usage is to our knowledge still undecided. In the previous figure, equal protection privileges were assumed for local and foreign transmitters. In order to study the effects of a more liberal protection ruling, we have conducted a similar simulation assuming that TV channels are only protected up to the border of their respective home countries. In Figure 2-8 we can observe that the channel availability largely improves in the border region, with up to 10 more channels becoming available. We found that whereby in 49.36% of the focus region up to 19 channels are encountered unprotected, this ratio is raised to 59.36% if the neighbor protection is lifted. In the following, to distinguish between these two types of regulatory implementation, we denote the generic rule as "General Protection Rule" (GPR), while the latter shall be called "No-Neighbor protection rule" (NPR).

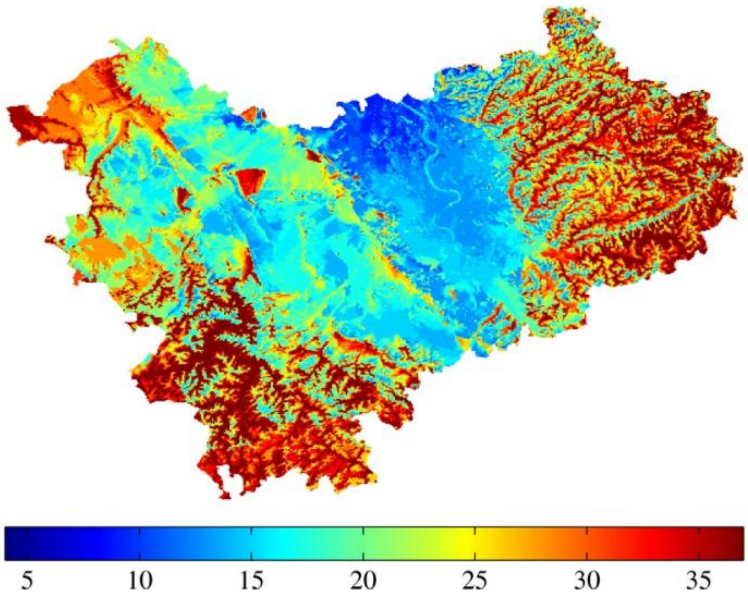


Figure 2-8: Spatial distribution of the number of available channels in the focus area assuming protection of out-of-country transmitters is only guaranteed up to the respective country's border.

Another aspect of the actual exploitation capabilities of TVWS through secondary devices is the technical feasibility to carrier aggregation. Most radio technologies in current radio transceivers are capable of combining adjacent channels into a larger composite frequency band. However, RF frontends are not capable to do the aggregation if the channels are found to be non-adjacent. For future TVWS-WSD devices the capability of arbitrary aggregation of unused channels is envisioned. But whether this will be commercially feasible is still unknown due to higher prospective manufacturing costs. This leads to the question of how strongly the TVWS is fragmented and hence how critical this transceiver feature will become. In Figure 2-9 we show the complementary cumulative distribution function (CDF) of the number of accessible channels by a single secondary transmitter in the TVWS. A channel is deemed accessible if the location of the secondary transmitter is outside the protection area and the RF frontend is capable of accessing the channels jointly, i.e. a transceiver with a more sophisticated RF frontend will be capable of accessing all available channels, while a simpler frontend will be able to access only the biggest connect channel chunk. We see that the fragmentation of TVWS is indeed a serious issue for the exploitation capabilities. In well below 40% of the focus area, more than 5 adjacent channels are found to be free. The long-tail distribution of free adjacent-channel originates from the mountain area where most likely only very few channels are available at all. A reasonable assumption is that the TV network is designed for optimal adjacent channel interference protection, i.e. TV networks will have channel allocations made that spread over the whole TV frequency spectrum. Furthermore, channel allocation is aligned to have neighboring TV networks use intermediate channels so to minimize the effects of channel leakage to their neighbors. For the secondary network, this results in a high level of fragmentation up to the worst case channel chunk sizes of maximum 3-4 channels each.

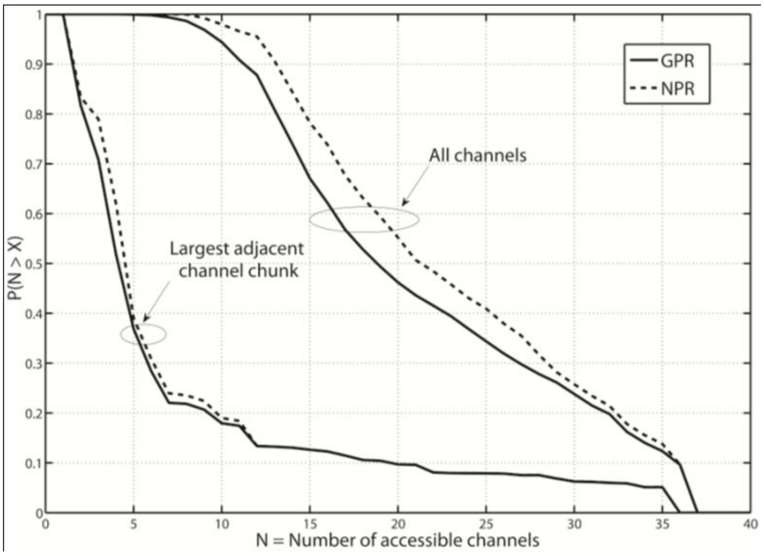


Figure 2-9: Complementary cumulative distribution function of the number of accessible channels in the focus area.

2.2.1.4 Theoretical throughput for single user

As noted earlier, lifting the NPR can be largely beneficial in terms of channel availability for WSDs located close to the border of the country. We found the exploitation capabilities of these "regulatorily-freed" channels to be of limited use for secondary deployments though. The underlying issue with these channels is the interference from the primary transmitters. In Figure 2-10 we show the additional overall interference from the primary system encountered by the secondary transmitters when they are using neighbor-country channels. Transmitters at the border experience up to 60 dB more interference than compared to the case when they only use channels according to the generic protection rule and they may be seriously hampered in their communication capabilities, though the interference is focused in those channels that have additionally become available.

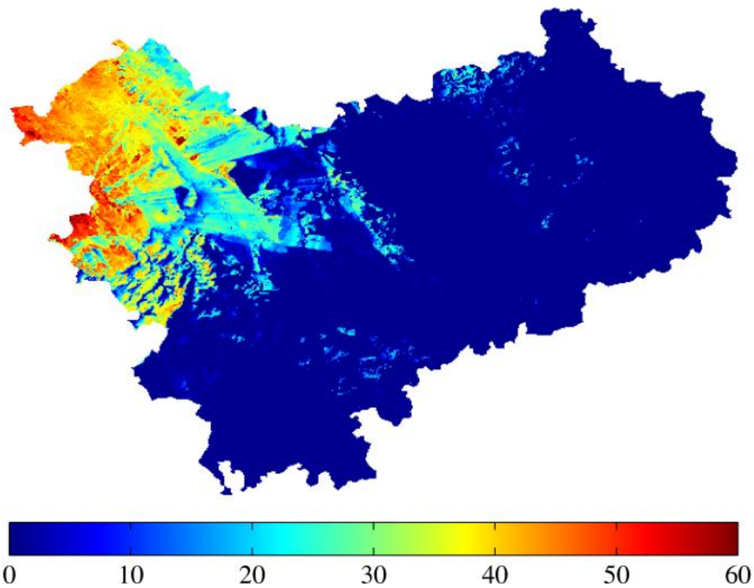


Figure 2-10: Additional interference [dB] from out-of-country transmitters relative to local interference level.

The extent to which a single secondary transmitter may benefit from a loosened protection rule may be considered limited. In Figure 2-11 we show the additional achievable link throughput for a single transmitter-receiver pair. We include interference from the primary system as well as natural noise floor. The transmitter uses the highest power level possible without interfering with the primary network. Note that the throughput in Figure 2-11 is the theoretically achievable limit for the given permissible power. The secondary link is modeled lossless for sake of comparability. Due to computation complexity, the reverse link to the protection zone was modeled using the simpler ITU-R P.1546-3 model, giving a lower boundary to the path loss component [P1546]. We observe that, contrary to previous assumption, only secondary links further away from the border benefit from the NPR.

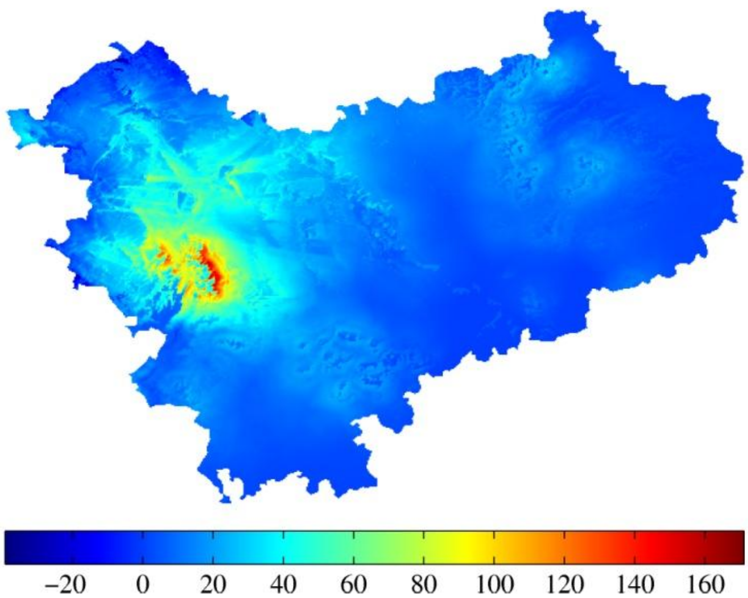


Figure 2-11: Additional throughput [Mbps] achievable through introduction of NRP protection rule.

Figure 2-12 shows the theoretical throughput achievable by a single secondary link in the focus area under the previously described assumptions. The throughput is calculated through classical application of Shannon-Hartley theorem with a single transmitter/receiver antenna. For the all-channel case the throughput shows a rough slope in the logarithmic scale, particularly for the NPR case. This may be interpreted as a semi-static exploitation capacity of the secondary network. We consider this to be an effect of the distribution of protection zone distances, which likely even outs over the entire channel set. Studying only the largest channel chunk, no similar behavior can be reproduced. The CCDF takes a linear shape in the logarithmic scale, i.e. an exponential scale in the linear scale. Nevertheless, the assumed maximum achievable throughput is still significantly high.

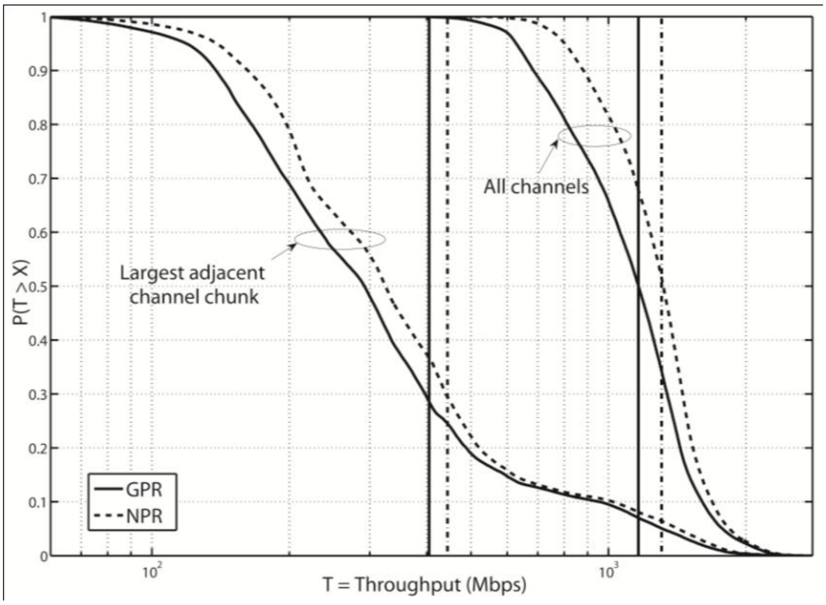


Figure 2-12: Complementary cumulative distribution function of achievable throughput of a single transmitter in the focus area.

2.2.1.5 TVWS capacity in the Germany

We have extended our study to the area of an entire country, in this case Germany. We were aiming at averaging out region-specific effects such as shielding from mountains or cross-border issues to gain a better understanding of the amount of TVWS available for secondary use.

Channel availability

In Figure 2-13 we show the spatial distribution of available TV channels for the country, derived with the same methodology as for the focus area [APM12]. First, we observe that the previously studied focus area is indeed a special case of TVWS with low channel availability compared to the rest of Germany and particularly challenging terrain properties. Another observation is the strong difference in regional scattering and availability of TV channels. While in the most Western parts of the country show low channel availability, mostly due to the excessive use of DVB-T channels by the Netherlands and the dense population in these areas with many regional stations, the Eastern parts are likely to have high numbers of unused channels. One exception to this is the Berlin area in the East, where also some test networks for DVB-T have been deployed. Northern Germany, which is largely flat land, suffers from low channel availability likely from the good propagation characteristics. The Southern parts such as the state of Bavaria with more mountain areas show medium channel availability. This is rather surprising given the previous observation that more singular TV networks as necessary for rough terrain would require more channel capacity.

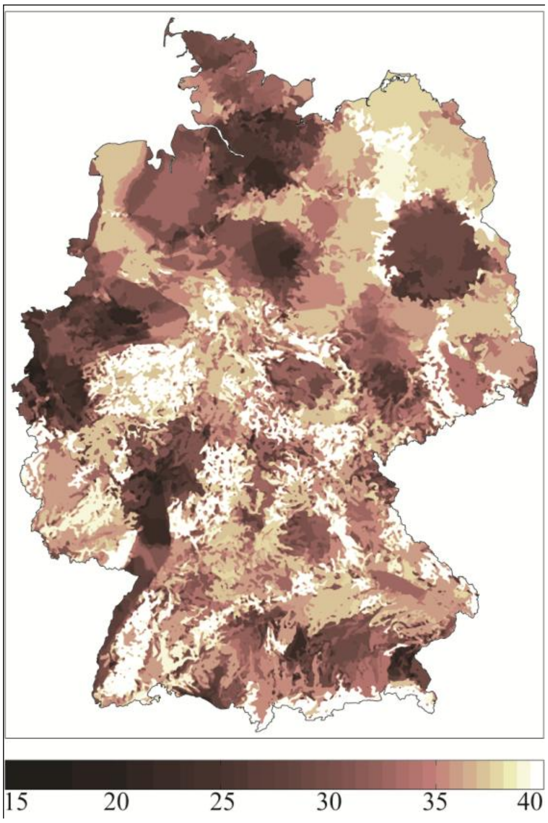


Figure 2-13: Spatial distribution of the number of available channels in Germany assuming generic protection rules for out-of-country transmitters.

In order to extend the previous observation on the spatial dependency of channel availability and with reference to the potential deployment of a secondary macro-cellular network, the reasonable size of a single macro-cell was derived. We assume that in secondary cellular networks the most likely configuration will have mobile devices and the base station in one cell share a common channel for communication. The channel should therefore be available at both, the location of the base station and the mobile users. The size of a cell hence becomes the limiting factor to channel usage, because with increasing cell sizes it becomes more likely that mobile devices at the cell edge will be within the contours of the protection zone. In Figure 2-14 we show the detrimental effect of the cell radius on the channel availability. The mean number of accessible channels is being reduced to 30 and 23 for circular cells of radius 2km and 20km, respectively. For sparsely distributed cellular networks, this will likely affect the exploitation capabilities due to the predominately large macrocells necessary for providing contiguous coverage.

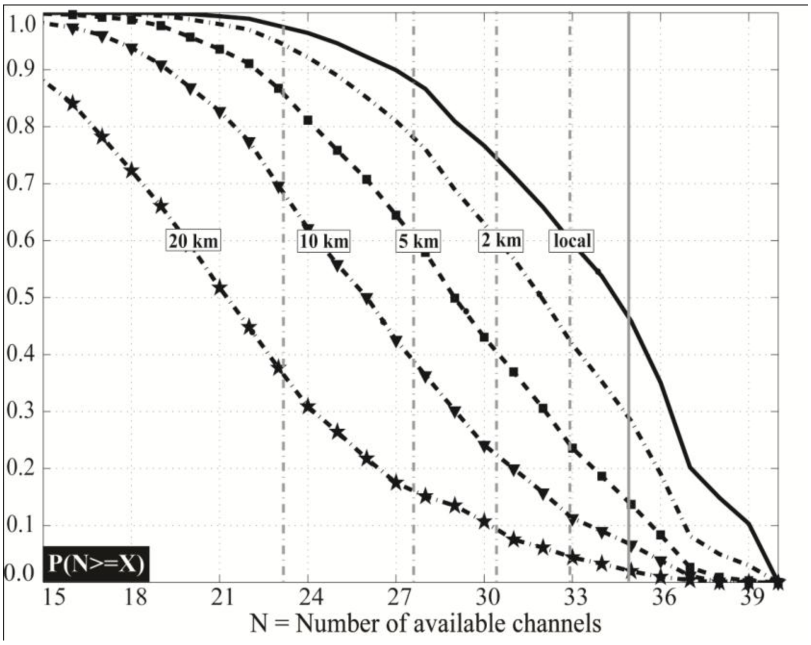


Figure 2-14: Number of available channels for single cell assuming that the channel must be available in a circular area with radius R around the cell center.

Distance to the protection zone

With a flexible power allocation for the SU as envisioned in the SE43 working group in Europe’s CEPT [ECC159], the distance to the protection zone is the main determinant to the achievable secondary performance of a single transmitter. Already in the small-area study we have implicitly included distance measures to derive the maximum allowed transmit power and the resulting SINR/throughput. In the larger study of Germany, we have more explicitly analyzed the distance relations predominantly found. In Figure 2-15 we show the mean distance to those channels that are available at a particular location for secondary usage. A large difference becomes visible here in the current TV network deployment in Germany. The Eastern parts of the country show large mean distances compared to the rest of the country. The TV tower deployment is less dense in this case and a lower channel reuse factor was applied. Similarly in the Northern flat-terrain areas, the distances tend to increase. The distance measure does not capture the effect of terrain. The central parts of the country, where denser network deployments become necessary due to the geographical structure, the mean distance goes down. The metric does not capture the effect of natural shielding of the primary network against secondary interference and hence must be considered only a valid metric for secondary availability if terrain-agnostic propagation is assumed.

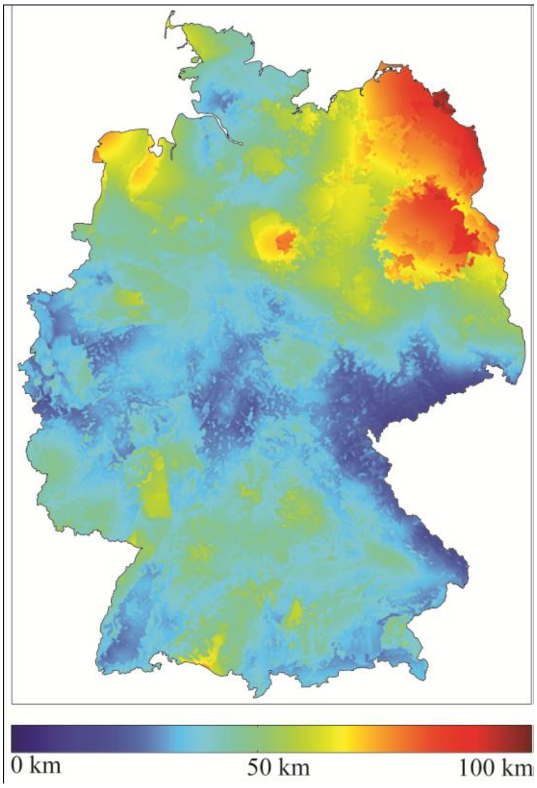


Figure 2-15: Spatial distribution of mean distance to protection zone of all channels.

Extending the analysis of the distance relationship encountered in the study area, we have derived the best-case distance, i.e. the farthest distance to any primary protection zone encountered by a single transmitter, plotted in Figure 2-16. While the most distant protection zone is on average 152km away from the secondary transmitter location, i.e. the channel reuse of the primary system seems to be close to 300km, the second most is already 30km closer. The mean distance shows to be slowly degrading in the ranking. Furthermore, the slope of the complementary cumulative distribution function is becoming steeper with lower ranks. The results show that only few primary protection zones have a very large distance to the secondary transmitter location and the majority of unprotected channels are similarly far away. Only for the highest-ranked channels the distance will therefore make a geometry-based power difference, while for the less highly ranked channels the distance can be approximated statically.

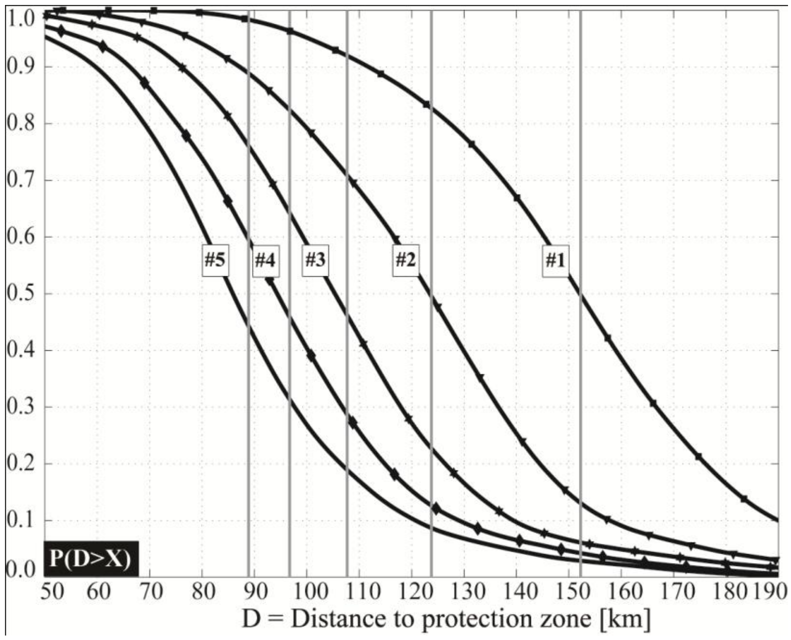


Figure 2-16: Complementary cumulative distribution function of the distance to the Nth furthest away protection zone.

2.2.2 **Comparison of standalone and augmented systems**

From the regulatory point of view, every TV channel that allows non-zero transmit power for WSDs can be used by WSDs. In practice, however, the allowed EIRP levels and also the interference WSDs receive from the TV transmitters vary over a wide range. This means that depending on the purpose/requirements of WSDs, a channel may or may not be useable. Therefore, in order to estimate the amount and utility of the radio spectrum that is available for cellular networks in the TVWS from a SU's point of view, certain use case scenarios and corresponding channel availability criteria based on the requirements of the use case have to be defined.

In this section, we will discuss the use case of a standalone macro cellular LTE network that solely uses TVWS as radio resource, and additionally, the use case of a LTE cellular network deployed in regular radio spectrum, but with the ability to dynamically expand into DTT spectrum in order to offload traffic. We will call this use case dynamic spectrum access (DSA) -enabled cellular network.

The use cases are evaluated separately per pixel for a regular grid of pixel-locations in Germany. The analysis is based on per-pixel data such as TV reception location probability, coverage area affiliation, maximum permitted WSD EIRP and aggregated TV interference power. Additionally, population density data is known per pixel.

2.2.2.1 Standalone macro cellular network

In this use case scenario, we assume an LTE network to be deployed entirely in DTT spectrum. For the newly built network, site locations can be freely chosen, but the site density (or, equivalently, the Inter-site Density, ISD) is assumed to be limited by economic constraints. The maximum allowed ISD in a pixel is chosen according to the population density in that pixel.

For a newly built cellular network it is essential that it provides contiguous coverage. There are different ways to quantify contiguous coverage and we define two criteria as follows:

Criterion 1*:* If the outage probability is smaller than 5% (or 1%), the coverage is considered contiguous. The outage probability is the percentage of the user-bit-rate distribution, which corresponds to a throughput of zero bit/s.

Criterion 2: If the median user-bit-rate is higher than 10 % (or 50 %) of the median user-bit-rate in the interference-limited case, the coverage is considered contiguous. The throughput in the interference-limited case is the maximum possible throughput of a cellular network for a given inter site distance (ISD) and for a freely chosen transmission power.

A channel is counted as available for cellular network use, if criterion 1 or criterion 2 is met for a minimum required ISD. Maximum transmit power, TV interference as additional noise, and the required ISD are determined according to the local circumstances.

We assume that time division duplex (TDD) is used; hence interference to the primary system can only originate from either the eNodeBs or the UEs of the secondary system, but not from both entities simultaneously. The aggregate interference from multiple cells is only considered by including a 3dB interference margin that was subtracted from the overall maximum permitted WSD EIRP. Furthermore, we assume an ideal carrier aggregation capability in the WSD, so we assume that the WSD RF supports the entire DTT band (i.e., the frequency range 470-790 MHz) and an arbitrary number of channels can be aggregated, regardless of potential fragmentation. In addition, we made the assumption of a frequency re-use factor of one, so all cells use the same channel or set of channels. Moreover, the full 8 MHz, corresponding to 40 sub-bands in LTE are supported.

Please keep in mind that we simulate a cellular network with the given assumptions for the conditions in each pixel. The size of the pixel and the actual size of the network are here not considered, neither are overlapping effects to other pixels. Only statistical values characterizing the cellular network performance are determined.

To be able to evaluate the criteria, system level simulations of the cellular network become necessary. The following sections will describe setup and results of the used simulator.

2.2.2.2 Simulator setup

With a system level LTE simulator, we would like to obtain the user-bit-rate distribution for a cell of the LTE network. As described before, a system level simulation for each pixel becomes necessary. Among the pixels, maximum permitted WSD power, interference from the DTT network, as well as the population density can vary. Moreover, the simulations must be done channel-wise; the carrier aggregation of LTE is not simulated, just assumed to be possible, so throughput results per channel are summed up in the end.

The used simulator evaluates performance metrics for a LTE network on a system level. For the underlying link layer, realistic performance models are employed that are based on calibrated link level simulation models and measurements.

To make the simulations computationally manageable, we introduced a quantization. Instead of simulating for each channel for each pixel, we simulate for each channel and for each relevant maximum transmit power and interference pair. Thereby, the introduced quantization error is kept within reasonable bounds (<3dB). To take the local variation of population density, and thus the required ISD into account, we simulate additionally for each pre-defined ISD. By this, we use the population density to ISD mapping as defined in Table 2-5.

Table 2-5: Population density to inter site distance (ISD) mapping.

Population density [inh./km2]	Inter-site distance [m]
>1000 (dense urban)	400
500-1000 (urban)	600
50-500 (suburban)	1800
<100 (rural)	5000

To evaluate Criterion 2, we additionally need to determine the user-bit-rate distribution of a reference simulation, the interference-limited case. Therefore, we simulate in a second run the cellular network with different freely chosen transmit powers and without additional interference from the DVB-T network. We are looking for the (self-) interference limited case, it is the case where the throughput goes into saturation, thus reaching its maximum, when gradually increasing the transmit power. Eventually the throughput distribution provided by this case is taken as a reference for Criterion 2.

In our simulations, we assumed a maximum transmit power of 23dBm for UEs and 60dBm for eNodeBs.

2.2.2.3 Results

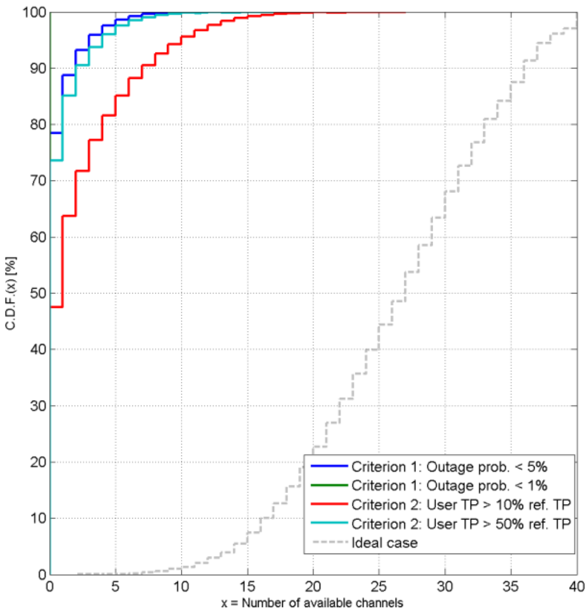


Figure 2-17: Standalone; Number of available channels according to use case criteria.

Figure 2-17 shows the influence of the different criteria on the channel availability. A channel is available for secondary use, if the criterion is fulfilled. The ideal case describes the criterion of a pixel not belonging to a coverage area. Since secondary usage is prohibited in coverage areas, the ideal case can be seen as an upper limit for the channel availability. We can see that the channel availability according to the defined criteria for a standalone cellular network greatly diminishes. Only in 21% of the cases (locations in Germany) is more than one channel available according to the Criterion 1 with 5% or Criterion 2 with 50%. The strictest criterion is Criterion 1 with 1 %, it becomes obvious that 1% outage probability is never possible. Some more channels are available if one is satisfied with Criterion 2 with 10% of the reference performance, but even the resulting availability is far from the ideally expected one.

In order to estimate the utility in terms of capacity for the cellular network, we plotted the sum of the cell throughputs for the available channels in Figure 2-18. The cell throughput evaluated here is the median achievable bit-rate per 8 MHz for a given cell load. The cell load chosen here is 0.8 and affects both the achievable bit rate and the fraction of spectrum being utilized. Shown in the plots is the sum of the cell throughputs of the 40 x 8 MHz UHF channels. It becomes obvious, that the provided capacity is in general quite poor. In the downlink, a significant reduction as compared to the sum of the cell throughputs for the ideal case, where all capacities of channels not in primary coverage areas are summed up, becomes obvious. This is not the case for the uplink and it indicates that channel availability according to the criteria is mainly limited by the UL. Remember that the criteria need to be fulfilled by both DL and UL, what results here with the uplink as a limiter in a low DL sum cell throughput. In general terms, we can say, that 30 Mbit/s in DL and 8 Mbit/s in UL are available in 10% of the locations for the weakest criterion.

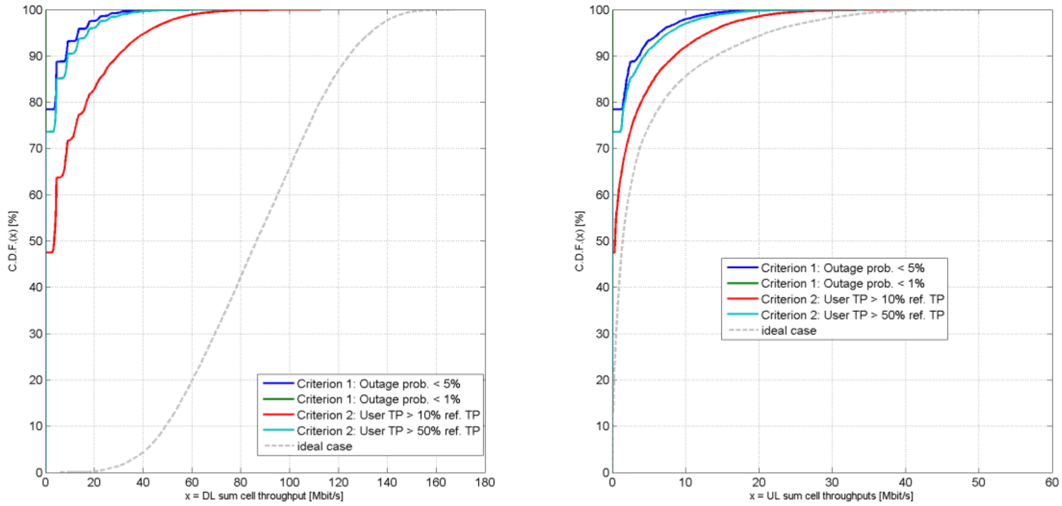


Figure 2-18: Standalone; Available sum cell throughput for DL and UL.

With the previous Figure 2-17 and Figure 2-18 we had a first overview of the available throughput on a country wide scale. The following Figure 2-19 will analyze the WS usability for separate types of regions, corresponding to different required ISDs. The criteria for channel availability were evaluated for the urban, suburban and rural/remote areas separately. A generally higher availability can be observed for urban areas, where the required ISD is lower, but the number of theoretically available channels (dashed plot) also is lower. This indicates more protected regions in urban areas than in suburban or remote regions. Moreover, we can follow that the effect on the channel availability of the lowering of the ISD is stronger than the effect of lower theoretical channel availability, higher interference and lower powers near primary coverage areas. Approximately 5 to 10 Mbit/s can be achieved for the suburban to urban scenario. Fewer channels are available for rural areas. Since for 20%, 40%, 70% for urban, suburban, rural areas no channels are available at all, we can speak of a heterogeneous availability for each of the region types separately. The capacity provided per region, which results from the channel availability, is similar to the low capacities shown in Figure 2-18.

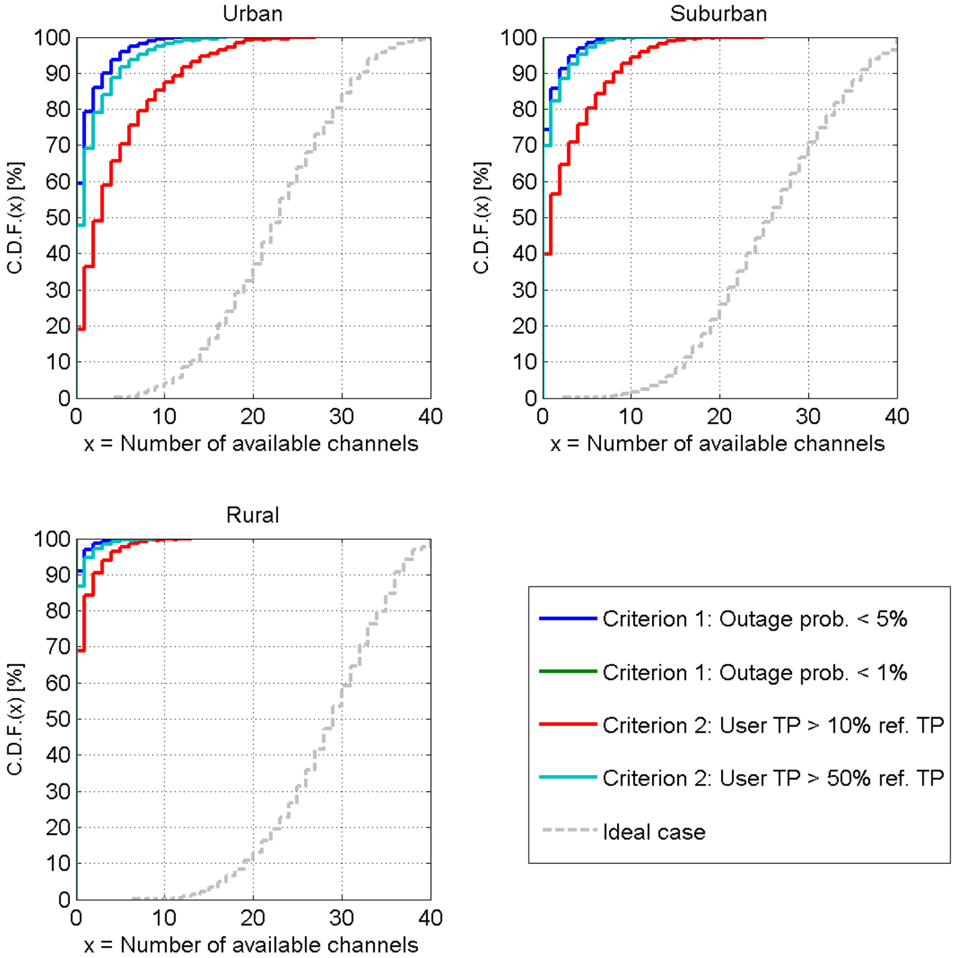


Figure 2-19: Standalone; Number of available channels for different area types.

2.2.2.4 DSA-enabled cellular network

The use case DSA-enabled cellular network describes how an already deployed LTE cellular network (which operates normally in dedicated IMT spectrum) is able to opportunistically expand into the DTT spectrum. Thus, it is able to use the TV white spaces as a capacity booster. In LTE such an operation can be realized in a carrier aggregation scheme.

We assume here that the extension carriers are either pure uplink or pure downlink. Moreover, since only one SU is allowed to transmit per channel at a given time, aggregated interference is neglected. Additional SUs are accounted with the 3dB margin introduced in the maximum WSD EIRP calculation.

The ISD is assumed to be known according to the prior deployment of the network, here it is chosen according to the population density to ISD mapping of Table 2-5. As the criterion for channel availability, we define that a certain link spectral efficiency for a reasonable fraction of the users in a cell must be supported by the extension carrier. Here we define, that 50% of the cell area, so a distance of sqrt(0.5) *ISD has to be supported.

We will find for a given location some channels permitting only low transmit powers and/or having very high interferences from the DTT network. These channels would not be considered as usable.

System level simulations are not necessary to evaluate the criterion for channel availability in this use case, because only the supported link spectral efficiency needs to be determined and afterwards compared with a threshold value. In this work, we will use thresholds for UL and DL of 0.5, 1.0, 1.5 and 2.0bit/s/Hz to quantify our criterion. A channel is deemed available if the threshold value is met. System level simulations are only done for the throughput analysis resulting from the usable channels.

2.2.2.5 Results

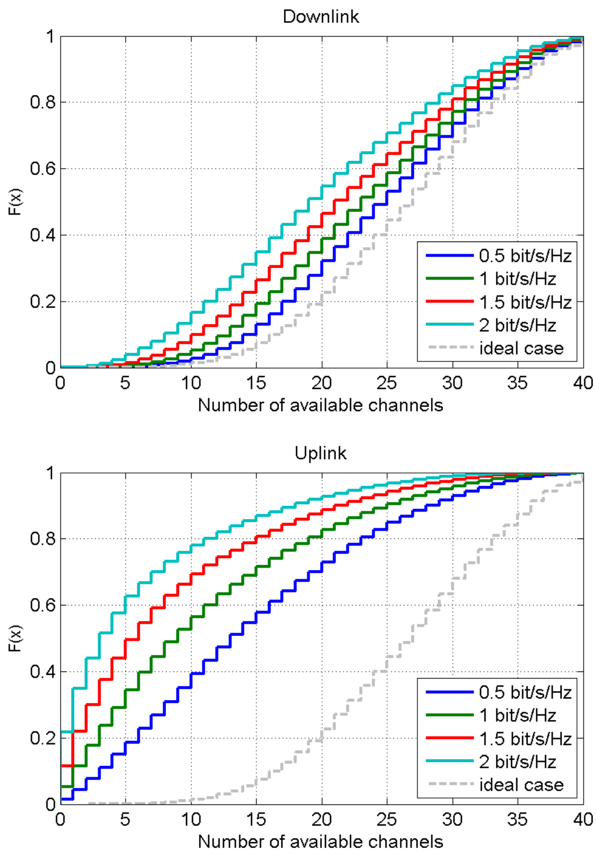


Figure 2-20: DSA-enabled; Number of available channels according to use case criteria in DL and UL.

In Figure 2-20 we can see the distribution of the number of available channels for use as expansion carriers for the DSA-enabled use case. The in general high availability for DL and also UL becomes apparent. Approximately 17-25 channels are available for requirements of 2-0.5 bit/s/Hz in the DL and 3-12 channels are available for requirements of 2-0.5bit/s/Hz in the UL. We can argue that the UL has a worse link spectral efficiency due to the more severe TV interference at the base station receiver, as well as the uplink transmit power cap of 23dBm. Furthermore, a heterogeneous availability of the channels becomes obvious in the maps shown in Figure 2-21. We will find locations with both high and low extremes of secondary channel availability, which is a general downside in the WS usage, especially for cellular networks, when aiming at a country-wide support.

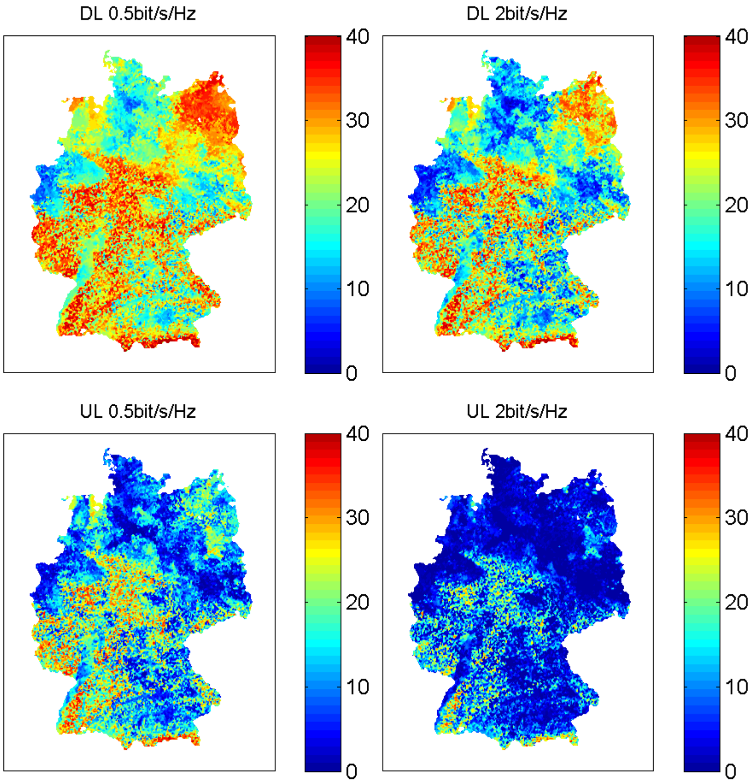


Figure 2-21: DSA-enabled; Maps depicting number of available channels for different criteria in DL and UL.

The system level simulated sum cell throughput resulting from the given channel availability is shown in Figure 2-22. The link spectral efficiencies are only used as a criterion for availability but do not determine the available cell throughput. For all used criteria, a simulated sum cell throughput of more than 60 Mbit/s in DL and about 2 Mbit/s in uplink is achievable. Especially in the DL the throughput suggests good usage but keeping in mind that this throughput corresponds to 312 MHz of spectrum, we find that the average effective spectral efficiency is quite low. The situation in uplink with only 2Mbit/s on average is even more severe.

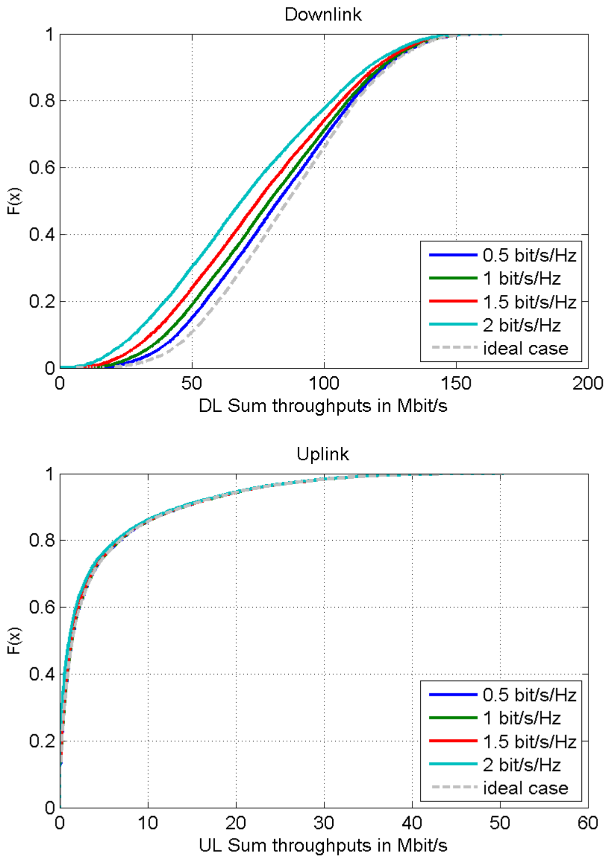


Figure 2-22: DSA-enabled; Available sum cell throughput for DL and UL.

The spectrum availability situation is further analyzed in the plots of Figure 2-23 for DL and Figure 2-24 for UL. Like in Figure 2-19 for the standalone network, the graphs of Figure 2-23 and Figure 2-24 show the availability situation separately per area type for the DSA-enabled network use case. For the DL case, a generally high availability of 20 channels on average can be observed. Here it also becomes obvious, that the rural scenario offers the highest channel availability. It seems that the higher required ISD in rural areas is leveraged by higher average higher transmit powers and lower TV interference, since rural areas tend to be in areas far off primary coverage.

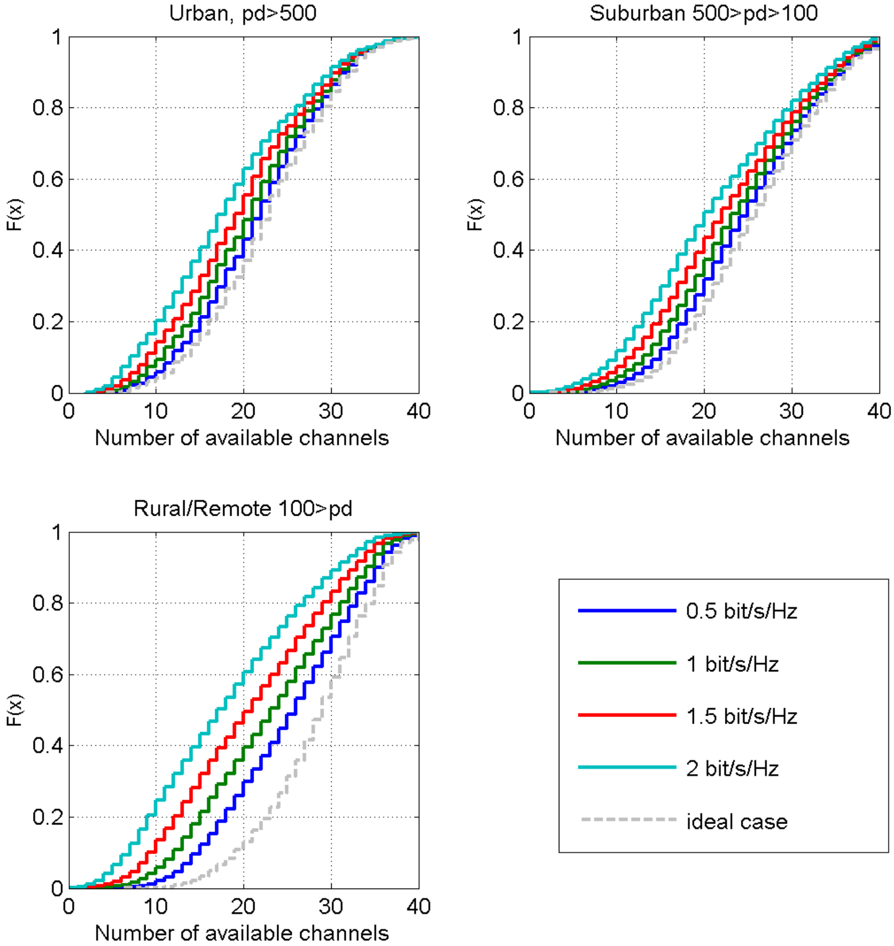


Figure 2-23: DSA-enabled; Number of available channels for DL.

For the UL direction, the highest availability can be observed in the urban areas, probably because the transmit power is capped by 23dBm in all the areas, what is most constraining parameter for high required ISD links in rural areas. But in general, a reasonable amount of channels is still available for the UL transmission in all area types.

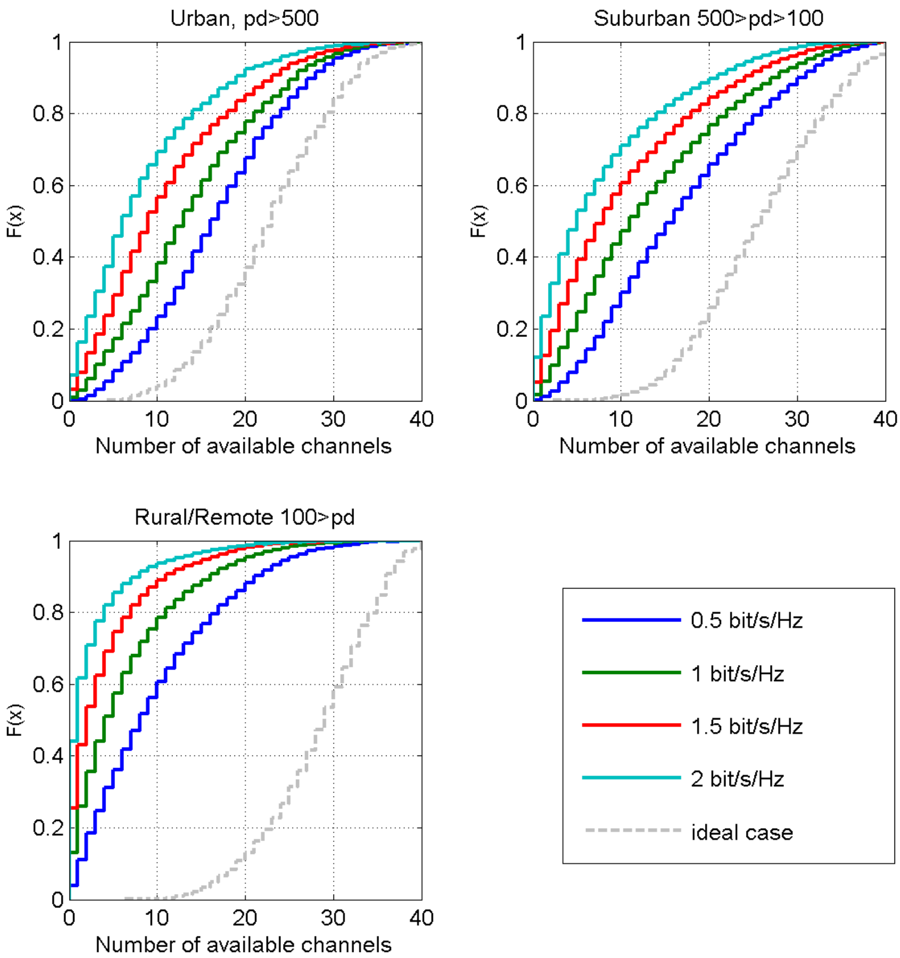


Figure 2-24: DSA-enabled; Number of available channels for UL.

2.2.2.6 Summary

For the standalone white space networks we saw for a deployment with typical ISDs that in only 20% of Germany at least one channel allows outage of less than 5%. As far as the performance is concerned, we saw only one channel having more than 10% of dedicated spectrum reference performance on average. No location supports more than 50% of dedicated spectrum reference performance or less than 1% outage. For the entire white space spectrum, a sum cell throughput of 30 Mbit/s in DL and 8 Mbit/s in UL can be foreseen on average and for the weakest criterion. We can follow that a contiguous coverage under these criteria and with the typical site density is not possible. The throughput of the white space spectrum would be significantly lower than for a network in dedicated spectrum. Looking on the availability per area, we can follow that a contiguous deployment becomes even more difficult in rural areas where high ISDs are required. Of course these limitations can be overcome by a denser (thus more expensive) deployment.

As far as the DSA-enabled cellular networks are concerned, a capacity boost of 80 Mbit/s in DL and 2 Mbit/s in UL as the sum of the cell throughputs for all available channels, can be observed. On average we find 17 to 24 channels available that provide a link spectral efficiency of 2 bit/s/Hz to 0.5 bit/s/Hz for the DL direction. In the UL we still have 4 to 14 channels available for 2 bit/s/Hz to 0.5 bit/s/Hz. When looking on the map depicting the availability situation in Germany we saw a heterogeneous distribution. In contrast to the standalone scenario, the differences between the area types are not very high for the DSA-enabled network. A reasonable high availability can be foreseen for both DL and UL in all area types.

In a conclusion we can say, that cellular networks are not suitable for a country-wide deployment with contiguous coverage. When the network is deployed in dedicated spectrum and white space is opportunistically used as a capacity booster, high capacity gains can be observed in certain locations. However, these gains are provided by all 40 WS channels, and their capacity is only in the ranges of what an LTE network would provide in dedicated spectrum, so the effective spectral efficiency for these capacity boosters is quite low.

2.2.3 Comparison of FCC and ECC approaches

In the following we compute the available TVWS in Finland considering DVB-T as primary system and assuming cellular type of secondary system. The assessment uses both FCC and ECC rule set. Analysis and methodology is similar that was reported in D5.1 [D5.1], except in this analysis we take user density into account and use different sized cells in different parts of the country.

2.2.3.1 Cell size selection based on user density

In D5.1 we analyzed the secondary cellular capacity by using homogenous cell sizes across the country [D5.1]. This kind of analysis can give some idea about the available secondary capacity and makes comparisons easy, but it is not very realistic scenario, since the population density varies significantly throughout the country. In highly populated areas like city centres, smaller sized cells are used for getting more capacity. In rural areas where less capacity per area is needed, larger cells are used in order to reduce the number of sites.

In this analysis we decided to use square-shaped secondary cells for the sake of simplicity. Three different secondary cell sizes were chosen. The cell allocation algorithm was made simple. First large cells were allocated for the whole country coverage. Then if some of these cells had more than 10000 users, it was split to medium sized cells. If some of these medium sized cells had also more than 10000 users, it was divided into small cells. The used cell sizes and their allocated amounts are shown in Table 2-6.

Table 2-6: Used cell sizes.

Name	Size	Coverage [km^2]	Number of cells
small	1x1km	1	1744
medium	4x4km	16	5459
large	32x32km	1024	327

Finland is sparsely populated with average population density of 17,7/km^2. Most of the population is concentrated to southern part around cities. Population density is show in Figure 2-25 next to allocated cell sizes. The size here is the radius of the cell meaning the distance from the center of the cell to the center of its side.

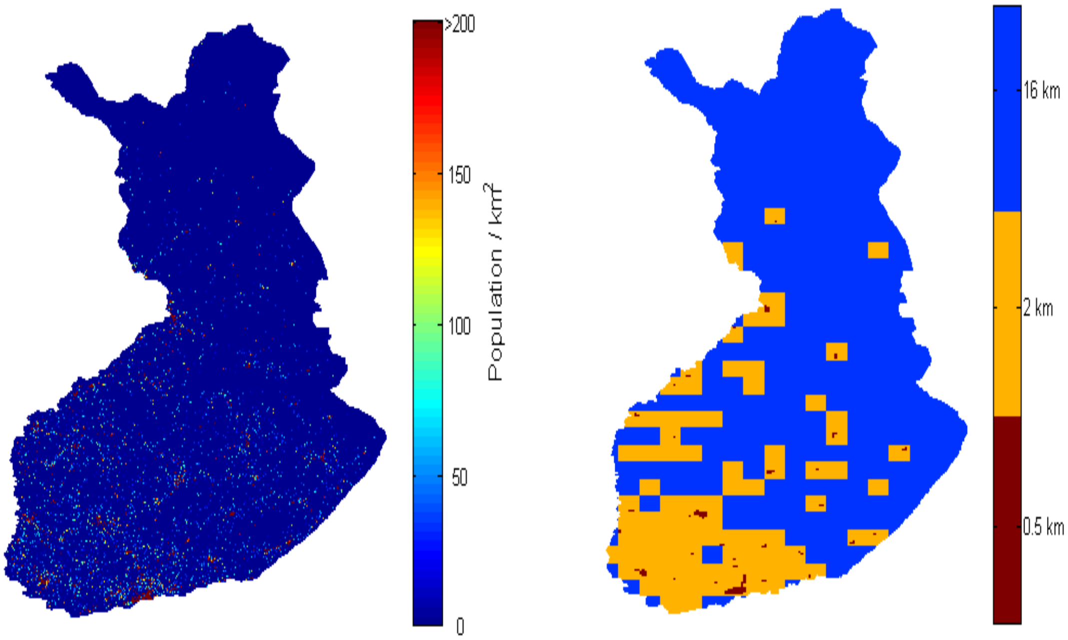


Figure 2-25: Population density in Finland (left) and Allocated cell sizes based on population density (right).

2.2.3.2 Average capacity per cell by FCC and ECC rules

First thing that limits the secondary use on TVWS is the number of available channels. The FCC rules exclude using co-channel and first adjacent channels within protection distance. ECC rules only exclude using the co-channel. The number of available channels available in each cell for both set of rules is shown in Figure 2-26. The channel must be available within the entire cell in order to be available. This requirement reduces the number of available channels in the large cells. It can be seen that with FCC rules some large cells have only 1 available channel, whereas with the ECC rules lowest number is 10 available channels.

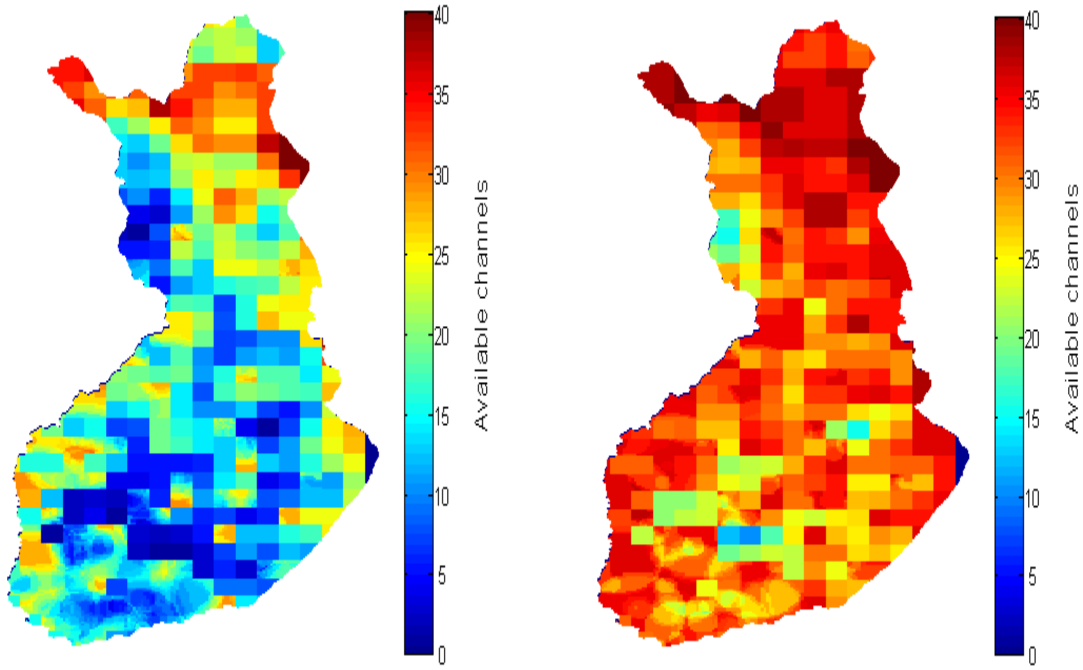


Figure 2-26: Available channels per cell using FCC (left) and ECC (right) method.

In these simulations we assumed secondary antenna to be located at 30m height for all cell sizes. Hata-model in suburban environment was used for computing the secondary path losses and ITU-R P.1546-model was used for TV path losses. Secondary transmission powers were selected according to FCC or ECC method maximum allowed power.

The FCC method uses same 4 W transmit power in each secondary cell. Transmission is allowed if transmitter is outside certain protection distance. According to FCC rules, this 30m height antenna gives protection distances of 14.4 km for co-channel and 0.74 km for closest adjacent channels. It can be seen Figure 2-27 that FCC method gives rather good capacity in small and medium sized cells. Large cells are able to provide good capacities only in areas where the number of available channels is high. Also large cells close to medium and small cells suffer from higher self interference and therefore have not much usable capacity.

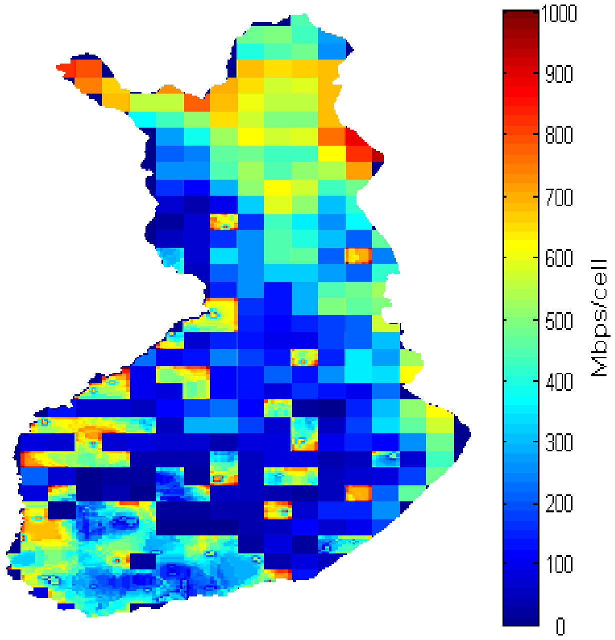


Figure 2-27: Average capacity per cell using FCC method.

In the ECC method, the secondary transmit power depends on the distance to the primary cell, safety and multiple interferer margins, spectrum masks and reference geometry. Reference geometry means the smallest distance between secondary transmitter and primary receiver. Usually 22 meters is used, but here for comparison also 100 meters was used. In our simulations 6dB and 10dB IM margins were used. IM margin includes both safety and multiple interferer margins.

The average capacity per cell results for the ECC method is presented in Figure 2-28. Also now the capacities in large cells are small in middle of Finland. Reference geometry has significant impact to the capacity in medium and small sized cells, since this increases the allowed transmission power by over 10dB. Changing the margin from 10dB to 6dB does not have significant effect. Large cells suffer again from higher interference when located near to medium and small cells, but they provide also decent capacities in the north, due to the high number of available channels. Compared to the FCC method, the ECC method gives higher capacities in small cells.

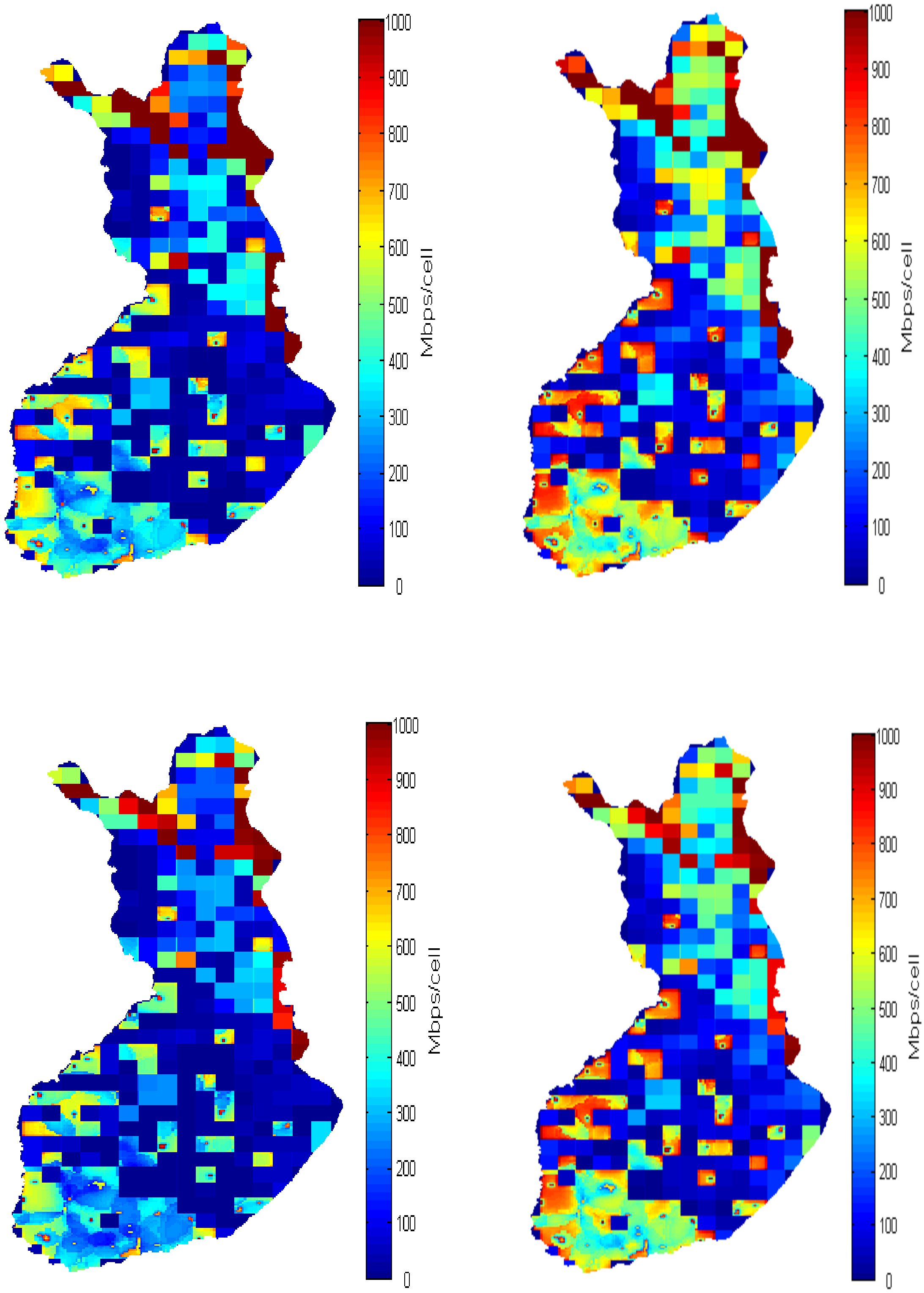


Figure 2-28: Average capacity per cell using ECC method: Upper-left IM=6dB and RG=22m, Upper-right IM=6dB and RG=100m, Lower-left IM=10dB and RG=22m, Lower-right IM=10dB and RG=100m.

2.2.3.3 Average capacity per user comparison between FCC and ECC method

Figure 2-29 shows the cumulative distributions of the capacities per user for the FCC and ECC methods. These capacities are calculated by dividing the average cell capacity with the number of people living within cell's coverage area. The ECC method offers for most users' better capacity than the FCC method. Changing the margin in the ECC method does not change the capacity much, but increasing the reference geometry from 22m to 100m increases the capacity per user. The median values of all simulated cases are between 100 kbps and 200 kbps, but this assumes that the whole population is using the system at the same time. If we assume that 5% of the population uses secondary network at the same time, half of them would get more than 2Mbps-4Mbps "connection" depending on the used method.

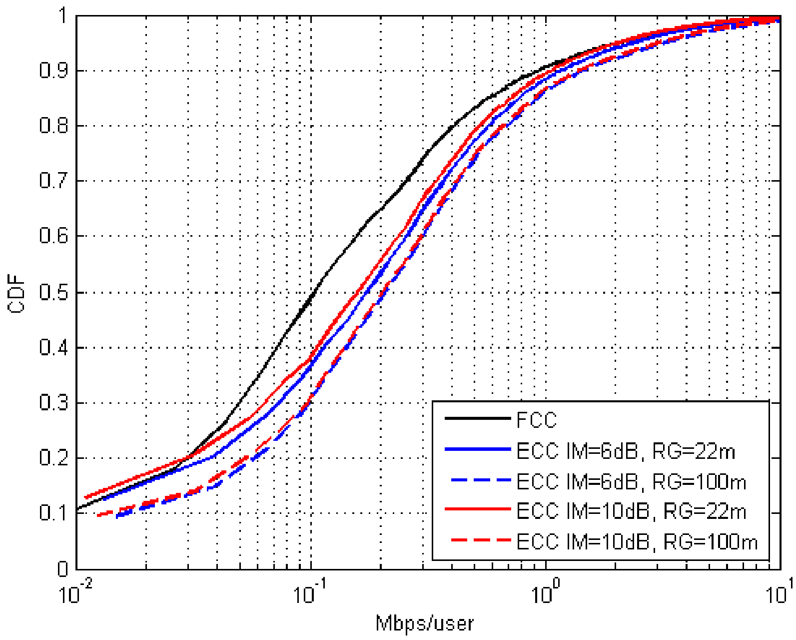


Figure 2-29: CDF of capacity per user using different methods and constraints.

2.2.3.4 Impact to the TV reception

Protecting TV reception sufficiently well is the most critical task when allowing secondary use on the TV-bands. As we have mentioned before, the FCC and ECC methods are not taking aggregate interference very well into account. We computed the TV SINR at test points located at TV cell borders. Interference on channel *N* includes the total aggregate secondary interference over all SUs between channels *N-10* and *N+10*. The interference on each adjacent channel is weighted with the TV-receiver's protection mask. In our computations we assume that the TV SINR without any secondary interference is about 23dB.

Figure 2-30 presents the mean SINR CDF at the primary TV coverage border test points, when the secondary cellular system is using transmission powers computed by the FCC and ECC rules. The FCC method causes the most interference to the primary system and yet provides the worst capacity per user. When using the ECC rules, chosen margin and reference geometry play significant role. Increasing RG from 22 meters up to 100 meters increases the allowed secondary transmit power and therefore also severe interference is caused to the primary. Larger interference margin affects also to the allowed secondary transmit power by reducing it. It can also be considered as the multi-user interference margin of the ECC method. However it is observable that using higher 10dB margin is not enough to protect the PU.

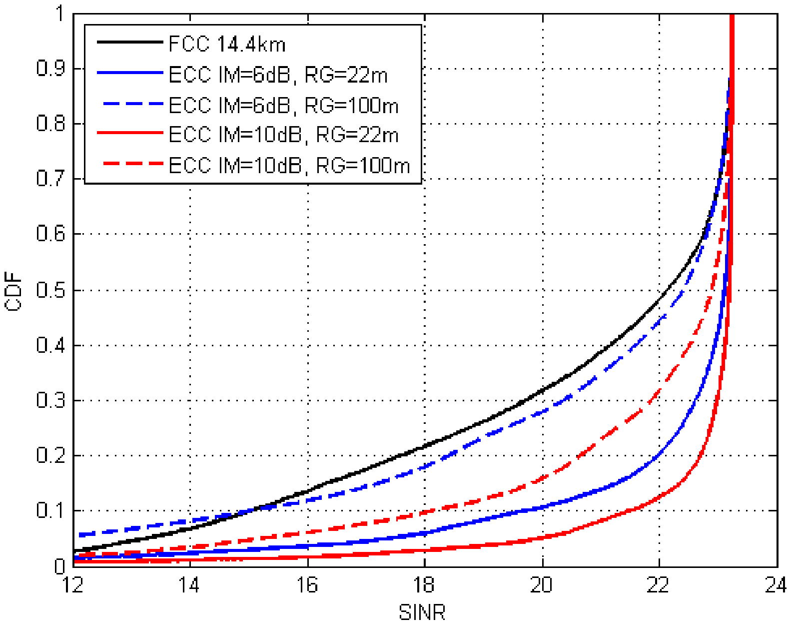


Figure 2-30: SINR distribution at the TV cell borders computed with aggregate interference from all secondary transmitters by using FCC rules and ECC rules with different reference geometry assumptions (RG) and interference margins (IM).

2.2.4 Concluding remarks for macro cellular use of TVWS

In Section 2.2.1, it is observed that different ways of considering neighboring countries result in huge difference in channel availability. It is also shown that the amount of contiguous channel chunks is considerably less than the total available channels, implying that the channel aggregation capability of secondary system plays an important role in exploiting TVWS.

In Section 2.2.2, we can say that cellular networks in TVWS under SE43 rule are not suitable for a country-wide deployment with contiguous coverage. When the network is deployed in dedicated spectrum and white space is opportunistically used as a capacity booster, high capacity gains can be observed in certain locations. However, huge geographical difference is observed in the capacity gain. Compared to the average, only about 30% of capacity is obtained in the 10%-worst area.

From Section 2.2.3 it can be concluded that the current FCC and ECC methods are not suitable for cellular type of secondary use. This is due to their insufficient protection of PU when the interference is coming from cellular type of system. In many cases the methods thus tend to overestimate the availability of secondary spectrum. From the SU point of view, problems especially arise when we have cells with different sizes. Small cells and large cells are allowed to use same transmit power and this distributes their capacity unevenly.

In general, the analysis in this section relied on the rules currently being considered by regulatory bodies. Different rules for the permissible secondary power levels will provide different availability result. In the deliverable D5.3, we plan to propose a power allocation method that satisfies the protection criteria of the TV system. The proposed method will take into account the non-uniform cellular layout due to the population density and allocate different power levels at cells with various sizes. The method will result in slightly less SU capacity compared with the one computed by using current standardization rules but the protection criteria of TV receivers will be satisfied.

2.3 Wi-Fi-like system as secondary user

The idea of building a Wi-Fi type of network in the UHF bands has been strongly adopted by industry players, such as network operators and Internet providers, and standardization bodies. TVWS are potentially very attractive for providing cost-effective high data rate services and good coverage. Recently several studies on possible design and implementation as well performance analyses of a Wi-Fi type of network in the UHF bands have been published [Deb09, Bahl09, KN10, FNK11]. Moreover the IEEE 802.11af working group has been set up to define a standard for Wi-Fi like technology in TV bands [IEEEaf]. Additionally, trials are currently being undertaken in the UK by industry to test this on the island of Bute, Scotland and in Cambridge [MS11]. The UK regulator, Ofcom has put forward plans to run an "enhanced Wi-Fi" service using the white space within the existing TV spectrum. Since these activities are in the early stages and no real deployments are available, we still lack deep understanding of the performance of this so-called "super Wi-Fi".

As discussed in D5.1, the study of a Wi-Fi type of secondary system operating in the TV bands is of key interest to QUASAR. In this section we firstly present a detailed evaluation of the performance of such a system and then, as an example, we investigate the availability of TVWS for Wi-Fi like secondary deployment in Macedonia.

2.3.1 Performance analysis of a Wi-Fi-like system deployed in TVWS

In this section we analyse the performance of a Wi-Fi type of network operating as a secondary network in the TV bands, with a view towards obtaining a realistic estimate of the achievable range and data rate. Alongside results for the single SU case, we present a preliminary analysis of the multiple SU case.

2.3.1.1 System model of the Wi-Fi-like secondary network

We consider Wi-Fi-like access points (APs) operating as SUs in TVWS. We assume that the secondary APs use the CSMA/CA MAC protocol. For the sake of simplicity, we assume traffic is downlink and saturated and analyze the case of a single user terminal associated with each secondary AP. Our results therefore represent an upper-bound on the performance of a secondary Wi-Fi-like system in TVWS; in practice, a single AP would be likely to support multiple users and the per-user achievable throughput would be reduced accordingly.

Secondary AP coverage model

We assume that the secondary APs employ an auto-rate function $\rho(\beta)$, whereby the raw bit rate ρ provided by an AP to its associated user is determined by a minimum received SINR (signal-to-interference-plus-noise ratio) value β at the user terminal. We model the auto-rate function $\rho(\beta)$ as a piecewise constant function, as given by the spectral efficiency and minimum receiver sensitivity specifications in the IEEE 802.11g standard [80211]. Table 2.7 details the resulting raw bit rates and minimum SINR values for different secondary channel bandwidths of 8 MHz, 16 MHz, and 24 MHz (corresponding to aggregation of up to three 8 MHz TV channels).

The auto-rate function defined in Table 2-7 is implemented as follows. Let $SINR_{u,x}$ be the SINR at user u associated with AP x. If $SINR_{u,x} \geq \beta_n$, user u obtains a raw data rate of at least ρ_n and is said to be β-covered by AP x. Specifically, we assume that an AP will provide its user the highest possible raw bit rate allowed by its SINR, such that the rate is equal to ρ_8 if $SINR_{u,x} \geq \beta_8$, ρ_7 if $\beta_7 \leq SINR_{u,x} < \beta_8$, etc. If $SINR_{u,x} < \beta_1$, user u is not covered by AP x and the rate it obtains is equal to 0.

Table 2-7: Definition of $\rho(\beta)$ auto-rate function used by secondary APs.

Index, n	Modulation, coding rate	Spectral efficiency (bps/Hz)	Minimum SINR, β_n (dB)	Raw bit rate, ρ_n (Mbps) 20 MHz channel (802.11g)	8 MHz channel (TVWS)	16 MHz channel (TVWS)	24 MHz channel (TVWS)
1	BPSK, 1/2	0.3	4	6	2.4	4.8	7.2
2	BPSK, 3/4	0.45	5	9	3.6	7.2	10.8
3	QPSK, 1/2	0.6	7	12	4.8	9.6	14.4
4	QPSK, 3/4	0.9	9	18	7.2	14.4	21.6
5	16-QAM, 1/2	1.2	12	24	9.6	19.2	28.8
6	16-QAM, 3/4	1.8	16	36	14.4	28.8	43.2
7	64-QAM, 2/3	2.4	20	48	19.2	38.4	57.6
8	64-QAM, 3/4	2.7	21	54	21.6	43.2	64.8

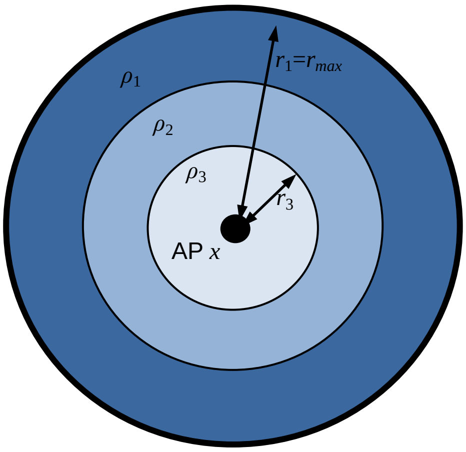


Figure 2-31: Illustration of the auto-rate function $\rho(\beta)$ employed by a secondary AP; a user terminal located within a range of r_n from AP x obtains a raw bit rate of ρ_n (for clarity only up to n=3 shown). The boundary of the coverage area (cell) of AP x corresponds to the maximum coverage range r_{max} of AP x.

It follows that in this subsection we may define the coverage area, or cell, of AP x as the set of user locations $\boldsymbol{U}_x$ at which $SINR_{u,x} \geq \beta_1$. Similarly, the maximum (cell-edge) coverage range of AP x, $r_{\max}$, is the mean distance between AP x and user locations on the edge of its coverage area (i.e. the contour for which $SINR_{u,x} = \beta_1$), as illustrated in Figure 2-31. Analogously, we may define r_n to be the maximum range corresponding to a given raw rate ρ_n (where $r_{\max} = r_1$). It is important to note that Figure 2-31 depicts the contours representing the β_n -coverage boundaries of AP x as circles for ease of illustration only. In practice, the exact shape of these coverage boundaries depends on the geographical distribution of interference created by other co-channel transmitters.

Secondary network model

We investigate three potential deployment scenarios for a secondary Wi-Fi-like network operating in TVWS: (a) outdoor urban, (ii) indoor urban, and (iii) outdoor rural. We analyse the performance of a network of secondary APs located within a study area of 2km by 2km, 500m by 500m, and 5km by 5km for the respective scenarios. We model the locations of the secondary APs using a homogeneous Poisson point process with density λ. We take the German city of Aachen as an example of an urban area and assume an outdoor AP density of λ =12.5 APs/km2, based on the population density of 6250 people/km2 in central Aachen (Landscan data set, 2006 release [BBC02]) and an assumption of one outdoor hotspot AP per 500 people. We assume an AP density of

λ =0.25 APs/km2 for the outdoor rural scenario, corresponding to the population density of 125 people/km2 in the example rural area around Wipperfürth in Germany. For the indoor urban scenario, we assume an AP density of λ =125 APs/km2 (assuming one indoor AP per 50 people), which is similar to the measured density of IEEE 802.11 Wi-Fi APs in an urban centre such as Las Vegas or Atlanta [JL07]. An example realisation of the secondary Wi-Fi-like network is illustrated in Figure 2-32 for the outdoor urban scenario, generated via the **spatstat** [Spa05] package in R, software for statistical computation. [R08].

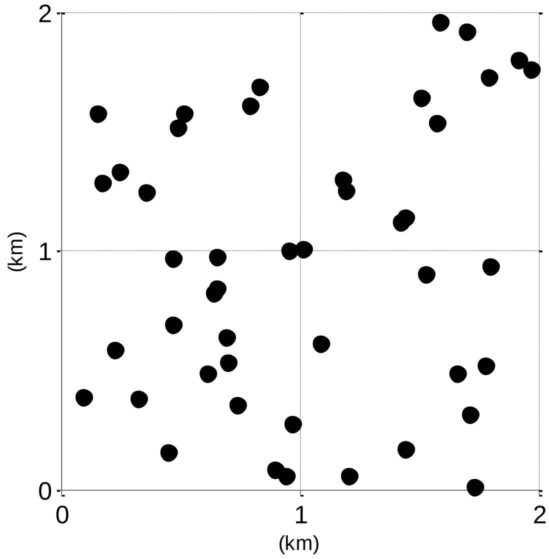


Figure 2-32: Example of a secondary Wi-Fi-like network realisation for the outdoor urban deployment scenario, showing random AP locations generated using a Poisson point process with density of λ =12.5 APs/km^2 over a study area of 2 km by 2 km.

2.3.1.2 Interference and propagation modelling

Propagation model

In our analysis we assume the log-distance path loss model [Rap02], where the average path loss L at a transmission distance d is given by

$$L = L_{ref} d^k , \tag{2-4}$$

where L_{ref} is the path loss at the reference distance of 1 m and k is the path loss exponent. The reference path loss may be obtained using the free space path loss formula,

$$L_{ref} = \frac{(4\pi)^2 d_{ref}^2 f_c^2}{c} , \tag{2-5}$$

where the transmitter and receiver antennas are assumed to have unity gain, d_{ref} = 1 m, c is the speed of light, and f_c is the carrier frequency. Without loss of generality, we set f_c =630 MHz for secondary APs operating in TVWS (centre of the 470-790 MHz frequency band corresponding to DVB-T channels #21-60), regardless of the actual TV channel the secondary transmitter occupies.

We characterise the considered deployment scenarios by the associated typical values of path loss exponent, setting k =3, k =4, k =2.5, for the outdoor urban, indoor urban, and outdoor rural scenario, respectively. For the indoor urban scenario, we assume an additional wall penetration loss of 18dB, corresponding to an average of 3 obstructing walls causing 6dB loss each. It should be noted that we deliberately opted to employ a relatively simple propagation model, in keeping with the system-level nature of our analysis. Importantly, the adopted model enables us to effectively characterise the three considered deployment scenarios whilst examining the fundamental effects of operating in the TV frequency range.

Primary-to-secondary interference

We take into account the interference from the PU DVB-T transmitter to the SU terminal receiver by making the conservative assumption of maximum interference from the DVB-T system outside the primary's protection contour. Specifically, in our analysis we set the PU interference power I_{PU} equal to the received power of -87.5 dBm which defines the PU protection contour (as in Section 2.2.1 and [APM11]).

Secondary-to-primary-interference

The issue of aggregate secondary interference to the primary DVB-T system is central to the analysis of the achievable performance of a multiple SU system in TVWS. This issue will be addressed in deliverable D5.3 [D5.3], the focus of which is dealing with the multiple SU case. The preliminary analysis of a multi-user secondary network presented here instead considers the performance of the Wi-Fi-like secondary system for a range of different values of secondary AP transmission power. The *permissible* transmission power of secondary APs will be then determined once the extent of aggregate secondary interference to the primary DVB-T system is evaluated.

Secondary-to-secondary-interference

We adopt the model proposed in [NBK07] to take into account the impact of interference among co-channel secondary APs on the downlink throughput achievable by the secondary Wi-Fi-like system. In this preliminary multi-user secondary network analysis, we assume all secondary APs operate on the same TV channel (or aggregation of up to three adjacent TV channels). We plan to extend our analysis to consider secondary APs operating on one of a set of available TV channels in the study area, as a part of our full treatment of the multiple SU case in D5.3.

Let $\boldsymbol{A}$ be the set of all co-channel secondary AP transmitters in the network and $\boldsymbol{A}_x$ be the set of all co-channel APs that are in the contention domain of a given AP x. We may define a pair of co-channel APs to be in a common contention domain if they receive each other's signal with a power greater than the carrier-sense detection threshold. Specifically, we follow the specification in the IEEE 802.11 standard [80211] and assume the carrier-sense detection threshold to be equal to β_1, the SINR required for the lowest supported data rate. Using the CSMA/CA MAC protocol, an AP will refrain from transmitting if another AP in its contention domain is already doing so (i.e. all other APs in the set $\boldsymbol{A}_x$ will refrain when AP x is transmitting). Therefore, only the set of co-channel APs which are outside the contention domain of AP x will cause interference during its transmission. We may thus define the SINR at user u associated with the secondary AP x as

$$SINR_{u,x} = \frac{P_{tx}(L_{u,x})^{-1}}{N_0 + I_{PU} + \sum_{y \in \boldsymbol{A} \setminus \boldsymbol{A}_x} P_{tx}(L_{u,y})^{-1}}, \quad (2\text{-}6)$$

where P_{tx} is the transmission power of the secondary AP, $L_{u,x}$ is the average path loss on the link between transmitter x and receiver u (as given by (2-4)) and N_0 is the noise power at the receiver.

Let M_x denote the fraction of time that AP x is granted channel access by the CSMA/CA MAC protocol. Since other APs sharing AP x's contention domain (in the set $\boldsymbol{A_x}$) will also be contending for access to the shared wireless medium, the channel access of AP x will be less than 100% (i.e. $M_x < 1$ if $\boldsymbol{A_x} \neq \emptyset$). Therefore, we may estimate the downlink throughput of a user u associated with AP x as

$$R_{u,x} = M_x \rho(SINR_{u,x}), \quad (2\text{-}7)$$

where $\rho(SINR_{u,x})$ is the raw bit rate obtained by user u from AP x, as given by the auto-rate function $\rho(\beta)$ and the SINR from AP x at user terminal u. Assuming fair channel access, we may approximate the channel access time of an AP by the inverse of the total number of APs in its contention domain. Namely, we may define

$$M_x \approx \frac{1}{|\boldsymbol{A_x}|}, \quad (2\text{-}8)$$

and re-state (2-7) as

$$R_{u,x} = \frac{\rho(SINR_{u,x})}{|\boldsymbol{A_x}|}. \quad (2\text{-}9)$$

2.3.1.3 Performance analysis of the Wi-Fi-like secondary network

In this section we analyse the performance of a secondary Wi-Fi-like system in TVWS for our three considered deployment scenarios, in terms of the achievable range and throughput of the secondary system. Alongside results for the single SU AP case, we present preliminary results for a network of multiple secondary APs, based on the interference model introduced in Section 2.3.1.2. Throughout our analysis, we assume all secondary APs use the same transmission power P_{tx} and consider operation on different secondary channel widths of 8, 16, and 24 MHz. We also compare the performance of a secondary Wi-Fi-like system operating in TVWS against that of the existing IEEE 802.11g Wi-Fi standard [80211] operating in the f_c = 2.4 GHz ISM (industrial, scientific, and medical) band.

For the case of a single SU AP operating in TVWS, the achievable range r_n for a given throughput ρ_n may be calculated for each deployment scenario by using (2.4)-(2.6) together with the definition of $\rho(\beta)$ in Table 2-7. For the multiple user case, we obtain simulation results in MATLAB by considering potential user terminal locations on an evenly spaced grid over the study area and calculating the obtainable downlink throughput at each location for each AP in the network. This then enables us to determine the coverage area of each AP and the downlink rate for user within its cell.

Figure 2-33 presents a plot of the achievable secondary AP downlink throughput for a given maximum AP range, for different secondary channel widths and deployment scenarios. The secondary AP transmission power is set to P_{tx} = 20 dBm. For the single secondary AP case (dashed curves), Figure 2-33 is a plot of throughput ρ_n vs. range r_n; for the multiple secondary AP case (solid curves), Figure 2-33 is a plot of throughput $\overline{R}_n$

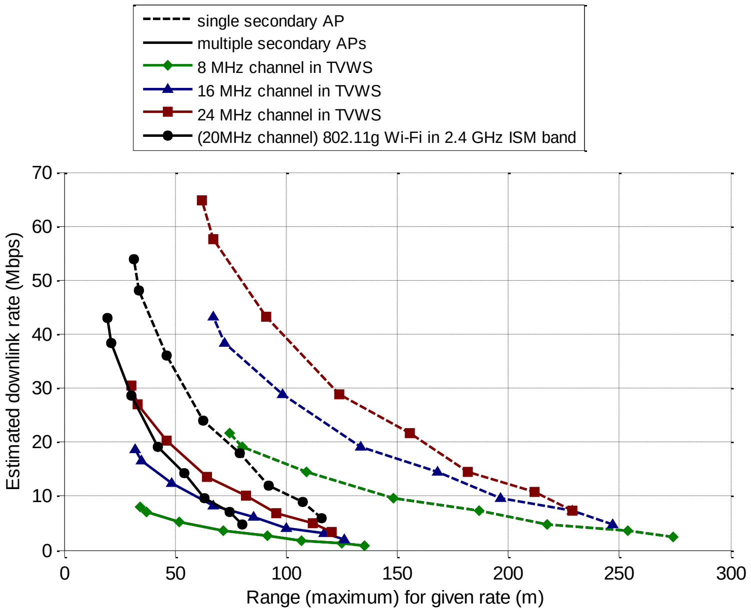
vs. range $\bar{r}_n$, which are defined as follows. With multiple co-channel secondary APs, the maximum downlink throughput of AP x at a range of $r_{x[n]}$ is defined as

$$R_{n[x]} = \frac{\rho(\beta_n)}{\left|\boldsymbol{A}_{\boldsymbol{x}}\right|}, \tag{2-10}$$

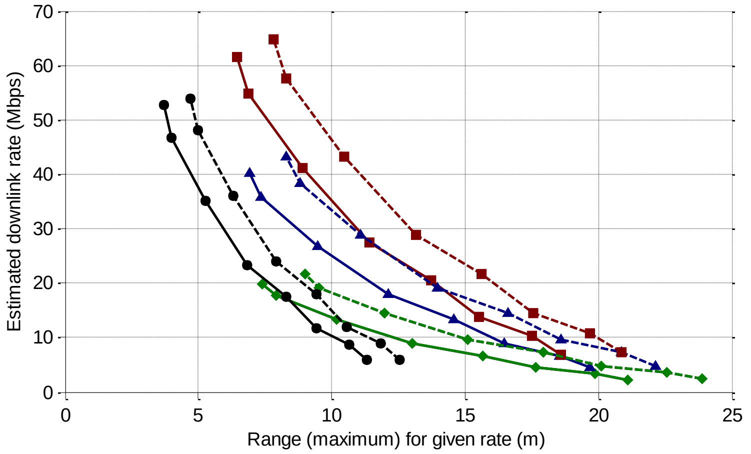
where $r_{x[n]}$ itself is defined as the maximum range for a given raw data rate $\rho(\beta_n)$ provided by AP x and is determined by calculating the mean distance between AP x and user locations on the edge of its β_n -coverage area (i.e. the contour for which $SINR_{u,x} = \beta_n$, as illustrated in Figure 2.31). The number of co-channel APs within the contention domain of AP x, $\left|\boldsymbol{A}_{\boldsymbol{x}}\right|$, is found via simulation. The typical performance over the network of multiple secondary APs may then be characterised by the average rate over the whole network of $|\boldsymbol{A}|$ APs,

$$\bar{R}_n = \frac{1}{|\boldsymbol{A}|} \sum_{x \in \boldsymbol{A}} R_{n[x]}, \tag{2-11}$$

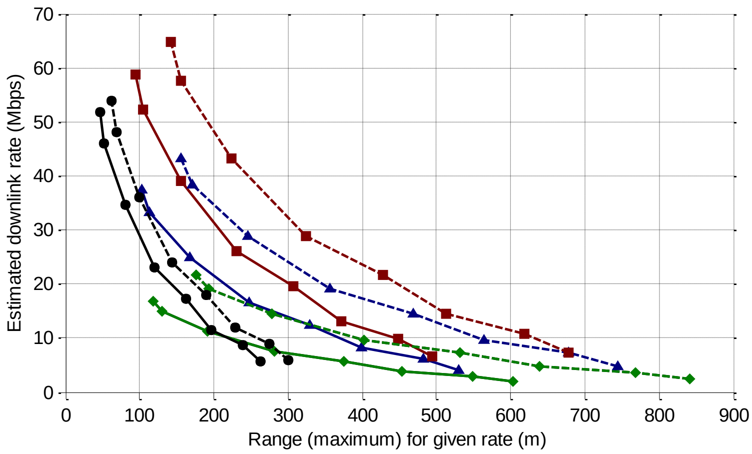
and the mean AP β_n-coverage range over the network, $\bar{r}_n$, which is defined analogously. For the single secondary AP case, Figure 2-33 demonstrates that operating in the lower TV frequency band significantly increases the communication range compared to traditional Wi-Fi at 2.4 GHz, while providing downlink rates proportional to the channel width. For example, Figure 2-33(a) shows that for the outdoor urban scenario, operating with a 24 MHz channel in TVWS nearly doubles the communication range of IEEE 802.11g Wi-Fi at 2.4 GHz for a given data rate. For low data rates (<20 Mbps), even operating on a single 8 MHz TV channel improves the communication range of IEEE 802.11g Wi-Fi at 2.4 GHz for a comparable data rate. For example, Figure 2-33(b) shows that for the indoor urban scenario, using a single 8 MHz TV channel yields up to 25% greater communication range compared to IEEE 802.11g Wi-Fi for a data rate of around 9Mbps, whereas Figure 2-33(b) demonstrates a 45% increase for the outdoor rural scenario. It should be noted though that the β_n-coverage range is greater for a lower-bandwidth channel (e.g. 8MHz vs. 16MHz) in Figure 2-33 due to a correspondingly lower noise power N_0 when assuming a fixed thermal noise power spectral density and P_{tx}.



(a)



(b)



(c)

Figure 2-33: Rate vs. range (P_{tx} =20 dBm), for different deployment scenarios: (a) outdoor urban, (b) indoor urban, (c) outdoor rural.

However, once the effects of secondary-to-secondary interference are taken into account in the multiple SU case, Figure 2-33 reveals that the advantage of operating in TVWS suggested by the single secondary AP analysis can be substantially diminished. The reduction in both range and downlink rate is most pronounced for the outdoor urban case in Figure 2-33(a), which shows that the communication range difference between operating in TVWS (24MHz) and IEEE 802.11g reduces to at most around 30 m (*cf*. a difference of up to over 100 m for the single user case). The nature of this secondary-to-secondary interference in a Wi-Fi-like secondary system is further illustrated in Figure 2-34 for the outdoor urban scenario. The contention domain of AP x in Figure 2-34 is shown to include three other secondary APs, which reduce the channel access time of is AP x to 25%, as per the CSMA/CA MAC protocol. All other co-channel secondary APs in the network (i.e. those outside the contention domain of AP x) cause interference during its transmission, thus reducing the coverage range of AP x by decreasing the SINR at its associated user. For the indoor urban scenario in Figure 2-33(b), the coverage range of secondary APs appears to remain small enough to largely maintain non-overlapping AP contention domains, such that the extent of inter-AP interference is similar for multiple secondaries operating in TVWS as for the traditional IEEE 802.11g network. Similarly, Figure 2-33(c) shows that the effects of secondary-to-secondary interference are not as dominant for the outdoor rural scenario (compared to an urban deployment), due to a much more sparse AP deployment which results in a lesser overlap of contention domains.

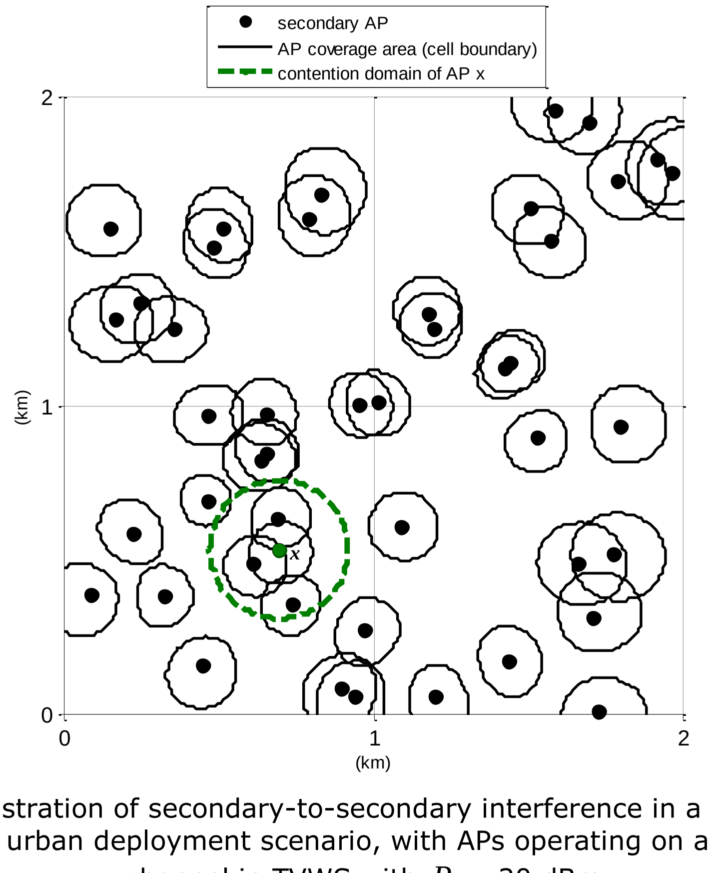


Figure 2-34: Illustration of secondary-to-secondary interference in a Wi-Fi-like network for the outdoor urban deployment scenario, with APs operating on a common 24 MHz channel in TVWS with P_{tx} =20 dBm.

Figure 2-35 and Figure 2-36 present the performance of the Wi-Fi-like secondary system as the secondary AP transmission power is varied, in terms of the maximum (cell-edge) AP coverage range and the downlink throughput for a user randomly located within coverage range, respectively. For the single secondary AP case, Figure 2-35 and Figure 2-36 are plots of maximum cell-edge range $r_{\max}$ vs. secondary transmission power P_{tx} and average rate $\overline{R}$ vs. secondary transmission power P_{tx}, respectively. For this case, it is straightforward to analytically derive the estimated downlink throughput for a user randomly located within the cell of secondary AP as

$$\overline{R} = \sum_{n=1}^{8} W(r_n)\rho(\beta_n), \qquad (2\text{-}12)$$

where $W(r_n)$ is a weighting factor given by the fraction of the coverage area corresponding to rate $\rho(\beta_n)$ (as illustrated in Figure 2-31). For the multiple SU case, Figure 2-35 and Figure 2-36 are plots of $r_{max}^{\boldsymbol{A}}$ vs. P_{tx} and $\overline{R}_{\boldsymbol{A}}$ vs. P_{tx}, respectively; in this case, the coverage area of each AP and the downlink rate for a user within its cell are determined via simulation, as follows. The estimated downlink throughput for a user randomly located within the cell of AP x is given by

$$\overline{R}_x = \frac{1}{|\boldsymbol{U}_x|} \sum_{u \in \boldsymbol{U}_x} R_{u,x}, \qquad (2\text{-}13)$$

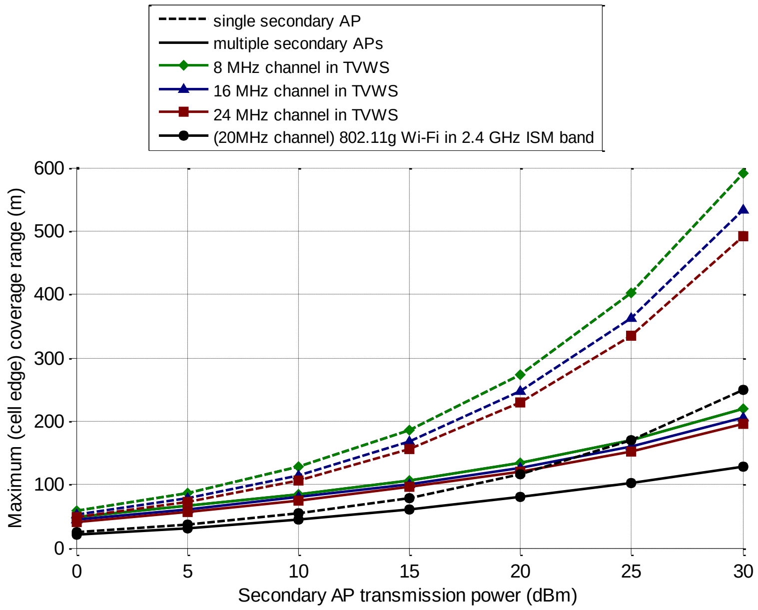
where $R_{u,x}$ is given by (2-7) and $\boldsymbol{U}_x$ is the set of user locations which are covered by AP x (i.e. $u \in \boldsymbol{U}_x$ if $R_{u,x}$>0). Determining the maximum (cell-edge) coverage range of AP x, $r_{\max}$, follows the definition given in Section 2.3.1.1. The typical performance over the network of multiple secondary APs may be characterised by the mean estimated downlink rate over the whole network of $|\boldsymbol{A}|$ APs,

$$\overline{R}_{\boldsymbol{A}} = \frac{1}{|\boldsymbol{A}|} \sum_{x \in \boldsymbol{A}} \overline{R}_x, \qquad (2\text{-}14)$$

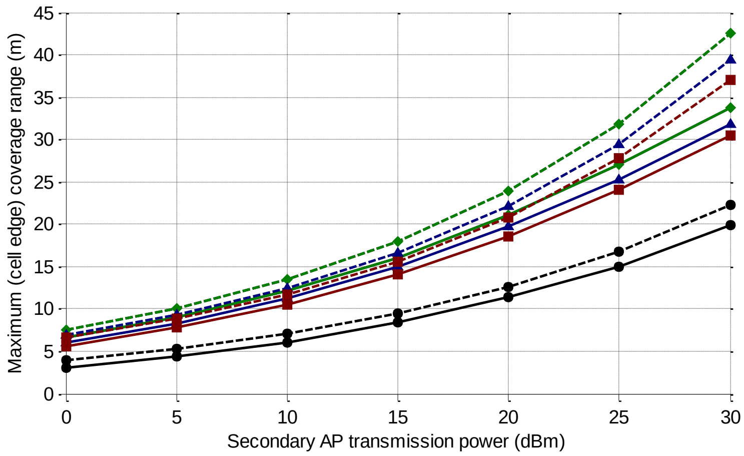
and the mean cell-edge AP coverage range over the network, $r_{max}^{\boldsymbol{A}}$, which is defined analogously.

Figure 2-35 confirms that although a greater AP coverage range is obtained by operating in TVWS compared to IEEE 802.11 Wi-Fi in the ISM band, the extent of the range extension is significantly diminished for multiple co-channel secondary APs, with both of these trends becoming more pronounced as the secondary AP transmission power is increased, for all deployment scenarios. Correspondingly, Figure 2-36 shows that the average estimated downlink throughput is increasingly reduced as the secondary AP transmission power is increased, precisely because of larger and thus increasingly overlapping contention domains.

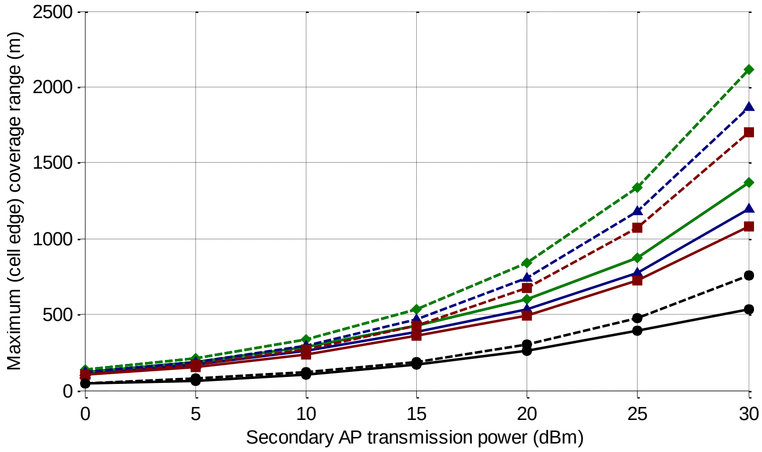
In summary, our analysis has confirmed that operating a Wi-Fi-like secondary network in TVWS has favourable characteristics such as enabling an extended coverage range for a given power budget, especially for the indoor deployment scenario. However, our preliminary analysis of the multiple AP scenario has shown that it is crucial to properly evaluate the effect of multiple SU interference on the performance of the system. We plan to extend the preliminary analysis presented here in [D5.3], by incorporating actual TVWS channel availability estimates (such that different APs select one of a set of available TV channels rather than all necessarily operating on the same TV channel) and examining the resulting aggregate secondary-to-primary interference, in order to refine our estimates of the realistically achievable rate and range of a Wi-Fi-like secondary network operating in TVWS.



(a)



(b)



(c)

Figure 2-35: Maximum coverage range vs. secondary transmission power for different deployment scenarios; (a) outdoor urban, (b) indoor urban, (c) outdoor rural.

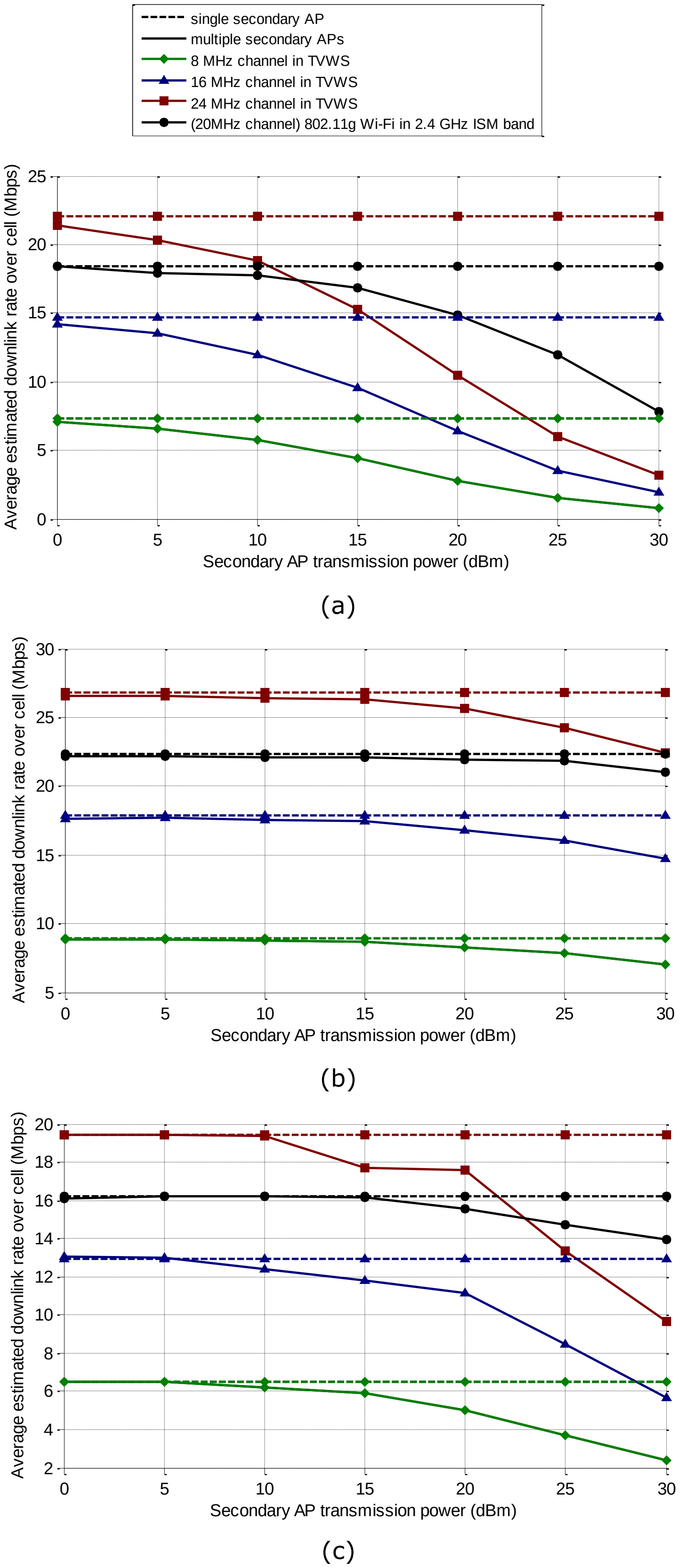


Figure 2-36: Average downlink rate over AP's cell vs. secondary transmission power for different deployment scenarios; (a) outdoor urban, (b) indoor urban, (c) outdoor rural.

2.3.2 Assessment of TVWS availability for a Wi-Fi-like secondary system: a case study in Macedonia

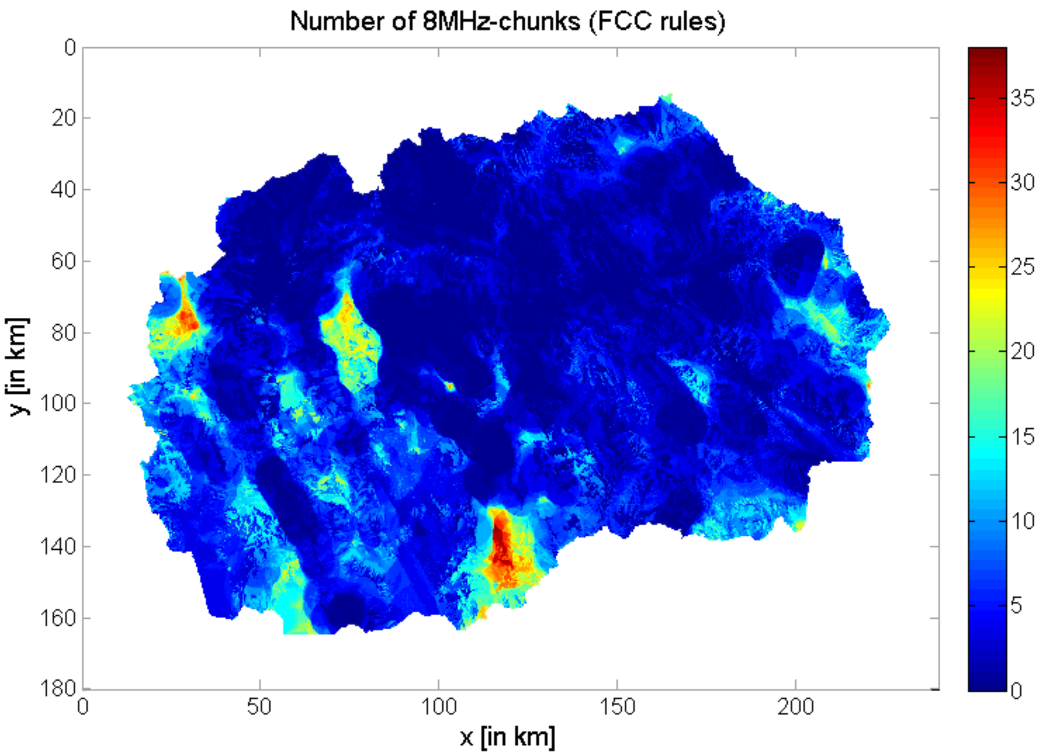
This section presents a countrywide assessment of TVWS availability for a Wi-Fi-like SU, using the Republic of Macedonia as one of our example study areas. As the current Wi-Fi communication systems typically utilize 20 MHz channels, the first step is to investigate the presence of available frequency chunks (multiple consecutive TV channels) within the UHF band for every pixel of the study area. Each pixel represents 120m x 120m of the real terrain. According to the FCC rules, an Nx8 MHz frequency chunk is considered to be available at a certain location, if there are N consecutive TV channels for which the pixel is out of the TV coverage and co-channel protection area (in this case defined according to the FCC rules for unlicensed device with maxEIRP of 20 dBm and antenna height less than 3m). Additionally, the pixel needs to be out of the adjacent channel protection zone for the ±1 adjacent TV channels of the Nx8 MHz chunk where the WSD will operate. On the other hand, ECC rules require calculating the maximum tolerable WSD EIRP for each pixel. For this purpose the analysis uses the reference geometry for adjacent channel situations assuming a portable WSD [ECC159] and protection of ±10 adjacent TV channels. In this case, an Nx8 MHz chunk is available if the pixel is allowed with maxEIRP equal or higher than 20 dBm for all N consecutive TV channels.

Table 2-8 shows the percentage of the territory with a non-zero number of available frequency chunks, considering different values of TV channels per chunk (N). The values in the table reveal that there is a scarce availability of locations in Macedonia where the secondary system can utilize 24 MHz channels (or wider). Additional investigation has revealed that these few locations are situated in highly remote rural places with low population densities.

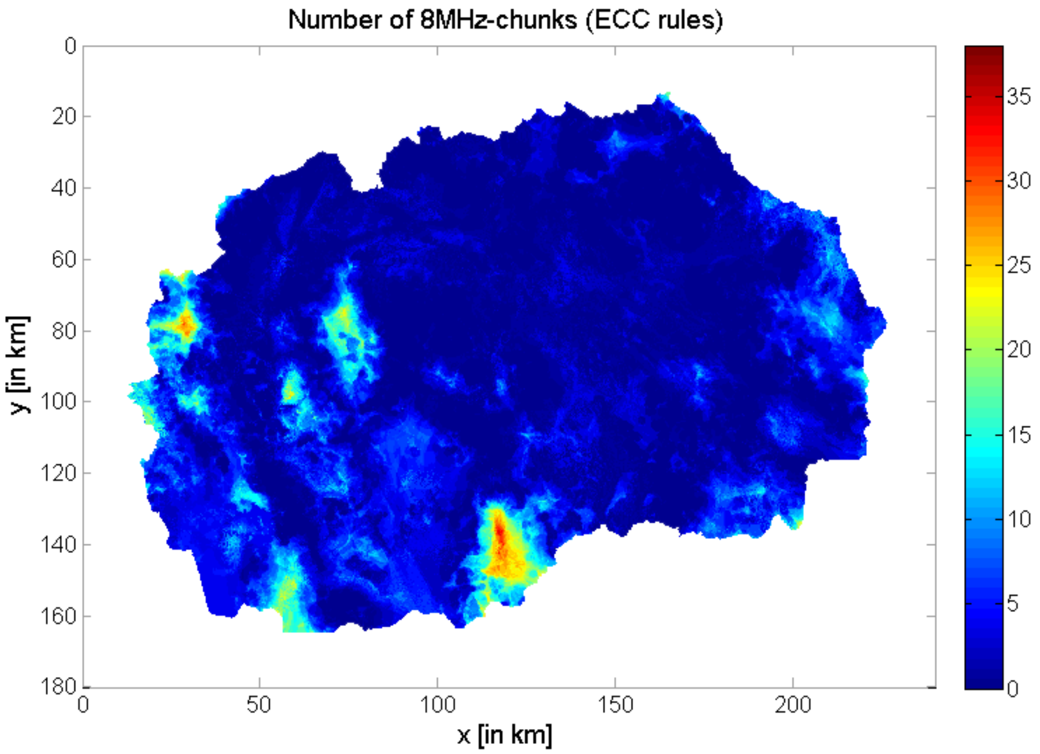
In the following we investigate the usage of TVWS by Wi-Fi-like secondary systems that utilize 8 MHz or 16 MHz channels. Figure 2-37(a) and Figure 2-37(b) show that such TVWS chunks are almost uniformly distributed throughout the country. The figures present the case of 8 MHz channels when FCC and ECC rules are applied for protection of the DTT system. The maps, which present the 16 MHz chunks distribution throughout the country, are similar to the maps in Figure 2-37, only with lower values for the number of available chunks per pixel. In order to make an appropriate comparison between these two cases, Figure 2-38 shows the histogram of the maximum number of available frequency chunks per pixel over the territory of Macedonia, for all combinations of ruling (FCC or ECC) and channel width (8 or 16 MHz).

Table 2-8: Percentage of the territory of Macedonia where at least one Nx8 MHz TVWS frequency chunk is available.

	N = 1	N = 2	N = 3	N = 4	N = 5
FCC rules	77.1 %	33.2 %	14.9 %	7.9 %	4.3 %
ECC rules	64.7 %	25.8 %	12.4 %	5.4 %	3.0 %



(a)



(b)

Figure 2-37: Number of available 8 MHz channels throughout Macedonia; (a): according to the FCC (b): according to the ECC.

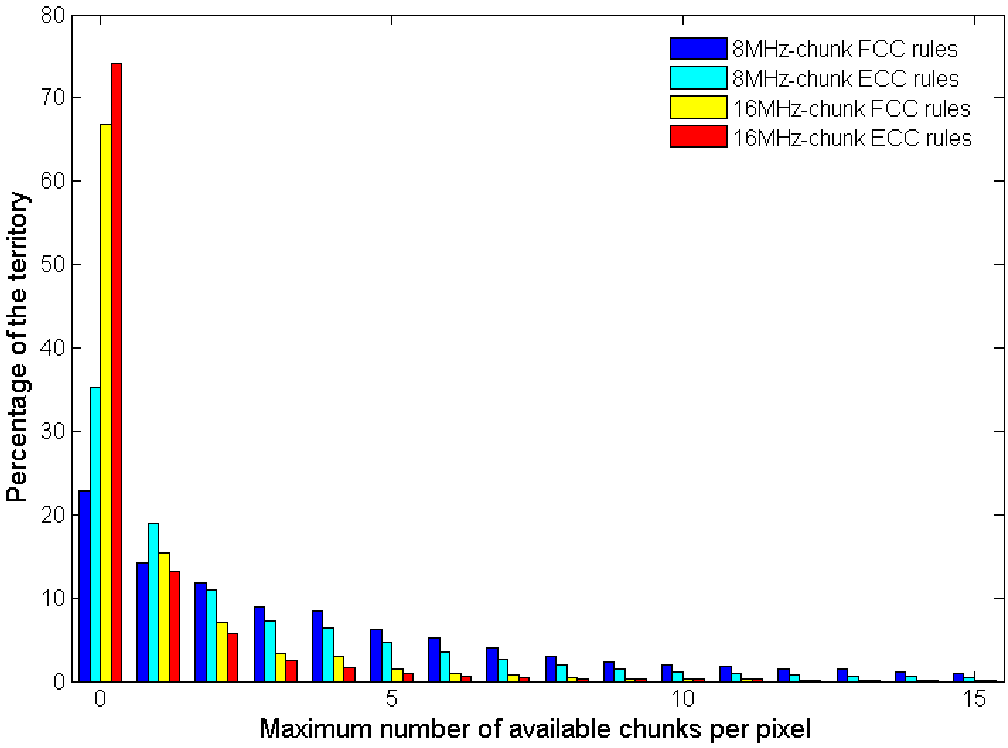


Figure 2-38: Maximum number of available TVWS frequency chunks per pixel as a percentage of the territory of Macedonia.

Table 2-8 shows that generally the case of FCC-based DTT system protection provides the highest coverage of the territory with a non-zero number of available chunks, but Figure 2-38 additionally reveals that the ECC rules result in a higher percentage of the territory with a maximum of one 8 MHz available chunk per pixel.

Here we consider a Wi-Fi-like secondary system operating in a TVWS frequency chunk, consisting of one Wi-Fi-like access point communicating with one Wi-Fi-like user. In particular, we assume the existence of one such secondary link in each available frequency chunk. Because the chunks are non-overlapping, we assume that there is no interference between secondary links.

The aim of the following analysis is to calculate the achievable throughput for each of the secondary links and then to sum the obtained values, providing in such way the total achievable throughput for each pixel. The achievable throughput for each SU is calculated according to the auto-rate function specifications in the existing Wi-Fi IEEE 802.11g standard, by mapping the current SINR into the appropriate value for the link rate. Because the IEEE 802.11g standard assumes 20 MHz channels, we need to scale down the achievable rates to fit the analyzed 8 MHz and 16 MHz channels. Then the achievable rates are additionally corrected according to the [Bia00] and [SL08] taking into account the operation of CSMA/CA protocol on MAC layer. Similarly to [Bia00], the calculation assumes saturation conditions of the link traffic load. The mapping of SINR to data rate is according to Table 2-9. Although we consider only one user connected to each access point, the MAC-layer procedures still reduce the achievable bitrates of the link. The Deliverable D5.3 [D5.3] will treat scenarios with multiple Wi-Fi users per access point, where the reduction of the achievable data rate is expected to be more significant.

As we do not assume any particular indoor scenario geometry (walls, access point and user positions), the analysis investigates the achievable throughput taking values for the receiving signal strength of the secondary system as an independent variable. When calculating the SINR, we take *N* as thermal noise at room temperature, and *I* as interference only from the DTT system. The TV signals, which penetrate from the outdoor environment inside the room, are assumed to be reduced by 5 dB as a result of the wall penetration. This very same wall penetration loss is taken into consideration when calculating the influence of the secondary to primary system, i.e. when calculating the number of available frequency chunks per pixel.

As a final result of this analysis we provide the achievable summarized MAC-layer throughput by all independent secondary systems operating in a pixel on different frequency chunks, averaged over the analyzed territory. Figure 2-39 presents the averaged throughput over all pixels with non-zero number of available frequency chunks, i.e. pixels where at least one secondary link can operate. On the other hand, Figure 2-40 averages the throughput for all pixels within the territory of Macedonia, including those with zero throughput.

Table 2-9: Mapping of SINR to MAC layer throughput.

SINR (dB)	21	20	16	12	9	7	5	4
MAC layer throughout (Mbps) for 8 MHz channel	10.24	9.73	8.28	6.32	5.15	3.74	2.94	2.05
MAC layer throughout (Mbps) for 16 MHz channel	20.49	19.46	16.56	12.65	10.30	7.48	5.89	4.11

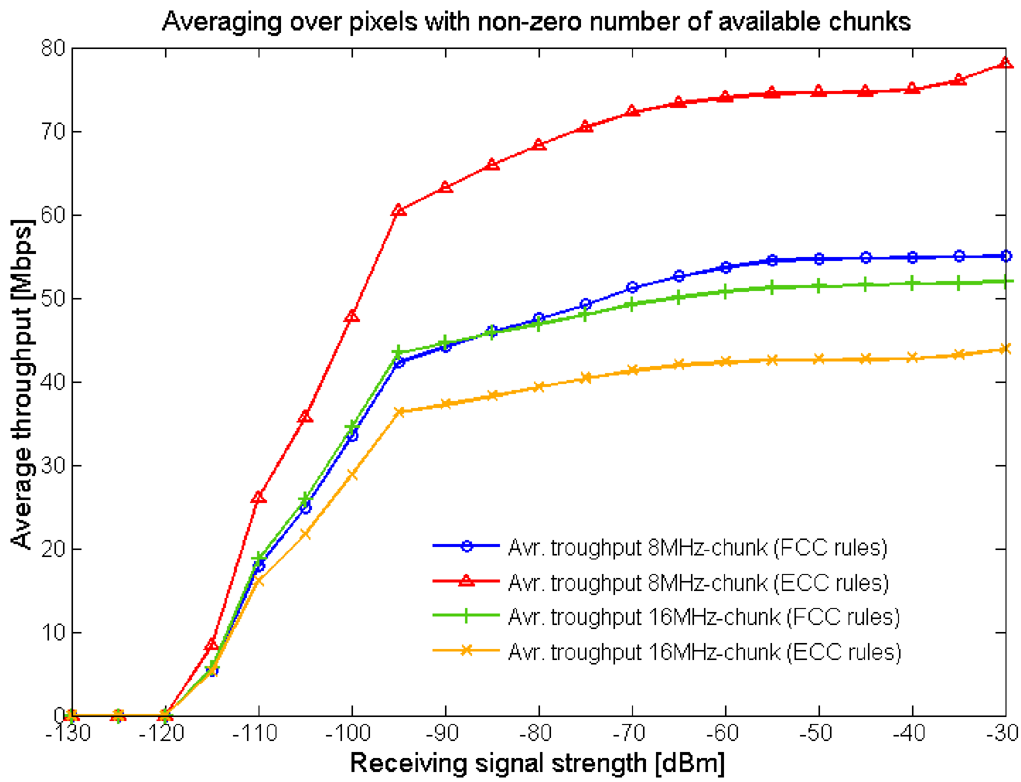


Figure 2-39: Average combined throughput of independent Wi-Fi-like SUs in TVWS in Macedonia (averaged over locations where at least one frequency chunk is available).

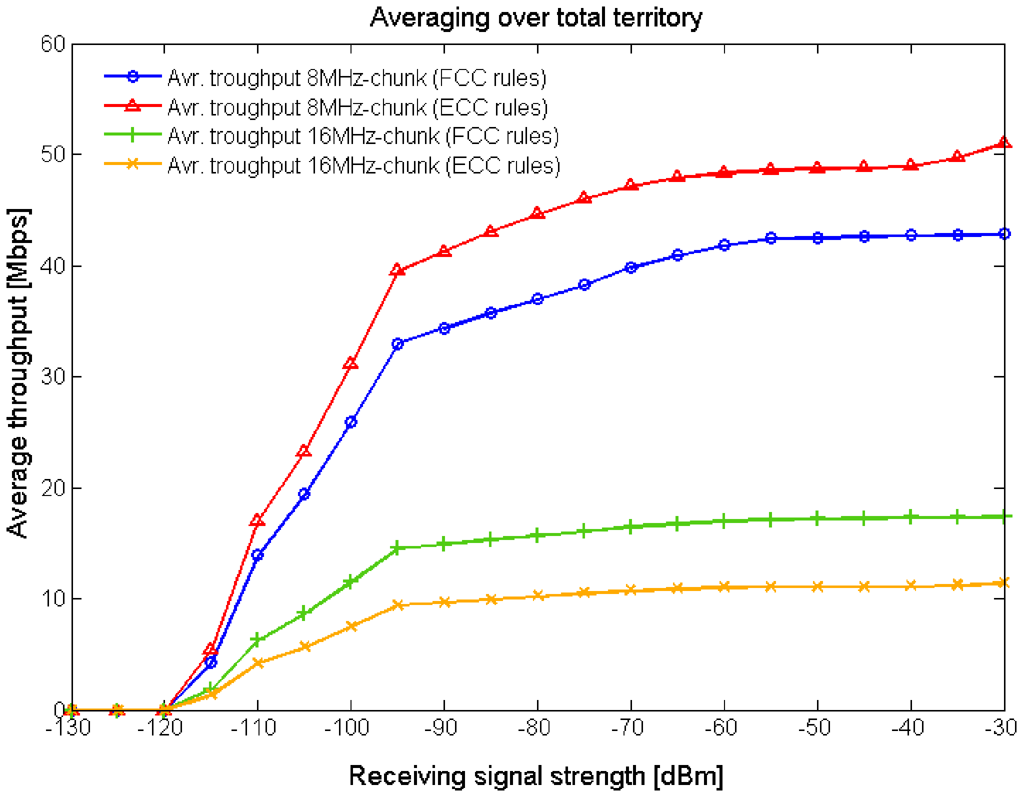


Figure 2-40: Average combined throughput of independent Wi-Fi-like SUs in TVWS in Macedonia (averaged over all locations).

Figure 2-39 shows that when considering only the locations where TVWS is available (at least one frequency chunk), the average throughput per pixel varies between approximately 40 and 75 Mbps in the case of satisfactory received signal strength (between -70 and -30 dBm), depending on the applied primary system protection ruling (FCC or ECC) and the available TVWS utilization (in 8MHz chunks or 16 MHz chunks). Generally when applying the ECC rule-set, the utilization of TVWS in 8 MHz chunks provides much higher average throughput compared to the 16 MHz chunks case. In the FCC case the averaged throughput is almost the same for 8 and 16 MHz chunk utilization. However, the 8 MHz organization of the chunks provides more uniform and wider geographical distribution of the availability, covering almost twice as large a territory when compared to the 16 MHz chunk case (see Table 2-8). This is more obvious when considering Figure 2-40, where the throughput is averaged over all pixels within Macedonia. In this case, the 8 MHz channel usage dominates regarding the averaged throughput values, both for the ECC and FCC rules.

The comparison of the average throughput in the case where 8 MHz chunks are used shows that the ECC case provides higher values compared to the FCC. This can be explained by the existence of higher number of pixels with maximum one available 8 MHz chunk in the ECC case compared to the FCC case (see Figure 2-38). For the other values of maximum number of available chunks per pixel (two or more), FCC performance is better than ECC.

In summary, our analysis suggests that the usage of TVWS according to the ECC rules by a Wi-Fi-like secondary system should be organized by applying 8 MHz secondary system channels, thereby providing the highest TVWS availability coverage throughout the country and the highest average throughput for the secondary system, compared to exploiting wider secondary channel widths. Furthermore, the previous analysis shows that there is a substantial TVWS opportunity which can be exploited by short range Wi-

Fi-like secondary systems, via illustrative case study investigating the TVWS availability in Macedonia. The achievable throughput for Wi-Fi-like secondary systems highly depends on the organization of the detected secondary spectrum. Although the presented case investigates scenario which includes only one SU connected to an access point, the analysis suggests that scenarios which include multiple users are feasible and could provide significant throughput per user.

3 Secondary use of radar and aeronautical spectrum

3.1 Description of primary systems

In this section, we describe two potential primary systems: air traffic control (ATC) radar operating in 2.7-2.9 GHz band and aeronautical distance measuring equipment (DME) operating in 960-1215 MHz band. Their operational characteristics and protection thresholds are explained.

3.1.1 Description of radar

3.1.1.1 Basic characteristics of radar

Radars account for large portion of useful spectrum under 6 GHz. Typical spectrum allocation for radars and their main purposes is shown in Table 3-1. Some parts of 5 GHz (5150-5350 MHz and 5470-5725 MHz) have already been available for RLAN devices since 2003 [EN893]. However, there is a lack of interest considering the low utilization of 5725-5875 MHz ISM band.

Table 3-1: Typical spectrum allocation to radars under 6 GHz.

Spectrum	**Main purpose**
2.7-2.9 GHz	Air traffic control, meteorological aid
2.9-3.1 GHz & 3.5-3.65 GHz	Maritime navigation
5.25-5.85 GHz	Meteorological aid

In this deliverable, we will focus on 2.7-2.9 GHz spectrum since it has preferable propagation characteristics to mobile systems and is adjacent to 2.5-2.7 GHz IMT spectrum. ATC radars are globally in use in 2.7-2.9 GHz. In Europe, meteorological radars are also operating in the same frequency band, but only in southern part [OPERA]. Thus, the following assessment will focus on ATC radars. Note that, in principle, evaluation methodology will be the same for all ground-based radars. Information of ATC radars can be found in [M1464][M2112]. Table 3-2 summarizes the characteristics of the ATC radars operating in 2.7-2.9 GHz. Three representative radars are depicted in an alphabetical order. In this deliverable, we choose radar A as the primary system of interest.

Table 3-2: Characteristics of ATC radars in 2.7-2.9 GHz [M1464].

Parameters	**Radar A**	**Radar B**	**Radar C**
Peak transmit power (dBm)	92	91	74
3 dB receiver bandwidth (MHz)	5	0.653	15
Receiver noise figure (dB)	4.0 (max)	4.0 (max)	3.3
Antenna main beam gain (dBi)	33.5	33.5	34
Antenna azimuthal beamwidth (deg)	1.35	1.3	1.45
Antenna elevation beamwidth (deg)	4.8	4.8	4.8
Antenna horizontal scan rate (deg/s)	75	75	75
Antenna height (m)	8	8	8
Pulse width (μs)	0.6	1.03	1.0, 89
Pulse repetition rate (pps)	973-1040	1059-1172	722-935 (short) 788-1050 (long)
Maximum duty cycle (%)	0.07	0.14	9.34

The ATC radar has two distinct features to be considered in the assessment of spectrum availability. First, it employs an antenna with very sharp azimuthal (horizontal) beam width (see Table 3-2). Second, in many cases, the antenna rotates 360 degrees in a regular and predictable manner. This means that it would be too pessimistic to assume a SU facing the radar main beam all the time. If the SU can exploit the regular temporal behaviour of radar, the availability of sharing radar spectrum will increase. We will investigate this effect in Section 3.2.3. For simplicity, the horizontal antenna pattern of the radar is modelled as follows:

$$G_{rad} = \begin{cases} G_{\max} & \text{if } 0 \le \theta \le \theta_{MB} \\ 0 & \text{otherwise} \end{cases} . \quad (3\text{-}1)$$

A radar antenna has typically a max gain in the range of 30-45 dBi and first side lobe in the range of 10-20 dBi. The above simplification can be compensated by using a larger θ_{MB} value than given in Table 3-2.

3.1.1.2 Protection threshold of radar

Since the ATC radar performs a function concerning safety-of-life, a strict protection rule should be applied to any potential secondary access scheme. The susceptibility of radar to interference is usually defined by interference to noise ratio (INR). The INR of -6 dB is generally accepted by radar systems [M1461]. However, ATC radars may require stricter INR threshold. We use INR of -10 dB as proposed in [M2112]. This is a reasonably conservative value because a measurement result shows that real-life ATC radars can tolerate 3-7 dB higher interference than INR of -10 dB [OFC09].

Due to the random nature of the radio propagation in wireless systems, the interference protection should be considered as a form of probability. We employ the following interference constraint:

$$\Pr\left(I_{su} \ge THR_{rad}\right) \le \beta_{rad} . \quad (3\text{-}2)$$

Notations used above are

I_{su} : received interference power at the radar from the SU,

THR_{rad} : interference threshold value for the radar ($THR_{rad} = I_{tol} - M_{saf}$),

I_{tol} : maximum tolerable interference power derived from INR,

M_{saf} : safety margin additionally imposed on I_{tol} , and

β_{rad} : maximum allowable probability of interference violation.

From the parameters in Table 3-2 (receiver bandwidth and noise sensitivity), we get I_{tol} = -113 dBm for radar A. We consider M_{saf} =16 dB. Regarding M_{saf} , apportionment of 6 dB is assumed, i.e. interference from the considered secondary access accounts for 25% of total interference to the radar. The appropriate value of apportionment margin should be elaborated depending on the extent of PU protection and secondary licensing scheme. Margin of 10 dB for Multiple SUs is also included in M_{saf} . Note that the impact of multiple SUs will be addressed in the deliverable D5.3 [D5.3]. Reasonable value of β_{rad} has not been fully investigated in the literature either. We use β_{rad} =0.001% as used in [M2112], although it may result in too pessimistic result. Practically it means zero percent of violation. Moreover, β_{rad} does not mean the event of radar failure. It rather means the probability that I_{su} exceeds THR_{rad} , which is already conservative.

3.1.2 Description of distance measuring equipment

3.1.2.1 Basic characteristics of distance measuring equipment

DME is a type of secondary radar which measures the slant distance between airborne equipment (interrogator) and a ground station (transponder). DME system operates in the 962-1213 MHz frequency band. The channel bandwidth of DME is 1 MHz, i.e. there are 252 channels in total. Interrogators and transponders are allocated 126 channels each.

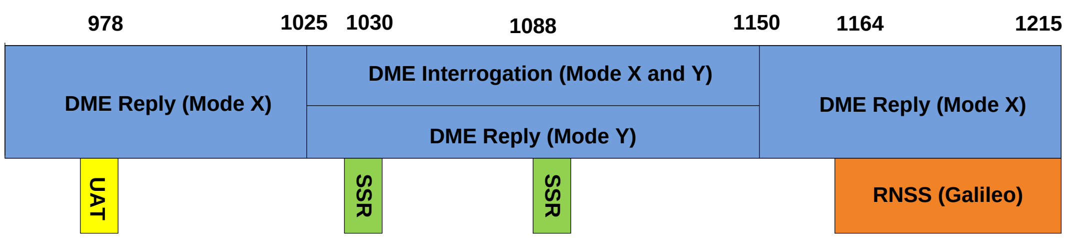


Figure 3-1: Frequency allocation to civil aeronautical systems in 960-1215 MHz.

In Figure 3-1, we show in detail the frequency allocation for the 962-1213 MHz. The upper part of the spectrum, 1164-1215 MHz, is planned to be used by the Galileo, the European radio navigation satellite system (RNSS). Due to the ubiquitous locations of potential receivers and the low receiver sensitivity, this upper part of the spectrum is expected to be infeasible for the secondary access. As depicted in Figure 3-1, some of frequencies are also shared by other aeronautical systems such as secondary surveillance radar (SSR) and universal access transceiver (UAT). In the rest of the band, the most of the spectrum is allocated solely to DME. Thus, the assessment of this sub-section is limited to the portion of spectrum allocated only to the DME system. The bandwidth of interest is then about 180 MHz out of 252 MHz in the frequency band [D5.1][SOZ11].

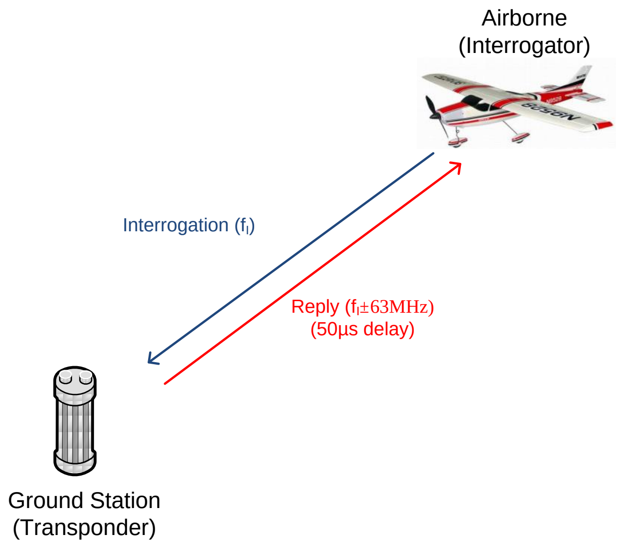


Figure 3-2: Basic operation of DME systems.

Figure 3-2 illustrates the basic working principle of the DME. The airborne equipment sends an interrogation signal to the ground station. Then, the transponder responds on a frequency of +63 or -63 MHz from the interrogation frequency after a delay of 50 micro seconds. The airborne interrogator can determine the distance between the ground transponder and itself based on the round trip delay of the signal. The interrogator and the transponder exchange short Gaussian pulses with duration of 3.6 microseconds [TW07][SHD10].

The transmission power in a DME system can reach up to 300 W for the interrogator and up to 2 kW for the transponder. Receiver sensitivity of the airborne is -83dBm/MHz and of the transponder is -91dBm/MHz. In our analysis, we consider the worst case scenario that the SU is facing the main beam of the DME antenna. The maximum DME antenna gain is 5.4 dBi as specified in Recommendation ITU-R M.1639. In Figure 3-3, a typical DME selectivity mask is shown. For interference received in frequencies with two channels (2 MHz) or larger difference from the central frequency, attenuation of 60dB is applied at the DME receiver.

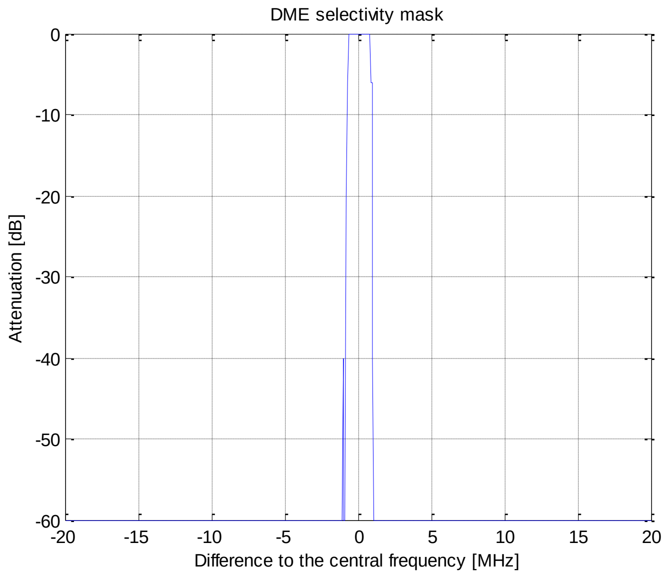


Figure 3-3: DME selectivity mask.

3.1.2.2 Protection threshold of distance measuring equipment

We consider that the primary receiver can tolerate a maximum interference power of A_{thr}. The generated interference that exceeds A_{thr} is considered as harmful interference. Then, the interference of the SU is regulated as follows:

$$\Pr\left(I_{SU} \geq A_{thr}\right) \leq \beta, \quad (3\text{-}3)$$

where I_{SU} is the interference power at the DME from the SU and β is maximum probability of harmful interference. According to the literature, A_{thr} for airborne interrogator is -99 dBm/MHz which specifies a minimum carrier to interference ratio (CIR) of 16 dB given that the receiver sensitivity is -83dBm/MHz [ICA05][LZ07]. For the choice of β and additional margin, refer to Section 3.1.1.2. Interference tolerance for ground stations is not clearly specified in the literature. Thus, we apply the same reasoning for determining the A_{thr} for ground stations. Table 1-3 shows the maximum allowed interference power from SU (A_{thr}) [SOZ11].

Table 3-3: Maximum allowed interference to DME.

Parameters	**Values**
Receiver sensitivity of airborne interrogator	-83 dBm/MHz
Receiver sensitivity of ground transponder	-91 dBm/MHz
Minimum required CIR	16 dB
Safety margin	6 dB
Apportionment of secondary interference	6 dB
A_{thr} for airborne interrogator	-111 dBm/MHz
A_{thr} for ground transponder	-119 dBm/MHz

Notice that the aforementioned thresholds are applied to the co-channel usage. If the SUs employ adjacent DME channels, higher interference is allowed from the SUs because the interference power attenuates as it goes through the spectrum mask of the PU, as shown in Figure 3-3.

These thresholds represent the worst case, i.e. the airplane operates at the maximum DME link range. As the airborne interrogator located in the airplane gets closer to the ground station, it will be able to tolerate more interference. For the case of ground station, the worst case assumption is reasonable because it can serve up to 100 airplanes at the same time, and thus there is a high probability of having an airplane near the maximum range. As for the airborne equipment, A_{thr} can be determined to keep the same CIR. We call it CIR protection rule.

3.2 Secondary sharing with ATC radar in 2.7-2.9 GHz

3.2.1 Secondary use case

3.2.1.1 Description of secondary system

This deliverable considers scenarios where there is only one SU. In the case of radar spectrum, we assume an indoor broadband wireless secondary system with physical layer parameters similar to LTE HeNB [TR921] or Wi-Fi. It is reasonable to assume that physical layer parameters of downlink and uplink are not much different from each other in the indoor broadband wireless system. Moreover, the distance between access point and mobile node in the indoor environment is negligibly short compared to the distance between the radar and the secondary system. Thus, we will not distinguish the downlink and uplink of secondary system. Height of indoor system is usually considered to be 1.5m. We also consider the height of 30m since the demand for secondary access will be higher in urban area with high-rise buildings than rural and sub-urban areas [RK11]. Parameters of the SU are given as follows:

Table 3-4: Parameters of SU.

Parameters	**Secondary user**
Bandwidth (MHz)	20
Transmit power (dBm)	0-30
Antenna gain (dBi)	0
Antenna height (m)	1.5 (below clutter), 30 (above clutter)
Activity ratio (%)	100

3.2.1.2 Protection threshold of secondary user

Similar to the radar, the protection threshold of SU is defined in terms of violation probability:

$$\Pr\left(I_{rad} \geq THR_{su}\right) \leq \beta_{su}\,, \qquad (3\text{-}4)$$

where

I_{rad} is received pulse power at the SU from the radar,

THR_{su} represents interference threshold value for the SU, and

β_{su} is maximum allowable probability of interference violation.

Since radar emits short bursts with low duty ratio, we assume that the impact of interference from radar on the SU performance is negligible. However, the receiver of SU can be saturated if the received radar pulse power is too high. Thus, THR_{su} is considered to account for the receiver saturation. We assume that the saturation begins when the received pulse power is higher than -30 dBm [NTI10]. Then, the protection probability of 1% is employed for β_{su}. Note that the actual impact on the SU receiver needs further investigation. Although radar pulses are short with low duty ratio, the SU reception might be damaged by repetitive pulses if the frame rate of SU is similar to the pulse repetition rate.

3.2.1.3 Opportunity detection mechanism

Due to the safety-of-life operation of ATC radar and its high interference susceptibility, a wrongful transmission of the SU may be detrimental if it happens in the close vicinity of the radar. Thus, we preclude purely sensing-based opportunity detection. Instead, we consider the following two alternatives.

Sharing via geo-location database

The SU is attached to a geo-location database which decides whether the SU can use the frequency band with a certain transmission power. Fading effect on the path between the radar and the SU leads to an uncertainty about the propagation loss. Thus, a margin should be considered to compensate the fading. In this deliverable, we assume that the database has an accurate estimate of median distance-based path loss, but does not have knowledge about shadow fading and fast fading.

Sharing via spectrum sensing aided by database

The receiver of radar is in most cases collocated with the transmitter. This means that the SU can estimate the propagation loss to the radar by sensing the pulse emitted from the radar. This is the main difference between the secondary access to radar and TVWS, because it is not available to know the location of TV receivers. Thus, spectrum sensing is a promising technical means to share the radar spectrum. We assume that the SU can make an accurate estimation of propagation loss in slow time scale, i.e. distance-based path loss and shadow fading, with the help of database information about the radar location, maximum pulse power, antenna gain, and rotating pattern. However, the instantaneous variation of signal power due to fast fading still makes uncertainty in propagation loss to some degree.

3.2.2 **Assessment methodology**

3.2.2.1 Link budget analysis

Let us first consider the interference from the SU to the radar. The received interference power at the radar can be calculated as follows

$$I_{su} = P_{tx,su} + G_{rad} + G_{su} - L_{oth} - FDR_{rad} - PL(d) + X_{shad} + X_{rayl}\,, \tag{3-5}$$

where $P_{tx,su}$ denotes the transmission power of SU. G_{rad} and G_{su} are the antenna gains of the radar and the SU, respectively. L_{oth} represents other losses including insertion losses, polarization mismatch, and wall penetration loss.

Frequency dependent rejection (FDR) is divided into two parts: on-tune rejection (OTR) for on-channel impact and off-frequency rejection (OFR) for additional impact coming from adjacent channel if the interferer and the victim are separated in frequency. When the system is pulsed and the transmit power is based on peak power, OTR is defined in dB as

$$OTR = \max\left[0, 20\log_{10}\left(BW_{tx}/BW_{rx}\right)\right]. \tag{3-6}$$

OFR is a complicated function of the adjacent channel leakage ratio (ACLR) of SU transmitter, adjacent channel selectivity (ACS) of the radar receiver, and the frequency separation between them. It is difficult to specify ACLR and ACS of the SU and radar because different products can have different values. Thus, instead of determining a fixed value of FDR, we investigate the impact of FDR on the performance of SU, i.e. to examine the required separation between radar on SU as a function of FDR.

$PL(d)$ is the path loss when the SU is d km away from the radar. X_{shad} and X_{rayl} denote gains due to shadow fading and Rayleigh fading. We use different probability distributions to model the fading effect for each opportunity detection mechanism.

Sharing via geo-location database

We adopt the approximation used in [HS93] that the composite power level of X_{shad} and X_{rayl} follows a Gaussian distribution in dB domain with standard deviation of σ_{comp}. This is a valid assumption when the standard deviation of shadow fading σ_{shad} is greater than or equal to 6dB. σ_{comp} becomes about 2dB higher than σ_{shad}. Geo-location database is considered to have an accurate estimate of $PL(d)$.

Sharing via spectrum sensing aided by database

Spectrum sensing with the radar information fed by a database enables the SU to have an accurate estimate of $PL(d) + X_{shad}$. Note that the SU cannot separate these two elements in the estimation. The instantaneous power variation due to Rayleigh fading, X_{rayl}, is assumed to follow an exponential distribution with unit mean [ZK01].

The interference from the radar to SU can be calculated in a similar way to the opposite path:

$$I_{rad} = P_{tx,rad} + G_{rad} + G_{su} - L_{oth} - FDR_{su} - PL(d) + X_{shad} + X_{rayl} \,. \quad (3\text{-}7)$$

I_{su} and I_{rad} are put into the constraints Eq.(3-2) and Eq.(3-4) to obtain the required separation between the radar and the SU. For simplicity, we do not consider the power control of the SU. Under the assumption of a certain transmission power, the SU will make an on/off decision of whether to transmit or not. It is mathematically formulated as

$$P_{tx,su} = \begin{cases} P_{tx,su}^{\max} & \text{if } \Pr\left(I_{su} \geq THR_{rad}\right) \leq \beta_{rad} \text{ and } \Pr\left(I_{rad} \geq THR_{su}\right) \leq \beta_{su} \\ 0 & \text{otherwise} \end{cases} , \quad (3\text{-}8)$$

where the parameters are considered in linear scale.

The basic values for the parameters used in the availability assessment are summarized in Table 3-5.

Table 3-5: Basic parameters for assessment.

Parameters	**Basic values**
$P_{tx,su}^{\max}$ (dBm)	10
$P_{tx,rad}$ (dBm)	92
G_{rad} (dBi)	33.5 (main beam) 0 (side lobe)
G_{su} (dBi)	0
Insertion loss for radar (dB)	2
Insertion loss for SU (dB)	0
Polarization mismatch (dB)	3
Wall penetration loss (dB)	5
OTR for radar (dB)	12.04
OTR for SU (dB)	0
σ_{shad} (dB)	8
σ_{comp} (dB)	11

3.2.2.2 Performance metric

The main performance metric for the scenario of the secondary access to radar is the probability that the SU can transmit at a specific location. This will be investigated as a function of FDR and various interference situations, e.g. the SU is facing radar main beam/side lobe and the SU height is below clutter (1.5m)/above clutter (30m).

3.2.3 **Assessment result**

3.2.3.1 Minimum required separation between the radar and the SU

We examine the performance of the opportunity detection mechanisms. Minimum required separations between the radar and the SU under difference detection mechanisms are shown as a function of interference violation probability in Figure 3-4. Note that the minimum required separation is obtained from Eq.(3-8). β_{su} is fixed to 0.01. It is observed in Figure 3-4 that pure database-based mechanism suffers from the lack of shadowing and fast fading information, and thus requires considerable amount of fading margin. The fading margin increases sharply as smaller value of β_{rad} is considered. On the contrary, spectrum sensing aided by database only needs a margin to compensate Rayleigh fading since the SU can estimate the average propagation loss (distance-based path loss and shadow fading) by averaging the received pulse power over time. The availability by the sensing method does not show a dramatic change with the varying β_{rad}. From Figure 3-4, we can conclude that the sensing with database gives significantly higher availability to the SU than pure database-based detection under the assumptions in Section 3.2.1.3. Therefore, we will show the results for the sensing with database hereafter.

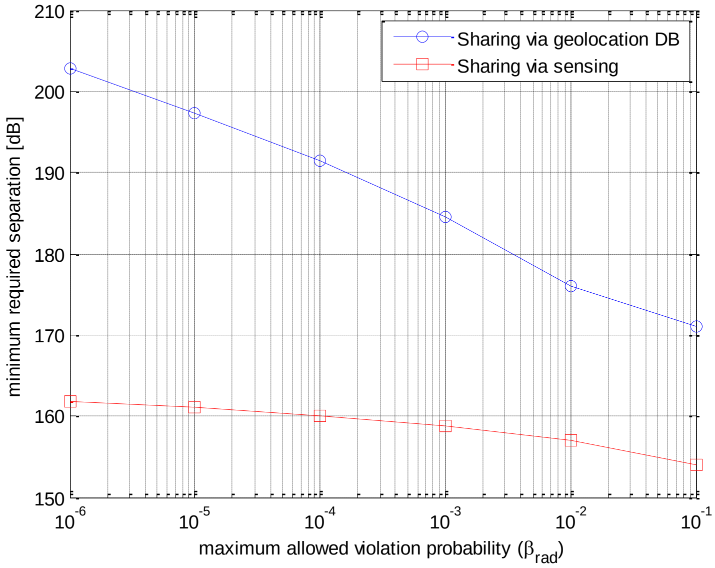


Figure 3-4: Performance of opportunity detection mechanisms.

When the SU has an access to adjacent channel of radar, FDR plays an important role for the availability of the secondary use. Figure 3-5 illustrates the combined impact of FDRs (radar receiver and SU receiver) on the minimum required separation. It shows that the required separation is dominated by the receiver with inferior FDR. For example, the separation of 153 dB is needed between the radar and the SU when FDR of radar receiver is 20 dB even if FDR of SU is as good as 70 dB. The figure also shows that the availability increases significantly as the FDR of the receivers improves. The needed separation is only 102 dB if both the radar and the SU have the FDR of 70 dB.

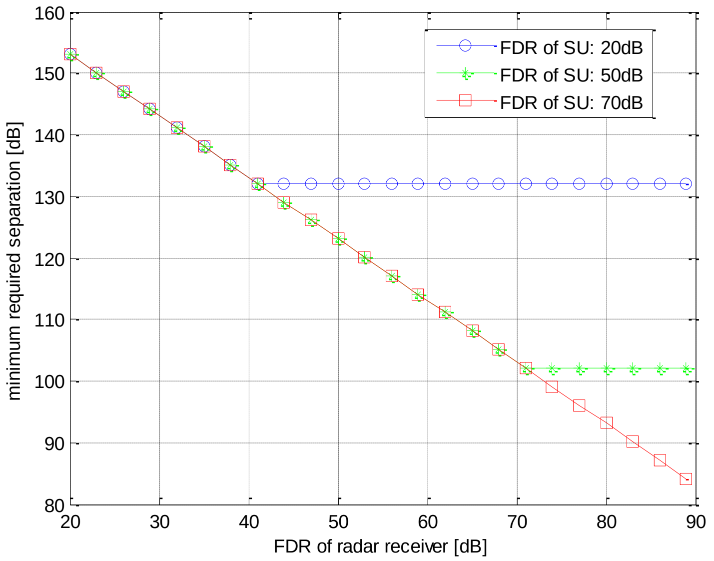


Figure 3-5: Performance of adjacent channel sharing.

3.2.3.2 "Virtual" availability in Stockholm area

Unlike the TVWS scenarios where information about TV transmitters is available in most of European countries, the detailed operational facts of the ATC radars are not readily open to public. Thus, we assume virtual locations of radars in order to investigate the availability of secondary access for a single SU in an inbuilding environment in the city area. It is not likely that radars are located inside urban or dense urban areas. Rather, it will be more reasonable to assume that the ATC radars are located near airports.

Let us consider Stockholm area for the investigation of availability. We will consider Bromma airport as a potential location of the ATC radar. It is chosen as the virtual location of radar because it will give a conservative estimate of availability in Stockholm city center. Note that Bromma is a city airport which is close to residential area and only 7km away from the city center. (In fact, it is known that this airport currently does not employ ATC radar in 2.7-2.9 GHz.)

Figure 3-6 shows the map of area to examine and its terrain height. It shows that Stockholm has a fairly flat terrain. We employ ITU-R P.1546 propagation model that takes into account effect of terrain.

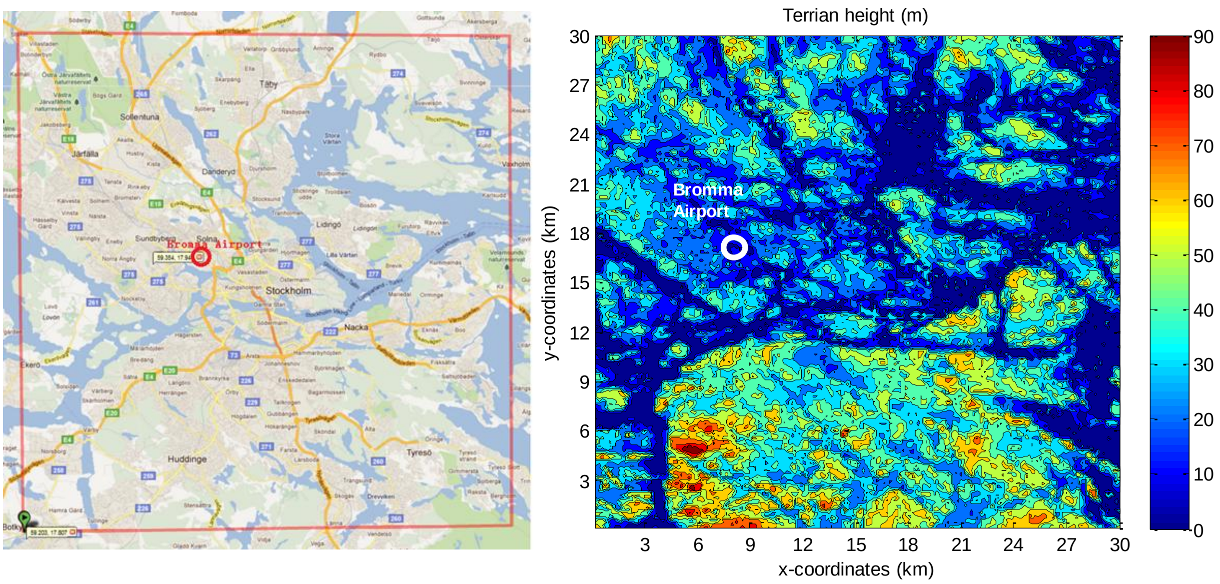


Figure 3-6: Map and terrain information of assessment area
(the left image is taken from Google maps).

First, we consider co-channel secondary access to radar band. Figure 3-7 illustrates the probability that the SU can transmit without interfering/interfered with the radar. Note that the SU can transmit when both interference constraints (interference from SU to radar and interference from radar to SU) are satisfied. Shadow fading of 5.7 dB is considered in the figure. It is observed that the availability of SU depends on area, and thus the SU needs caution when the distance from the radar is less than 20 km.

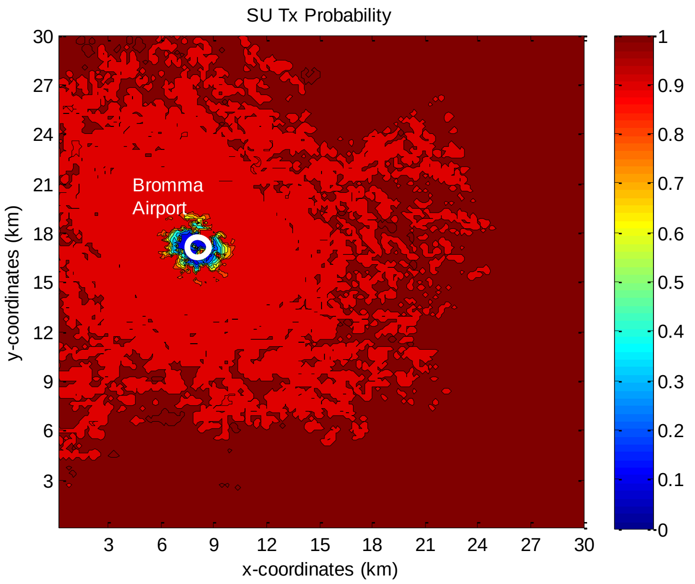


Figure 3-7: Probability of SU transmission for co-channel access (SU height is 1.5m).

It is easy to find high-rise offices and residential buildings in surrounding areas of city centre. Thus, the availability of the SU at the height of 30m is provided in Figure 3-8. It shows that an exclusion area of 10km radius is needed. Rest of areas cannot have full availability either. Thus, the co-channel sharing of radar spectrum may not be viable for the SU in the high-rise building.

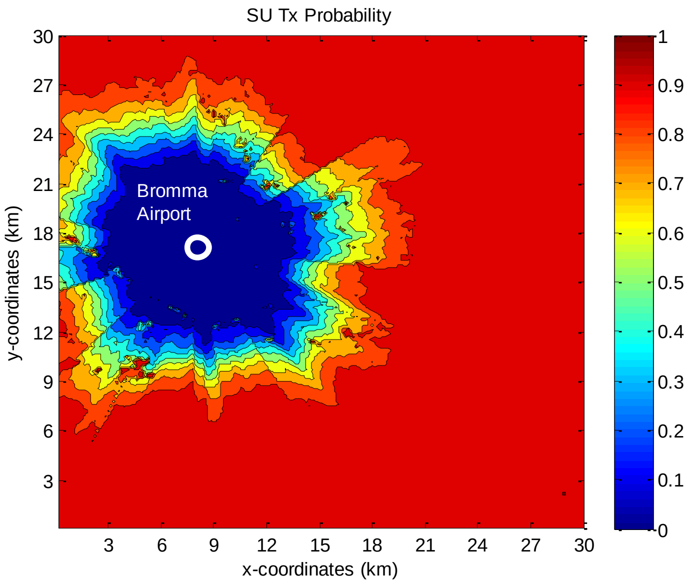


Figure 3-8: Probability of SU transmission for co-channel access (SU height is 30m).

As it has been discussed in Figure 3-5, the use of adjacent channel can increase in the availability of the SU. In Figure 3-9, we assume that FDR of radar and SU receivers are both 50 dB. The secondary access is available even when the SU is close to the radar.

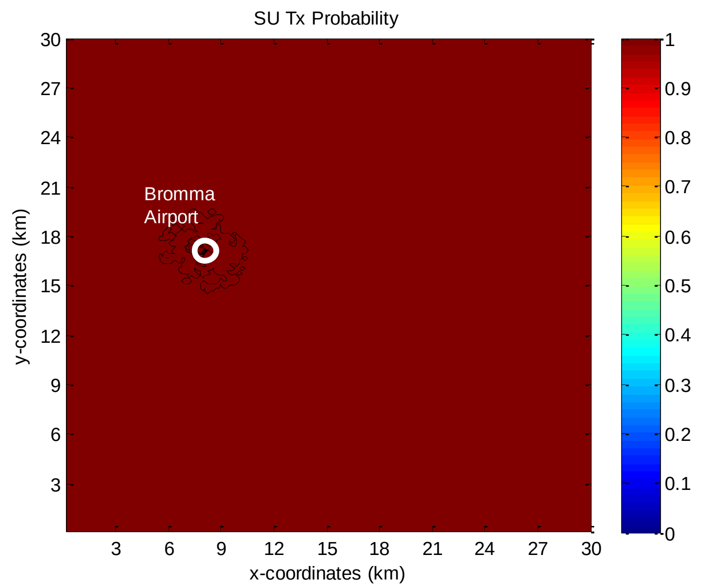


Figure 3-9: Probability of SU transmission for adjacent channel access (SU height is 1.5m and FDR=50dB for both receivers).

So far, we have assumed that the SU is facing the main beam of the radar. This is a rather pessimistic assumption because radar has an antenna of sharp horizontal beam width which is rotating in a regular manner. In [TSZ11], it is argued that the availability of the SU can be improved significant by exploiting the temporal aspect of the radar.

In summary, for the employed assumptions, the secondary access to co-channel needs caution and may not be available to make a business case. When FDR values of radar and SU receivers are in a reasonable range (e.g. 50dB), adjacent channel usage of radar spectrum looks promising. This brings about a substantial opportunity for the secondary access to the radar spectrum since the radars are not heavily allocated in over the large chunk of spectrum, i.e. the available amount of adjacent frequencies is large. Spectrum sensing with the aid of geo-location database is considered to be the method of opportunity detection in the assessment. It should be emphasized that only a single SU was considered in the assessment. The impact of multiple SUs will be investigated thoroughly in the QUASAR deliverable D5.3 [D5.3].

3.3 Secondary sharing with DME in 960-1215 MHz

3.3.1.1 Description of secondary system

We consider a secondary system where Wi-Fi like indoor devices provide short range broadband services. The distance between the mobile station and the access point is negligible compared to the communication range of the DME link. Thus, each Wi-Fi network can be treated as a single SU by assuming the same transmission power for the mobile station and the access point. SU employs OFDM technology; therefore the use of some channels can be avoided. For simplicity, we assume the SU has the same channel bandwidth as the DME channel bandwidth. We also assume fixed transmission power for SU.

3.3.1.2 Secondary access scheme

Ground transponder as primary victim

For this case, we assume that the SU knows its location as well as the location of the primary victim. This assumption is reasonable since ground station locations are known and an approach similar to geo-location database in TV white space can be applied. SU also performs sensing in the channel allocated for PU transmission. Since the SU is connected to a database, the distance-based component of the path loss is assumed to be known as well. We consider a protection rule described in Eq.(3-3) which in this case can be rewritten as follows:

$$\Pr\left(P_{SU} + L + X \geq A_{thr}\right) \leq \beta \, , \qquad (3\text{-}9)$$

where P_{SU} is the transmission power of the SU, L is the distance-based path loss (such as Okumura-Hata), and X is the combined fading effect of the shadowing and multi-path fading. According to the operation of the DME, there is 63 MHz frequency separation between the interrogation and the reply path. The SU will sense the reply path but it will cause interference to the ground station in the interrogation path, as it is illustrated in Figure 3-10.

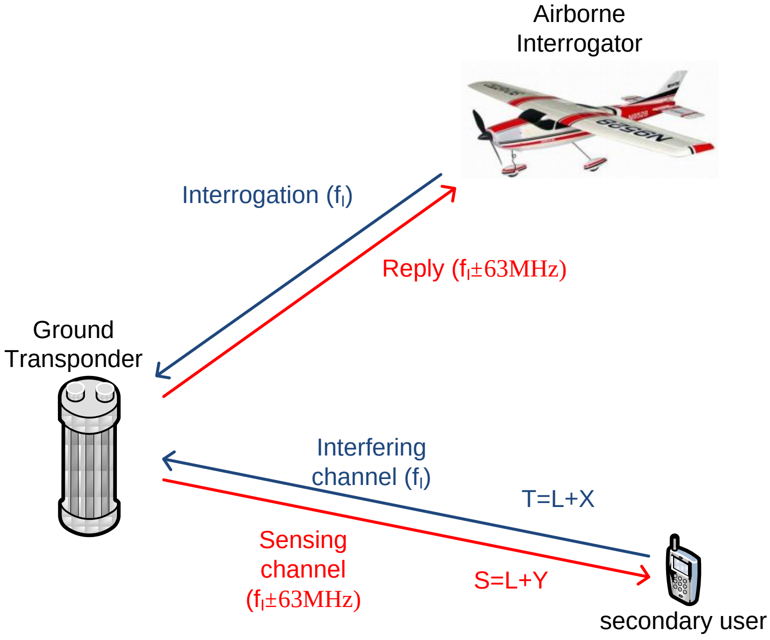


Figure 3-10: Fading uncertainty on the interference from SU to DME ground station.

Since frequency separation between these two paths is large, we cannot assume that the fading in the reply path (X) is full correlated with that in the interrogation path (Y). Depending on the correlation coefficient (ρ) between X and Y, the SU adds a fading margin (M) to account for errors in the fading estimation.

Airborne interrogator as primary victim

For the airborne interrogator, the SU is connected to a real-time database where location of the primary victim is provided. We consider this assumption feasible, since there is already an amateur real-time database which provides location of the airplanes [FR24]. Figure 3-11 shows an example snapshot of the amateur data-base. An official database would provide more precise and reliable information about the current location of the airplanes.

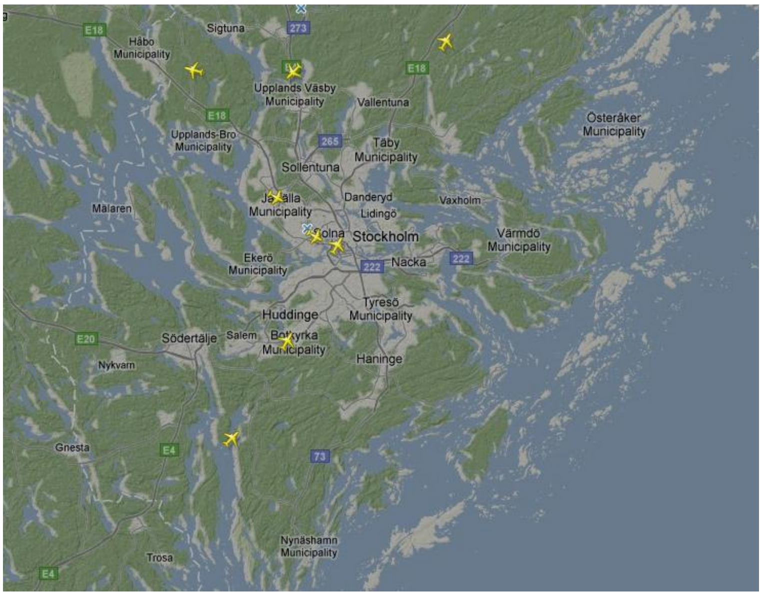


Figure 3-11: Real time map of airplanes near Stockholm. Image taken from [FR24].

For airborne interrogator, we assume free-space propagation model. Thus, fading effect is not considered in the path between the airborne equipment and the SU. However, there is an uncertainty about the location of the PU. Since the location of the PU is varying quickly, SU receives the position of the airborne with an update delay (t_u). According to the value of t_u , SU has an error region for the location of airborne interrogator. If the SU is located inside the error region, it will consider the worst case, i.e. the airplane is exactly above itself. This means the exclusion region around the primary victim (airborne) will be enlarged depending on the value of t_u .

3.3.2 Assessment methodology

Let us first consider the interference from the SU to the DME ground station. Fir simplicity, we assume an ideal secondary transmitter with zero out-of-band interference. The received interference power at the primary victim can be calculated as follows:

$$I_{su} = P_{su} + G_{DME} + G_{su} - L_{oth} - ACS - PL(d) + X_{fading} . \tag{3-10}$$

P_{su} denotes transmission power of SU. G_{DME} and G_{su} is the antenna gain of the DME and the SU, respectively. L_{oth} represents other losses including insertion losses, polarization mismatch, and wall penetration loss. ACS is adjacent channel selectivity which depends on the frequency separation from the central frequency of the DME. $PL(d)$ is the path loss when the SU is d km away from the DME. X_{fading} denotes the combined gain due to shadowing and multi-path fading in the interfering channel. However, SU decision will be based on:

$$\tilde{I}_{su} = P_{su} + G_{DME} + G_{su} - L_{oth} - ACS - PL(d) + Y_{fading} \,. \tag{3-11}$$

Y_{fading} denotes the combined gain due to shadowing and multi-path fading in the sensing channel. Then, the protection rule for the primary system can be expressed as:

$$\Pr\left(I_{su} \geq A_{thr} \left| \tilde{I}_{su} < \tilde{A}_{thr} \right.\right) \leq \beta \,, \tag{3-12}$$

Where

$$\tilde{A}_{thr} = A_{thr} - M(\rho) \,. \tag{3-13}$$

$M(\rho)$ is the margin in dB depending on the correlation coefficient ρ between X and Y. Since the fading components follow Gaussian distributions in dB scale, (3-12) can be expressed as follows:

$$\Pr\left(I_{su} \geq A_{thr} \left| \tilde{I}_{su} < \tilde{A}_{thr} \right.\right) = \left[1 - \Phi(B) \int_{-\infty}^{A} \frac{1}{\sqrt{2\pi}} \Phi\left(\frac{B - \rho x}{\sqrt{1-\rho^2}}\right)\right], \tag{3-14}$$

where

$$A = A_{thr} - \left(P_{su} + G_{DME} + G_{su} - L_{oth} - ACS - PL(d)\right),$$

$$B = \tilde{A}_{thr} - \left(P_{su} + G_{DME} + G_{su} - L_{oth} - ACS - PL(d)\right).$$

From (3-14), $M(\rho)$ can be obtained.

3.3.2.1 Performance metric

The main performance metric for the scenario of the secondary access to DME is the maximum SU transmission power. This will be investigated as a function of correlation coefficient ρ and the update delay t_u. We also show the interference of DME to the SUs.

3.3.3 **Assessment result**

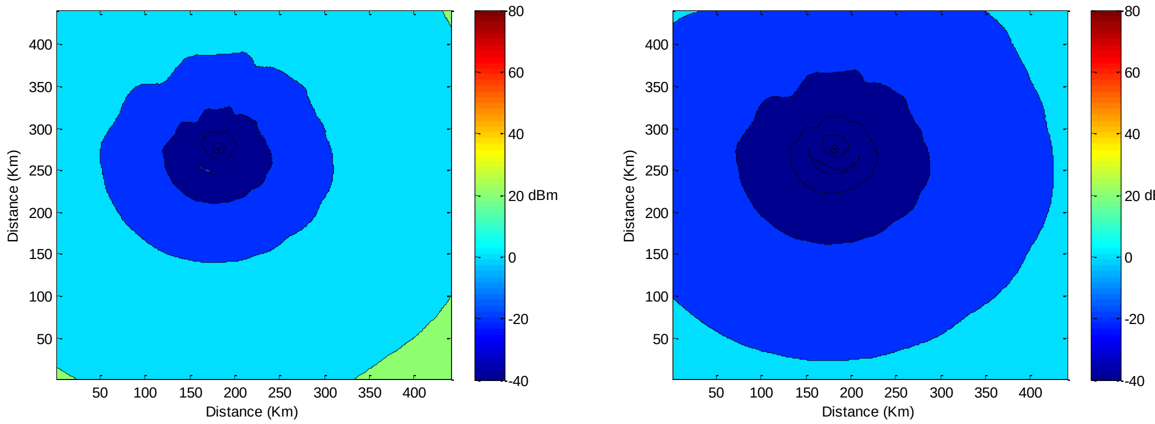
The parameters used for numerical evaluation are summarized in Table 3-6.

Table 3-6: Basic parameters for assessment.

Parameters	**Basic values**
$P_{tx,rad}$ (dBm) - Ground transponder	60
$P_{tx,rad}$ (dBm) - Airborne Interrogator	55
G_{rad} (dBi)	5.4 (main beam)
G_{su} (dBi)	0
Wall penetration and other losses (dB)	10
σ_{fading} (dB)	10

3.3.3.1 Impact of fading uncertainty on the maximum secondary user transmission power (for the case of ground station)

We investigate the impact of fading uncertainty on the maximum permissible SU transmission power. From Figure 3-12, we can observe that when the SU is experiencing uncorrelated fading, the maximum SU transmission power can be reduced up to 15 dB. This would make the SU operation not feasible even for low-power devices in the close proximity of the primary victim. However, in Figure 3-13 we observe that the impact of uncorrelated fading is negligible for ρ >0.3, which means that no margin needs to be applied when calculating the permissible transmission power of the SU.



(a) (b)

Figure 3-12: Maximum transmission power for single SU (Co-channel usage, β =0.001%) (a) perfect correlation (ρ =1), (b) no correlation (ρ =0.01).

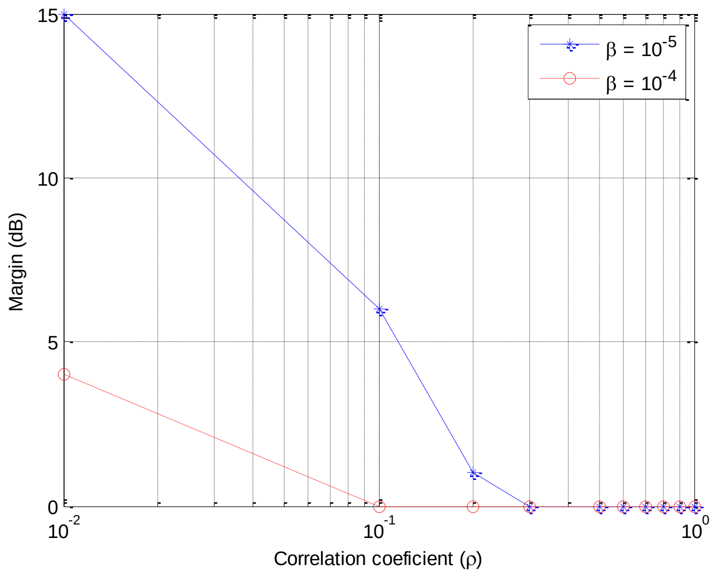


Figure 3-13: Additional margin for different correlation coefficients when β =0.001% and β =0.01%. Single SU is considered.

From Figure 3-13, we can also observe that effect of fading uncertainty will highly depend on β . This means that for loose requirement of β , the effect of fading uncertainty could be neglected when considering single SU. It is important to notice that this evaluation considers only single SU; therefore the impact of fading uncertainty when aggregate interference is considered still remains an open issue.

3.3.3.2 Impact of update delay on the maximum Secondary user transmission power (for the case of airborne equipment)

The impact of t_u on the maximum permissible SU transmission power is shown in Figure 3-14. Below the error region, the SU remains conservative and reduces its transmission power. Note that, even inside the error region, single SU can transmit with transmission power higher than 0 dB. This would mean that low-power indoor operation of single SU is possible in any location, even if information about the location of the primary victim is not accurate.In this experiment, a pessimistic scenario is considered. Then, the airborne is located close to coverage boundary of the transponder, e.g primary link distance (d_{PU}) is 180km, and the aircraft altitude (h) is 1km.

An extreme case is shown in Figure 3-15 where no information about the primary victim (airborne interrogator) location is known to the SU. Only the location of the ground transponder is known. The SU will be conservative and assume that the sky is full of airplanes and the aircraft altitude (h) is 1Km. Under these pessimistic assumptions, maximum permissible SU transmission power is above 0dB and low-power indoor operation would still be possible for single SU.

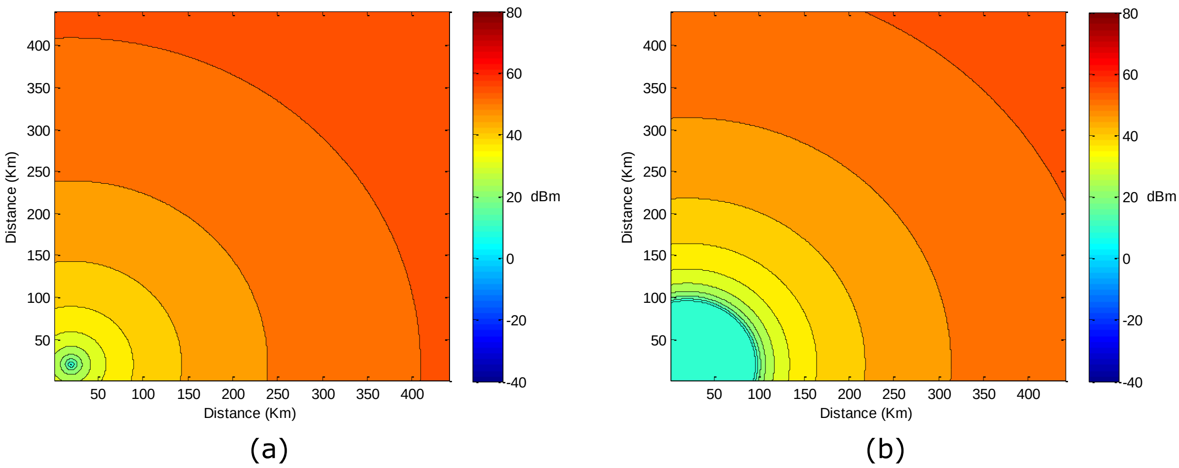


Figure 3-14: Effect of update delay of primary location on the maximum permissible transmission power for single SU when d_{PU} = 180Km and h=1 km (Co-channel usage). (a) t_u = 0mins, (b) t_u = 5mins. CIR protection rule.

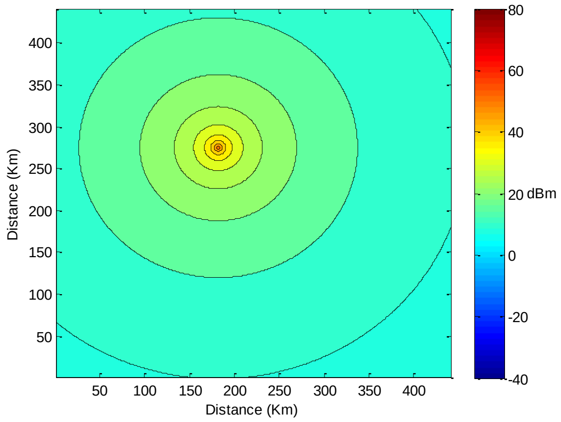


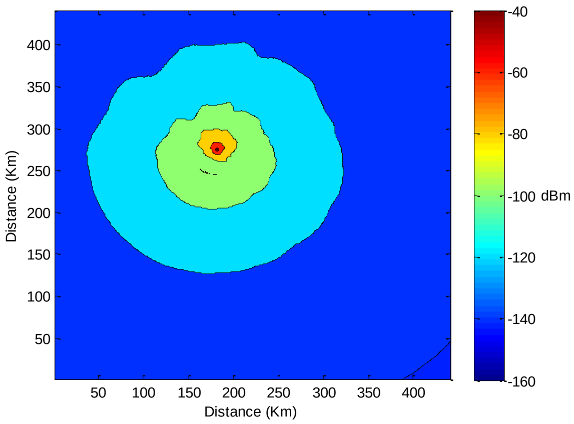
Figure 3-15: Maximum transmission power for single SU when location of the primary victim is unknown and h=1 km (Co-channel usage). CIR protection rule.

Figure 3-14 and Figure 3-15 show the maximum permissible SU power when co-channel secondary usage is considered. For adjacent-channel case, increment of 60dB in the maximum permissible power can be applied for single SU scenario. This is due to the primary receiver selectivity mask shown in Figure 3-3.

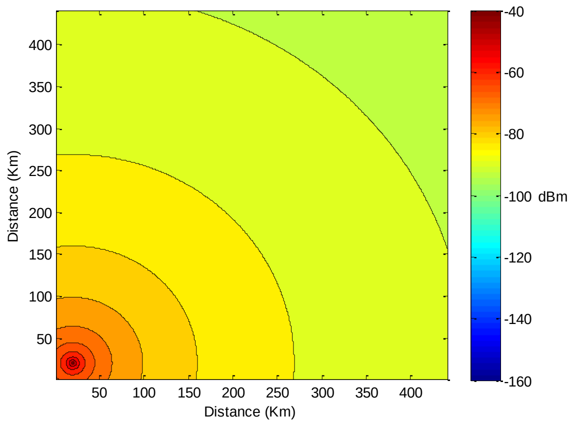
3.3.3.3 Interference from DME to secondary user

In Figure 3-16 we show the interference from the PU to the secondary for ground transponder and airborne interrogator. When the separation distance between SU and the PU is approximately less than 25 km, the SU could experience high levels of interference from the PU (around -70dBm). For larger separation distances, the levels of interference are lower than -110dBm and -90dBm for ground transponder and airborne interrogator, respectively. Note that for the airborne interrogator case, a constant height of 1Km is considered. This is a pessimistic assumption, since aircraft are generally above 10Km height.

Considering noise level of -110dBm/MHz, we show the impact of the interference from the PU for co-channel and adjacent channel in Figure 3-17. For co-channel case, the interference from the airborne interrogator could have an effect on the operation of the SU. For the adjacent channel case with the ACS of 60dB, the interference from PU is negligible for ground transponder and airborne interrogator.

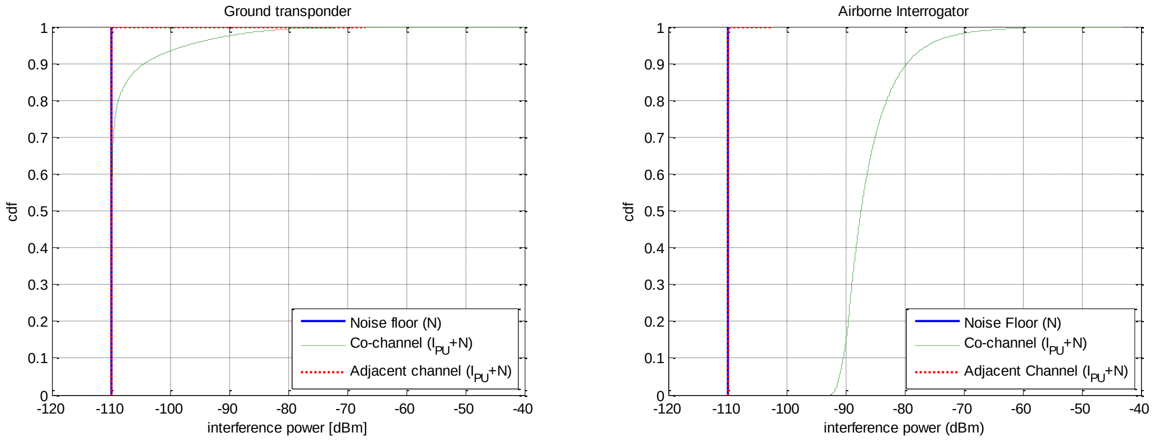


(a)



(b)

Figure 3-16: Interference at the SU for co-channel usage. (a) Ground station. (b) Airborne interrogator with h=1Km.



(a) (b)

Figure 3-17: CDF of the interference from DME to the SU for co-channel and adjacent channel secondary usage. (a) Ground transponder (b) Airborne interrogator with h=1km.

In summary, the availability of secondary access to the DME band depends on the regulatory parameters such as protection threshold, maximum allowed probability of exceeding the threshold, and protective margin. The uncertainty in the propagation information makes the co-channel use difficult. However, adjacent channel usage still looks feasible. Similar to the ATC radar scenario, a considerable opportunity is expected for the low-power indoor devices when it comes to the adjacent channel use of the DME frequency.

4 Conclusion

This deliverable presented the results of spectrum availability assessment for selected QUASAR secondary access scenarios. The basic assessment framework provided in QUASAR deliverable D5.1 has been adopted and refined to capture the characteristics of the specific scenarios. Based on the expectation that wireless and mobile broadband services will comprise the majority of traffic in a near future, a focus has been given to the scenarios related with the mobile broadband services. The following four scenarios were chosen and analyzed in detail:

- *Macro cellular use of TV white spaces*,
- *Wi-Fi-like use of TV white spaces*,
- *Indoor broadband in radar spectrum*, and
- *Indoor broadband in aeronautical spectrum*.

In Section 2, TV white spaces (470-790 MHz) were considered as the primary spectrum. The availability of secondary use by macro-cellular and Wi-Fi-like systems was examined. First, terrestrial digital TV broadcasting system has been reviewed, and the results of TV coverage assessment were illustrated. Then, the availability of macro-cellular deployment was investigated by taking Germany and Finland as examples. Finally, Wi-Fi-like system was considered as the SU, and its potential performance was discussed in terms of capacity and coverage.

Regarding the macro-cellular use of TVWS, it is demonstrated that contiguous coverage is difficult to achieve in urban area. Thus, TVWS can be better utilized as a capacity booster in a certain areas. The result also shows that the current secondary access methods considered by FCC and ECC are not suitable for cellular type of secondary use, which necessitates an improved scheme for permissible power of SU. As for the Wi-Fi-like usage, not only indoor but also limited outdoor coverage is considered. Due to the favourable propagation characteristics of TV broadcasting spectrum, a performance improvement is obtained compared to 2.4 GHz ISM band. However, impact of multiple SUs on secondary-primary and secondary-secondary interference needs to be investigated more carefully.

In Section 3, ATC radars in 2.7-2.9 GHz and aeronautical DME in 960-1215 MHz were considered as primary systems, and then low-power indoor broadband device such as LTE HeNB was chosen as the secondary system. As for the secondary sharing with the radar, it is suggested that spectrum sensing can assist the opportunity detection if the secondary device is fed information about radar such as location, centre frequency, EIRP, and rotation pattern via a database. For the aeronautical spectrum, two different types of primary victims should be considered: ground station and airborne equipment. Practical methods of secondary spectrum access were proposed for each type of primary receiver, and the availability was evaluated in Stockholm area.

It is observed that the co-channel usage of secondary spectrum is challenging due to the large separation distance requirement between the primary victim and secondary transmitter. On the other hand, adjacent channel usage is feasible in most of city areas. The availability of secondary access to radar and aeronautical spectrum depends on the regulatory parameters such as protection threshold, maximum allowed probability of exceeding the threshold, and protective margin. Nonetheless, a substantial opportunity is expected for the secondary access to adjacent channels in urban areas even with the conservative parameters.

It should be emphasized that the assessment works throughout the document were performed under the assumption of a single secondary interferer in the system. This assumption was adopted to investigate the availability of secondary access in a rather simple environment where the focus is given to the modelling of PU, SU, and their relationship. It is essential to extend the assessment to the cases of multiple SUs. This will be done thoroughly in the next QUASAR deliverable D5.3.

Acronyms

Acronym	Meaning
ACIR	Adjacent Channel Interference Ratio
ACLR	Adjacent Channel Leakage Ratio
ACS	Adjacent Channel Selectivity
AP	Access Point
ATC	Air Traffic Control
BER	Bit Error Rate
CDF	Cumulative Distribution Function
CEPT	European Conference of Postal and Telecommunications Administrations
DME	Distance Measuring Equipment
DSO	Digital Switch-Over
DTT	Digital Terrestrial Television
DVB-T	Digital Video Broadcasting-Terrestrial
ECC	Electronic Communications Committee
EIRP	Equivalent Isotropically Radiated Power
FCC	Federal Communications Commission
FDR	Frequency Dependent Rejection
GPR	General protection rule
IF	Intermediate Frequency
INR	Interference to Noise Ratio
ISD	Inter-Site Density
ISM	Industrial, Scientific, and Medical
ITU	International Telecommunication Union
NPR	No-neighbor Protection Rule
OFR	Off-Frequency Rejection
OTR	On-Tune Rejection
QEF	Quasi Error Free
RNSS	Radio Navigation Satellite System
SFN	Single Frequency Network
SINR	Signal-to-Interference-plus-Noise Ratio
SSR	Secondary Surveillance Radar
TVWS	TV White Space
UAT	Universal Access Transceiver
WSD	White Space Device

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