QUASAR Deliverable D5.3

Methods and tools for estimating spectrum availability: case of multiple secondary users

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Editors:	Ki Won Sung (KTH)
Participants:	Andreas Achtzehn (RWTH), Vladimir Atanasovski (UKIM), Torsten Dudda (Ericsson), Liljana Gavrilovska (UKIM), Tim Irnich (Ericsson), Riku Jäntti (Aalto), Jörgen Karlsson (Ericsson), Santosh Kawade (BT), Jussi Kerttula (Aalto), Konstantinos Koufos (Aalto), Pero Latkoski (UKIM), Reihaneh Malekafzaliardakani (Ericsson), Maziar Nekovee (BT), Evanny Obregon (KTH), Marina Petrova (RWTH), Kalle Ruttik (Aalto), Lei Shi (KTH), Ljiljana Simić (RWTH), Ki Won Sung (KTH)
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Abstract

This deliverable presents the results of spectrum availability assessment in the presence of multiple secondary users. Four selected secondary access scenarios are investigated considering macro cellular system, WiFi-like hotspot, and indoor broadband as the secondary use cases. Digital TV, radar, and aeronautical navigation systems are the candidate primary systems. For each scenario, the assessment methodology to account for the multiple secondary users is described. Then, in-depth analysis is performed to examine the impact of the multiple secondary users. Finally,

[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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the availability of the secondary spectrum use is quantified. In TV white spaces, macro cellular deployment turns out to be difficult, whereas WiFi-like usage is more promising. However, the current CSMA/CA is not suitable for high traffic density. In radar and aeronautical spectrum, massive use of low-power indoor broadband looks feasible. However, regulatory rules and parameters in the spectrum, which are critical to the secondary access availability, have not been openly discussed.

Keywords List

Secondary spectrum access, spectrum availability, quantitative assessment, multiple secondary users, aggregate interference, white spaces, digital TV broadcasting, radar, aeronautical navigation, macro cellular system, WiFi-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 in the presence of multiple secondary users. In the previous QUASAR deliverable D5.2, we selected four secondary use scenarios and provided intermediate assessment results by assuming that there is only a single secondary user in the system. As a continuation of D5.2, in-depth analysis of the impact of multiple secondary users is performed in this deliverable.

Detailed secondary access scenarios and the scenario-dependent assessment methods elaborated in D5.2 are adopted here with necessary modifications to take into account multiple secondary users. The impact of aggregate interference is thoroughly analyzed in all scenarios. Mutual interference between secondary users is also investigated in the WiFi-like scenario.

The considered scenarios and the assessment results are summarized as follows:

Macro cellular use of TV white spaces

The possibility of macro cellular deployment in TV white spaces is examined in this scenario. It is observed that the aggregate interference considerably reduces the availability of secondary access opportunities. Contiguous cellular coverage in TV white spaces is difficult to achieve and the use of TV white spaces as a capacity booster in limited local areas looks more plausible. However, this does not realize the benefit of favourable propagation characteristics in TV white spaces. It is also demonstrated that current regulatory approaches considered by FCC and ECC are not suitable for multiple cellular-type secondary users. An improved scheme for permissible secondary power levels is proposed which provides better availability.

WiFi-like use of TV white spaces

Hotspot service in TV white spaces based on WiFi-like technology is considered which covers not only indoor but also limited outdoor. It is demonstrated that the WiFi-like secondary usage achieves large coverage with limited power budget benefitting from the favourable propagation characteristics of digital TV broadcasting spectrum. Therefore, use cases such as community network and outdoor hotspot look promising. However, the self-interference under the CSMA/CA medium access control scheme significantly undermines the performance of the secondary users in the dense deployment of secondary users. It is suggested that the CSMA/CA is not the best access scheme in TV white spaces particularly in high traffic load, which necessitates better access control and channel selection mechanism for this scenario.

Indoor broadband in radar spectrum

Air traffic control (ATC) radars in 2.7-2.9 GHz are considered as the primary system, while low-power devices like LTE HeNBs act as secondary users for indoor broadband. The impact of aggregate interference is shown to be significant in this scenario. Large amount of additional protection margin is required to account for the high density of low-power secondary users. Nevertheless, massive secondary use of radar band is feasible in the spectrum overlapping radar centre frequency with a few kilometres of separation distance. Exploiting the predictable rotation pattern of a radar antenna provides much higher secondary access availability. However, secondary users in high-rise buildings need more separation from the radar, and spectrally non-overlapping use of 2.7-2.9 GHz

spectrum is the only feasible option to them. Overall, there is a substantial opportunity in radar band considering the sparse placement of the radars.

Indoor broadband in aeronautical spectrum

The distance measuring equipment (DME) system for aeronautical navigation in 960-1215 MHz is considered as the primary system in the presence of low-power secondary users suitable to indoor broadband. The impact of aggregate interference is significant, similar to the case of ATC radar. Additional technical challenge comes from the uncertainty in propagation loss estimation due to the difference in estimating and interfering paths. Co-channel access is difficult as a large separation is found to be required between the primary victim and the secondary interferers. However, adjacent channel usage is found feasible in most of areas. The available amount of spectrum is quantified in Germany and Sweden. The results show that large portion of spectrum can be utilized by the secondary users if they have a good capability of spectrum aggregation.

Contributors

First name	Last name	Company	Email
Andreas	Achtzehn	RWTH	aac@inets.rwth-aachen.de
Vladimir	Atanasovski	UKIM	vladimir@feit.ukim.edu.mk
Torsten	Dudda	Ericsson Germany	torsten.dudda@ericsson.com
Liljana	Gavrilovska	UKIM	liljana@feit.ukim.edu.mk
Tim	Irnich	Ericsson Germany	tim.irnich@ericsson.com
Riku	Jäntti	Aalto	riku.jantti@aalto.fi
Jörgen	Karlsson	Ericsson AB	jorgen.s.karlsson@ericsson.com
Santosh	Kawade	BT	santosh.2.kawade@bt.com
Jussi	Kerttula	Aalto	jussi.kerttula@aalto.fi
Konstantinos	Koufos	Aalto	konstantinos.koufos@aalto.fi
Pero	Latkoski	UKIM	pero@feit.ukim.edu.mk
Reihaneh	Malekafzaliardakani	Ericsson AB	reihaneh.malekafzaliardakani@ericsson.com
Maziar	Nekovee	BT	maziar.nekovee@bt.com
Evanny	Obregon	KTH	ecog@kth.se
Marina	Petrova	RWTH	mpe@inets.rwth-aachen.de
Kalle	Ruttik	Aalto	kale.ruttik@aalto.fi
Lei	Shi	KTH	lshi@kth.se
Ljiljana	Simić	RWTH	lsi@inets.rwth-aachen.de
Ki Won	Sung	KTH	sungkw@kth.se

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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 is there a real opportunity for secondary access? The EU FP7 project QUASAR [1] 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 [2]. The basic methodology and results have been elaborated in the deliverable D5.2, where four detailed secondary use scenarios were selected, and assessment methods were refined and fine-tuned in order to account for the specific aspects of each scenario [3]. The results provided in D5.2 are intermediate in the sense that only a single secondary user was considered.

1.1 Scope of D5.3

In this deliverable, the impact of multiple secondary users is thoroughly investigated for the scenarios chosen in D5.2. Therefore, this deliverable can be regarded as a natural extension of D5.2. However, it should be emphasized that this is not a minor extension, since it is an immense challenge to investigate the cases of multiple secondary users.

It is known from [2] that the assessment requires detailed secondary usage scenarios, i.e. primary system and spectrum, secondary system, access and sharing scheme, and geographical area. In [3], four broadband-related scenarios have been described in detail. The same scenarios are considered in this deliverable with appropriate changes to take multiple secondary users into account. The chosen scenarios are as follows:

- *Macro cellular use of TV white spaces*
- *WiFi-like use of TV white spaces*
- *Indoor broadband in radar spectrum*
- *Indoor broadband in aeronautical spectrum*.

The first two scenarios consider options for secondary use of TV white spaces. They consider different secondary systems, macro cellular and WiFi-like systems. The latter scenarios target the frequency 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 D5.3

The remainder of the deliverable has the following structure: Section 2 addresses the assessment of the first scenario: macro cellular use of TV white spaces. In Section 3, WiFi-like systems for indoor and hotspot services are assessed as a potential secondary system in TV white spaces. Indoor broadband usage of 2.7-2.9 GHz is investigated in Section 4, where air traffic control radar is considered as the primary system. In Section 5, a similar type of indoor broadband service is examined in 960-1215 MHz where distance measuring equipment for aeronautical navigation is the primary system. Finally, Section 6 concludes the deliverable by emphasizing the main findings from the assessments.

2 Macro cellular system as secondary user

Cellular secondary use of TVWS was studied previously in D5.2 section 2.2 [3]. In this following section that is continued by taking the true nature of cellular system with intra-system self-interference better into account. In the first part the capacity of cellular TVWS network is estimated in Germany by setting coverage constraints. Two use-cases are studied: system that only uses TVWS resources and system that uses TVWS to offload traffic. In the second part two different optimization strategies for allocating available resources in TVWS cellular network are studied in Germany. In the third part cellular system capacity is estimated in Finland by using different secondary power allocation methods without coverage constraints. It should be noted that the deployment of the TV broadcast network in Germany and Finland are very different. In Germany each state has its own broadcast network and many regions are covered by multiple networks while in Finland the broadcast network is built only for coverage.

2.1 Capacity estimation of cellular networks in TVWS with coverage constraints

In a cellular system the same frequency channel is typically used in all cells simultaneously, which creates interference among neighbouring cells. For the case of cellular systems deployed in TVWS, this intra-system interference represents an additional constraint on top of the power limitations for protecting the primary user, and the interference from TV transmitters, which WSDs have to accept due to their regulatory status. In this section the achievable performance of cellular networks is studied with emphasis on accurately modelling the intra-system interference arising from simultaneous use by multiple WSDs on a given TV channel. In addition, it is considered that – although from regulatory point of view every TV channel that allows non-zero transmit power for WSDs can be used by WSDs – in practice the large variations of allowed EIRP levels and interference from TV transmitters imply that not every theoretically available channel is actually sufficiently useful to justify its usage. Therefore, in order to estimate the amount and utility of radio spectrum that provides sufficient utility for cellular networks, corresponding channel availability criteria, based on the use case's requirements, are applied and the resulting availability after this down-selection is determined.

In this section, we will discuss the use-cases of a standalone macro cellular LTE network that solely uses TVWS as radio resources, and additionally, we will investigate the use-case of an 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. From a previous analysis, TV reception location probability, coverage area affiliation, maximum permitted WSD EIRP and aggregated TV interference power are known for each pixel. Additionally, population density data are known per pixel.

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.

2.1.1 Simulator setup and evaluation methodology

With a system level LTE simulator, we would like to obtain the user-bit-rate distribution for a cell of the LTE network. 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 separately for each UHF channel considered in the analysis.

The used simulator is based on the Monte Carlo approach and evaluates statistics of performance metrics for an LTE network on a system level. For the underlying link layer, realistic performance models are employed that are based on measurements and thus include the effects of many real world imperfections in the RF chain that are typically not included in simulated link layer performance data, allowing a very realistic estimate of the link layer performance in the considered scenario.

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. In this context we apply an automatic adaptation algorithm for the granularity of the covered interference/power grid, so that the introduced quantization error is kept within reasonable bounds (<3dB) by automatically decreasing the spacing between the points in the interference/power plane that are covered by a simulation. To take the local variation of population density, and thus the required inter-site distance (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 2-1.

Table 2-1: 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

For the comparison with LTE network performance in dedicated spectrum, which is needed at some places in our analysis as described below, we additionally need to determine the user-bit-rate distribution of a reference simulation, which is called the “interference-limited case”. Therefore, we simulate in a second run the cellular network with (for a given inter-site density) optimally chosen transmit power and without interference from the DVB-T network. The (self-) interference limited case is defined by the point where the throughput goes into saturation when gradually increasing the transmit power. Eventually the throughput distribution provided by this case is taken as the reference performance of an LTE system in dedicated spectrum.

In addition to these deliberations we assumed a maximum (conducted) transmit power of 23dBm for UEs and 60dBm for eNodeBs.

2.1.2 **Use case 1: stand-alone 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 is assumed to be limited by economic constraints. The maximum allowed inter-site density (ISD) in a pixel is chosen according to the population density in that pixel, see Table 2-1 above.

Essential for a newly built cellular network is 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 achievable cell edge (CE) user-bit-rate[2] is higher than 10 % (or 50 %) of the achievable cell edge user-bit-rate in the interference-limited case, the coverage is considered contiguous. As explained above, the interference-limited case is

[2] Defined as the 5th percentile of the achievable user bit rate distribution. Achievable user bit rate is the SINR directly mapped onto the assumed link layer performance model, i.e. without layer 2 protocol overhead and without consideration of cell capacity sharing between active users.

defined as the performance of the system with given ISD with optimally dimensioned BS transmit 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 for each pixel.

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 considered by including a 3dB interference margin that was subtracted from the overall maximum permitted WSD EIRP. This is the currently foreseen concept for managing aggregate interference in both, CEPT ECC SE43 [5] and Ofcom approaches, respectively. Furthermore, we assume an ideal carrier aggregation capability in the WSD, so we assume that the WSD RF supports the entire 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.

For simplicity we assume that each considered pixel is infinitely large so that we can assume homogeneous conditions for the whole LTE network simulation area. The size relations of the pixel and the actual size of the network are hence not considered, neither are overlapping effects to other pixels. Only statistical values characterizing the cellular network performance are determined.

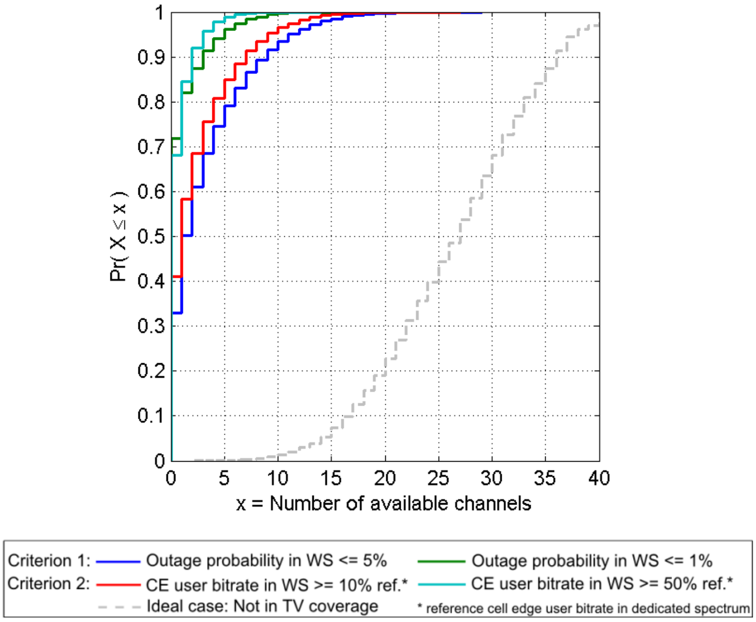


Figure 2-1: Standalone: Number of available channels according to use-case criteria.

Figure 2-1 shows the influence of the different criteria on the channel availability. A channel is available for secondary use, if the corresponding criterion is fulfilled. The ideal case describes the criterion of a pixel not belonging to a TV transmitter's coverage area. Since secondary usage is prohibited in coverage areas, the ideal case can be seen as a theoretical 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. For the blue and red graphs, where the outage probability must be lower than 5% and the cell edge user bitrate should be 10% of cell edge user bitrate in dedicated spectrum respectively, we see that for 50% of the locations at least 1 channel fulfils this requirement. In green and cyan, we see the results for the stricter versions of these requirements, where even less channels are available.

In general we can say that a contiguous coverage of the WSD network is only possible in few locations.

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 2-2. 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 0.2, which affects both the achievable bit rate (due to selecting a relatively low intra-system interference level) and the fraction of time the spectrum is being utilized. Shown in the plots is the sum of the cell throughputs of the 40 x 8 MHz UHF channels. In the downlink, we observe a significant reduction compared to the ideal case, where all capacities of channels not in primary coverage areas are summed up. This is not the case for the uplink and it indicates that channel availability according to the criteria is mainly limited by the UL (Recall that the criteria need to be fulfilled by both DL and UL, which results here in the uplink functioning as a limiting factor for the DL sum cell throughput). In general terms, we can say, that 3-5 Mbit/s in DL and 1-2 Mbit/s in UL are available in 50% of the locations for the weakest criterion.

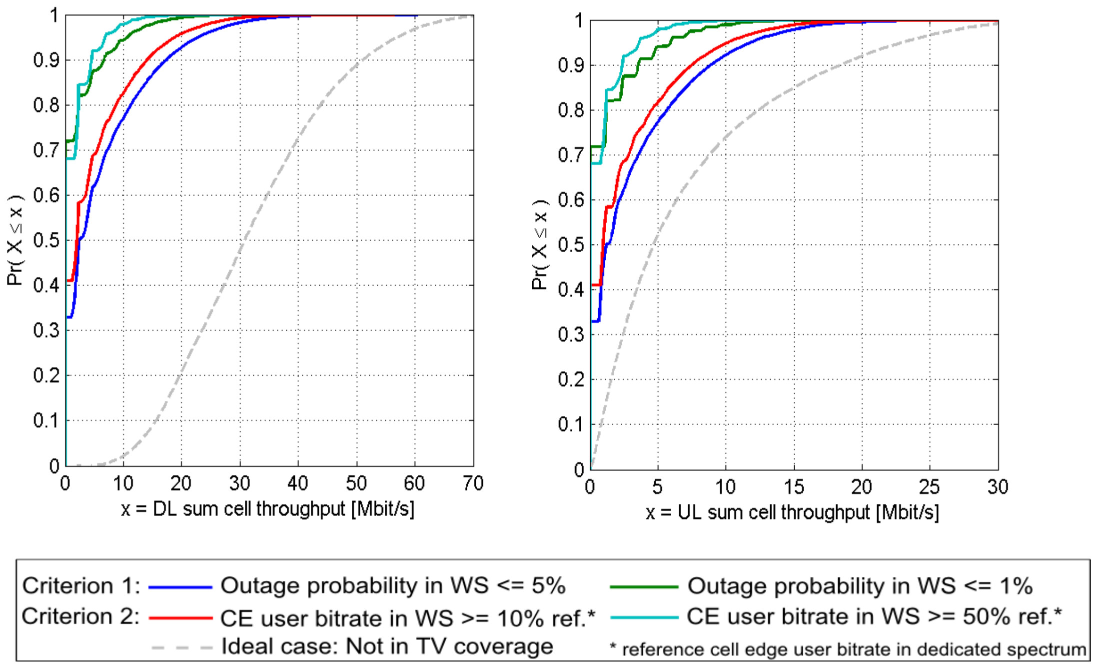


Figure 2-2: Standalone: Available sum cell throughput for DL (left) and UL (right).

Figure 2-3 compares the sum cell throughput using all available TVWS channels with the achievable cell throughput in 100 MHz dedicated spectrum based on our previously introduced reference case. It becomes obvious in the DL (left picture), that WS outperforms 100 MHz dedicated spectrum, if we apply our requirements for contiguous coverage, only in ~3% of locations in Germany. Similar values are observed for the uplink (right picture). In contrast to that, if the throughput of all WS channels, not in TV coverage areas, was summed up, this would be higher than 100MHz dedicated clean throughput in 50% of the locations for the DL, and in UL in 15% of the locations. Overall this indicates that all the channels that are “filtered away” by our channel selection criteria would in fact contribute considerably to the overall TVWS capacity. However, in order to leverage this potential the TVWS network would either have to be deployed with a considerably higher site density (compared to values typical for deployment in dedicated spectrum), or one would have to live with being able to serve only a limited fraction of the actually covered area (i.e. users outside those areas could not be served and would have to fall back to dedicated spectrum).

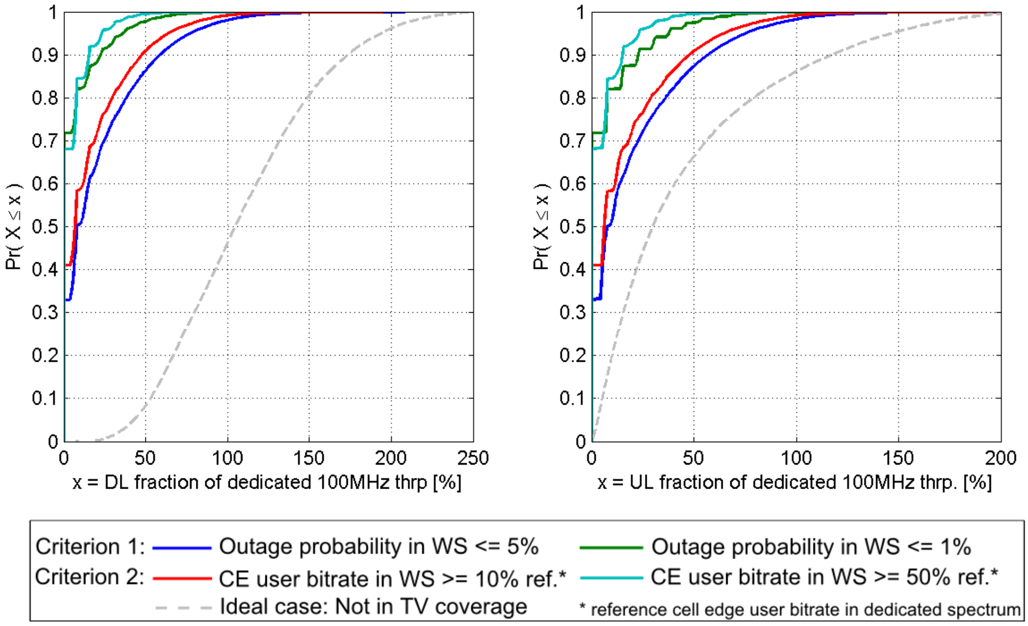


Figure 2-3: Cell throughput using all selected TVWS channels compared with cell throughput using 100 MHz dedicated spectrum for DL (left) and UL (right).

The deliberations above give rise to the question if the performance in the selected channels (which can be considered to be the "best" ones, i.e. least constrained by TX power limitations and TV interference) comes close to the performance that can be achieved in dedicated spectrum (since that is the objective of our channel selection criteria). To this end we have separately, for DL and UL, plotted the relative achievable spectral efficiency in the WS channels which are available according to the requirements. The relative spectral efficiency is the ratio of the cell throughput spectral efficiency in the available WS spectrum to the cell spectral efficiency that is achievable in regular dedicated spectrum. This metric is given on the x-axis in Figure 2-4.

When applying no criteria, we see that the relative spectral efficiencies are quite low, 50% in DL and 15% in UL for the median among the WS locations. The UL performance in WS is far worse, since in the UL receiver, the base station is more exposed to the interference from the TV towers.

If we apply the use case criteria, we see that for 50% of the available White Space, more than 75% of the dedicated performance can be achieved in both DL and UL. This is also shown that the weaker the criterion for availability, the worse the relative spectral efficiency.

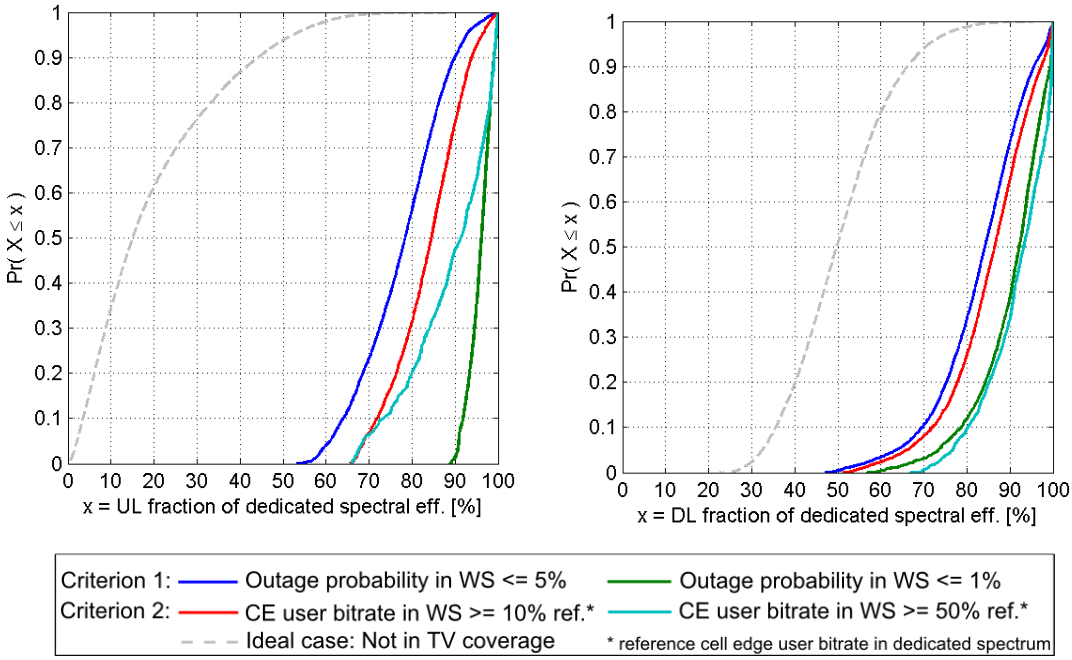


Figure 2-4: Relative spectral efficiency compared to dedicated spectrum.

In our further performance assessment, we analyzed sensitivity of available channels towards the assumed site density. We simulated once more with increased site densities of 50% and 100% and found out that, the availability is still very low and Increasing the site density in all locations leads only to marginally higher availability of channels. The results are shown in Figure 2-5. We can thus conclude that the selected ISD-to-population density mapping does not significantly influence the results and that our conclusions are generally valid.

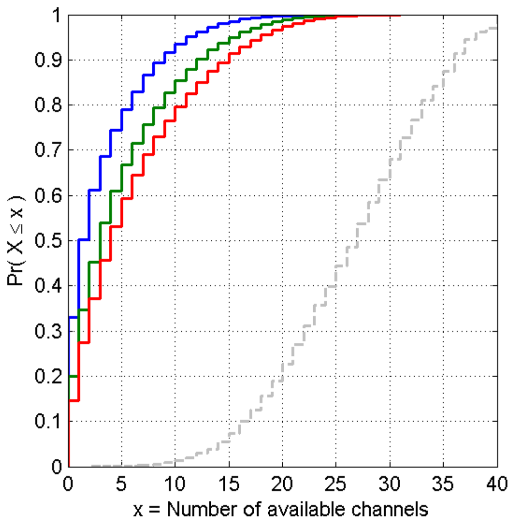


Figure 2-5: Sensitivity of the number of available channels towards the assumed site densities (blue: original assumption, green: 50% more sites, red: 100% more sites).

Finally, for standalone macro cellular network use case, we have assessed the sensitivity of number of available channels towards different cell loads. In all previous evaluations the cell load was always assumed to be 20% fractional load but here we increase it to 80% fractional load. Needless to say that higher cell load increases system internal interference which in turn results in lower WS channel availability, since the channel selection criteria are more difficult to fulfil. Figure 2-6 depicts this result.

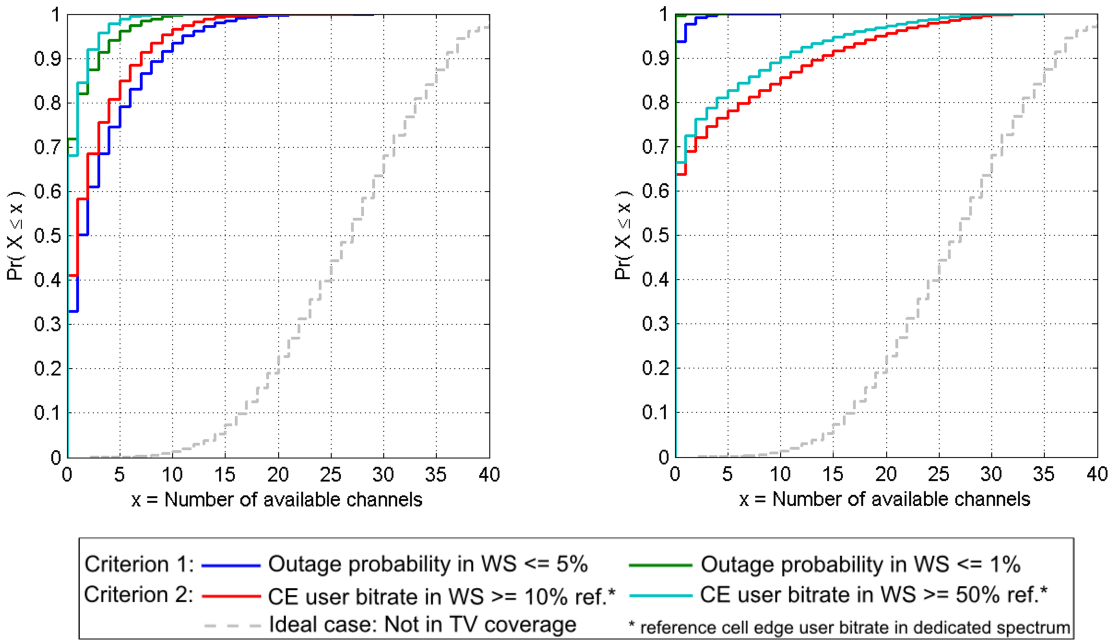


Figure 2-6: Sensitivity of available channels to cell load, Left: 20% fractional load Right: 80% fractional load.

2.1.3 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 using Rel-8 Carrier Aggregation functionality. With the Rel-9 carrier aggregation enhancements and furthermore with the lean carrier concept currently envisaged for Rel-11, this will be further simplified.

We assume here that the extension carriers operated in a given TVWS channel are either pure uplink or pure downlink. Moreover, for the sake of simplicity, we assume that only one secondary user is scheduled per channel at a given time, and thus aggregated interference from multiple users in the same system can be neglected in the UL direction. Interference from multiple secondary systems is accounted for with the 3dB margin introduced in the maximum WSD EIRP calculation as explained above.

The ISD is assumed to be set due to the network planning for the dedicated spectrum the system is based on; here it is chosen according to the population density to ISD mapping of Table 2-1.

As the criterion for channel availability, we define that the average cell spectral efficiency (cell throughput divided by used frequency bandwidth) has to be higher than 25% or 50% of what could be achieved in dedicated spectrum under otherwise equal conditions. As an alternative criterion we consider the median of the user bit rate distribution, which also has to be higher than 25% or 50% of what can be achieved in the dedicated spectrum reference case.

E.g., 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.

It should be mentioned that we evaluate the criteria separately for DL and UL for this use-case, since we assume that each TVWS channel is either used for operating a downlink or uplink extension carrier, respectively. We see that for example if 25% of the cell spectral efficiency as achievable in dedicated spectrum are defined as the requirement for channel availability, in DL in 50% of the locations at least 22 channels would be available, and in UL at least 7. If we formulate the requirements stricter, fewer channels are available.

We see that this use case offers a much higher potential as the standalone network use case because more spectrum is available under the defined requirements, but again the question is what the real value of the channels is that we defined as available. It should be noticed that criteria are overall less stringent than for Standalone use case.

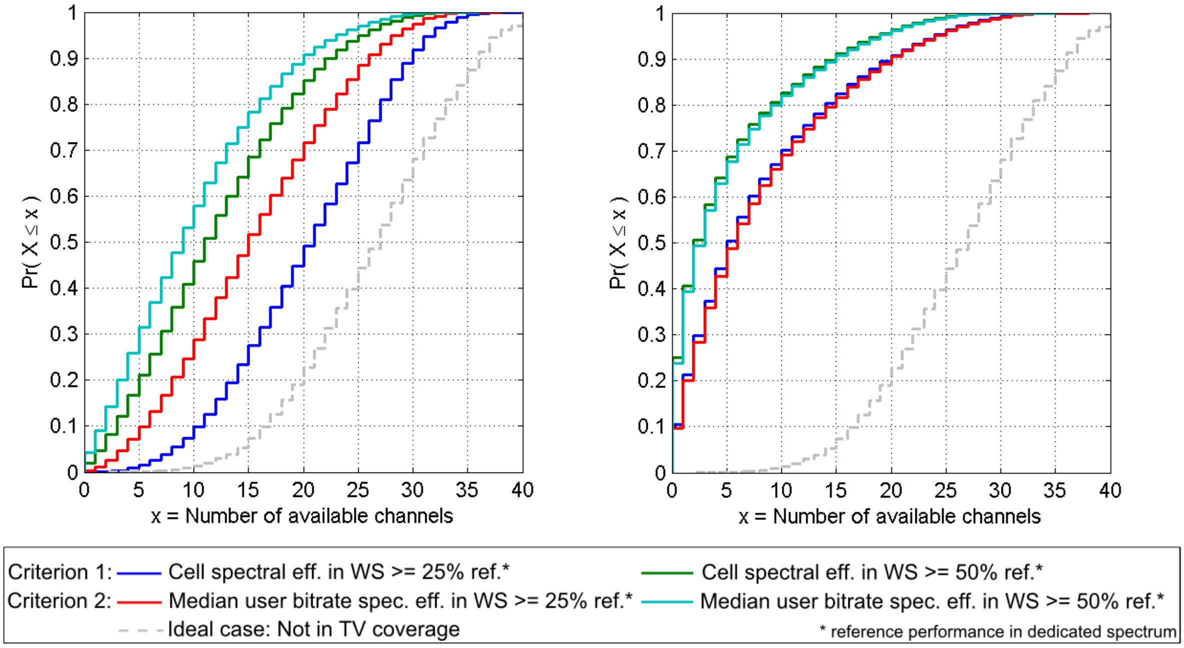


Figure 2-7: DSA-enabled: Number of available channels according to use-case criteria in DL (left) and UL (right).

In Figure 2-7 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. At the median approximately 8-22 channels are available for the different requirements in the DL and 3-7 channels are available for the requirements in the UL case. UL has a lower availability due to the more severe TV interference at the base station receiver, as well as the uplink transmit power cap of 23dBm.

The total sum cell throughput in all WS channels which were declared available with the metrics shown in Figure 2-7 are illustrated in Figure 2-8. We can see that in 50% of locations, at least 30-50Mbit/s can be achieved in DL and 5-10Mbit/s in UL which are considerable sum cell throughput for all DL and UL available TVWS channels respectively. This corresponds again to the entire TV band and 20% fractional load.

Especially in the DL the throughput suggests good usage but keeping in mind that this throughput corresponds to 320 MHz of spectrum. Comparing with LTE reference cell throughput in dedicated spectrum, 320 MHz FDD with 20% cell load: DL 180 MBit/s, UL 100 Mbit/s, we find that the average effective spectral efficiency is quite low. The situation in uplink with only 5-10Mbit/s on average is even more limited.

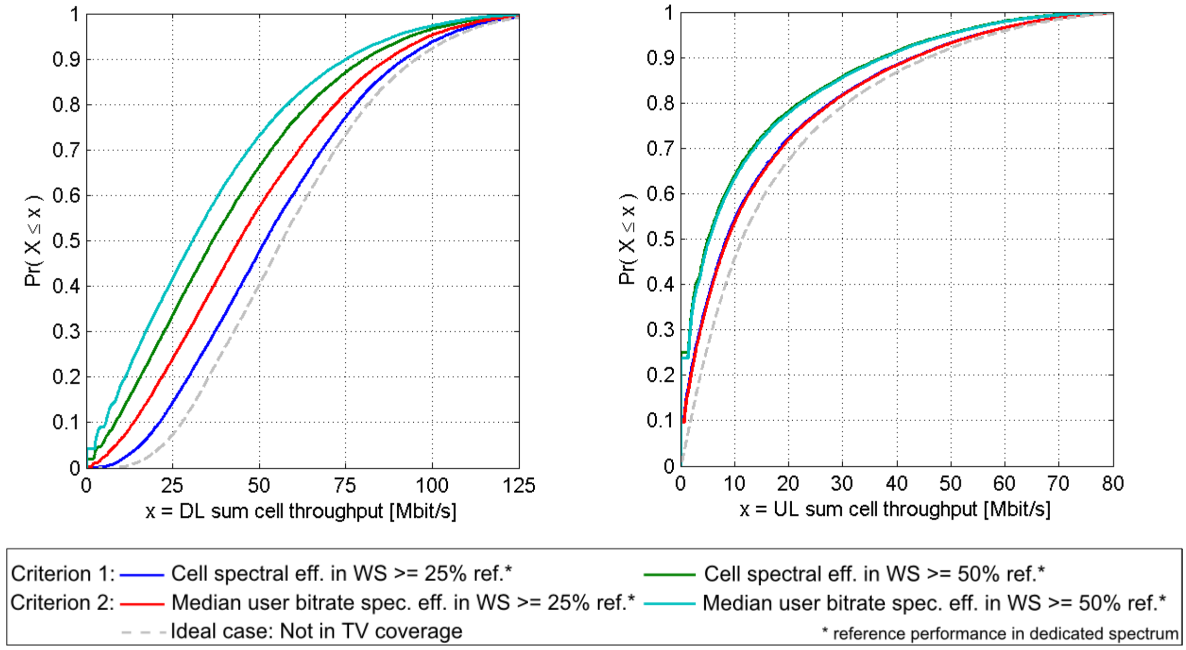


Figure 2-8: DSA-enabled: Available sum cell throughput for DL (left) and UL (right).

The DSA-enabled macro-cellular network performance is further analyzed in Figure 2-9 for DL and UL. If channels fulfil the spectral efficiency criterion of 25%, the actual spectral efficiency in 50% of the locations is higher than 55% in DL and UL and lower than 80% for all the criteria. This is less compared to the Standalone use case, but we have to remember that a larger number of channels, thus spectrum, are available with these spectral efficiencies.

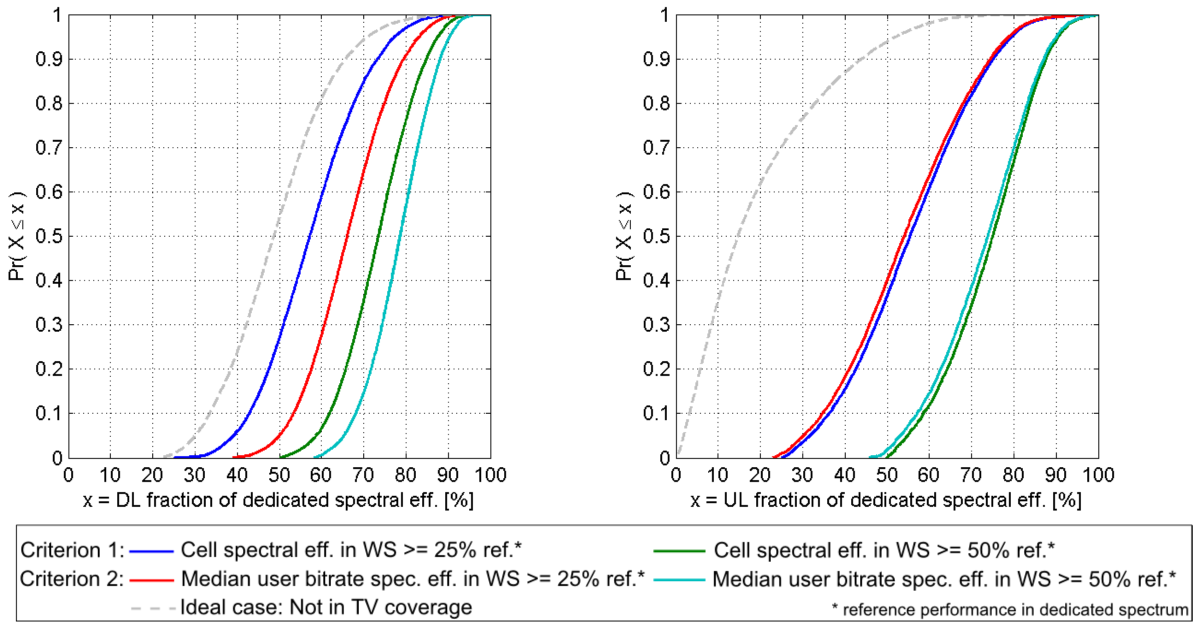


Figure 2-9: DSA-enabled: Achievable relative spectral efficiency in DL(left) and UL(right).

As defined in standalone use case section, Figure 2-10 shows the performance evaluation between DSA-enabled secondary WS usage and 100 MHz dedicated spectrum. In DL, dependent on the applied availability criterion, in 20-40% of the locations DSA-enabled WS outperforms the throughput achievable in 100MHz clean LTE spectrum. Meanwhile in the UL only in 10-15% of the locations WS outperforms LTE.

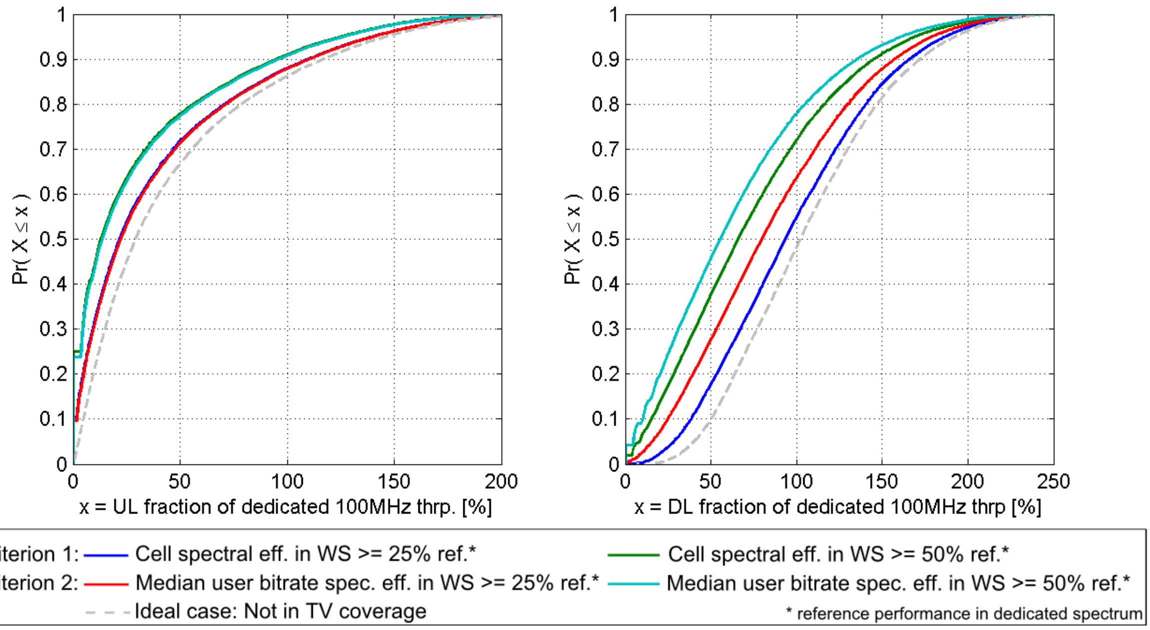


Figure 2-10: Cell throughput using all selected TVWS channels compared with cell throughput using 100 MHz dedicated spectrum, DL (left) and UL (right).

Finally, Figure 2-11 shows sensitivity analysis of available channels towards the assumed site density. In Channels with at least 25% cell throughput of system in dedicated spectrum, we can see only marginal improvement when number of sites is doubled.

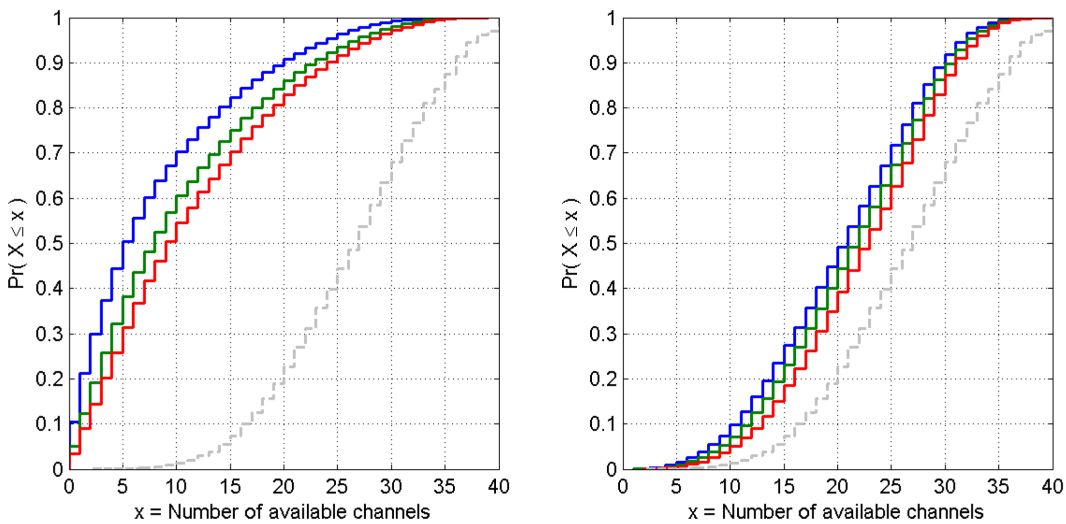


Figure 2-11: Sensitivity of the number of available channels towards the assumed site densities (blue: original assumption, green: 50% more sites, red: 100% more sites), DL (left) and UL (right).

For the stand-alone white space networks we saw for a deployment with typical ISDs that in only 70% 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. Only in 30% of location more than 50% of dedicated spectrum reference performance is supported on at least one channel, similar numbers are observed for less than 1% outage. The comparison with 100 MHz dedicated spectrum shows that in only less than 5% of locations the user benefit from TVWS would be higher than from re-purposing 100 MHz of TV spectrum to dedicated mobile broadband spectrum. In more than 95% of the area of Germany 100

MHz of dedicated spectrum would provide higher value for the use cases and channel selection criteria we have considered. We have also shown that even if stringent channel selection criteria are used to filter out only those channels that provide conditions that are reasonably close to those found in dedicated spectrum, the spectral efficiency of networks operating in TVWS is only in the range of between 70 and 100% of what can be achieved in dedicated spectrum. Finally, we have demonstrated that our results are rather insensitive to the assumed mapping between population density and ISD, which shows that our conclusions are generally valid.

As far as the DSA-enabled cellular networks are concerned, a capacity boost of up to ~100 Mbit/s in DL and 65 Mbit/s in UL as the sum of the cell throughputs for all available channels (both values represent the 95% percentile of the CDF over locations), can be observed. On average we find 9-21 channels available (depending on channel selection criterion) that on average provide a link spectral efficiency of 55-80% of what can be achieved in dedicated spectrum for the DL direction. In the UL we have 3 to 5 channels available for the same channel selection criteria. Overall it can be observed that TVWS is much better suited for offloading than for building stand-alone networks, since the relatively low TX power budgets and the quite noisy environment favour short distance communication scenarios.

2.2 Optimization strategies for enhancing capacity in TVWS cellular network

In QUASAR deliverable D5.2 section 2.2.1, we have analyzed the performance of a cellular network deployment for Germany if only a single secondary user/base station is allowed to access TVWS resources opportunistically [3]. We have derived the number of locally available channels, the local interference from the primary system, the allowable transmit power, and, assuming a single link in the near-field of the secondary transmitter, the achievable throughput. In the following, we are extending our initial assessment assuming multiple centrally coordinated transmitters such as in a cellular network. The focus in this scenario is on the joint interference originating from the secondary network. Contrary to the previous study, the achievable performance of the secondary transmitters is not only affected by the absolute constraints induced by the primary protection requirements, but also by the means of sharing the secondary resources between transmitters that is applied. The multiple transmitter case is hence a complex optimization problem for which the single user case provides us with the local upper bounds.

Two optimization strategies for downlink capacity enhancement have been studied in the multiple user case. In a first step we have studied the opportunity of extending an existing cellular network deployed in the focus area of Southern Rhineland. The locations of the cellular network have been provided to us by a local network operator. We have aimed at providing contiguous coverage aligned to the coverage of the original cellular network to ease management of spectrum resources in the RAN-RRM plane. The second optimization strategy, which we subsequently evaluated for the study area of the whole country of Germany, is better suited for newly deployed TVWS-enabled cellular networks where more freedom is granted to power selection mechanisms and base station placement.

2.2.1 Cellular network TVWS enhancement in Southern Rhineland

In the focus area scenario of the Southern Rhineland, the set of available base stations is used to provide coverage throughout the entire area [6]. As the exact spatial dimensioning of each single cell is unknown, we approximate it through Voronoi decomposition [7], i.e. we assume that a user is served always by the closest base station to its current location. While this approximation is rather coarse in the specific case, it becomes reasonable if user locations are unknown and average coverage is of relevant concern. To ease computation, we assume each base station to be equipped with an omni-directional antenna. A possible sectorization is not taken into consideration for the spectrum resource allocation.

Optimization is conducted on a per-channel basis. In order to operate a base station in a specific TV channel and provide connectivity even at the cell edge, a minimum power constraint at the furthest point within the cell needs to be fulfilled. To accommodate a smooth handover between base stations, we have additionally enlarged the original cell size by 70m in each direction which maps to a 2 second grace time for handovers if the velocity is assumed to be 250 km/h. We aim at providing a particular SINR target level which maps through the Shannon formula into an achievable capacity. The minimum required transmit power of base station *i* in channel *c* to fulfill the SINR target can be calculated as

$$P_{min,i,c} = 10log_{10}\left(I_{max,c,DVB}[mW] + 3.2 \times 10^{-11}\right) + PL_{BS \to CE}[dB] + SINR_{target} \quad ,$$

whereby $I_{max,c,DVB}$ is the maximum interference from the primary system and PL is the path loss between base station location and cell edge. The constant offset in the logarithmic term models the residual noise floor for an 8 MHz DVB channel. A base station is only eligible to use a channel if the interference power received at the closest point within the coverage area of the primary TV system is below a fixed threshold, e.g. -105.2 dBm, if, similarly to the value used for the implicit interference threshold of the FCC distance calculation, equality to the noise floor is required.

Due to the accumulation of interference to the primary system, not all base stations that may use a particular channel given the above constraints are allowed to operate at once. For the sum interference it must hold that

$$\sum_i P_{min,i,c}[mW] \times PL_{BS \to p} \times \psi_{c,i} < 3.2 \times 10^{-11}$$

where we use $\psi_{c,i}$ as an indicator function which takes the value of one if base station i uses channel c, zero otherwise. To minimize the effect of co-channel interference within the secondary system that could otherwise significantly lower the secondary network performance, we require that cells using the same channel do not share an edge of their respective Voronoi contours.

We define the **singular utility function** of the allocation task as a function

$$f(\psi_{c,i} = 1) \to v_{c,i}$$

that assigns a positive value to allocating a channel to a base station. We can in the following describe the optimization problem as a maximization of the **joint sum utility function** where

$$\Psi_c^* = argmax \sum_i v_{c,i} \times \psi_{c,i}$$

for each channel. In the following we report on the results of optimization if the absolute population within a cell, the coverage area and the population density are taken as optimization objective.

2.2.2 Simulation results for TVWS-enhanced cellular network

By investigating the complementary cumulative distribution of the number of channels allocated to each of the 925 base stations in the Southern Rhineland scenario we see in Figure 2-12 that the number of used channels significantly differs from the number of available channels that were derived for in QUASAR deliverable D5.2 [3].For the case of a general protection rule (GPR) that treats foreign country channels equal to local ones, approximately 60 percent of the base stations cannot use any TVWS. Similarly shaped results but with higher availability were found for the no-neighbour protection case (NPR) where foreign channels are not protected in the study area. This result is surprising given that in our previous observations in essentially all parts of the focus area at least 15 channels were available for secondary use. We furthermore found that, regardless of optimization criterion, no base station was eligible to access more than 5 channels at any given location.

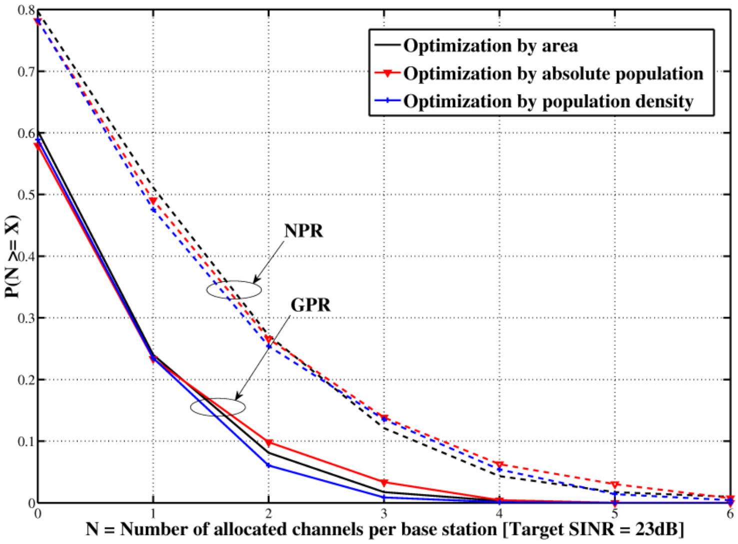


Figure 2-12: Complementary cumulative distribution function for the number of allocated channels per base station if a target SINR of 23 dB is assumed.

A depiction of the spatial distribution of channel allocations within the focus area in Figure 2-13 reveals that large macro-cell sites are not capable of acquiring any significant TVWS resources. We found that the interference imposed by the large base stations for a fixed SINR target is too high and causes them to be removed from the set of base stations that are considered to channel assignment. Only smaller cells, e.g. in the urban and suburban central areas of the region, can gather channel resources. Due to the implied frequency reuse scheme and the more complex spatial structure of the cells, they are required to share the accessible channels among the sites.

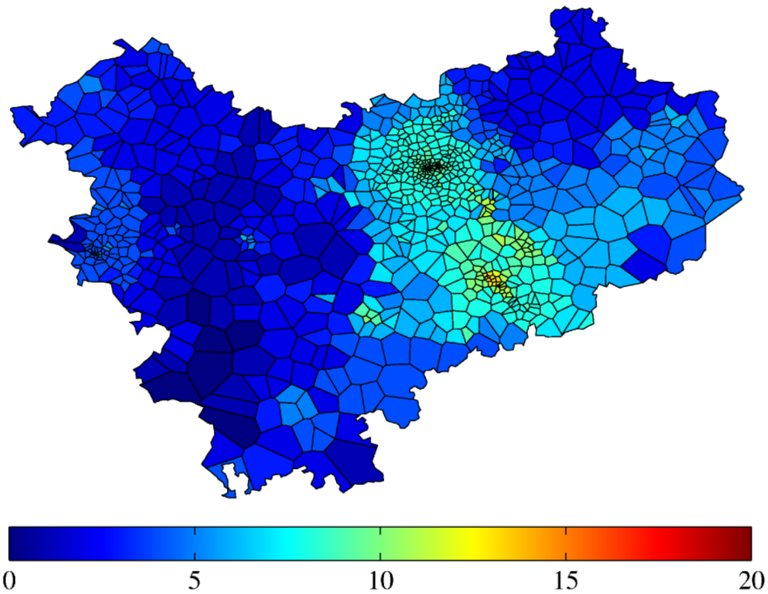


Figure 2-13: Number of used channel under the optimization criterion of covered population maximization for target SINR of 23 dB.

The relationship of cell size versus the number of accessible channels in the optimization task is shown in Figure 2-14 where the furthest distance to the cell edge within any cell is shown in comparison to the number of channels the cell's base station may access.

The tendency of excluding large cell sites from the optimization becomes clearly visible here. The original average availability of up to 15 channels is only preserved for very small cells with radii smaller than 1km. Those cell types are predominant in urban areas where more users will need to share the cell capacity simultaneously.

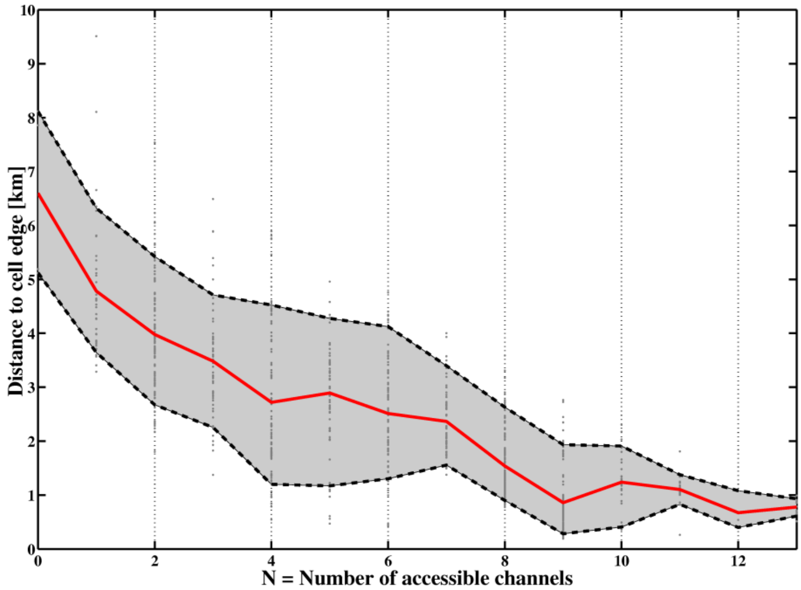


Figure 2-14: Number of accessible channels for cells of different sizes for a target SINR of 23 dB. The red line denotes the median, and the gray area is delimited by the 10th and 90th percentile.

The results of this focused study are significant for policy making regarding TVWS. Any benefit of allowing access to TVWS for the users in the rural areas where transmitter density is lower than in cities is hampered by the strict interference regulations. The larger availability of unused channels in general in these areas cannot make up for this limitation. Contiguous coverage as required for cellular networks is impossible to achieve in the TVWS with the optimization problem as defined above. Only micro cellular deployments such as in the central region of the focus area can gain capacity from the use of TVWS frequencies.

2.2.3 **Viability of TVWS allocation strategy for utility maximization**

The objectives of policy making any network planning can be represented through assignment of viable utility function values to the outcomes of channel assignment for the optimization problem. We have studied how sensitive the overall utility is to the target SINR parameter. This parameter determines the bias between smaller and larger cell sites. The larger the target SINR is chosen, the higher the in-cell capacity will become. A low target SINR value allows more cells to be eligible to TV channel access as shown before, but the users in those cells will have only very small capacity. A larger capacity is therefore only achieved if a large target SINR is chosen.

The cross-comparison of optimization objective of utility value in Figure 2-15 shows that the optimization method is indeed superior in their respective optimization target. For example, the optimization by area provides higher average served areas per channel than any of the other methods. Up to a target SINR of 23 dB, the area optimization provides stable results. By further increasing the SINR parameter, the macrocells become incapable of fulfilling the protection requirements and are removed from the network. The size of the average served area collapses in this case, because smaller cells at surrounding the large macrocells cannot compensate for the losses. For the population density optimization a similar tradeoff between macrocell and microcell sites can be observed. With higher SINR targets, the under-populated macrocells are replaced by the denser microcells. The maximum is reached at 25 dB SINR, after which also densely populated microcells are being removed from the result sets and the performance in terms of population coverage degrades. This is also reflected in the population density figure, which assumes a minimum in the 25 dB point.

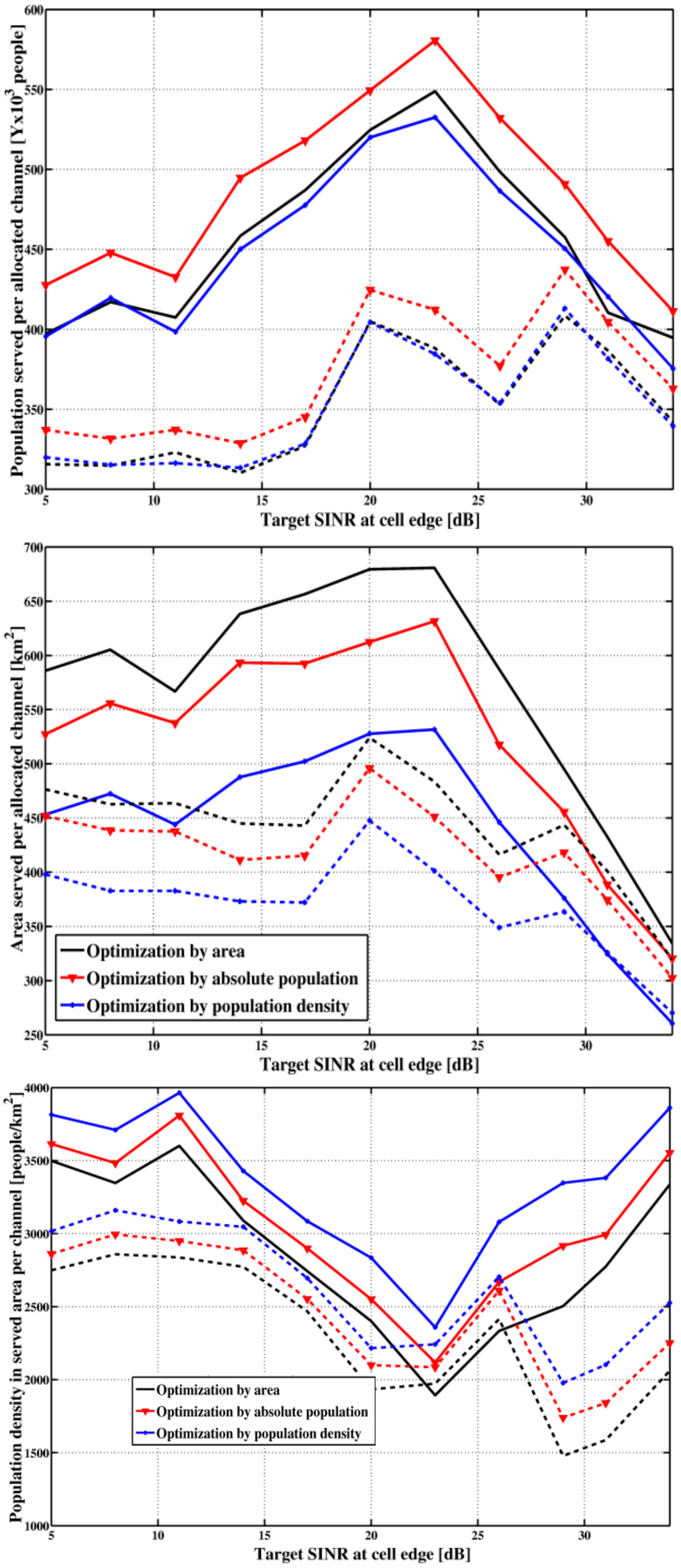


Figure 2-15: Joint utility function value depending on the target SINR for different optimization objectives. Dashed lines denote the general protection rule, and solid lines represent the no-neighbour protection rule.

2.2.4 Spectral efficiency optimization for country-scale cellular networks

The investigation in the focus area of Southern Rhineland has revealed that macro-cellular deployments are incapable of exploiting TVWS resources due to the limitations on the aggregate interference from multiple cells. An extension of the work to a more flexible power control in the macro-cellular case has been conducted to improve the performance in the downlink direction. The computational requirements for planning a cellular network are more challenging in this scenario due to the increased number of controlled parameters. The QUASAR project has developed a new method for network planning in interference-to-primary constrained networks [8] that formulates the optimization tasks in terms of a multiple-choice nested knapsack problem (MC-NKP) [9]. In the following, we will give a brief overview on the applied algorithm and present our results for country-sized cellular networks in Germany.

We aim at maximizing the composite downlink spectral efficiency in all base stations of the network by selecting the transmit powers $P^i_{TX,c}$ in each base station *i* on each channel *c* in accordance with the aggregate interference constraint. For this purpose we derive

$$O^* = \max_{P^i_{TX,c}} \sum_i \sum_c \kappa^i_c (P^i_{TX,c})$$

where κ^i_c is the downlink spectral efficiency in bps/Hz that depends upon the ratio between received power at the cell edge and the sum interference from primary network and residual noise floor. Maximizing the spectral efficiency in a given channel equals to maximizing the capacity. In case of the AWGN channel, we derive the spectral efficiency as

$$\kappa^i_c = \log\left(1 + \frac{P^i_{TX,c}}{PL_{BS\to CE}\left(I^i_{P_r,c} + N\right)}\right)$$

To ease the optimization of the best power level for each base station, we define for each combination of base station *i* and channel *c* a discrete function that maps a positive integer index value j^i_c to a tuple $(\kappa^i_c, P^i_{TX,c})$. The mapping function is chosen as follows

$$j^i_c \to \left(\Delta\kappa \times j^i_c, \frac{\left(2^{\Delta\kappa \times j^i_c} - 1\right)(I^i_{Pr,c} + N)}{PL_{BS\to CE}}\right)$$

The first tuple element is the discretized cell edge spectral efficiency, which increases linearly with the index value. The granularity $\Delta\kappa$ can be freely chosen, e.g. to 0.5 bps/Hz, to control the computational complexity. The second element refers to the required base station power to achieve the respective spectral efficiency. By increasing the index value, we will increase the interference power in the channel by the difference between the previous transmit power and the new transmit power. The expected aggregate interference at each location within the protection contour increases accordingly. The interference is discounted only by the distance-dependent path loss between base station and protection contour point that limits the effect of far-away located base stations. Index values can be increased until in at least one point in the protection contour for at least one channel the interference level exceeds the acceptable threshold. For a finite number of points in the protection contour |P| and a fixed number of channels, the problem can be interpreted as a MC-NKP with $m = c \times |P|$ bins.

The MC-NKP is known to be NP hard. However, observing some regular patterns in the geometrical structure and specific to the network planning problem, the following heuristic algorithm has been derived that is capable of approximating the optimal solution within reasonable time: We initially set each j^i_c to the maximum value that fulfills the interference constraint to the nearest point in the protection zone if no other interferer is present (single user case). After calculating the aggregate interference at each point in the protection contour we select in each iteration of the algorithm the index value which, if decreased by one, lowers the interference in the most interfered point/channel combination maximally. The procedure is repeated until all interference constrains are fulfilled.

2.2.5 Simulation results for various cellular network sizes

To study the influence of the locations of the base stations in the secondary cellular network, two different placement strategies have been evaluated for different numbers of base station towers. In the first scenario, base stations were placed "blindly" according to a Poisson point process [10]. The resulting distribution is known to have stable average distances between locations which is beneficial for maximizing coverage and minimizing inter-cell interference. A second placement strategy that exploits knowledge on the spatial structure of the TVWS has in addition been applied. Here, nodes where placed with a colored Poisson point process with a density proportional to the L^2 norm of protection zone distance for all available channels in the respective locations. This placement strategy will maximize the individual distance to the protection contours which may yield higher power budgets but also a more clustered network.

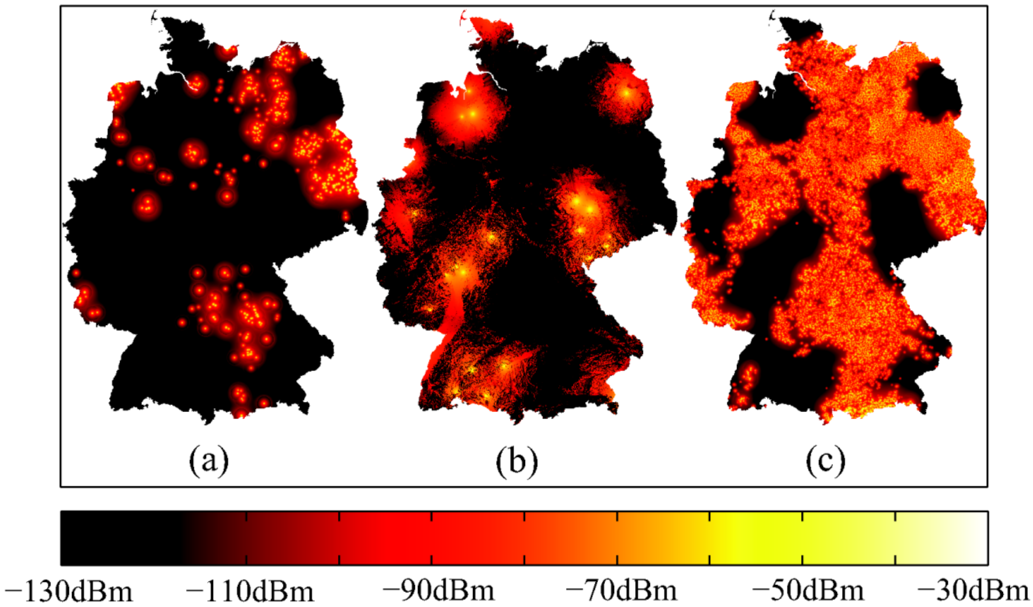


Figure 2-16: Received power from secondary base stations in channel 22 after optimization for (a) 5,000 randomly distributed base stations and (c) 50,000 base stations. Figure (b) shows for comparison the received power from the TV system in this channel.

The number of base stations determines how efficiently the secondary network can exploit the TVWS resources. Similar to our previous observations, we found that smaller cells are better suited to align the power levels to the interference protection contours of the primary network. In Figure 2-16 this becomes visible when the measured power levels of the secondary system are plotted in comparison to the primary TV channel powers. The sparse secondary network with 5,000 cell locations shows high secondary received powers mostly in the larger regions of the TVWS of the channels. More complex TVWS structures with shorter distances to the protection contours show only low power levels. The situation improves when more secondary base stations are deployed: A secondary network with ten times more base stations almost perfectly exploits the whitespace resources of the channel by setting low transmit powers for individual cells.

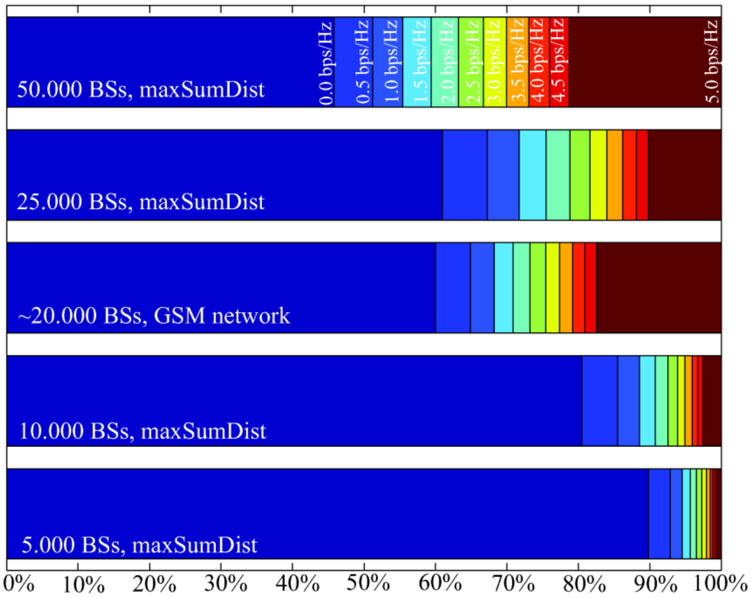


Figure 2-17: Distribution of per-channel selected target spectral efficiency for the different network sizes. The distance to protection contour maximizing placement strategy is used.

With a high number of secondary base stations deployed, the optimization algorithm is more often able to select high spectral efficiency index values for the base stations as shown in Figure 2-17. For the 50,000 base station case, more than 20 percent of the base station/channel combinations can operate at the highest spectral efficiency level. Approximately 45 percent of the base station/channel combinations are deactivated, an indication of the overall usage of TV frequencies in the study region. The remaining 35 percent of combinations are almost evenly distributed between the different efficiency levels. The situation changes entirely when lower network densities are assumed. In the 5,000 base station case almost 90 percent of the base station/channel combinations are deactivated, expressing the inability of the secondary network to efficiently exploit TVWS resources. Surprisingly, if the locations of a real GSM network are used, the performance is improved over the TVWS-aware placement strategy. We found this to originate from the specific inhomogeneous location density which allows some microcell base stations in urban areas to achieve efficiencies with comparably low transmit powers. This result needs to be treated with some caution though, because inter-cell interference becomes significantly higher.

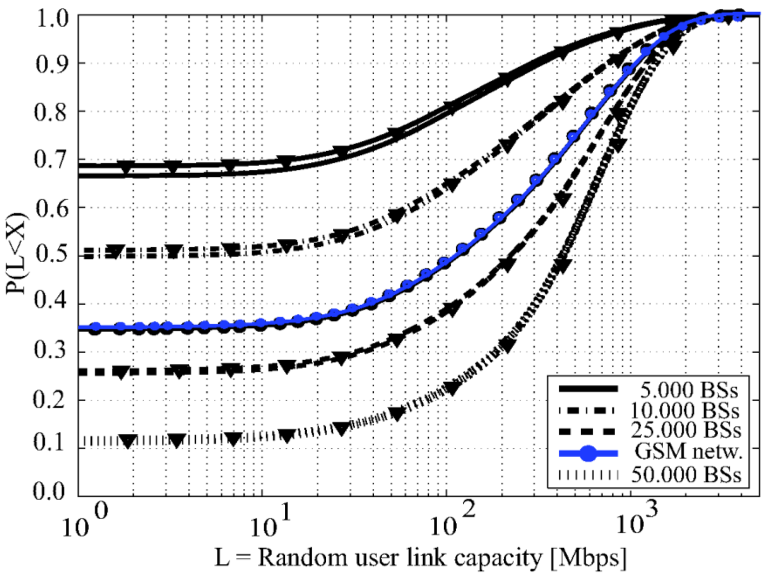


Figure 2-18: Cumulative distribution function of the link capacity of a user that is randomly placed within the study area. Marked lines denote the distance to protection contour maximizing placement strategy.

By looking at the probability distribution of the link capacity of a user that is randomly placed in the study region, the coverage as well as the overall system performance can be estimated. As depicted in Figure 2-18, the likeliness of having no connectivity through TVWS resources at all reaches almost 70 percent for the sparse 5,000 tower network. Only very few cell locations show high downlink capacities, and the effect of placement strategies is only marginal for all network sizes. The steepness of the cumulative distribution function underlines another observation from the outcome of the optimization: The result biases towards locations that are either very well equipped with whitespace resources such as those that are in the centre of low TV coverage areas and almost entirely assigns high index values to those. For users this is undesired, because they will experience strong variations in achievable throughput depending on their current location.

2.3 Cellular TVWS capacity in Finland

In this section we study a TVWS cellular system in Finland that is dimensioned according to the user density in the cells. In classical dimensioning approach, the cell size is a variable and selected such that the cell throughput meets the demand in the cell. However when the network operates on TVWS, the approach has to be different. In this analysis we first set the cell size to contain certain amount of demand based on the population information, and then compute the downlink data rate in each cell. The data rate computation takes into account the available TVWS spectrum, TV interference, allowed secondary power level in each cell, and secondary self-interference. Analysis is done for TVWS spectrum usage rules outlined by Federal Communications Commission (FCC) [11] and Electronic Communications Committee (ECC) [5]. Results are compared with system that has exclusive right to use the spectrum, such as current cellular network. In addition we use power density based method for allocating secondary powers. The analysis is continuum for the results presented in deliverable D5.2 section 2.2.3 [3]. Compared to the analysis done in Sections 2.1 and 2.2, we don't set constraints for the secondary system's cell edge performance, but instead observe the cumulative distribution of the achievable data rate. The outage probability for given cell edge data rate constraint can be observed directly from the CDF. Also the TV transmitter density has differences between Finland and Germany - in Finland the density is much smaller.

Traditional cellular system is dimensioned to meet the users' demand. Usually the amount of frequencies allocated for the system is fixed and the demand is met by selecting appropriate cell sizes: smaller cells in areas with high traffic density, larger cells in areas with lower traffic density. Compared to the traditional network planning, the design of a system using TVWS has a different nature. In TVWS the entire spectrum is not always available for secondary use and also the available bandwidth and transmission powers depend on the coverage areas of the TV transmitters and on the WS usage rules. This means, that the capacity of the cellular system using TVWS frequencies cannot simply be estimated by using the cell sizes. The secondary network has to be dimensioned around an unknown amount of spectrum.

2.3.1 Dimensioning and computation method

In the dimensioning process we determine the cell sizes that are required to meet the demand. In TVWS we do not know the available spectrum beforehand and therefore we start the dimensioning process by allocating cell sizes based on population density. Used dimensioning process has the following steps:

1) Cell size allocation based on user density.
2) Channel and power allocation based on TVWS usage rules.
3) Computation of the capacity.
4) If desired capacity target is not met, split cells or increase power.

We compare the performance of the cellular network designed based on the above described steps with the network having uniform (constant) cell size.

Cell sizes are allocated using the same procedure as in D5.2. Densely populated areas are covered by smaller sized cells. Rural areas, where less capacity per area is needed, larger cells are used in order to reduce the number of sites. We use square-shaped secondary cells with three different sizes. The cell size allocation algorithm is simple: if population within cell coverage area exceeds 10000, it is divided into smaller cells. Resulting non-uniform cellular layout is shown in Figure 2-19.

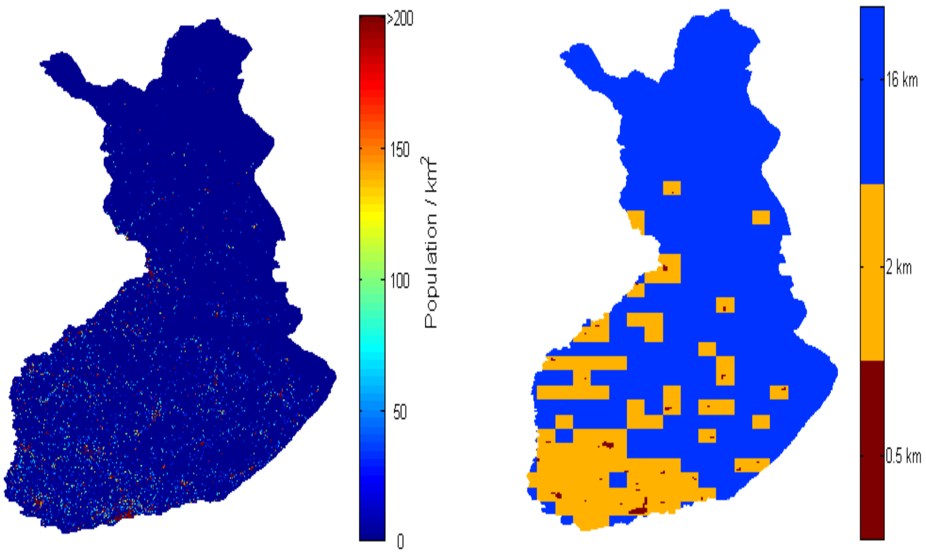


Figure 2-19: Population density in Finland (left) and Allocated cell sizes based on population density (right).

Results are computed by using the same method as in D5.2. 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. In addition we use power density based method. For comparison, result for standalone network (no primary interference and no power limitations) are also computed as well as result for uniform cellular layout (constant cell size throughout the country).

2.3.2 Power density based power allocation method

The FCC and ECC methods do not take into account the secondary cell sizes in any way. Also their ability to handle the aggregate interference is limited. In fact, FCC method doesn't have any additional parameter that limits the allowed secondary power when we have large number of transmitters. ECC method has the multiple interference margin (MI) that can be used to reduce the allowable transmission power when we have multiple interfering secondary transmitters. Power density (PD) based power allocation [12][13] takes the secondary cell size into account. This makes the cell capacities more evenly distributed between different cell sizes compared to FCC and ECC methods. When the cell sizes are allocated based on the user density, it should also provide more evenly distributed capacities between all users.

Allowed power density is computed individually for each channel and we set it to be uniform through the whole country. Power density is calculated from allowed interference margin. We use 20dB SINR target for the TV when computing the PD for each channel. In these simulations TV cell edge SINR is about 23.3 dB without secondary system, so we assume that about 3.3 dB decrease in cell edge SINR is allowed. Power density is computed for each channel by first combining the aggregate interference from all secondary transmitters that are outside defined protection distance from TV cell border. The aggregate interference is computed to all test points that are placed on the TV cell edge. Then the power density is chosen based on the test point that experiences the highest aggregated interference. Based on the worst test point, we then set the power density to be uniform throughout the country. We must note that we set the power density without taking the adjacent channel interferences into account. However, as results show later, the impact of this is not crucial. However, we must emphasize that we analyze only downlink. In the uplink case, the impact could me more severe.

2.3.3 Capacity per cell results

From operator's point of view, the capacity per cell is an important metric. It tells where and how reasonable it is to use TVWS cells. Capacity per cell in these computations means the average spatial downlink capacity in each cell. It is calculated by computing first the Shannon capacity in 32 points inside each cell's coverage area, and then taking the mean over them. Shannon capacity is calculated based on the SINR, which takes into account interference from TV, secondary self-interference and noise. In the dedicated spectrum case interference from TV transmitters is not present. For the non-uniform cell structure the cell capacity CDF curves are shown in Figure 2-20 (left), when using ECC rules and dedicated 20 MHz spectrum. ECC method gives 10-times more capacity in small cells and about 5-times more capacity in medium sized cells compared to stand-alone network. Problem arises in large cells. Due to the power limitations, the capacity of large TVWS cells is lower than in standalone for about 30% of the sites. This suggests that the main potential of TVWS usage is on small and medium sized cells. Results for uniform cellular layout is shown in Figure 2-20 (right). Now the difference between ECC and FCC method can be seen clearly. For 1 km cells, ECC method gives slightly more capacity than FCC, but with 5 km cells FCC gives more capacity per cell. This is again caused by the fact that ECC method has more available channels, but the allowed transmission powers are in most locations smaller than what FCC allows. In fact, cell size has very little effect to the cell capacities in FCC and stand-alone networks. As expected, in the stand-alone case, almost all cells give the same amount of capacity.

However, small portion of the cells that are located at the border areas can provide higher capacity, due to fewer interfering secondary cells.

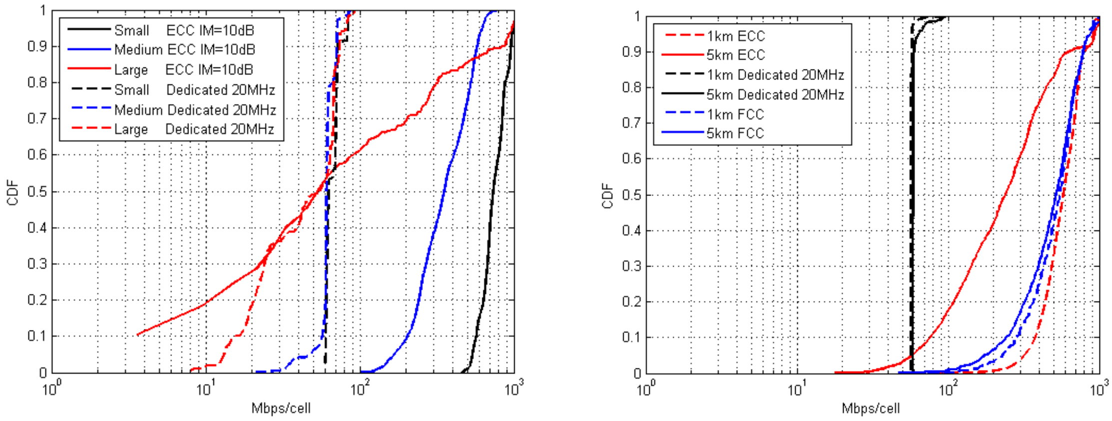


Figure 2-20: Average capacity per cell distributions for different sized cells with non-uniform (left) and uniform cellular layout (right) calculated for FCC rules, for ECC rules with 10dB IM margin and for dedicated system with 20MHz bandwidth.

Power density method shows much more prominent average capacity per cell results compared to ECC method. This is shown in Figure 2-21. Because PD method allocates more power to larger cells, the capacities are similar regardless of the cell size. In fact, the results for all cell sizes are close to the results that ECC rules can give with the small cells. The main problem in ECC method, which is the poor capacity in large cells, can potentially be solved by using PD based power allocation.

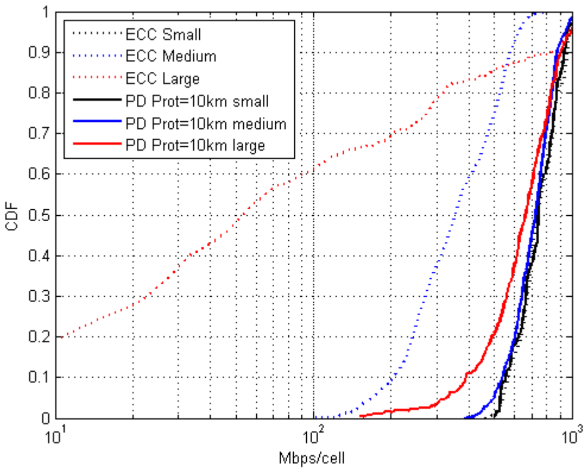


Figure 2-21: Average capacity per cell distributions for different sized cells with non-uniform cellular layout calculated for power density method with 10km co-channel protection distance.

Unlike in a traditional cellular network, network operating on TVWS has strict power limitations. As can be seen from Figure 2-21, this causes noticeable effect in large cells. Power limitations cause the cell to become noise limited, resulting to significant capacity decrease. PD method seems to be better in this perspective, but we also assessed two different methods for increasing their capacities when ECC rules are applied. One option is to split the cells having low capacity into smaller ones. We split cells that had average capacity less than 100 Mbps into 4 smaller ones and then recomputed the capacity. About 60% of the large cells are split. Other option is to increase the transmission power in large cells. In ECC method the power is usually limited by the reference geometry (RG) which means the expected distance to the closest TV receiver. RG is considered to be 22 meters in the ECC rules. Large cells are usually located in rural areas where population density is small. Therefore it is reasonable to assume that this distance can be higher. Also in rural areas the sites can be more freely located further away from buildings having a TV receiver.

Capacity results for large cells before and after the splitting, and with larger 100 meter reference geometry are presented in Figure 2-22. By splitting the chosen cells, the lowest 10th percentile capacity moves from 4 Mbps up to 20 Mbps. splitting can naturally be done several time, however, it might not be economically attractive solution since more cells are needed in areas where capacity is not needed so much. More tempting is to assume larger 100 m reference geometry. Now, the lowest 10th percentile capacity moves up to 45 Mbps, which is more than 10-times better than with 22m reference geometry.

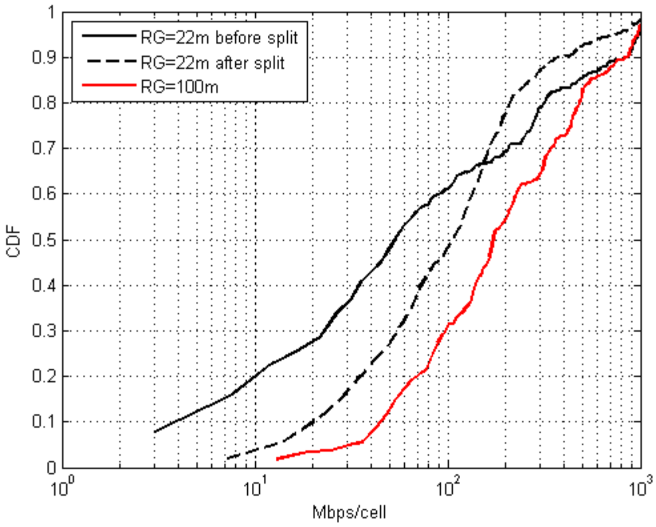


Figure 2-22: Average capacity per cell distributions with non-uniform layout, calculated for large cells only with 22m reference geometry before and after cell splitting and 100m reference geometry, ECC rules with 10dB margin used.

2.3.4 **Rate per user results**

The following graphs show how much theoretical capacity can be achieved per user. Results are calculated by dividing the mean spatial downlink capacity in each cell with the number of people living inside its coverage area. We assume that in each cell there is at least one person. For the non-uniform and uniform cellular structure results are shown in Figure 2-23. User rates from FCC and ECC methods are close to each other. ECC method gives slightly better capacity in general than FCC. However, in the lowest 10th percentile FCC method gives more capacity. Using 4dB larger margin (4dB lower transmission powers) in ECC method has only marginal effect to the results. Compared to standalone network with 20 MHz BW, the TVWS secondary usage with non-uniform cell structure gives up to 10-times more capacity per user. When the cellular structure is uniform throughout the country, the user rates are again about 10-times larger when using cells with 1km radius. When larger cells with 5 km radius are used, the rates are about 2-times larger. The relatively smaller increase in the larger cells can be explained by power limitation of the cells.

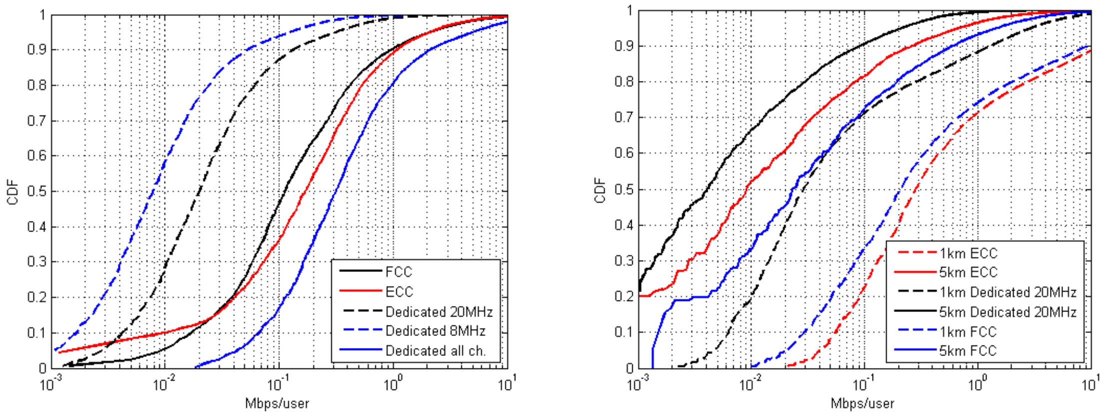


Figure 2-23: Average rate per user distributions with non-uniform (left) and uniform (right) cellular layout calculated for FCC rules, for ECC with IM=10dB and for dedicated system with different bandwidths.

The rates that power density method can provide depend on the used co-channel protection distance. Larger protection distance allows using higher powers, but reduces the number of available channels in each cell. The rate per user CDF-graphs are shown in Figure 2-24. As expected PD method can provide rates with lower variance compared to FCC and ECC methods. Large protection distances cannot provide as good mean rates as ECC method. When protection distance is 20 km or lower, the PD method provides in general more capacity compared to ECC method. The protection distance that provides the best rates in general is 10km. If the distance is further reduced, also the rates begin to decrease. With smaller distances the increase in available channels cannot compensate the capacity reduction due to reduced transmission powers. Therefore 10km seems to be rather optimal protection distance. With 10km protection distance the difference in median rate compared to ECC is not that significant, but in the lowest 10th-percentile rates the PD method can provide 7-times better rates.

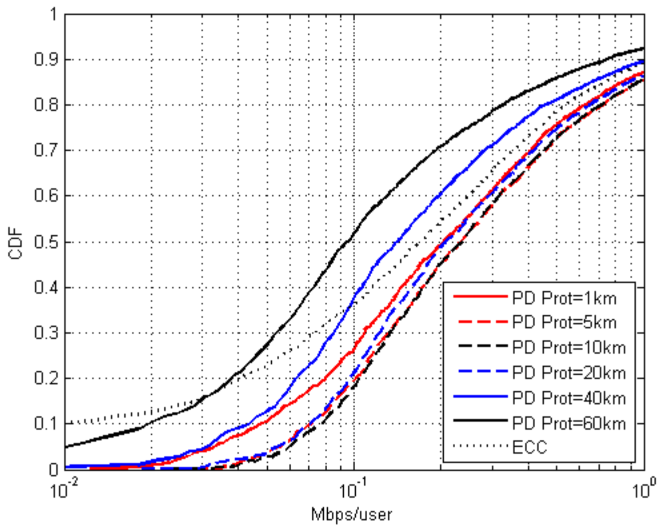
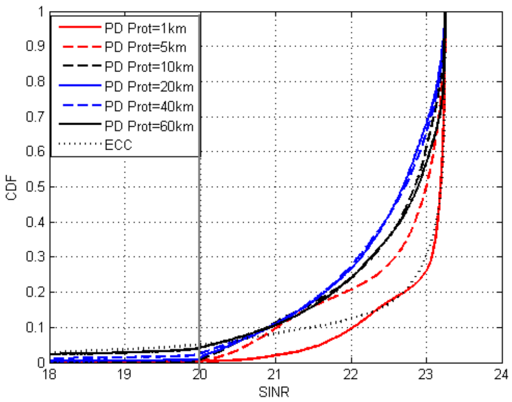


Figure 2-24: Average rate per user distributions with non-uniform cellular layout calculated for power density method with different co-channel protection distances.

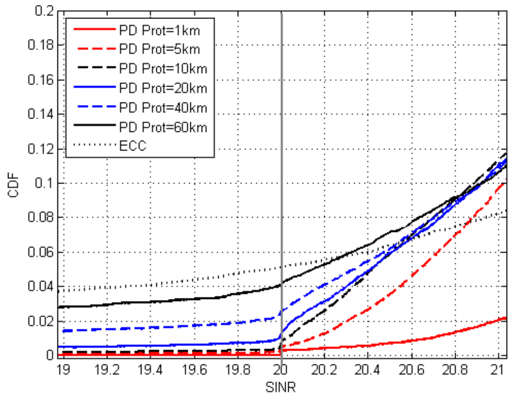
2.3.5 **Impact to TV reception**

Sufficient protection of the primary system should not be forgotten when analyzing the potential of secondary use. The FCC and ECC methods are not protecting the primary TV reception well when multiple interferers are present, since their rules do not scale sufficiently when the number of secondary users is increased. Here we show the TV SINR at test points located at TV cell borders for the analyzed cases. 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. We assume that the minimum distance between secondary transmitter and TV receiver (TV cell border test point) is 22 meters.

Power density based method can protect the primary reasonably well up to the targeted SINR level. This can be seen from Figure 2-25 (a) and (b), which is the zoomed version of (a). If adjacent channel interference is not taken into account, the PD method would not violate the targeted 20dB SINR limit at all. However, since we compute the power density for each channel based on co-channel interference, the target is slightly violated. In fact, with the 10km protection distance (that provided the best capacities), the target SINR is violated less than 0,5% of the test points, whereas the ECC method (IM=10dB, RG=22m) violates the target in about 5% of the test points. For comparison SINR is also provided for FCC and for ECC methods with different IM margins and reference geometries in Figure 2-25 (c).



(a)



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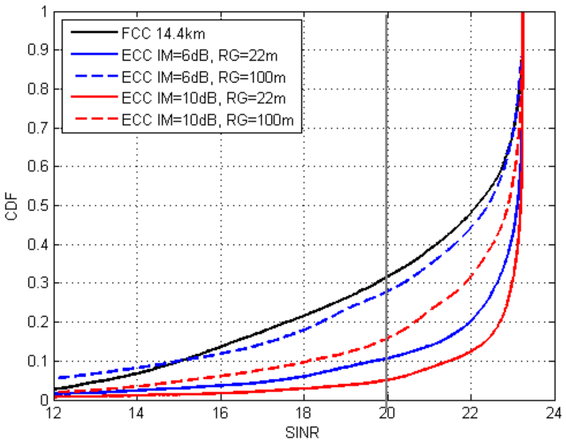


(c)

Figure 2-25: SINR distribution at the TV cell borders computed with aggregate interference from all secondary transmitters including adjacent channel interference by using power density based method with different protection distances (a) and zoomed (b), and by using FCC and ECC rules (c) with different reference geometry assumptions (RG) and interference margins (IM).

2.4 Concluding remarks

From Section 2.1, it can be concluded, that TVWS represents a problematic environment for cellular networks. Building contiguous coverage is challenging since the average distance between transmitter and receiver has to be strongly reduced, which at the same time significantly increases intra-system interference. For offloading scenarios addressing the users that are close to the base station the situation looks more promising, although it is somewhat questionable if similar gains could not easily be achieved in other (higher) frequency ranges. It appears that TVWS has difficulties to realize the key benefit of low frequencies, i.e. good coverage, long range and good indoor penetration. This hints that other ways of making TV band spectrum available might be preferable.

From Section 2.2, it becomes apparent that only high cell tower densities similar to those of cellular network in urban scenarios will be likely to provide coverage at the same level. The TVWS cellular network case is better suited to offer local coverage in specific locations where, by some means of spectrum reorganization or geographical peculiarities, larger quantities of TVWS resources with large distances to the protection contours are available. Unfortunately, the commercial viability in this case is dubious and low penetration rates may hamper technological evolution.

From Section 2.3, it can be concluded that there are substantial amount of available capacity in TVWS. However, the amount of capacity naturally is highly dependent on the area and country. Even if the density of broadcast towers in Finland is much lower than in Germany, the secondary system still has coverage problems in rural areas due to the interference limits. This could be overcome by using smaller cells, but due to low population densities in those areas this approach is not likely to be economically viable. It is worth noting that the existing protection rules are not appropriate for cellular SU deployment. Compared to ECC and FCC usage rules, the power density based secondary power allocation can provide more capacity and protect the primary users more efficiently.

3 Indoor Cellular & WiFi-like Secondary Use of TVWS

In this chapter we report on our extended study of deploying a WiFi-like multi-user secondary system in TVWS for a number of regions in Europe. Unlike deliverable D5.2 [3], in the present deliverable the impact of the aggregate interference from multiple secondary users is considered. The chapter is organized in four parts as follows. We begin the chapter with a follow-up on the study in Germany initially discussed in Section 2.3.1 in [3]. We estimate the performance of our system when aggregate interference is taken into account, and calculate the permissible transmit power for the secondary users. In the second part of the chapter we study the potential of enabling an inside-out connectivity by deploying a Wi-Fi type of network in TVWS in the UK. In the third part, we also describe a detailed picture on the limitations imposed by the aggregate interference caused by the secondary users to the primary system in a selected region in Macedonia.

3.1 Performance analysis of a WiFi-like secondary network deployed in TVWS

In this section we analyse the performance of a system of multiple WiFi-like secondary users operating in TVWS, in order to assert a realistic estimate of the achievable range and data rate for such a secondary system. We take into account real TVWS channel availability estimates, calculated for a region of Germany, and consider the effects of interference and congestion among secondary users sharing the same channel. We also investigate the amount of aggregate secondary interference from the multiple user WiFi-like network caused to the primary system, and the resulting maximum permissible transmit power of the secondary users and corresponding achievable performance of the secondary network.

The results and analysis reported in this section are an extension of the preliminary analysis reported in Section 2.3.1 of QUASAR Deliverable 5.2 [3] and are based on the same underlying system model and assumptions detailed in [3], unless stated otherwise. A part of the results presented in this section will be published in [14], which thus also serves as a reference for a detailed description of the system model and simulation parameters employed in the present analysis.

3.1.1 System model

As described in Section 2.3.1 of [3], we consider multiple WiFi-like access points (APs) operating as secondary transmitters in TVWS. The APs operate using a CSMA/CA MAC protocol, and we assume saturated downlink traffic with a single user terminal associated with each AP. We assume that the APs employ an auto-rate function $\rho(\beta)$, which maps minimum received SINR at the user terminal to the raw bit rate provided by the AP (e.g. from 6 to 54 Mbps for IEEE 802.11g Wi-Fi); $\rho(\beta)$ is a piecewise constant function given by the spectral efficiency and minimum receiver sensitivity specifications of the IEEE 802.11g Wi-Fi standard [15]. We define r_n to be the maximum AP coverage range corresponding to a given raw rate ρ_n.

We employ the log-distance path loss propagation model. AP locations are randomly generated over the network study area following a Poisson point process with density λ. We consider three secondary network deployment scenarios: outdoor urban, indoor urban, and outdoor rural. Each scenario is characterised by its AP density, the size of the study area, and the propagation environment characteristics, as listed in Table 3-1.

Table 3-1: System model parameters for different deployment scenarios.

	Outdoor Urban	Indoor Urban	Outdoor Rural
Propagation characteristics	k = 3	k = 4, 18 dB wall loss	k = 2.5
AP density	λ =12.5/km^2	λ =125/km^2	λ =0.25/km^2
Study area	2 km x 2 km	500 m x 500 m	5 km x 5km

TVWS channel availability

TVWS channel availability estimates for the Southern Rhineland region of Germany from [6] (based on the European draft SE43 protection rule) are used in our analysis, as a realistic and fairly typical example of TVWS availability. For the German city of Aachen, our example urban study area, the underlying data set from [6] reveals that channels {21, 22, 30-32, 39-48, 56, 60} are predicted to be available throughout the study area; for our example rural study area of Wipperfürth, channels {21, 23, 24, 32, 34, 38, 39, 41, 42, 44, 45, 47, 51, 54} are predicted to be available. We assume that up to three 8 MHz TV channels may be aggregated by the secondary device. Consequently, in our analysis we consider the following channel availabilities: seventeen 8 MHz channels or seven 16 MHz channels or four 24 MHz channels for urban deployment; and fourteen 8 MHz or four 16 MHz channels for the rural scenario. For comparison, the reference IEEE 802.11g Wi-Fi system operating at 2.4 GHz has three non-overlapping 20 MHz channels available.

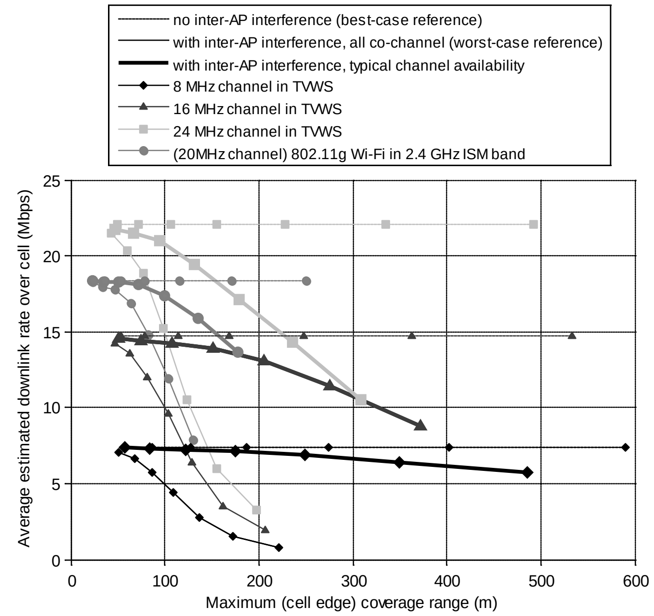
Modelling interference among co-channel secondary APs

In order to undertake a system-level analysis of the impact of congestion and interference among multiple co-channel secondary users, we estimate the resulting AP downlink rate by adopting the model proposed in [16]. Please note that the case of secondary users operating on one of multiple available TV channels considered here requires a slight modification of the equations in [3] characterising this secondary-to-secondary interference; for the exact formulation, please refer to [14].

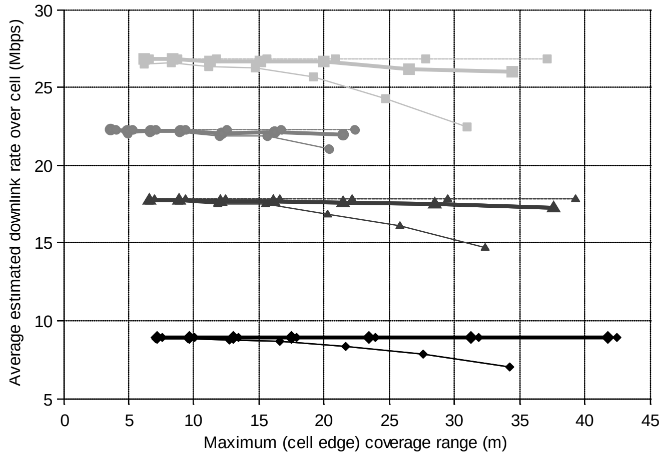
3.1.2 Performance analysis results

We analyse the performance of the secondary WiFi-like system operating in TVWS in terms of the achievable range and throughput of the secondary system. 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 (based on the interference model detailed in [3]). We assume all secondary APs transmit at the same power P_{tx}.

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, $\overline{R}_{\boldsymbol{A}}$, and the mean cell-edge AP coverage range over the network, $r_{max}^{\boldsymbol{A}}$ (as defined in [3]). Figure 3-1 presents simulation results of $\overline{R}_{\boldsymbol{A}}$ versus $r_{max}^{\boldsymbol{A}}$ for each considered deployment scenario, for different secondary channel widths and different inter-AP interference conditions. Each curve was generated by varying the transmission power of the secondary APs, P_{tx}={0,5,10,15,20,25,30} dBm (i.e. each point represents the achievable mean rate and coverage range for a given fixed P_{tx}). The dashed curves represent the "best-case" reference of ignoring the effects of inter-AP interference (equivalent to the single secondary user case), whereas the thin solid curves represent the worst-case reference of taking mutual interference into account when all APs operate on the same channel. The thick solid curves show the performance of the secondary network using the realistic example channel availabilities specified above, where each AP randomly selects a channel to operate on from the list of available channels advised by a TVWS database.



(a)



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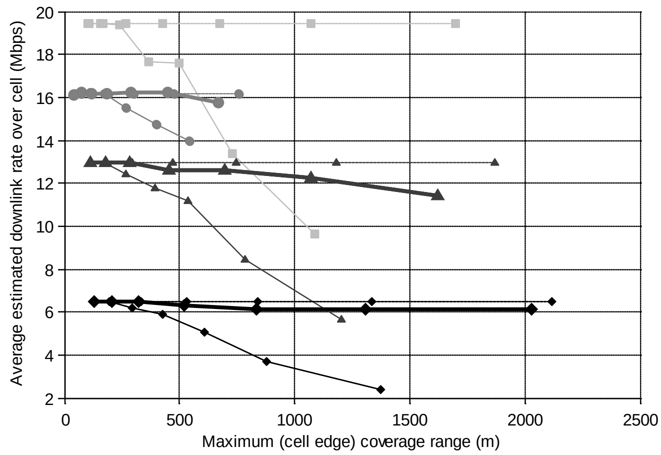


(c)

Figure 3-1: Average downlink rate for a covered user vs. maximum AP coverage range (corresponding to secondary AP transmission power Ptx={0,5,10,15,20,25,30} dBm), for the deployment scenarios of (a) outdoor urban, (b) indoor urban, and (c) outdoor rural.

As discussed in our preliminary analysis presented in [3], Figure 3-1 demonstrates that although a greater AP coverage range results from operating in the lower frequency TV bands compared to IEEE 802.11 Wi-Fi in the 2.4 GHz ISM band, this range extension is significantly diminished once we take into account the mutual interference among multiple co-channel secondary users, and increasingly so as the transmission power is increased. Accordingly, the AP downlink throughput in the case of multiple secondary users is increasingly lower for higher AP transmission powers, owing to increasingly overlapping shared contention domains among secondary APs which reduce the throughput for each individual AP.

Importantly, Figure 3-1 also reveals the extent of impact of inter-AP interference and congestion when we consider typical TVWS channel availabilities. For the outdoor urban scenario in Figure 3-1 (a), the effects of inter-AP interference on the performance of the secondary network remain pronounced, even when APs can choose to operate on one of a number of available channels. For example, for P_{tx}=30 dBm, operating in TVWS on one of four available 24-MHz channels still affords some range extension (of around 130m), but results in a 23% lower average throughput compared to operating at 2.4 GHz (i.e. IEEE 802.11g WiFi with three non-overlapping 20 MHz channels), despite a 20% higher channel width. The simulation results for the indoor urban scenario in Figure 3-1 (b) suggest a more favourable case for a WiFi-like secondary deployment in TVWS, since the secondary AP coverage remains short-range enough so that inter-AP interference is not as dominant a factor as for the outdoor case. However, as the obtained throughput is proportional to the channel width, in this case the TVWS spectrum simply provides a new ISM band with slightly extended range (10 to 20 m) compared to operating WiFi in the 2.4 GHz ISM band. For the case of an outdoor rural deployment scenario in Figure 3-1 (c), the AP deployment density is low enough that moderate congestion effects are observed for typical TVWS channel availability, while affording a significant range extension (of up to two-fold using 16 MHz TVWS channels). However, the business case for such a rural deployment with a small customer base is unclear.

3.1.3 **Aggregate secondary user interference considerations**

The results of the achievable performance of the secondary WiFi-like network in TVWS presented above (for various values of the secondary transmission power) do not take into account the further critical constraint of controlling the amount of aggregate secondary interference to the primary DVB-T system. To address this, we evaluate the extent of total secondary interference caused to the primary system from the operation of the network of multiple secondary WiFi-like APs. We thus determine the permissible transmission power of secondary APs. Conversely, we also consider the reduction in the number of TVWS channels which are actually accessible for a given fixed secondary transmission power, and the corresponding achievable secondary network performance when the prescribed limit on aggregate secondary interference to the primary is respected. For the sake of brevity, we only present results for the case of secondary operation in TVWS using 8 MHz channels, and omit the similar results for the case of 16 or 24 MHz channels.

Method of calculating aggregate secondary-to-primary interference

We evaluate the total interference caused to the primary system from the operation of multiple secondary APs as follows. For each available channel and the given study area (Aachen for urban and Wipperfürth for rural deployment), we determine the closest protected pixel to the centre of the defined study area using the underlying channel availability data from [6]. We then calculate the aggregate secondary user interference at the protected test pixel, from all transmitting secondary APs operating on that channel using

$$ASUI = \sum_{x \in \mathbf{A}_j} L_{PU,x} P_{tx} M_x \,, \qquad (3.1)$$

where A_j is the subset of all APs in the network operating on channel j, where $j = \{1,2,4,...,J\}$ is the index of each of J available non-overlapping channels, $L_{PU,x}$ is the path loss from each AP x and the nearest protected pixel serving as the test primary user location and maps from distance as given in [3], and M_x is the fraction of time that AP x transmits, having been granted channel access by the CSMA/CA MAC protocol.

As defined in [14], M_x is inversely proportional to the number of APs in the shared contention domain of AP x.

The availability of a given TV channel for secondary use in each pixel was determined in [6] by assuming 3 dB of interference to be coming from the secondary system. Namely, for the TVWS channel availability estimates used above, the maximum $ASUI$ for each channel is equal to the noise floor (-105.2 dBm). Thus, in order to determine whether a channel which was originally deemed to be available for secondary operation in [6] is in fact still *accessible* once the aggregate secondary user interference is taken into account, we employ the following threshold test. For each deployment scenario and secondary AP transmission power P_{tx}, if $ASUI$ < 105.2 dBm, then the total secondary interference is below 3 dB at the test point on the primary user protection contour, and the channel originally deemed to be available is indeed accessible. Otherwise, the channel is inaccessible for the given P_{tx} and number of secondary transmitters.

Results of aggregate secondary-to-primary interference evaluation

Figure 3-2 plots the aggregate secondary user interference calculated at the test point on the primary user protection contour for each TV channel originally deemed to be available for secondary operation, for the outdoor urban scenario in the Aachen study area and P_{tx} =20 dBm. Figure 3-2 reveals that only 8 out of the 17 TV channels remain accessible when the network of multiple secondary APs operates using the transmission power of P_{tx} =20 dBm. Figure 3-3 shows the number of accessible channels when ASUI is taken into account for the whole range of considered transmission powers, for each of the three considered deployment scenarios. Figure 3-3 (a) shows that for the outdoor urban scenario, the number of accessible channels drops steadily with increasing P_{tx}.

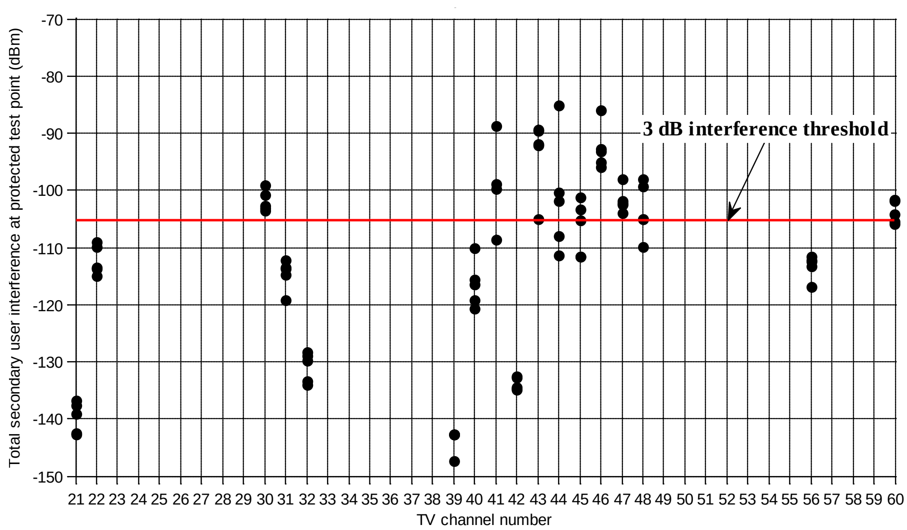
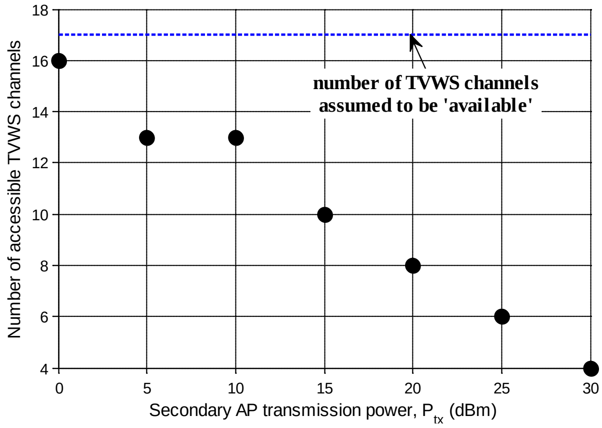
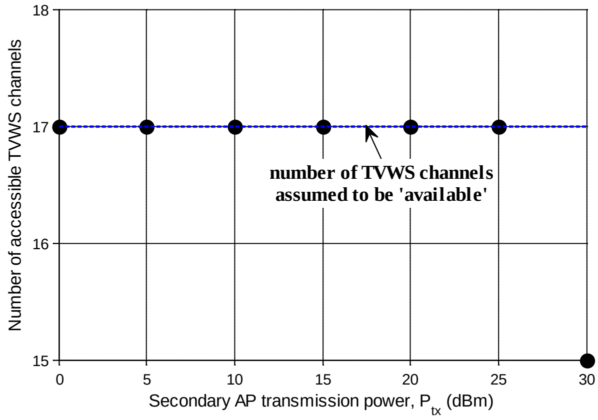


Figure 3-2: Aggregate secondary user interference at the protected test point for each available TVWS channel, for the outdoor urban scenario in the Aachen study area and Ptx=20 dBm (showing ASUI calculated for each of 5 simulation runs).



(a)



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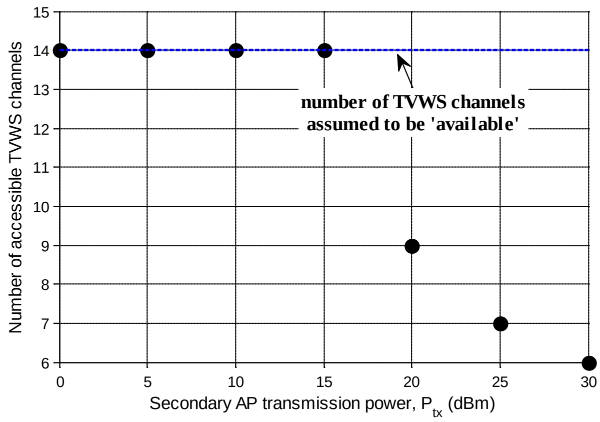


(c)

Figure 3-3: Number of accessible TVWS channels when aggregate interference to the primary system from the multiple secondary user WiFi-like network is taken into account vs. secondary AP transmission power Ptx, for the deployment scenarios of (a) outdoor urban, (b) indoor urban, and (c) outdoor rural.

Moreover, for the studied density of the urban network, none of the considered secondary transmit power levels are permissible with respect to secondary-to-primary interference (i.e. even at the lowest power of P_{tx} =0 dBm, operation of the secondary WiFi-like network causes excessive interference to the primary system on one of the 17 used channels, so it becomes inaccessible). The results for the indoor urban scenario in

Figure 3-3 (b) once again indicate a more favourable case, where the highest permissible secondary AP transmit power for operating on all 17 available TVWS channels is 25 dBm. However, for the outdoor rural scenario in Figure 3-3 (c), the highest permissible transmit power for operating on all 14 available TVWS channels is 15 dBm, which is rather low for an outdoor deployment.

Considering this reduction in the number of TVWS channels which are actually accessible, it is desirable to determine for a given fixed secondary transmission power the corresponding achievable secondary network performance when the prescribed limit on aggregate secondary interference to the primary is respected. For P_{tx} =20 dBm, which is the current transmit power limit for IEEE 802.11 Wi-Fi devices in the 2.4 GHz ISM band in Europe and the indoor limit in the US, the above results indicate that all 17 channels are accessible in the case of indoor use. Therefore, the performance results presented in Figure 3-1 (b) for P_{tx} =20 dBm hold even when the limit on secondary-to-primary interference it taken into account. However, as shown in Figure 3-3, for the other two deployment scenarios, not all channels remain accessible once secondary-to-primary interference is evaluated. Let us consider the example of P_{tx} =30 dBm, which would be a reasonable choice for an outdoor deployment and equates to the regulatory limit for outdoor Wi-Fi APs in the 2.4 GHz ISM band in the US. If secondary APs operate at P_{tx} =30 dBm, only 4 channels remain accessible for the outdoor urban scenario, as shown in Figure 3-3 (a). For the outdoor rural scenario, it was found that only 3 channels remain accessible if secondary APs operate at P_{tx} =30 dBm (Figure 3-3 (c) indicates 9 accessible channels, however this estimate is prior to reducing the total number of channels available to APs and recalculating the $ASUI$ with the greater loading of APs per channel; after several iterations of this $ASUI$ calculation, one arrives at only three accessible channels). The achievable performance of the secondary WiFi-like network degrades accordingly, as shown in Table 3-2. For the outdoor urban scenario, the average downlink throughput is almost halved once aggregate secondary user interference is controlled, whereas it is reduced by about 15% for the outdoor rural scenario. The coverage range is also reduced by 30% and 13% for the outdoor urban and rural scenarios respectively.

Table 3-2: Number of TVWS channels used by WiFi-like secondary network and corresponding achievable performance, for different deployment scenarios.

Number of 8-MHz TVWS channels	Outdoor Urban Scenario		Outdoor Rural Scenario	
	Average Rate (Mbps)	Maximum Range (m)	Average Rate (Mbps)	Maximum Range (m)
17 (urban), 14 (rural) channels assumed to be available	5.7	485	6.1	2030
4 (urban), 3 (rural) channels accessible when respecting the aggregate secondary interference limit, with P_{tx}=30 dBm	3.1	348	5.1	1760

3.1.4 **Summary**

Our analysis of the performance of a WiFi-like network of multiple secondary APs operating in TVWS confirms the favourable properties of operating in the lower TVWS frequency range of achieving a larger coverage area for the same power budget and enabling better propagation through walls. Our analysis also suggests that operating outdoor Wi-Fi hotspots in TVWS might be technologically attractive for rural areas where user demand is low. However, in dense urban areas where user demand is high, the increased congestion among APs caused by their extended coverage range when operating in TVWS rapidly limits the secondary system's capacity and makes a hotspot deployment in TVWS much less attractive. Moreover, our results indicate that, once secondary interference to the primary system is kept below the allowable limit, the achievable performance of a WiFi-like network deployed in TVWS is much more moderate than that predicted by more simplistic estimates.

3.2 Broadband delivery using inside-out in TVWS

Growing demand for high data-rate wireless service is putting stress on cellular networks leading to spectral congestion problem. Current cellular network operating costs are such that it may not be economically viable to use traditional macro network designs to provide same level of coverage for high data-rate services. This is mainly because of an increase in number of base stations that would be required due to the range reduction associated with increasing data-rates. Significant investments would have to be made for acquiring new spectrum, new sites and backhaul. Operators such as BT have adopted a different approach by deploying small-cell distributed networks that operate in license-exempt spectrum. Under the proposed architecture, the residential broadband customers share a portion of their home bandwidth with outdoor public users and on reciprocity incentive basis get free access to their home networks. This type of inside-out network build strategy is proving to be fastest and most cost-effective Broadband Wireless Access (BWA) network deployment model, with around 3 million WLANs in 2.4GHz ISM band currently available in the UK [17]. This study [18] presents an innovative proposal of extending the current inside-out network build strategy with use of TV White Spaces (TVWS) spectrum.

3.2.1 Scenario modelling and study details

Network Architecture

The proposed architecture of the resulting network is shown in Figure 3-4 is based on the use of geo-location technology for location determination combined with a database look-up. Each residential access point, also called a master device or hub, is assumed to be connected to a geo-location white space database that provides information on the availability of TVWS channels and corresponding power levels in a given location. Public users with a TVWS modem or dongle called as slaves connect to master devices via a TVWS channel that is periodically advertised via beacons by each access point.

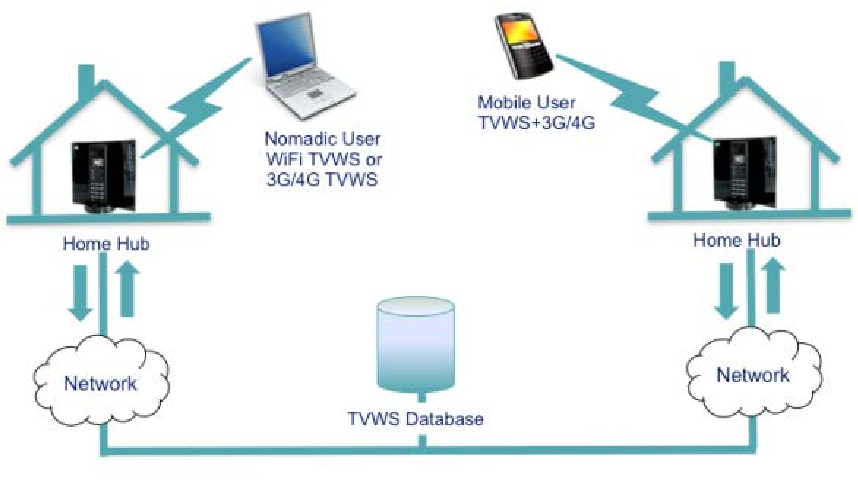


Figure 3-4: Example architecture of deploying inside-out BWA network with TVWS spectrum.

Simulation approach

Coverage and capacity performance comparison of a network operating in three spectral bands (5GHz, 2.4GHz and TVWS) in a square kilometre area of the three residential environments namely *dense-urban*, *urban* and *rural* is modelled. Dense-urban residential environment comprises of around 5000 houses/buildings in Central London, an urban residential environment comprises of around 2500 houses/buildings in Ipswich town and a rural environment comprising of around 150 houses of Westerfield village in rural Suffolk. Figure 3-5 provides a top view of representative residential environments selected for the simulation. The house and building layout data comes from a real geographical information system (GIS) database.

For a chosen residential environment, randomly selected houses are deployed with TVWS master hubs. The following range of hub penetration (0.5% to 40%) of the total houses is chosen for the study. At the detailed calculation level, the model uses an approach of dividing the total area into a grid of five square meter cells as shown in Figure 3-6. Master TVWS routers are placed in the grid cells that align with their selected locations. Power distributions within the grid are calculated at a grid-cell level granularity using appropriate propagation models to derive signal-to-noise-ratio (SNR). The propagation path loss profile value captures propagation effects based on environmental factors such as distance, geometry of the houses, number of walls and floors, etc as illustrated in Figure 3-6. This represents the best-case baseline results i.e. without any interference and set an upper bound performance for the chosen operating conditions.

Interference from neighbouring master hubs is then introduced to derive signal-to-interference-noise ratio (SINR) value of each grid-cell [19][20]. Interference from TV transmitters is accounted for by considering only those TV channels as white spaces which have a negligible interference capability on secondary systems. As the simulation run-times for a packet level simulation for deployment densities would become unacceptably long, certain mathematical tricks to reduce time complexity were adopted. The SINR value per grid cell determines the achievable data-rates, expected coverage or outage condition the studied grid cell. Statistics related to wider area are computed for different densities, geographies and spectral bands.

Figure 3-5: Examples of various representative residential environments, i.e., rural (leftmost), urban (centre) and dense-urban (rightmost side).

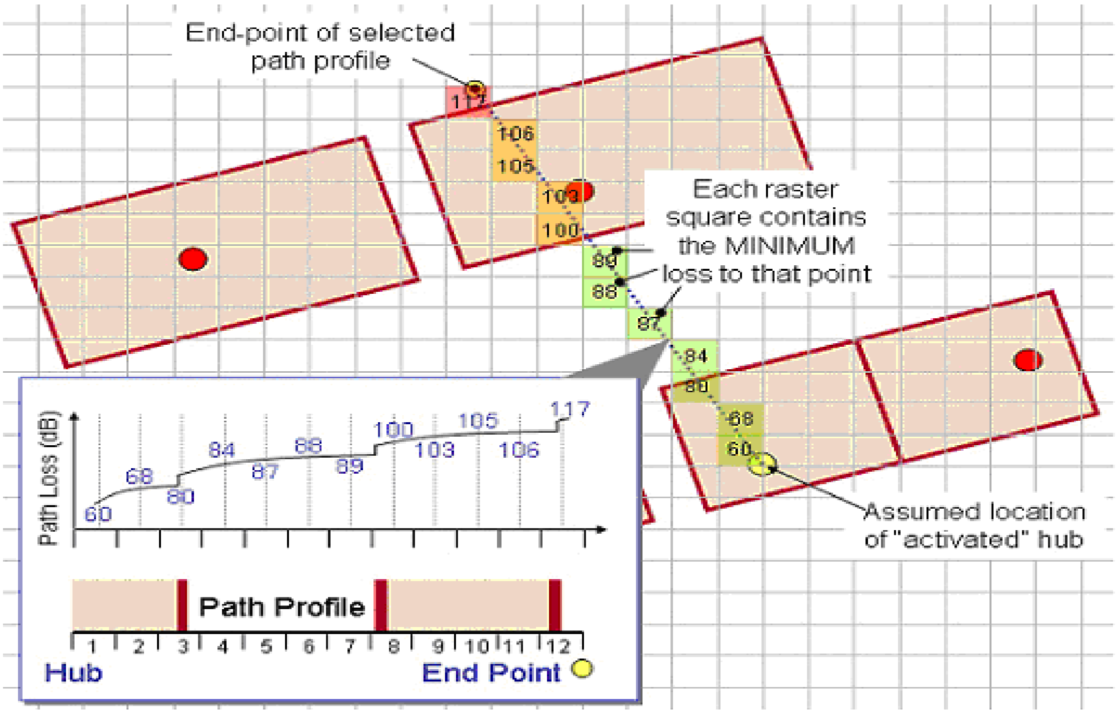


Figure 3-6: Path loss profile between TVWS master and each raster cell covered.

Interference modelling

The simulation model used for this study was built in MapInfo/MapBasic [28] software. MapInfo is a GIS platform to perform geographical mapping/analysis and includes support for geographic raster and vector database while MapBasic software is an application development environment for MapInfo. As simulation run-times for the packet level simulation for deployment densities selected here, would become unacceptably long, so an analytic simplification based on Poisson statistics and the Erlang traffic descriptors were used. The simplification used assumes that a packet stream being received by a TVWS master hub conformed to Poisson arrival statistics and that the packet size distribution is exponential. Then, each packet can be treated as an independent event and the average packet size can be taken to determine the average hold-time (*h*), which is one of the parameters needed to derive the traffic in Erlangs. The total traffic offered in Erlangs (*A*) is simply given by

$$A = \frac{L\,P}{R} = L\,h \tag{3.2}$$

where *A* is the offered traffic in Erlangs, *P* is the mean packet size in bits, *L* is the total traffic offered in packets per second, *R* is the data-rate available during busy hour in bit/s and *h* is the average hold-time.

For example, for an installation base of say 1500 TVWS master hubs in a square km that have an average data-rate of 4Mb/s in busy hour period with a mean packet size *P* of 1200 Bytes the total packets carried in the sq km system is *L*=625K i.e. 1500*4Mbs/(1200*8). This along with an underlying link rate of 10MBps results in an average hold-time *h*=P/R= (1200*8)/10Mbps. This results in the offered traffic *A* of 600 Erlangs in the system.

Next, to model interference at the slave device under study it becomes a statistical problem in that it is dependent upon how many of the other TVWS master hubs are actively transmitting a packet at the same time on the same channel and how far away they are from the slave. Consequently, this is a joint probability and combinatorics problem; joint probability to derive the probability of there being exactly *n* TVWS masters out of a total of *N*, transmitting a packet at the same time/ channel and combinatorics to derive the number of different combinations of *n* out of *N*, because from the perspective of the slave device the different combinations potentially create different interference levels depending upon their distances from the slave device. Under Poisson traffic flow assumption, the probability of exactly *n* masters transmitting a packet at the same time is given by the cumulate Poisson distribution or an incomplete Gamma function, which is

$$\Gamma_n = \Gamma(n+1,A) / \Gamma(n+1) \quad (3.3)$$

where *A* is the total traffic offered in Erlangs and Γ_n is the probability of up to *n* out of *N* home base stations simultaneously receiving a packet, *N* being the total number of home base stations.

For the assumptions made earlier in the example above, the 600 Erlangs equivalent traffic translates to about 660 masters being active for the chosen criterion of being simultaneously active 95% of the times as illustrated in Figure 3-7. The number of active master devices 660 here is finally split into the number of TVWS channels available in the particular location i.e. 110 masters per channel if 6 channels are available. The system simulation models then takes active interferers i.e. 110 for this example and runs hundreds of thousands simulation runs to model interference effects and generate SINR statistics per grid cell.

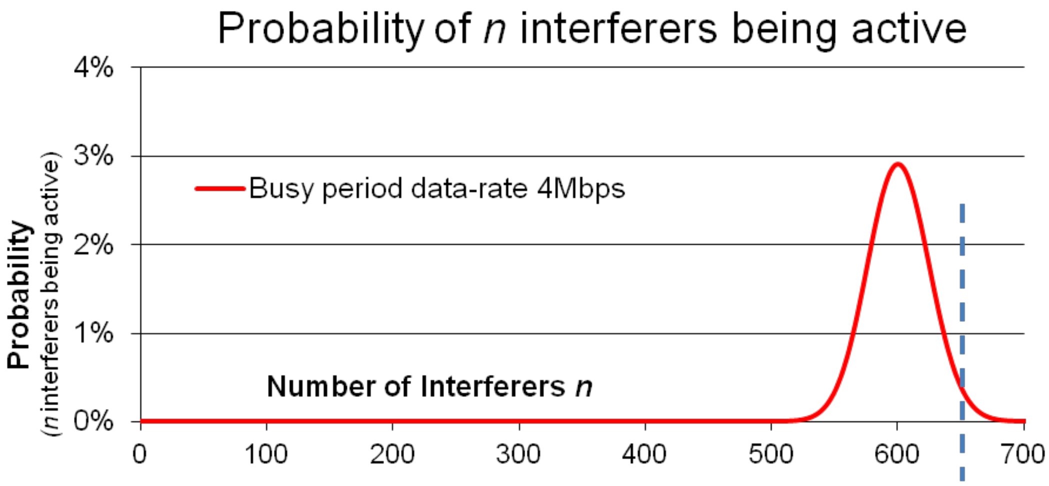


Figure 3-7: Number of n active interferers for the example presented.

List of assumptions

Table 3-3 lists the general assumptions made for the various wireless options, whereas further specific assumptions are listed below.

- Propagation models: ITU-R P.1238-5 [21], Multi-wall-floor model [22] and IEEE TGn channel models [23]
- 2x1 transmit diversity antenna scheme for 2.4 and 5GHz, no scheme for TVWS band due to λ/2 restriction, antenna radiation pattern isotropic
- Outside-wall loss: 10dB for 5GHz, 8dB for 2.4GHz, 4dB for TVWS band
- Indoor-wall loss: 4dB for 5GHz, 3dB for 2.4GHz, 1dB for TVWS band
- A 20dB margin assumed for fading, body, and cable losses.
- MAC layer overheads were assumed to be approximately 30% of the raw wireless link rate.

- Uplink performance not considered due to complexity of simulating WiFi client collision avoidance dynamics.

Table 3-3: Technological choices for comparing performance of various spectral bands.

Spectral band	2.4GHz	5GHz	TVWS
Frequency range	2.4 -2.483 GHz	5.15 - 5.35 5.47 - 5.75 GHz	470 - 862 MHz
Available Spectrum	83.5MHz	380MHz	50-150MHz Location dependent
Channel Bandwidth	20MHz	20MHz	8MHz
Transmit Power level	20dBm	23dBm	10dBm
Modulation Schemes	½ BPSK, ½, ¾ QPSK, ½, ¾ 16QAM 2/3, ¾, 5/6 64-QAM		
Duplex	TDD		
Wireless interface	OFDM		

3.2.2 Study results

Coverage results for the various spectral bands operating in different environments are presented in Figure 3-8 and discussed here with following observations. As seen from the figure, the TVWS band provides excellent coverage beyond 95% RF coverage of the total area with a mere 10-15% community access point penetration in dense-urban environments. The coverage performance results in urban environment show 95% coverage possible with 20% penetration while in rural environment the coverage is limited to about 30%. The lower percentage in rural areas is due to the nature of house-layout depicted in the earlier figure as the houses tend to be clustered in the centre of village. Results are not affected by interference, as there is high number of TVWS channels available in rural areas. Benefit of using lower frequencies in the TVWS band is reduction in penetration loss and increased coverage. Further, the in-band thermal noise is lower in TVWS band as it uses a lower channel bandwidth of 8MHz as compared to a 20MHz wide channel of 2.4 and 5GHz for an equivalent transmit power spectral density; thereby leading to an improved link budget.

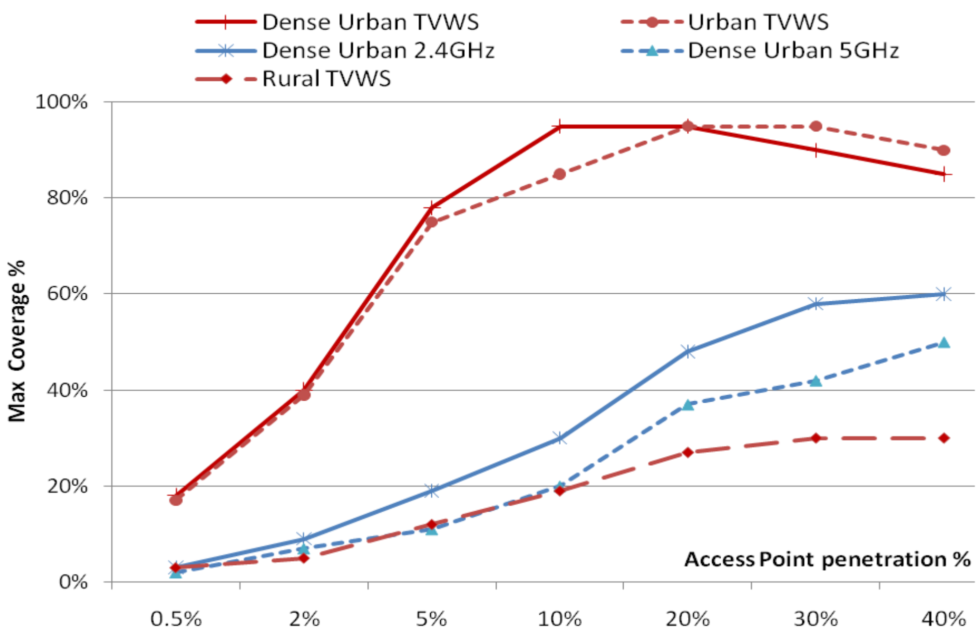


Figure 3-8: Network coverage with increasing access point penetration levels for various spectral bands and geographies.

The 5GHz band achieves RF coverage of about 55% at around 50% penetration level. The coverage is limited due to higher attenuation losses in higher frequency and a higher in-band noise as the channel is 20MHzwide. Further the non-uniform house layout makes it increasingly difficult to provide blanket coverage.

Performance of 2.4GHz, is between the two other spectral bands and achieves a max RF coverage of about 60% with around 40% penetration level. This ceiling is introduced due to the rising interference levels.

As seen from Figure 3-9, the best average data-rate corresponding for the covered RF area is available with 5GHz band (17Mbit/s), followed by 2.4GHz (14Mbit/s) and TVWS (9Mbit/s) band. This is due to combined effect of interplay of few fundamental factors which include (a) a larger channel bandwidth i.e. 20MHz as compared to 8MHz of a TVWS channel (b) minimal interference degradation due to large spectrum availability (about 380MHz in the UK) in 5GHz (c) use of higher frequency limits interference compared to the TVWS bands. Interference effects in TVWS networks kick in at relatively low deployment densities for dense-urban and urban scenarios. The results suggest that with the use of “density-adaptive” power control and dynamic channel selection algorithms are essential to avoid interference issues as the density of TVWS devices increases. Such functionalities provide a finer control to manage interference especially when spectral availability for a given area is constrained.

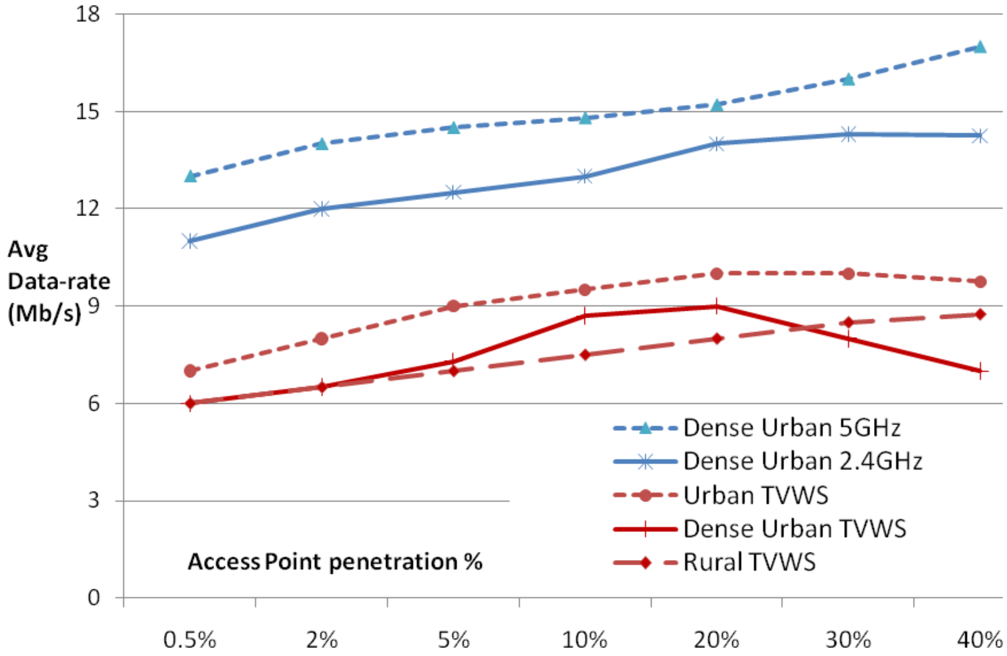


Figure 3-9: Average data-rates with increasing access point penetration levels for various spectral bands and geographies.

3.2.3 **Summary**

Overall the results show that a with modest adoption rate in TVWS spectral band, an extensive broadband wireless network is possible using an inside-out network build strategy with community networks. The TVWS spectral band is suitable for range limited services, as the access point density to provide ubiquitous coverage is significantly reduced as compared to the 2.4GHz and 5GHz band. The performance of 2.4GHz is limited due to interference while that of 5GHz is limited due to higher attenuation losses.

The use of TVWS band with an inside-out network build strategy enables migration to small cell topology and offers a powerful, fast and cost-effective broadband wireless delivery platform. Study results for dense urban and urban scenarios show, interference-effects kicks in at relatively low penetration rates. A good area to extend this work would be to consider various etiquette protocols, power control and database-centric approaches for interference mitigation and dynamic channel selection for these deployment scenarios. This, therefore suggests, that an advanced access control scheme with the use of “density-adaptive” power control and dynamic channel selection algorithms are required in order to achieve optimal coverage with TVWS systems. Such functionalities would provide a finer control to manage interference especially when spectral availability for a given area is constrained.

3.3 A case study in Macedonia

In this section we analyse the possibility to use a WiFi type of secondary network containing multiple SUs in the TV bands, presenting a case study in Macedonia. In particular, the analysis investigates the limitations imposed by the aggregate interference caused by the SUs to the primary system, assuming different levels of penetration of the secondary system.

3.3.1 Target area and system model

Primary system

Due to processing power requirements, the investigation takes a limited area which co-locates with the capital of Macedonia, Skopje. The target area is 15 km by 20 km, and belongs to urban type of environment.

The primary system model includes the actual TV transmitter locations and operational parameters within and near the target territory, operating on TV channels 21 to 60. The signal level determines the coverage area of each TV transmitter. For this purpose the Radio Mobile freeware [24] provides the needed calculations, incorporating the actual terrain elevation of the target area. As an example, Figure 3-10 presents the signal level in dBm for channel 43 over Skopje area. The coverage area contour is clearly visible for this channel.

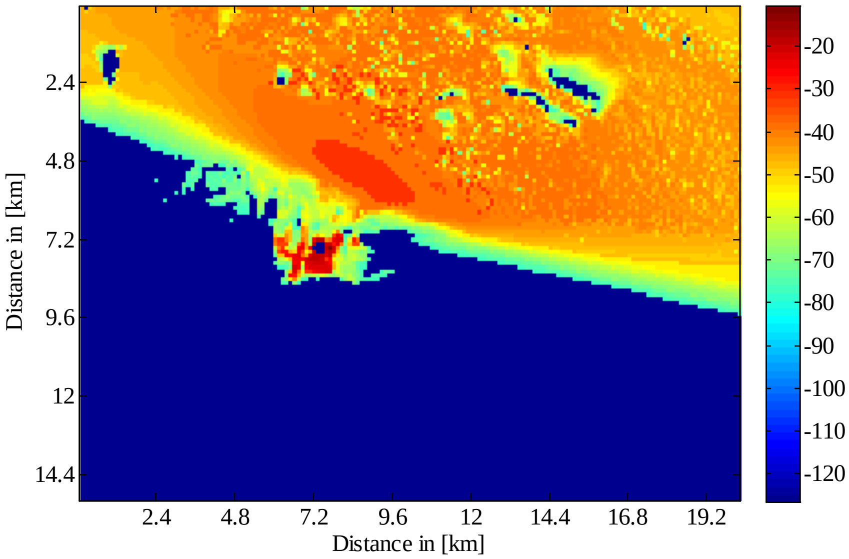


Figure 3-10: TV coverage area (in dBm) for channel 43.

Secondary system

The secondary network involves low power indoor WSDs randomly distributed within the target territory. Each WSD has maximum transmission power of 20 dBm. The analysis assumes wall penetration loss of 5 dB. According to the findings presented in [3] for the same case in Macedonia regarding the availability of TVWS frequency chunks, the following analysis assumes SUs which only exploit 8 MHz channel chunks.

The SUs locations represent a spatial point process in the given area of interest. As defined in [27], such point processes yield randomly distributed collections of indistinguishable locations $X = \{X_i\}_{i=1}^{n}$ in some regular enough region *E*. Both the individual locations $X_i \in E$ and the total number of points *n* are in general random but not independent of each other. According to [27] the *Geyer saturation process* is suitable for Wi-Fi location modelling in urban areas. The Geyer process is a generalized version of the *Strauss point process*. The following equation gives the probability density function of the Strauss process:

$$f(X) = \alpha \beta^{n} \gamma^{s_r(X)}, \tag{3-4}$$

where $s_r(X)$ denotes the number of point pairs of *X* that are closer than distance *r* apart, $\beta \geq 0$ and $0 \leq \gamma \leq 1$. α is used for normalization. Since $0 \leq \gamma \leq 1$, the Strauss process is a powerful tool for modelling regular point processes, but it cannot model clustered distributions of points. The Geyer saturation process further introduces the so called saturation threshold ζ which bounds the contribution of the exponent of γ and removes the limitation $0 \le \gamma \le 1$ of the Strauss process, so that γ can take values higher than 1 which corresponds to a description of clustered point processes. The probability density function of the Geyer saturation process is:

$$f(X) = \alpha\beta^n \gamma^{\min\{\zeta, s_r(X)\}}. \quad (3\text{-}5)$$

The analysis in this section exploits the model of WiFi node locations fitted by the Geyer saturation process to the publically available data from the Google Mountain View WiFi network [25] by means of maximum pseudo-likelihood fitting. The Geyer saturation process has the following parameters: $\beta \approx 3.329 \times 10^{-5}, \gamma \approx 0.4112, \zeta = 2, r = 150m$.

For a given density ρ (number of SUs per km^2), the Geyer process gives stochastically distributed realizations for the area of interest. Since random sample from the Geyer saturation process (whose PDF is given by (3-5)) is difficult to obtain, the analysis extensively uses the Metropolis-Hastings iterative algorithm with 10000 iterations. The chosen value of the number of iterations assures convergence of the Metropolis-Hasting algorithm. The SPATSTAT software suite in R carries out the needed calculations [26]. Figure 3-11 shows a sample realization of the Geyer saturation process using the fitted model.

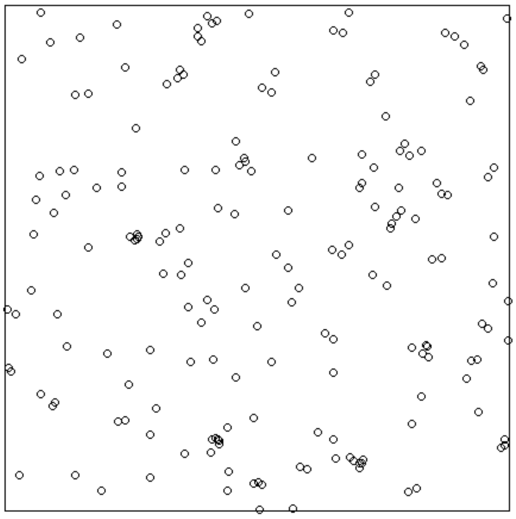


Figure 3-11: A sample realization of the secondary system.

3.3.2 **Evaluation methodology**

The analysis assumes a database operating in accordance to the ECC rules (SE43, Report 159), which has the needed knowledge to coordinate SUs operation in TV whitespace. The database contains the allowable transmit power calculated for a single SU operating in a given geographical location within the investigated region and on a specific 8 MHz channel. As an example, Figure 3-12 shows the allowable SU transmit power (in dBm) for channel 43 in the evaluated area.

In this analysis, a TV channel is available in a given location for secondary usage only if the permitted SU transmission power is equal or higher than the assumed SU's transmission power. Figure 3-13 shows the locations where a SU may operate on channels 42, 43 or 44 (orange colored pixels).

Table 3-4 contains the distribution of available channels within the analyzed territory, giving the percentage of the locations where *N*-number of TV channels are available to a SU.

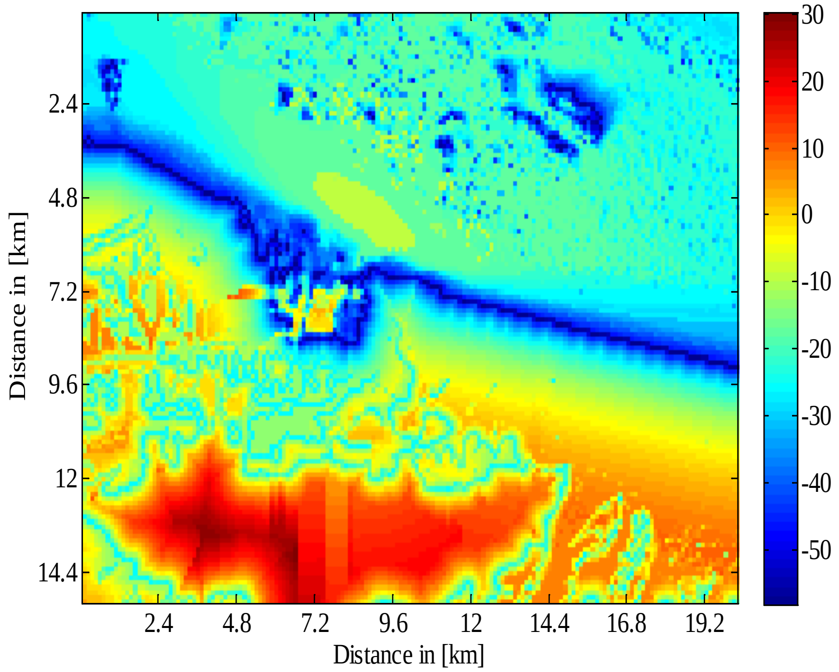


Figure 3-12: Allowable SU transmit power for channel 43.

Table 3-4: Percentage of the target territory where N TV channels are available.

	N = 0	N = 1	N = 2	N = 3	N = 4	N = 5	N = 6	N = 7
%	17.35	20.73	20.29	20.51	12.43	5.01	2.22	0.35

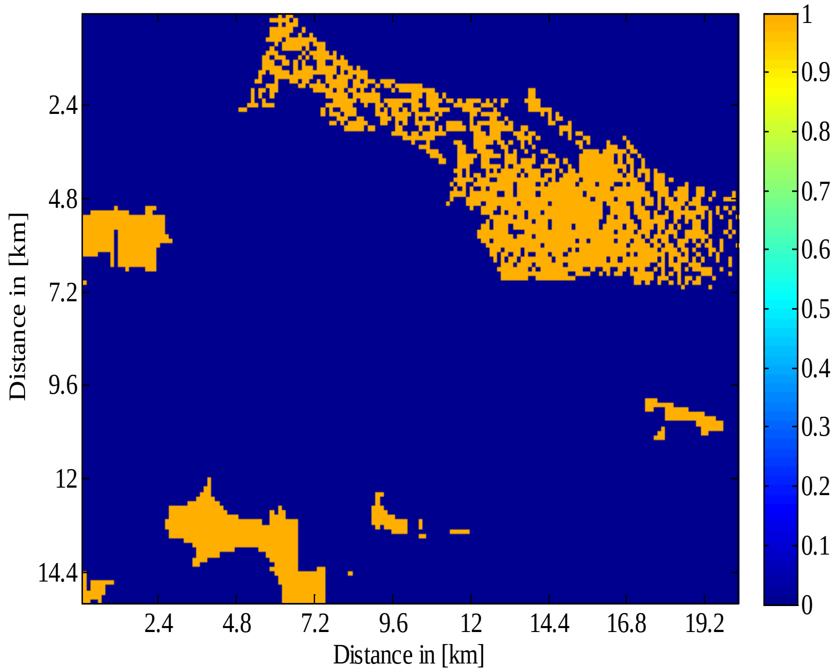


Figure 3-13: Combined channel availability locations for channels 42, 43 and 44.

The analysis additionally assumes an existence of a central entity (sharing manager) which coordinates the operation of the secondary system. It has constant access to the database. Each WiFi-like user attempting to begin secondary usage of TV whitespace sends a request to the central entity. The central entity handles these requests and uses the knowledge stored in the database to grant permission for secondary access or ban secondary usage for a SU if no channels are available in the specific geographical location. If permission for secondary access is granted, the central entity responds to the SU with the assigned channel on which the SU is allowed to transmit. The SUs are unaware of each other and operate in a non-cooperative manner. As they start transmitting on the assigned 8 MHz channel they begin to produce co-channel and adjacent channel interference to the PUs i.e. the TV receivers in the investigated region.

In order to evaluate the impact of the secondary system, the investigation uses Monte Carlo simulations based on 100 different realizations of SUs for various SU densities (SUs/km^2). SUs were generated with SU densities of 5, 10, 13, 20, 27, 34, 41, 70, 97 and 104 SUs per km^2. All generated SUs belonging to one realization simultaneously send transmission requests to the central entity and those that receive permission start operating on the assigned channel. The analysis then determines the aggregate co–channel and adjacent channel interference (from +/-1 adjacent channel). Both the co–channel interference and the adjacent channel interference are calculated only for the worst case scenario locations. The worst case scenario for the co-channel interference are the borderline pixels of the coverage area, whereas the worst case scenario for the adjacent channel interference are the pixels that are inside the coverage area for an adjacent channel and have SUs operating in the same pixel. The aggregate interference of a particular realization of SUs may be higher than the allowed, and such case will cause degradation in the location probability of the TV system. Figure 3-14 shows the co-channel interference produced from one realization of SUs with SU density of 104 SUs/km^2 operating on channel 43 in the evaluated region. Figure 3-15 shows the adjacent channel interference produced from SUs operating on channels 42 and 44. Figure 3-16 gives the total interference in the evaluated region for channel 43.

Since the database operates implying the ECC criterion originally developed for single SU, the total aggregate interference coming from multiple SUs can be higher than the permitted SU transmission power for some pixels. This analysis aims to determine the percentage of multiple SUs realizations for which the secondary system interference is intolerable. In other words, the aim is to find the so called acceptance rate of the SUs realizations, regarding the occurrence of intolerable multiple SUs aggregate interference.

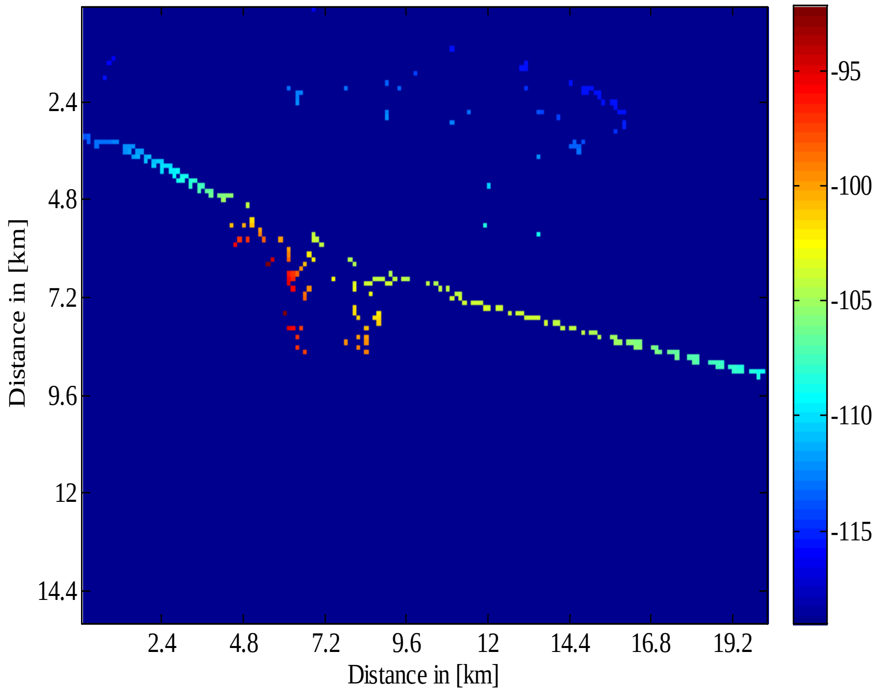


Figure 3-14: Aggregate co–channel interference for channel 43.

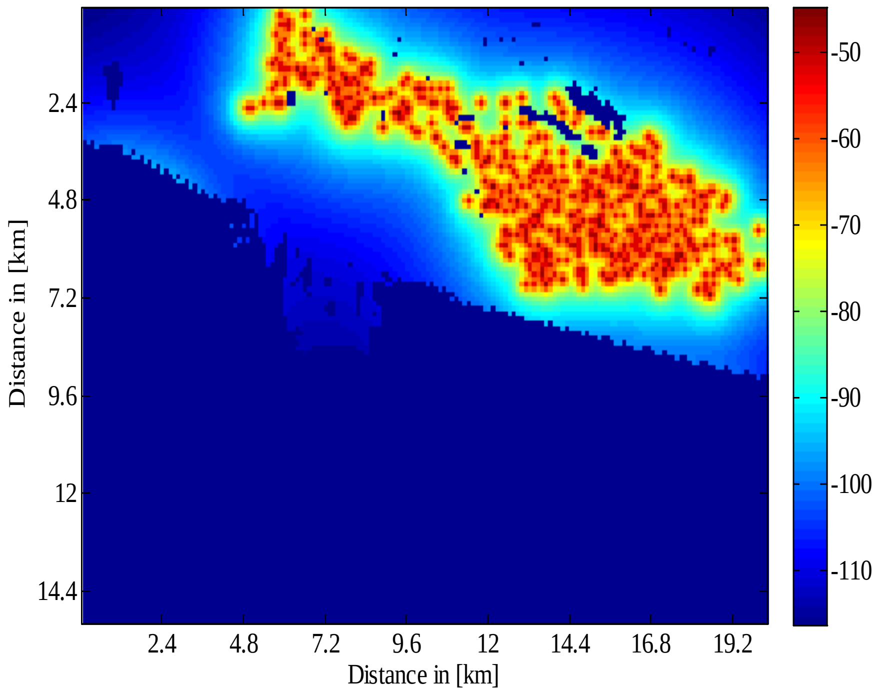


Figure 3-15: Aggregate adjacent channel interference for channel 43 coming from SUs that operate on channels 42 and 44.

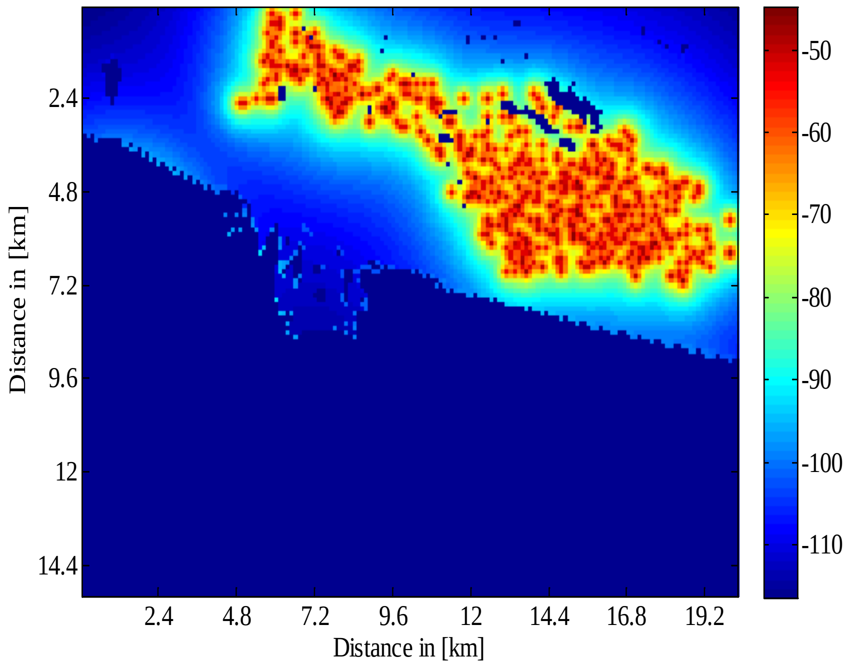


Figure 3-16: Total aggregate interference for channel 43.

3.3.3 Sharing schemes implementation

The analysis investigates three different approaches of sharing manager operation, i.e. channel allocation schemes. Initial investigation includes simple sharing scheme where the channel allocation is based on a random selection. The later channel allocation schemes add some intelligence into the channel dedication per secondary user, targeting increase in acceptance rate of SUs realizations even for scenarios with higher SU density.

Random based sharing scheme

The most general approach is random based channel allocation. The algorithm assumes database-based sharing approach in which the sharing manager is aware of the secondary users' locations and the available TV channels at each specific location. An 8 MHz wide available TV channel is dedicated to each secondary user in a random manner from a predefined known set of available channels. This approach keeps the generality and represents an uncontrolled channel allocation case. Figure 3-17 depicts the algorithm flowchart.

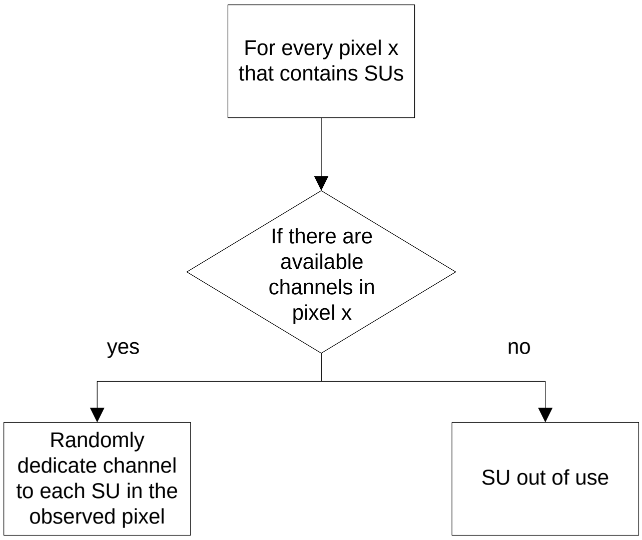


Figure 3-17: Random channel allocation scheme algorithm.

Power-weighted uniformly distributed channel sharing scheme

The second approach assumes that the sharing manager contains information on tolerable power level for every available TV channel at every SU location. The algorithm ranks the available channels based on the allowed secondary transmission power. The channel allocation is pixel based, meaning, the sharing scheme dedicates the available TV channels, ranked in a decreasing manner, to the secondary users in the observed pixel starting from the channel with highest allowed transmission power. The detailed algorithm is presented in Figure 3-18. This approach introduces simple power ranking scheme, forcing to use firstly the “more available” TV channels, for the observed pixel.

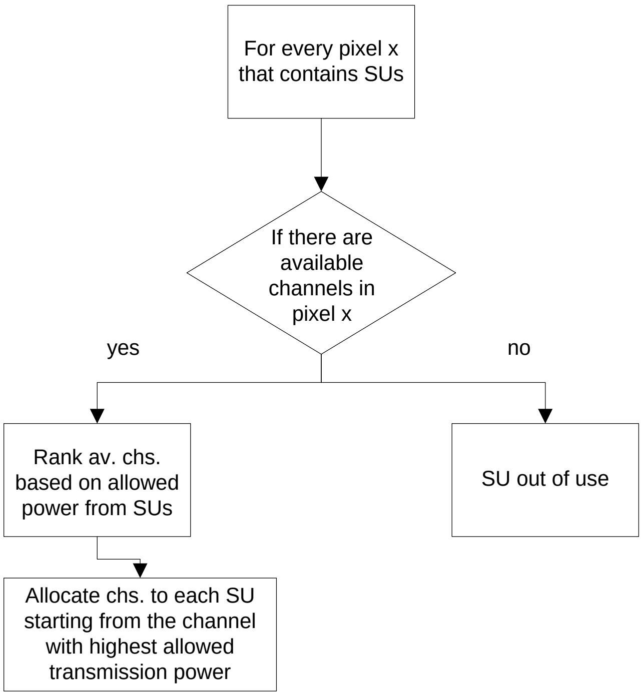


Figure 3-18: Power based ranking sharing scheme algorithm.

Power-weighted non-uniformly distributed channel sharing scheme

The third sharing scheme upgrades power ranking with additional features, targeting increase in acceptance rate of the SUs realizations. This algorithm also assumes TV channels ranking, based on allowed secondary transmission power. The sharing scheme is further upgraded adding weighted coefficients for each available TV channel. The algorithm forces use of "the most available" channel (meaning the available TV channel with the highest value for allowed secondary power transmission). The idea is based on real allowed secondary power experience for the target area. For this sharing scheme, every weight coefficient presents the percentage of secondary users in one observed pixel that would be allocated with the specific channel. The algorithm chooses the channel with highest value for allowed secondary interference and allocates this channel to proportional part of secondary users in the observed pixel that equals its weight coefficient. The algorithm is depicted in Figure 3-19.

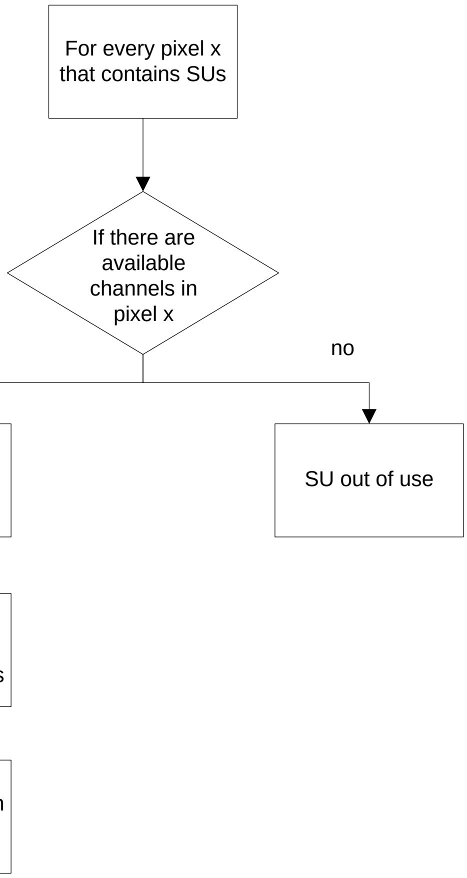


Figure 3-19: Power based weighted sharing scheme.

Further investigation would add better adaptation capabilities in terms of weight coefficients flexibility for the proposed sharing scheme. In this case the available channels are not uniformly populated with SUs. Consequently, a throughput evaluation should be performed for this particular scheme.

3.3.4 **Results**

The goal of this analysis is twofold: find the probability that a particular set of multiple SUs (a realization) will cause degradation of the location probability for the primary TV receivers and show the possible improvement reached through various sharing schemes. Using the evaluation methodology from above, the analysis investigates the rate at which the generated realizations of SUs will cause less interference to a given location than the one allowed according to the ECC rules. The percentage of "successful" realizations of SUs that have caused less interference to any investigated pixel according to the methodology is called the realizations acceptance rate and is derived using Monte Carlo simulations for various SU densities. Figure 3-20 shows the convergence of the realizations acceptance rate for various number of realizations used. It verifies that the use of 100 realizations in the Monte Carlo simulations is valid.

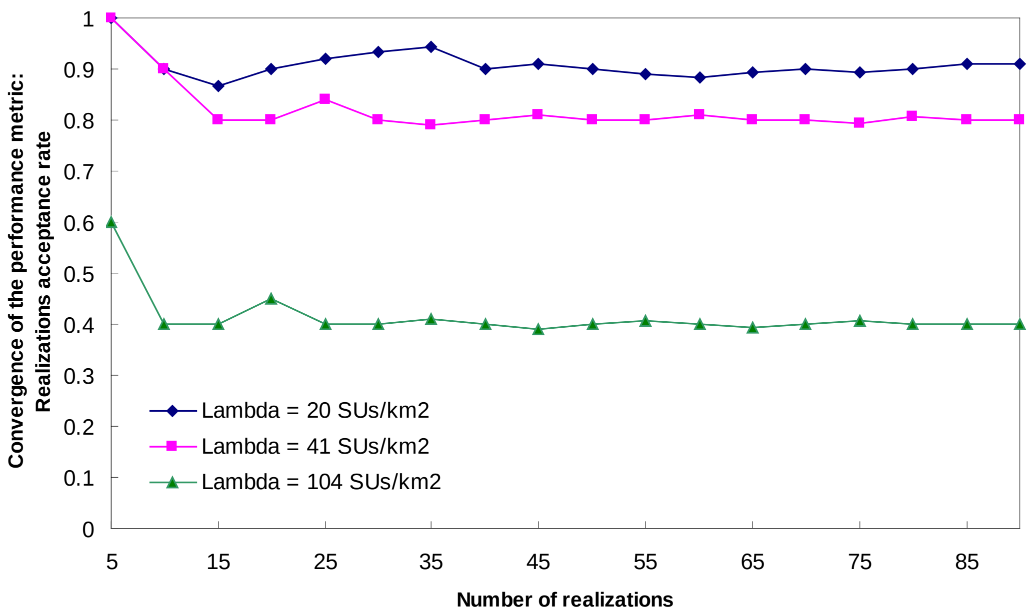


Figure 3-20: Convergence of the performance metric.

Figure 3-21 gives the realizations acceptance rate determined using the sharing schemes explained above. It is evident that the location probability can be preserved even for higher SU densities with the use of the power-weighted channel sharing schemes compared to the simple random channel allocation. The use of sharing schemes can mitigate the effect of the aggregate secondary user interference.

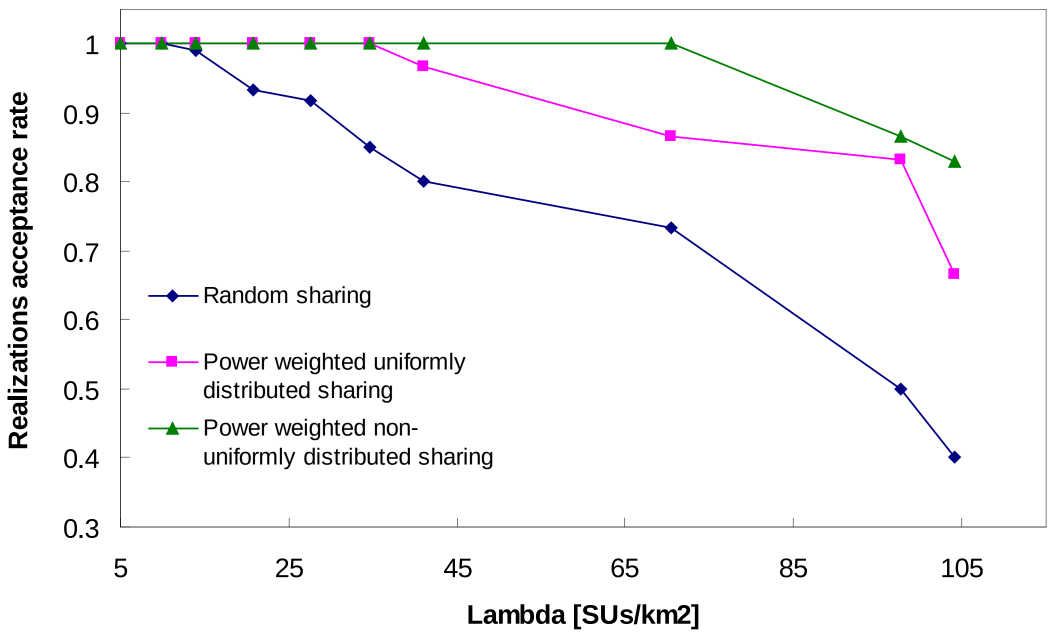


Figure 3-21: Influence of the aggregate interference.

3.3.5 Summary

ECC defines the maximum allowed transition power for a SU based on a controlled degradation of location probability of the primary system reception. Since the criterion defined in ECC Report 159 [5] originally takes into consideration only single secondary user, it is possible that multiple SUs for which the ECC database has allowed separate operation, to produce intolerable level of total aggregate interference (co-channel and adjacent-channel) towards the primary system. The obtained results in this case study revealed that adjacent channel interference usually is higher than the values of co-channel interference. The presented analysis investigated the percentage of acceptable random SUs realizations regarding the produced aggregate interference, for different densities of SUs within the analyzed territory. Implementing intelligent channel sharing schemes improves the acceptance rate even for higher SUs densities. This requires an existence of a sharing manager that coordinates the allocation, or SU feedback to the geolocation DB (i.e., case where the geolocation DB takes the role of sharing manager).

3.4 Concluding remarks

Based on our diverse case studies on deploying WiFi like multi-user secondary systems in the TWVS we can summarize our conclusions as follows. Our analyses have confirmed that operating such a secondary system in lower frequency bands will provide larger coverage for the same power compared to a traditional WiFi system operating in ISM band. Operating outdoor WiFi hotspots in TVWS might be technologically attractive for rural areas where user demand is low. However, in dense urban areas where user demand is high, the increased congestion among APs caused by their extended coverage range will rapidly limit the secondary system's capacity and make a hotspot deployment in TVWS much less attractive. Furthermore, one has to bear in mind that keeping the aggregate interference from the secondary system on an acceptable level will additionally decrease the performance of the system.

From the case study in the UK we have learned that the TV bands are suitable for insight-out small-cell community networks. This opens the possibility for an internet service provider to offer fast and cost-effective wireless broadband services for villages in rural areas, for example. However, these studies also show that aggregate interference is a serious issue in dense urban environments and an advanced access control scheme with “density-adaptive” power control and dynamic channel selection algorithms are required in order to achieve optimal coverage with TVWS systems. Similar conclusions on the impact of the aggregate interference can be also drawn from the case study performed in Macedonia.

4 Indoor Broadband Use of 2.7-2.9 GHz Radar Spectrum

The indoor broadband use of 2.7-2.9 GHz radar spectrum was studied previously in D5.2 section 3.2 [3] and represents a great potential for secondary spectrum implementation. This following section continues the study introducing more realistic scenarios where multiple secondary users exist. The section contains three parts: a mathematical analysis provided in the first subsection, a case study of Stockholm provided in the second subsection and a case study of Macedonia presented in the final subsection.

4.1 Scenario description and numerical analysis

4.1.1 Primary and secondary systems

In this section, air traffic control (ATC) radar operating in 2.7-2.9 GHz band is considered as the candidate primary system. The technical specifications of typical ATC radar can be found in the previous deliverable [3], as well as in ITU recommendation [33].

SUs are low-power devices providing indoor broadband access whose physical layer parameters are similar to LTE HeNB [34] or Wi-Fi. Since the physical layer parameters of downlink and uplink are not very different from each other in indoor environments, we will not distinguish the downlink and uplink of secondary system. Height of indoor system is usually considered to be 1.5m. We can 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 [35]. Parameters of the SUs are given in Table 4-1.

Table 4-1: Parameters of SU.

Parameters	**Secondary user**
Bandwidth (MHz)	20
Transmit power (dBm)	-10, 10, 30
Antenna gain (dBi)	0
Antenna height (m)	1.5 (below clutter), 30 (above clutter)
Activity ratio (%)	100

We consider multiple SUs spreading in a large geographical area. Therefore, aggregate interference generated by the SUs is of concern in protecting the radar. In this subsection, SUs are assumed to be uniformly distributed for mathematical analysis. In the following subsections containing case studies, the population density will be taken into account, including spatial statistics suitable for WLAN SUs. Contrary to the SUs number, there are only few radars operating in the same geographical region.

4.1.2 Radar protection rule

As it is shown in the examples of TVWS in previous sections of the deliverable, the protection rule for the primary user makes a huge impact on the performance of the secondary access. Since the ATC radar performs a function concerning safety-of-life, a strict protection rule should be applied to any potential secondary access scheme. We propose a rule based on the probability of harmful interference:

$$\Pr\left(I_{su}^{agg} \geq THR_{rad}\right) \leq \beta_{rad} \; . \qquad (4\text{-}1)$$

Notations used above are:

I_{su}^{agg} : received aggregate interference power at the radar from the SUs,

THR_{rad} : interference threshold value for the radar,

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

The value of THR_{rad} is determined by the required interference to noise ratio (INR) and protective margins such as apportionment margin and fast fading margin.

Although the proposed protection rule is based on probabilistic approach, the allowed interference violation β_{rad} should be sufficiently low to ensure the proper protection of the radar. Reasonable value of β_{rad} has not been fully investigated in the literature either. We use β_{rad} =0.001% as used in [36], although it may result in pessimistic result. Practically it means almost zero violation. Moreover, β_{rad} does not necessarily represent the event of radar failure. It rather means the probability that I_{su}^{agg} exceeds THR_{rad}, which is already conservative.

The aggregate interference I_{su}^{agg} depends on the decisions of SUs on the transmit powers. We assume a simple model that every SU employs the same transmit power $P_{tx,su}$, and then it makes an individual ON/OFF decision based on its estimation of propagation. Let us consider an arbitrary SU j. We define ξ_j as the interference power that the radar would receive from the SU j if it were to transmit. Also, let $\overline{\xi_j}$ be the estimate of ξ_j which is measured by the SU j. The decision of the SU j relies on the individual interference threshold I_{thr}, which is applied to every SU in the system. A proper value of I_{thr} should be determined depending on radar protection parameters (THR_{rad}, β_{rad}) and the aggregate interference caused by the SUs. As a result of the decision, the actual interference from the SU j to the radar is given by

$$I_j = \begin{cases} \xi_j, & \text{if } \overline{\xi_j} \le I_{thr}, \\ 0, & \text{otherwise.} \end{cases} \qquad (4\text{-}2)$$

Then, the aggregate interference can be expressed by

$$I_{su}^{agg} = \sum_{j=1}^{N} I_j , \qquad (4\text{-}3)$$

where N denotes the total number of the SUs in the investigated area.

Note that the above interference control scheme resembles the dynamic frequency selection (DFS) which is specified in ETSI standard EN 301 893 for WLAN devices who want the have access to radar spectrum in 5 GHz (5150-5350 MHz and 5470-5725 MHz) [37][38]. However, our scheme differs from the DFS in the sense that we consider adaptive adjustment of I_{thr} depending on the intensity of SU traffic in order to ensure the protection or the radar and to maximize the opportunity to the SUs.

4.1.3 **Opportunity detection mechanism**

Equation (4-2) implies that the accurate estimation of ξ_j is critical to the radar protection and SU opportunity. For the implementation of the DFS in the 5 GHz radar spectrum, spectrum sensing has been applied to detect the existence of the radar. In fact, spectrum sensing is a favourable technology for the secondary access to radar spectrum because radar transmitter and receiver are usually collocated and they employ the same frequency band. However, there are several drawbacks of the purely sensing-based mechanism.

First, various radars with different pulse shapes, durations and centre frequencies are operating in 2.7-2.9 GHz spectrum. Lack of knowledge about the radar operational facts may result in the misdetection of the radar, which could be detrimental. Second, detection of radar signal cannot be converted to the estimation of propagation loss unless the radar EIRP is known to the SUs. Third, aggregate interference control cannot be guaranteed unless I_{thr} is adaptive to the SU traffic load.

With these reasons, we consider the use of central database that feeds the information about radar and I_{thr} to the SUs. Therefore, the SUs employ ***spectrum sensing aided by database***. It is reasonable to assume that each SU can accurately estimate the mid-term propagation loss, i.e. distance-dependent path loss and shadow fading. Then, fast fading margin is considered to allow for the instantaneous variation of radio signal strength.

4.1.4 **Access to overlapping and non-overlapping channels**

Separation of primary and secondary users in frequency domain is one of practical means to reduce the interference. 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 non-overlapping channel if the interferer and the victim are separated in frequency. When the victim system is based on short pulses and the transmit power is based on peak power, OTR is defined [35] in dB as

$$OTR = \max\left[0, 20\log_{10}\left(BW_{tx}/BW_{rx}\right)\right]. \tag{4-4}$$

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.

4.1.5 **Exploiting temporal opportunities**

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. Second, in many cases, the antenna rotates 360 degrees in a regular and predictable manner[3]. 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.

Let us consider the following horizontal antenna pattern for simplicity:

$$G_{rad} = \begin{cases} G_{rad}^{\max} & \text{if } 0 \le \theta \le \theta_{MB} \\ G_{rad}^{\min} & \text{otherwise} \end{cases}. \tag{4-5}$$

A radar antenna has typically a maximum gain in the range of 30-45 dBi and first side lobe in the range of 10-20 dBi.

Let $\xi_j^{\max}$ be the value of ξ_j when the SU j faces $G_{rad}^{\max}$. If the SU does not have a precise knowledge about the rotation of the radar, it will have to make a conservative decision that it will always face the radar beam when it transmits, i.e. $\overline{\xi_j}$ equals to $\xi_j^{\max}$. As a result of this type of SU's decision, the interference from the SU j to the radar is given by:

[3] This normally applies to radars watching a large area in a continuous manner, e.g. weather forecast and air traffic watch. Radars for tracking a specific object do not follow the regular rotation pattern.

$$I_j = \begin{cases} \xi_j, & \text{if } \xi_j^{\max} \le I_{thr}, \\ 0, & \text{otherwise.} \end{cases} \quad (4\text{-}6)$$

This scheme will be termed ***static decision*** hereafter.

Now, we consider an ideal case that the secondary users are aware of the antenna gain and rotation pattern of the radar. We believe this is feasible to implement if the SUs are fed with relevant information by the central database. With this assumption, the secondary users can make refined decision based on the instantaneous interference rather than the worst case. Therefore, I_j is given by

$$I_j = \begin{cases} \xi_j, & \text{if } \xi_j \le I_{thr}, \\ 0, & \text{otherwise.} \end{cases} \quad (4\text{-}7)$$

This scheme will be termed ***temporal decision***.

4.1.6 Numerical analysis

It is important to accurately describe the characteristics of aggregate interference I_{su}^{agg} to quantify the availability of the secondary access to the radar spectrum. The probability distribution of I_{su}^{agg} has been investigated in the QUASAR project (see, e.g. [4], [38], [39]). In this subsection, we present the impact of multiple SUs on the secondary access availability. The results are under the assumption of overlapping channel usage.

Consider a large circle of radius R where the radar is located at the origin. SUs are uniformly distributed with the density of λ (SUs per km^2). Based on the mathematical aggregate interference model described in [4], we obtained the minimum required separation between the radar and SUs. Note that the separation refers to the path loss between the radar and the SU after taking antenna gain into account. For the numerical experiments, we consider the radar parameters in [33] by choosing *type-A* radar, which is one of representative radars in [33]. SU parameters appear in Table 4-1. Additionally, shadowing standard deviation of 8 dB and R of 150 km are employed. Distance-dependent path loss is calculated by Hata-like model for its simplicity. Wall penetration loss of 5 dB is additionally considered.

We will firstly present the results of overlapping channel usage under the static decision scheme. Figure 4-1 shows the minimum required separation between the radar and the SUs as a function of the SU density λ. It is compared with the case of single SU. It is observed for low traffic load ($\lambda \le 1$) a margin of less than 10 dB is enough to take into account the impact of multiple SUs. However, the required aggregate interference margin soars as λ increases. This suggests that the impact of aggregate interference is significant if the radar spectrum is heavily occupied by the SUs.

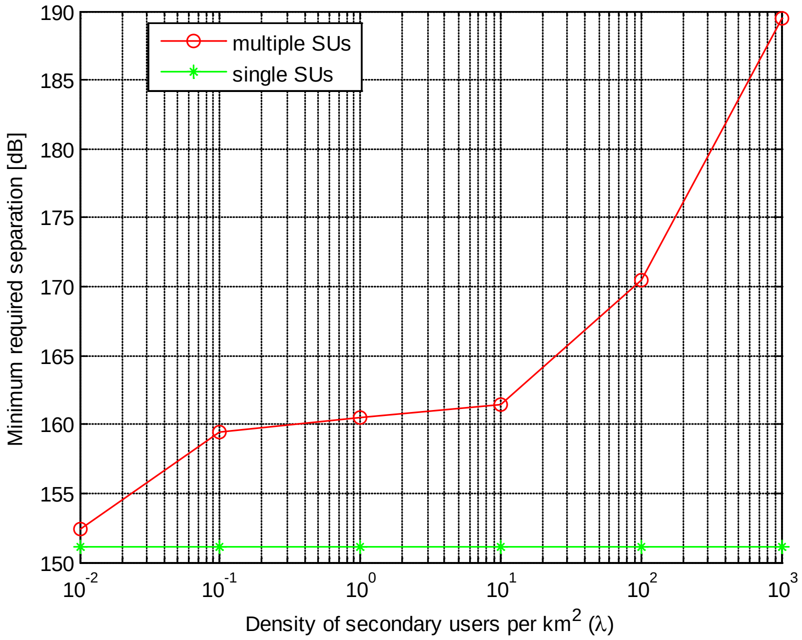


Figure 4-1: Minimum required separation between radar and SUs as a function of SUs density; SU transmit power is 10 dBm; Static decision scheme; SU height is 1.5m.

As it is observed in the figure above, the required separation depends on the density of SUs. The difference in the required separation between multiple SUs and single SU is termed *aggregate interference margin*. The aggregate interference margins depending on SU transmit powers are depicted in Figure 4-2. More aggregate interference margin is required when the SUs transmit with higher powers. Note that the separation for the single user is already as high as 171 dB when the SU uses 30 dBm transmit power. Therefore, it can be concluded that low-power SU applications are much preferable in dense deployment of SUs.

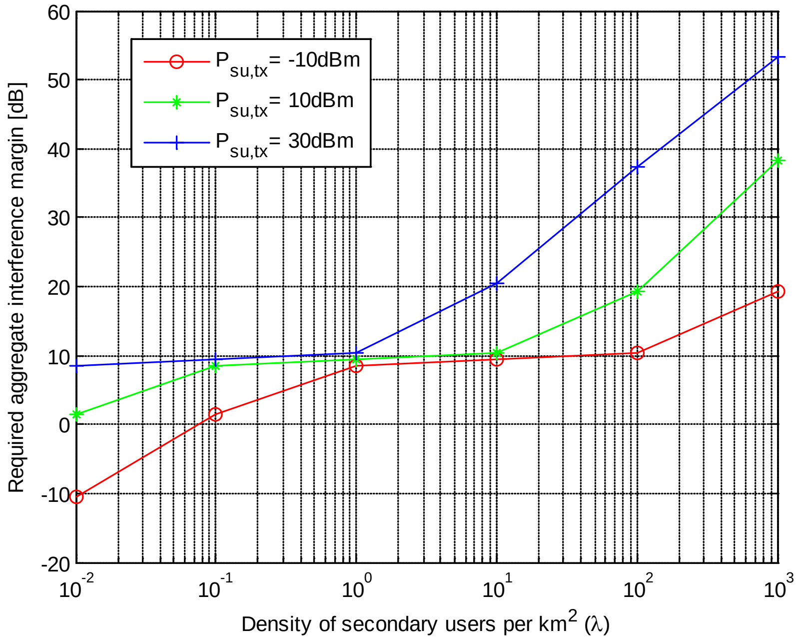


Figure 4-2: Required aggregate interference margin depending on SU transmit power; Static decision scheme; SU height is 1.5m; Minimum separation for single SU with

transmit power of -10 dBm, 10 dBm, and 30 dBm are 131.07 dB, 151.07 dB, and 171.07 dB, respectively.

Let us consider non-overlapping (adjacent) channel usage under the static decision scheme. Figure 4-3 illustrates the minimum required separation between the radar and SUs as a function of FDR. It shows that the separation requirement decreases almost linearly with FDR when $\lambda = 100$. For example, improving FDR from 20 dB to 50 dB (30 dB improvement) results in separation requirement decrease of 35 dB. The effect of the FDR is more favourable when the SU density is low.

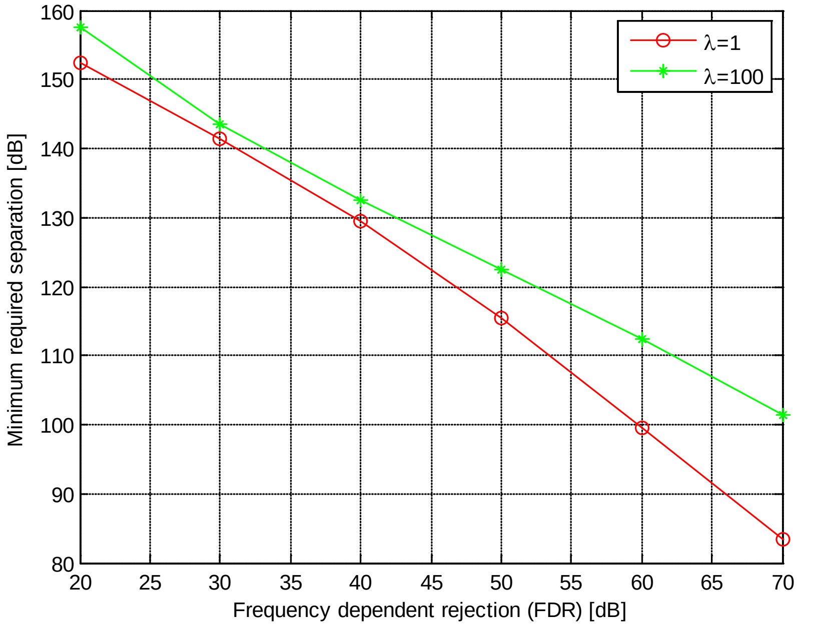


Figure 4-3: Minimum required separation between radar and SUs as a function of FDR; SU transmit power is 10 dBm; Static decision scheme; SU height is 1.5m.

So far, we have considered the static decision scheme. Note that the radar beam is very sharp, and thus affects a specific SU only during a small fraction of time. Thus, it is easily expected that the exploiting the temporal opportunity will bring about a significant improvement in the availability of secondary access. To quantify this expectation, assume a SU that is 3 km away from the radar when $\lambda = 100$. When the temporal decision scheme is employed, the probability of accessing spectrum varies over time as illustrated in Figure 4-4. Under the temporal scheme, the required separation for SUs facing main beam becomes larger than the separation under the static scheme. This is because the radar receives more interference from the SUs facing side lobe. However, the SUs face the radar main beam during a small fraction of time. Therefore, availability of the radar spectrum dramatically increases during most of the time, and slightly decreases only when the SUs face the main beam as demonstrated in the figure.

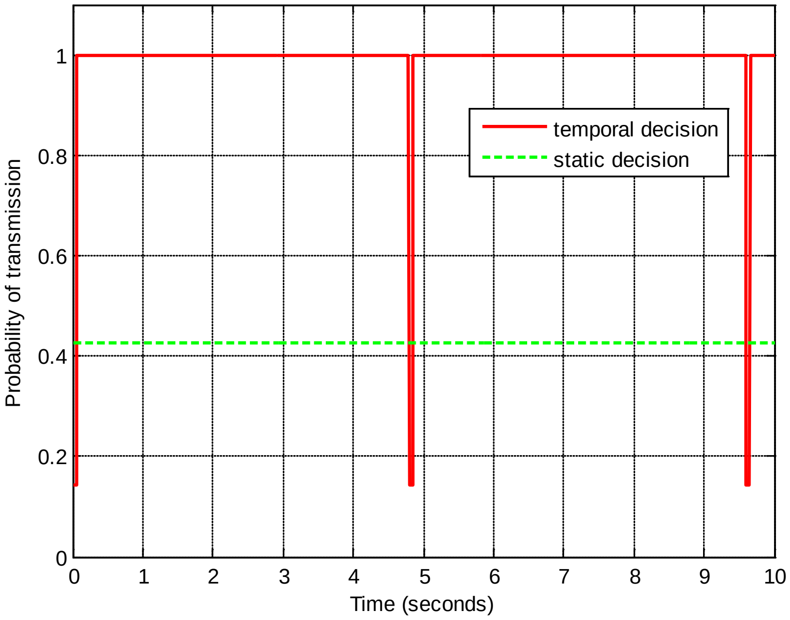


Figure 4-4: Probability of transmission as a function of time for a secondary user 3 km away from the radar; sweep time of the radar is 4.8 seconds; SU transmit power is 10 dBm; SU height is 1.5m.

4.2 Case study in Stockholm (virtual availability)

In this subsection, we take greater Stockholm area as an example to illustrate the availability of radar spectrum. In fact, it is known that there is no working radar in 2.7-2.9 GHz in Stockholm area. Therefore, we assume an imaginary case that the type-A radar is working in two airports in Stockholm, namely Bromma and Arlanda. In this context, what we illustrate in this subsection is a virtual availability. Figure 4-5 presents the map of evaluation area. Stockholm downtown is 8km away from Bromma airport, and 35km away from Arlanda airport. ITU P.1546 propagation model was employed for this case study.

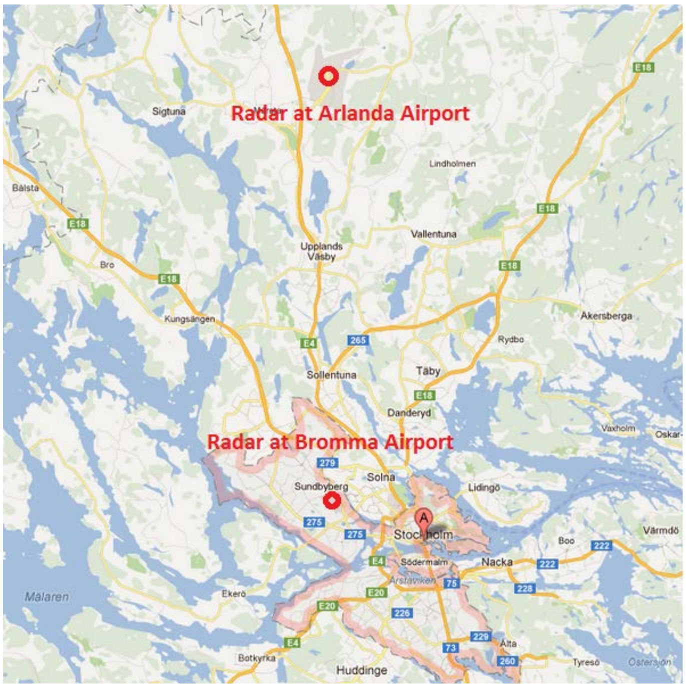


Figure 4-5: Illustration of greater Stockholm area (Image taken from Google Maps).

We assume that every resident in the region has his/her own secondary device, and 15% of devices are trying to use the same 20 MHz channel simultaneously. This is an extreme example of massive and heavy utilization. It corresponds to 100 users per km^2 on average. We applied the minimum separation calculated from the previous subsection to obtain the following figures.

4.2.1 **Case study results**

Figure 4-6 shows the probability of SU transmission depending on the location. For SUs below clutter (height of 1.5m), only a few kilometres of exclusion regions are needed for each radar. Therefore, most of downtown area enjoys high probability of accessing the frequency channel overlapping with radar operation.

In Figure 4-7, it is observed that the temporal decision scheme further enhances the availability of the access to overlapping radar spectrum. Even the area very close to the radar shows the transmission probability higher than 90%. Since the radar antennas rotate continuously over time, we randomly chose the angles of radar main beam to obtain the snapshot. Note that the areas facing the main beam exhibit lower chances of transmission under the temporal decision scehme.

The availability of secondary access is, however, hugely dependent on the propagation environment. Figure 4-8 shows the SU transmission probability when all the SUs are above clutter (height of 30m). Although it is an impractical assumption that such large number of SUs has the height of 30m, it clearly demonstrates that the SUs above clutter need more separation, and thus the use of overlapping channel in the downtown may not be feasible. The result of static decision in this case is not shown because the probability is quite low all over the area.

The effect of unfavourable propagation environment can be overcome by using non-overlapping frequency channels, since this brings an additional attenuation due to the transmission mask at the transmitters and frequency selectivity at the receiver. Figure 4-9 shows the result with the FDR of 50 dB. Though the SU height of 30m is applied to this figure, its shape is similar to Figure 4-6 which considers SU height of 1.5m. This means that the effect of SU height can be compensated by the additional FDR. It is needless to say that temporal decision scheme for this case will provide better result than Figure 4-9.

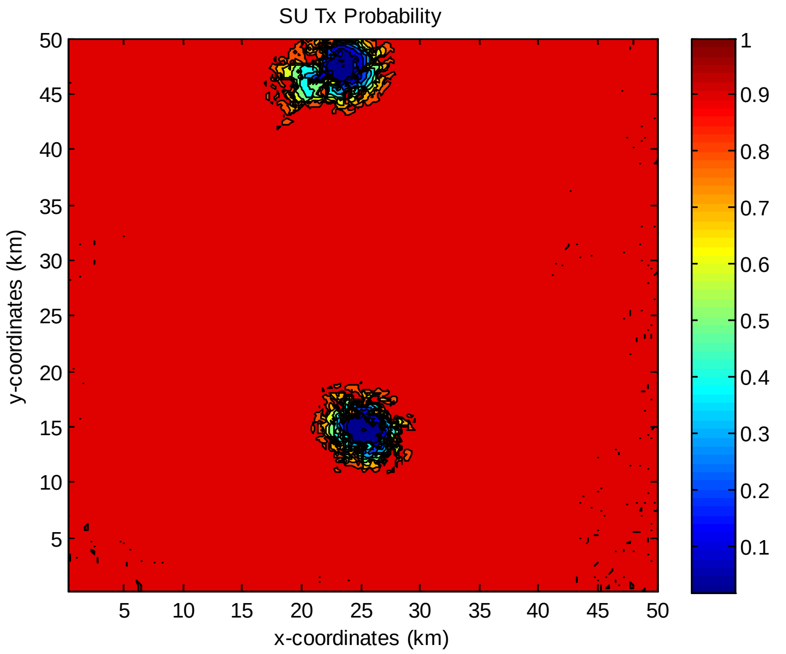


Figure 4-6: Probability of SU transmission for overlapping channel access; Static decision scheme is considered; SU transmit power is 10 dBm; SU height is 1.5m.

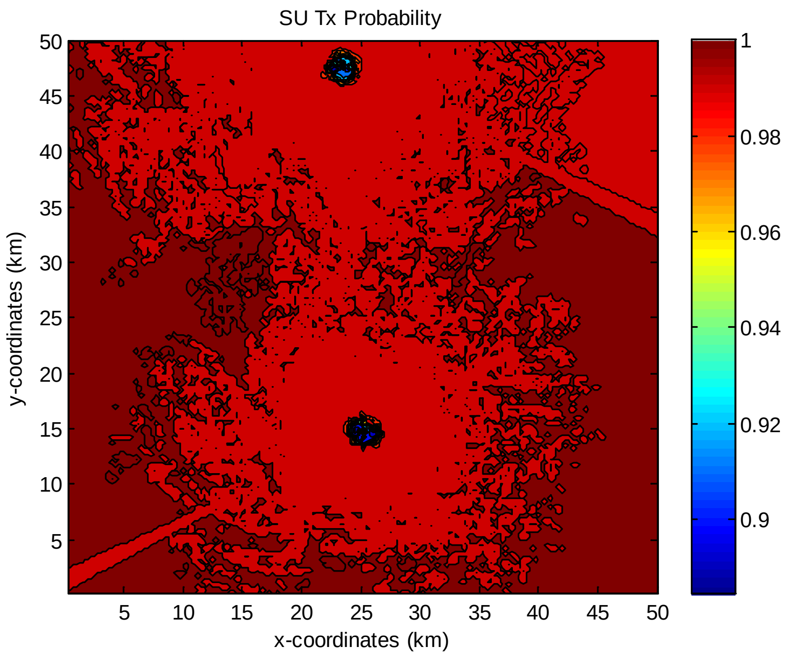


Figure 4-7: Probability of SU transmission for overlapping channel access; Temporal decision scheme is considered; SU transmit power is 10 dBm; SU height is 1.5m.

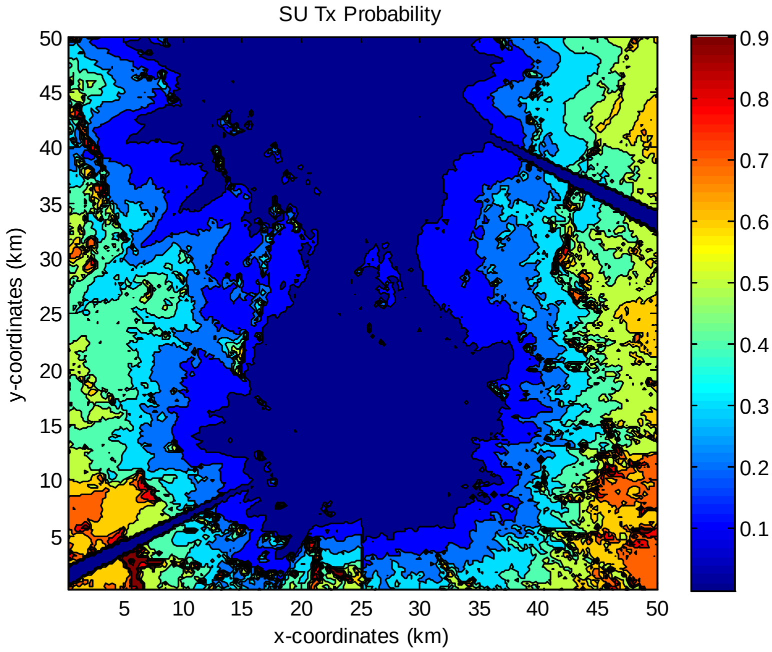


Figure 4-8: Probability of SU transmission for overlapping channel access; Temporal decision scheme is considered; SU transmit power is 10 dBm; SU height is 30m.

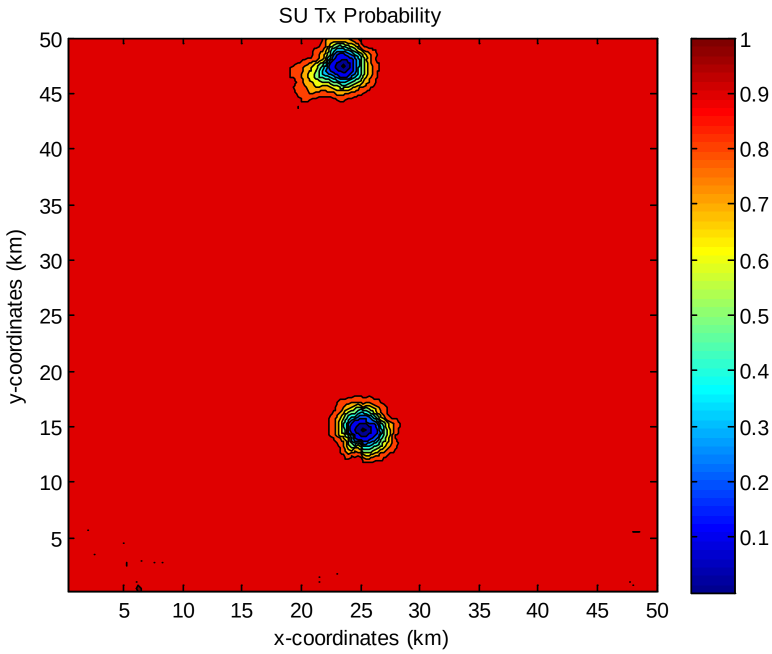


Figure 4-9: Probability of SU transmission for non-overlapping channel access; FDR of 50dB is considered; Static decision scheme is considered; SU transmit power is 10 dBm; SU height is 30m.

4.3 Case study in Macedonia

This subsection presents a country-wide analysis of indoor broadband secondary operation in ATC radar band, taking the territory of Macedonia as study area.

4.3.1 Description of primary system

The primary system consists of one ATC radar located near the Alexander the Great Airport in Skopje. Figure 4-10 presents the actual location of the radar. The centre of Skopje is 17 km away from the radar location.

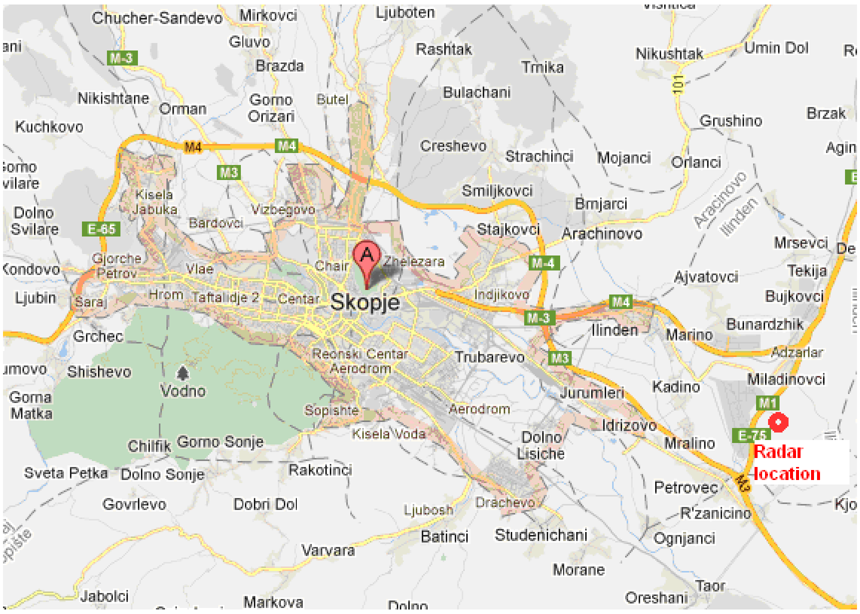


Figure 4-10: Location of ATC radar near Skopje (Image taken from Google Maps).

As the technical specifications of the radar located near Skopje slightly differ from any of the typical types found in the previous deliverable [3], the following Table 4-2 gives the actual radar parameters specified by the manufacturer of the equipment.

Table 4-2: Skopje radar parameters.

Parameter	**Value**
Tx power	72.8 dBm
Rx sensitivity	-124 dBm
Main lobe antenna gain	34 dBi
Antenna height	12 m
Frequency	2775 MHz
Mechanical tilt	3.5 deg.
3dB beamwidth	1.45 deg.
Pulse length	10 and 100 us
Pulse repetition frequency	793 Hz
Antenna rotation	15 rpm

Additionally, for the purpose of temporal opportunity analysis, this case study adopts the model of horizontal antenna pattern defined by Equation (4-5), where $G_{rad}^{\max} = 34\ dBi$ and $G_{rad}^{\min} = 10\, dBi$.

4.3.2 Description of secondary users

The SUs are indoor devices, where each SU consist of a pair of WiFi-like access point (AP) and one user connected to the AP. The analysis considers only the downlink communication. Table 4-3 gives the SU parameters.

Table 4-3: Secondary system parameters.

Parameter	**Value**
Tx power	10 dBm
Antenna gain	0 dBi
Antenna height	1.5 m
Bandwidth	20 MHz
Frequency	2775 MHz

The calculations assume Hata propagation model for the secondary system and additional signal losses of 10 dB for wall penetration, polarization mismatch and insertion loss. The standard deviation of shadow fading is 8 dB.

The model of SUs locations includes spatial point processes in selected areas within Macedonia that are collocated with the major cities. The analysis exploits the model of Wi-Fi node locations fitted by the Geyer saturation process to the publically available data from the Google Mountain View Wi-Fi network, by means of maximum pseudo-likelihood fitting (for more details please refer to Section 3.3 of this deliverable). Figure 4-11 shows one SUs realization of the Geyer saturation model.

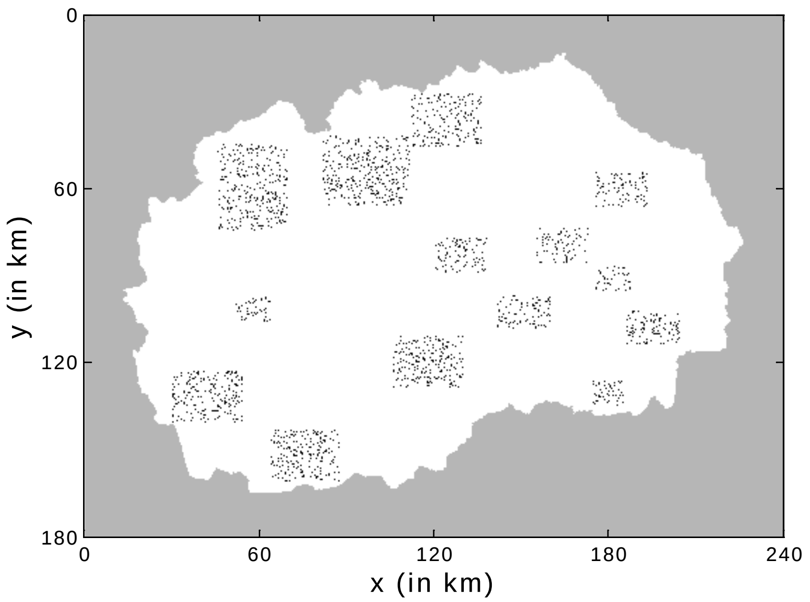


Figure 4-11: One realization of SUs distribution.

4.3.3 Aggregate interference calculation and scenarios definition

The analysis calculates the aggregate interference at the radar position coming from all SUs locations belonging to one realization. One must have in mind that the aggregate interference depends on the current direction of the radar antenna, i.e. its current azimuth angle (denoted by *n*). According to Equation (4-10), the aggregate interference when radar is facing the azimuth angle *n* ($I^{agg}_{su,n}$) is composed of incoming interference from pixels within the main lobe direction ($I^{agg}_{su,n,ml}$) and incoming interference from pixels which are facing the side lobe of the radar ($I^{agg}_{su,n,sl}$). Equation (4-8) gives the $I^{agg}_{su,n,ml}$, where $N_{n,ml}$ represents the number of SUs facing the main lobe being at azimuth angle *n*, while (4-9) gives the $I^{agg}_{su,n,sl}$ where $N_{n,sl}$ represents the number of SUs facing the side lobe of the radar.

$$I^{agg}_{su,n,ml} = \sum_{j=1}^{N_{n,ml}} \xi_{j,ml} \tag{4-8}$$

$$I^{agg}_{su,n,sl} = \sum_{j=1}^{N_{n,sl}} \xi_{j,sl} \tag{4-9}$$

$$I^{agg}_{su,n} = I^{agg}_{su,n,ml} + I^{agg}_{su,n,sl} \tag{4-10}$$

In Equation (4-8), $\xi_{j,ml}$ is the interference generated from the *j-th* SU facing the radar main lobe, while in Equation (4-9) $\xi_{j,sl}$ represents the interference generated from the *j-th* SU facing the side lobe.

In this realistic case study, for each SUs realization, the value of $I^{agg}_{su,n}$ varies with *n* and should not exceed the maximum safety threshold THR_{rad}. In other words, the maximum aggregate interference $I^{agg}_{su,\max}$ defined by (4-11), must fulfil the condition provided by (4-12).

$$I^{agg}_{su,\max} = \max[I^{agg}_{su,n}], \quad n \in [1,360] \tag{4-11}$$

$$I^{agg}_{su,\max} \le THR_{rad} \tag{4-12}$$

The aim of this analysis is to estimate the acceptance rate of random SUs realizations for different densities (SUs/km^2), regarding the condition (4-12).

There are 3 different scenarios of interest regarding the SUs behavior. The first scenario involves unaware co-channel operating SUs. It means that each SU operates continuously even if the radar's main beam is facing its location. This scenario is the worst case scenario of implementation involving SUs which are not controlled and coordinated.

The second scenario involves spectrum sensing aided by a database, where each SU makes ON/OFF decision according to the *static decision* rule defined by (4-6). In our analysis the SUs are using the value $I_{thr} = THR_{rad}$. In this way the radar is protected from each co-channel-operating SU which generates excessive interference level (higher than THR_{rad}). But still, the existence of multiple SUs can produce intolerable interference level at the radar location, violating the condition (4-12).

The third scenario assumes SUs which can make *temporal decisions* according to (4-7). In this scenario the interference generated from SUs facing the main lobe is

$I_{su,n,ml}^{agg} = \sum_{j=1}^{N_{n,ml}} \xi_{j,ml} = 0$. In this scenario only the side lobe interference contributes to the total aggregate interference.

All three scenarios only consider existence of SUs within Macedonia. A wider analysis must include SUs located in the neighbouring countries, as they have a potential to produce significant interference towards the ATC radar.

Additionally, the analysis investigates the influence of Wi-Fi principles such as Clean Channel Assessment (CCA). For this purpose each pixel (100m x 100m) is assumed to be one contention domain. Co-channel SUs are assumed to be in common contention domain if they receive each other's signals with power level greater then Clean Channel Assessment threshold. This imposes SUs to refrain from transition if another SU already uses the same channel. This procedure lowers the available capacity of the channel but, generates smaller level of interference towards the radar per SU [14]. The CCA threshold gives some sort of cooperative access to the channel between SUs, due to collision avoidance mechanism. The scenarios which involve this mechanism are denoted as cooperative scenarios.

Finally, we calculate the realizations acceptance rate for scenarios where the SUs operate in 10 MHz separation (adjacent channel case) from the radar operating frequency.

The percentage of successful realization is calculated using Monte Carlo simulations with 1000 realizations per SU density.

4.3.4 Case study results

For the purpose of obtaining relevant results, we use the simulation methodology described in [40], involving Radio Mobile software and actual elevation terrain of the evaluated area. Figure 4-12 presents the acceptance rate of SUs realizations for different scenarios described in the previous subsection. The acceptance rate is denoted by the percentage of realizations where the aggregated interference at radar location is lower than THR_{rad}. The results include all co-channel scenarios of SUs including both non-cooperative and cooperative mode of operation.

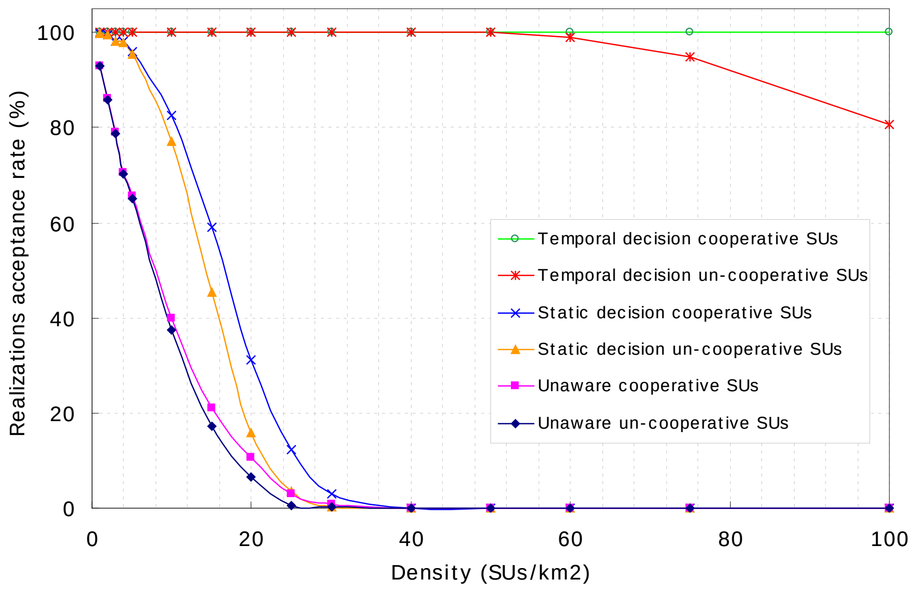


Figure 4-12: SUs realizations acceptance rate for overlapping channel access; INR = -16 dB; SU transmit power is 10 dBm; SU height is 1.5m.

Obviously the scenario which includes unaware SUs is unacceptable even for low densities of SUs. Similar conclusion goes to the static decision scenario. In this case, SU density of 5 SUs/km^2 drops the percentage of successful realizations, violating the requirement (4-1).

On the other hand, scenarios which involve temporal decisions by the SUs produce much lower aggregate interference towards the radar location, resulting in high values of the acceptance rate even for higher SU densities. The temporal decision scenario which involves un-cooperating SUs is unacceptable for densities close to 60 SUs/km^2, while the realizations acceptance rate for the temporal decision scenario which involves cooperative SUs is 100% even for density = 100 SUs/km^2.

The analysis of non-overlapping channels access revealed that for adjacent channel operation, every realization is successful for density range of 1 to 100 SUs/km^2.

4.4 Concluding remarks

Considering the results obtained from the mathematical analysis in subsection 4.1, as well as from case studies in subsections 4.2 and 4.3, it is obvious that the aggregate interference has a significant impact on the availability of secondary access to radar spectrum. In order to mitigate this problem, additional interference margin must be considered. Higher aggregate interference margin is required when SUs employ higher transmit power. Thus, low power devices are suitable for massive secondary use in radar spectrum. Making the SUs capable of exploiting temporal opportunity (i.e. periodic rotation of sharp radar antenna), increases the potential of spectrum availability. On the other hand, the level of SUs penetration (i.e. the number of SUs near the radar location) significantly influences the feasibility of the radar spectrum re-usage.

The first case study proved that massive scale of secondary access (e.g. 100 SUs per km^2) is feasible in most of downtown Stockholm. Temporal decision further increases the available area. SUs in high buildings may require larger separation from the radar. These users can also be effectively covered by using non-overlapping channel access.

The second case study revealed that when taking into consideration the actual terrain elevation and realistic spatial distribution of WiFi-like SUs, the level of aggregate interference significantly varies with radar antenna rotation. Depending on the SUs capabilities, different SUs densities can be allowed. The most promising scenario involves temporal decision enabled SUs, capable of Clean Channel Assessment as defined in [15]. If the scale of secondary access increases over 100 SUs per km^2, the non-overlapping channel access is the only feasible solution, considering the stringent protection requirements of the ATC radars.

5 Indoor Broadband Use of 960-1215 MHz Aeronautical Spectrum

In Section 3.3 of [3], we investigated the feasibility of low-power secondary user in 960-1215 MHz aeronautical spectrum. We extend our study to the case of multiple secondary users spreading over the large area in this section. Since there is a lack of open discussion about the protection rule and sharing scheme for this scenario, we firstly discuss these in Section 5.1. Then, assessment results are presented in Section 5.2. Impact of aggregate interference from the multiple secondary users is examined through mathematical analysis, and then the spectrum availability in Germany and Sweden is presented.

5.1 Scenario description and assessment methodology

5.1.1 Primary and secondary system description

Distance measuring equipment (DME) is a type of 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. The frequency allocation for different systems in the aeronautical spectrum is shown in Figure 5-1. Basic working principle of the DME system can be found in [3][41].

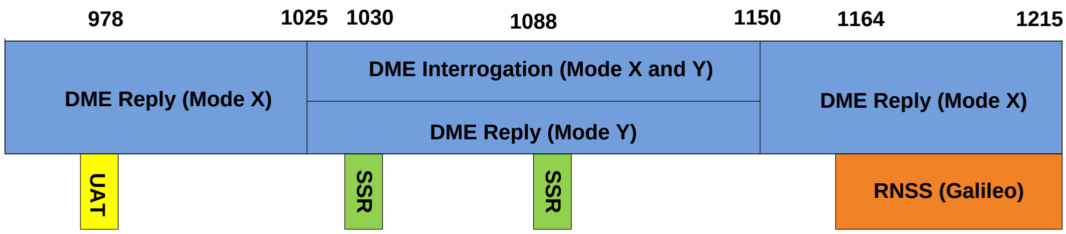


Figure 5-1: Frequency allocation to civil aeronautical systems in 960-1215 MHz.

We consider a secondary system where Wi-Fi or HeNB 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 secondary network can be treated as a single SU by assuming the same transmission power for the mobile station and the access point. SUs employ OFDM technology and therefore the use of some channels can be avoided. For simplicity, we assume the SUs have the same channel bandwidth as the DME channel bandwidth. We also assume fixed transmission power for SU. Main parameters of the primary and secondary systems are given in Table 5-1.

Table 5-1: Parameters of PU and SU.

Parameters	Basic values
$P_{tx,DME}$ (dBm) - Ground transponder	60
$P_{tx,DME}$ (dBm) - Airborne Interrogator	55
$P_{tx,SU}$ (dBm)	0,10
G_{DME} (dBi)	5.4 (main beam)

G_{su} (dBi)	0
Bandwidth (MHz)	1
Wall penetration and other losses (dB)	10
σ_{fading} (dB)	10

We assume that secondary users are spatially distributed according to a homogeneous Poisson point process in a two dimensional plane $\Re^2$, and the primary receiver is located at the center of the circular region. Then, the probability that k secondary users are inside $\Re^2$ depends on the total area A_R of the region:

$$\Pr\{N = k\} = \frac{(\lambda_{SU} A_R)^k}{k!} e^{\lambda_{SU} A_R} \quad (5\text{-}1)$$

where λ_{SU} is the density of secondary user per unit area. We also consider that the region $\Re^2$ is limited by two radii r_0 and R, which are the minimum and maximum distances from the primary receiver, respectively. Each secondary user decides whether it can access the DME spectrum or not by estimating the interference it will generate to the primary user. Let I_{thr} denote the interference threshold imposed on each secondary user. Then, the interference from a secondary user j is given by

$$I_j = \begin{cases} \xi_j, & \text{if } \tilde{\xi}_j \le I_{thr} \\ 0, & \text{otherwise} \end{cases}, \quad (5\text{-}2)$$

where ξ_j is the interference that the primary user would receive if the secondary user were to transmit, and $\tilde{\xi}_j$ is the estimate of ξ_j by the secondary user j. Note that $\xi_j = \tilde{\xi}_j$ only when the secondary user has the perfect knowledge of the propagation loss. Considering that there are N secondary users around the primary user, the aggregate interference is

$$I_a = \sum_{j \in N_t} I_j \quad (5\text{-}3)$$

where N_t is the set of transmitting secondary users.

5.1.2 **Protection criteria**

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. The values of A_{thr} for the ground transponder and the airborne interrogator are determined based on their respective sensitivity levels (detailed description on the values of A_{thr} is given in [3]). Then, the aggregate interference I_a is regulated as follows:

$$\Pr\left(I_a \ge A_{thr}\right) \le \beta_{PU}, \quad (5\text{-}4)$$

where β_{PU} is the maximum permissible probability of harmful interference at the primary receiver. Since the primary system performs a safety-of-life operation, β_{PU} needs to be extremely small. A reasonable range of β_{PU} has not been discussed well in the literature. We adopt a value used for air traffic control radar in 2.7-2.9 GHz, i.e. $\beta_{PU} = 0.001\%$.

The interference from the DME device to the secondary receiver is, on the other hand, negligible, since the DME generates only short pulses with sparse channel utilization (below 1%). However, the secondary receiver can be saturated if it receives a strong

DME pulse. Let I_{sat} be the saturation point of the secondary receiver. Then, the following condition should be satisfied:

$$\Pr\left(I_{PU} \geq I_{sat}\right) \leq \beta_{SU} , \tag{5-5}$$

where β_{SU} is the maximum saturation probability and I_{PU} is the received primary pulse power. We adopt a value of $\beta_{SU} = 2\%$ and $I_{sat} = -30$ dBm which is a typical saturation level of low noise amplifier (LNA) in WLAN receivers [42]. With the parameters in Table 5-1, a simple link budget analysis indicates that Equation (5-4) is the limiting constraint even before taking the effect of multiple secondary users into account. Therefore, in the remainder of the section we will focus on the protection of the primary user.

5.1.3 **Secondary sharing scheme**

5.1.3.1 Ground station as primary victim

We consider that the SUs detect the existence of the transponder via spectrum sensing with the help of geo-location databases. It may not be reliable to rely solely on the sensing considering that the DME performs the safety-of-life operation. We assume that the SUs are attached to a central database that provides the basic information of the transponder such as the transmission power, location, and frequency allocation of the primary victim.

The SUs detect the transponder on the reply (sensing) frequency, while the interference is given on the interrogation (interfering) frequency [3]. In both channels, propagation losses between the DME transponder and the SU consist of the distance-based path loss (L) and fading (shadowing and multi-path fading). Although it is reasonable to assume that the SUs accurately estimate the propagation loss of sensing channel, it does not necessarily mean that the estimation of interfering channel is also accurate. Due to the 63 MHz frequency offset between the sensing and interfering channels, *uncertainty* in the estimation of fading component of the propagation loss between the SUs and the ground transponder still remains. Different levels of *uncertainty* in the fading estimation are represented by a correlation coefficient ρ. Partial correlation $(\rho \neq 1)$ between fading values in these two channels does not allow the SUs to perfectly estimate its interference to the primary victim.

5.1.3.2 Airborne interrogator as primary victim

We assume that the SUs are connected to a real-time database where the locations of the airplanes are provided. A living example of such a real-time aircraft location map can be found in [43], where the database information is updated every 20-60 seconds and the map has only a limited coverage. However, we expect that such a database will be able to provide a reliable information if it is mandated and maintained by national authorities.

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 primary user whose location is rapidly changing due to high speed of the airplane. Due to the *delay* in the communication between the geo-location database and the secondary user, SUs could potentially experience *uncertainty* or imperfect information on the location of the airborne interrogator. To account for the potential imperfect information, we introduce the notion of *error region* which is determined based on the *delay (t)* and the speed of the airplane *(v)*. Inside the *error region,* SUs will assume the worst case scenario that the sky is full of airplanes while outside the *error region*, SUs will assume that the primary receiver is located at the closest border of the *error region*.

5.1.4 Assessment methodology

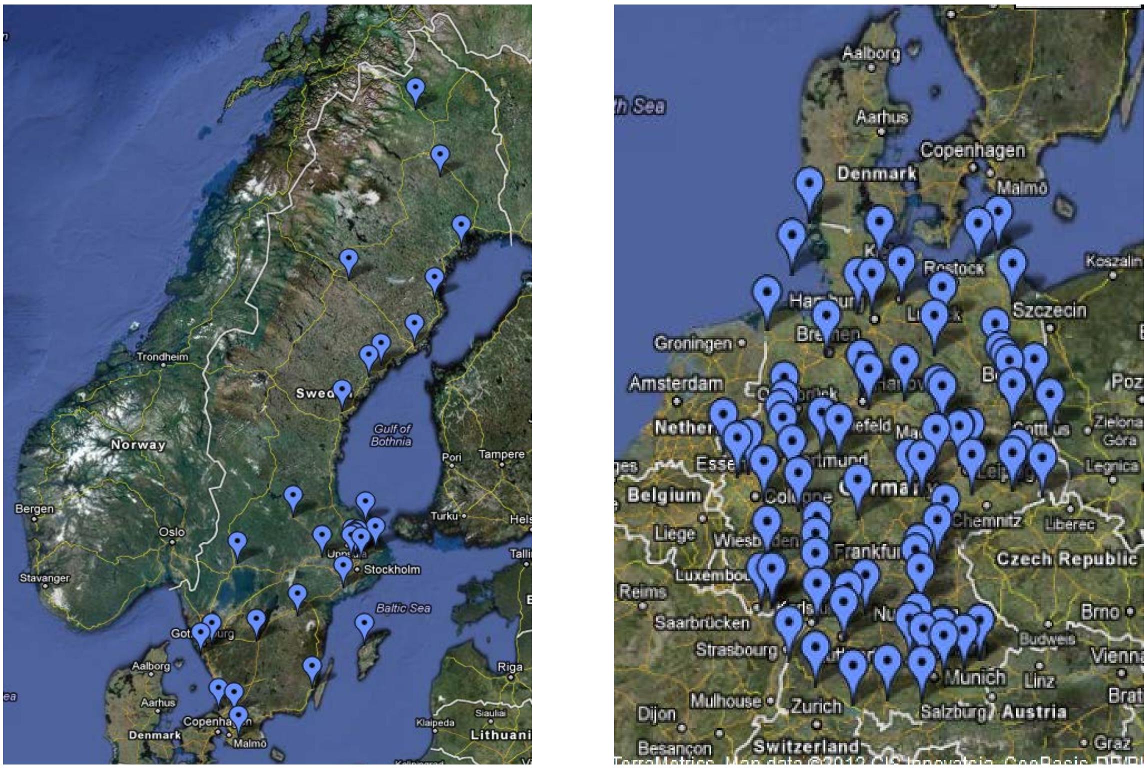
5.1.4.1 Methodology description

A mathematical framework for deriving the probability distribution of the aggregate interference I_a in the presence of *uncertainties* on the fading and the location of the primary victim has been presented in [44][4].

Initially our analysis focuses on single DME channel. We consider a circular area limited by the two radii radii r_0 and R where the primary victim is located at the origin. SUs are spatially distributed according to a homogeneous Poisson point process in a two dimensional plane $\Re^2$ with a density of λ_{SU} (SUs per km^2) and a fixed transmission power $P_{tx,SU}$. With the help of the mathematical model for I_a, we analyse the impact of the uncertainties on the requirements of secondary access. The requirements are given in terms of the I_{thr} or the minimum separation between the DME and the SUs.

We perform our numerical analysis for the co-channel and adjacent channel secondary usage. For adjacent channel usage, we apply higher interference thresholds since the interference is attenuated by the receiver filter. More detailed discussion on the protection thresholds can be found in [44].

Finally, we extend our analysis to a country-wide scenario. We analyse the availability of DME spectrum for secondary usage in two different countries, Sweden and Germany. Sweden with a large geographical area but rather low population density and small number of DME ground stations. On the contrary, Germany has a smaller geographical area but a high population density and a large number of DME ground stations. Locations of the DME ground transponder is shown in Figure 5-2[4].



(a) Sweden (b) Germany

Figure 5-2: Location of DME ground stations (image taken from Google maps).

[4] Locations and frequencies of the DME ground stations is based on http://worldaerodata.com/nav/. Last update in 2007

The total area of study is divided in pixels of 1 km^2. The requirements of secondary usage (I_{thr} and r_0) are calculated based on the assumption of flat terrain and homogeneous density (average density in a radius of 200 km from the primary victim) of SUs. Both primary receivers, ground station and airborne interrogator, are considered in our calculation. For a given required minimum probability of SU transmission, $\Pr\left(\tilde{\xi}_j \leq I_{thr}\right)$, we calculate the number of channels per pixel where the SUs can fulfil this requirement.

5.1.4.2 Performance metrics

For the single DME channel analysis, the main performance metric will be:

- Aggregate interference margin for different λ_{SU} and $P_{tx,SU}$;
- Individual interference threshold I_{thr} for different λ_{SU} , $P_{tx,SU}$, ρ ;
- Minimum probability of SU transmission, $\Pr\left(\tilde{\xi}_j \leq I_{thr}\right)$.

For the availability analysis, the main performance metric is the CDF of the number of available channels for different $P_{tx,SU}$ and ρ . Also, we present the average number of available channels by area and by population.

5.2 Assessment results

5.2.1 Multiple secondary users and single DME channel

5.2.1.1 Impact of aggregate interference

In Figure 5-3, we show the impact of the aggregate interference on the requirements of the DME ground station for co-channel usage. The required margin to account for the aggregate interference rapidly grows as the density of SUs (λ_{SU}) increases. For the case of airborne interrogator, the impact of aggregate interference is given in terms of minimum separation distance required to protect the primary victim. Figure 5-4 shows that the impact of aggregate interference is huge and large exclusion regions are needed even with low density of SUs λ_{SU} and low transmission power $P_{tx,SU}$.

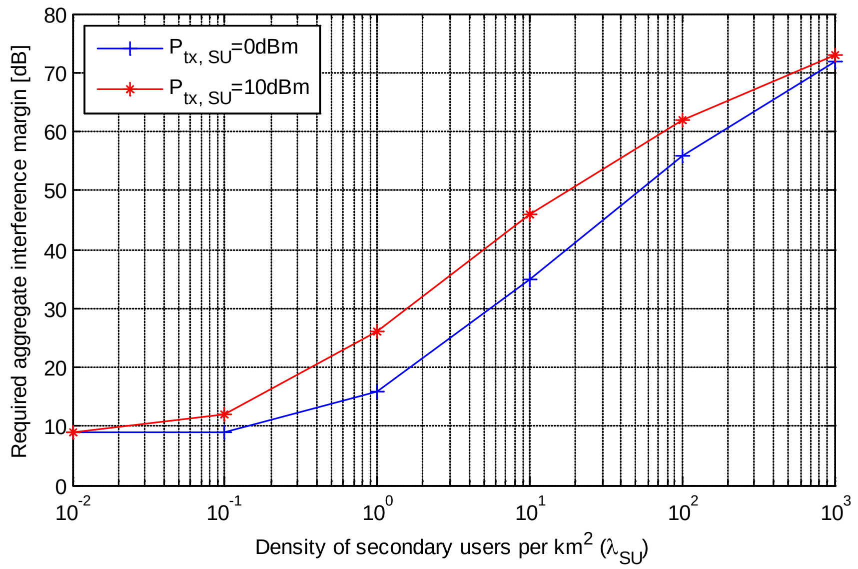


Figure 5-3: Aggregate interference impact on the requirement of SUs; Ground station as primary victim; Co-channel usage.

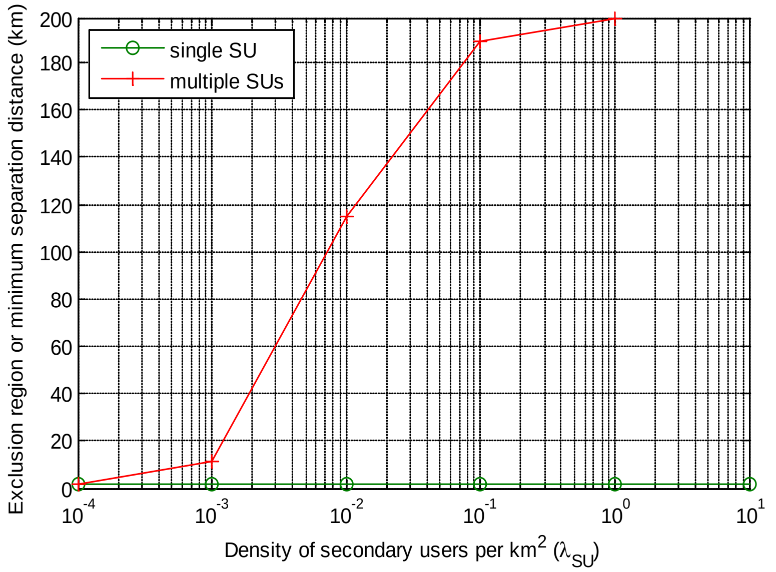
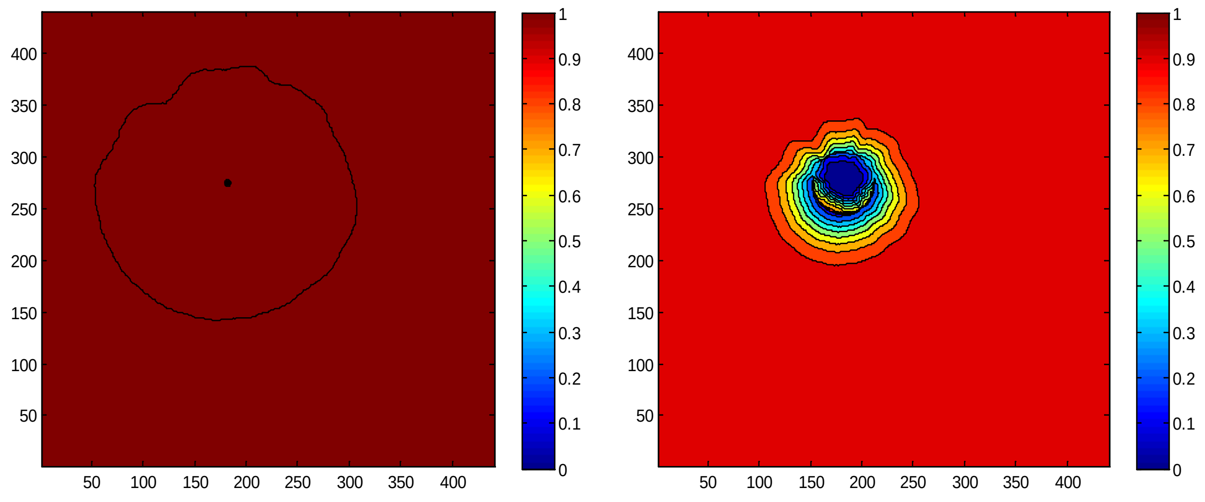


Figure 5-4: Aggregate interference impact on the requirements of SUs; Co-channel usage; $P_{tx,SU} = 0\text{dBm}$; Airborne interrogator as primary victim.

5.2.1.2 Impact of uncertainties: fading and location

Uncertainty due to fading leads us to be more conservative and make the requirements of secondary user stricter. Figure 5-5 shows how the transmission probability of the SU in an adjacent channel with FDR of 60dB decreases when uncertainty is present $(\rho \neq 1)$. Major impact is observed in the close proximity of the primary victim where SU transmission probability decreases from 100% to zero. In Figure 5-6, the impact of different *delay* periods on the exclusion region size is presented. No impact on the exclusion region size is observed when $\lambda_{SU} \leq 100/\text{km}^2$, even if there are long delays on the updating of the information.



(a)Adjacent channel usage, $\rho = 1$ (b)Adjacent chanenl usage, $\rho = 0$

Figure 5-5: Impact of uncertainty on the fading; $P_{tx,SU} = 10\text{dBm}$; Ground station as primary victim.

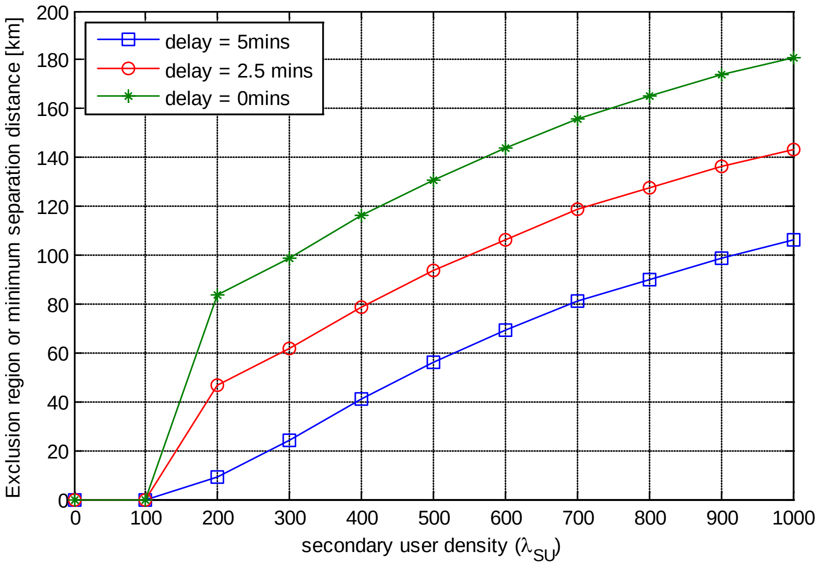


Figure 5-6: Impact of uncertainty on the location of the primary victim for adjacent channel usage; $P_{tx,SU} = 10\text{dBm}$; Airborne interrogator as primary receiver.

5.2.1.3 Impact of terrain elevation and heterogeneous density

In our mathematical models, we have considered homogeneous density of SUs and flat terrain. However, a more precise calculation should consider real SU density (heterogeneous) in a given region and the corresponding terrain elevation. We considered a DME ground station located approximately 50km away from the center of Stockholm. In this area, there is a background homogeneous user density with a hot spot with higher user density which corresponds to the city of Stockholm. This is a typical scenario for DME system where ground transponders are located various kilometers away from the city center.

In Figure 5-7, the effect of heterogeneous density and terrain elevation on the aggregate interference is shown. Heterogeneous density has a smaller impact on the I_a. This was also verified previously in [45] where it was concluded that heterogeneous density does not have a strong impact on the I_a for this particular scenario. The largest impact on the I_a is given by considering the terrain elevation. However, the difference of only a few dB is observed between the flat and irregular terrain in this example.

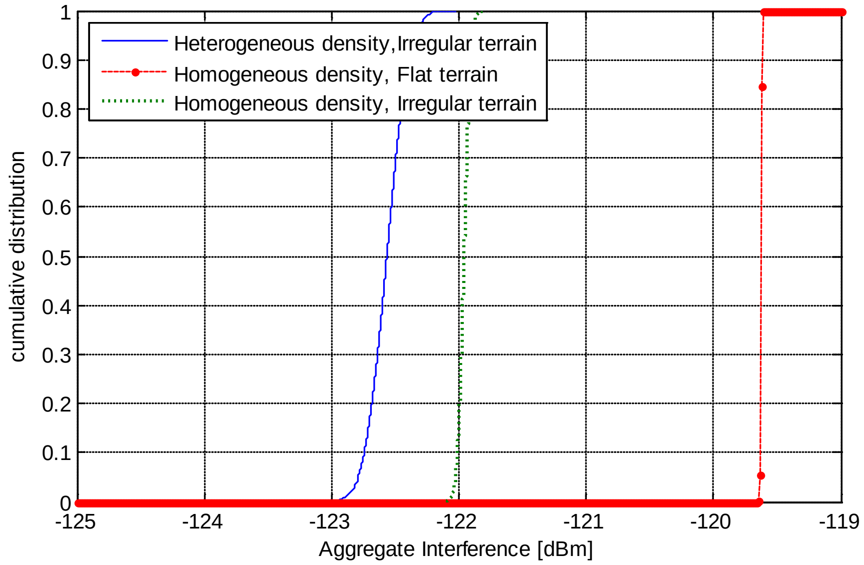


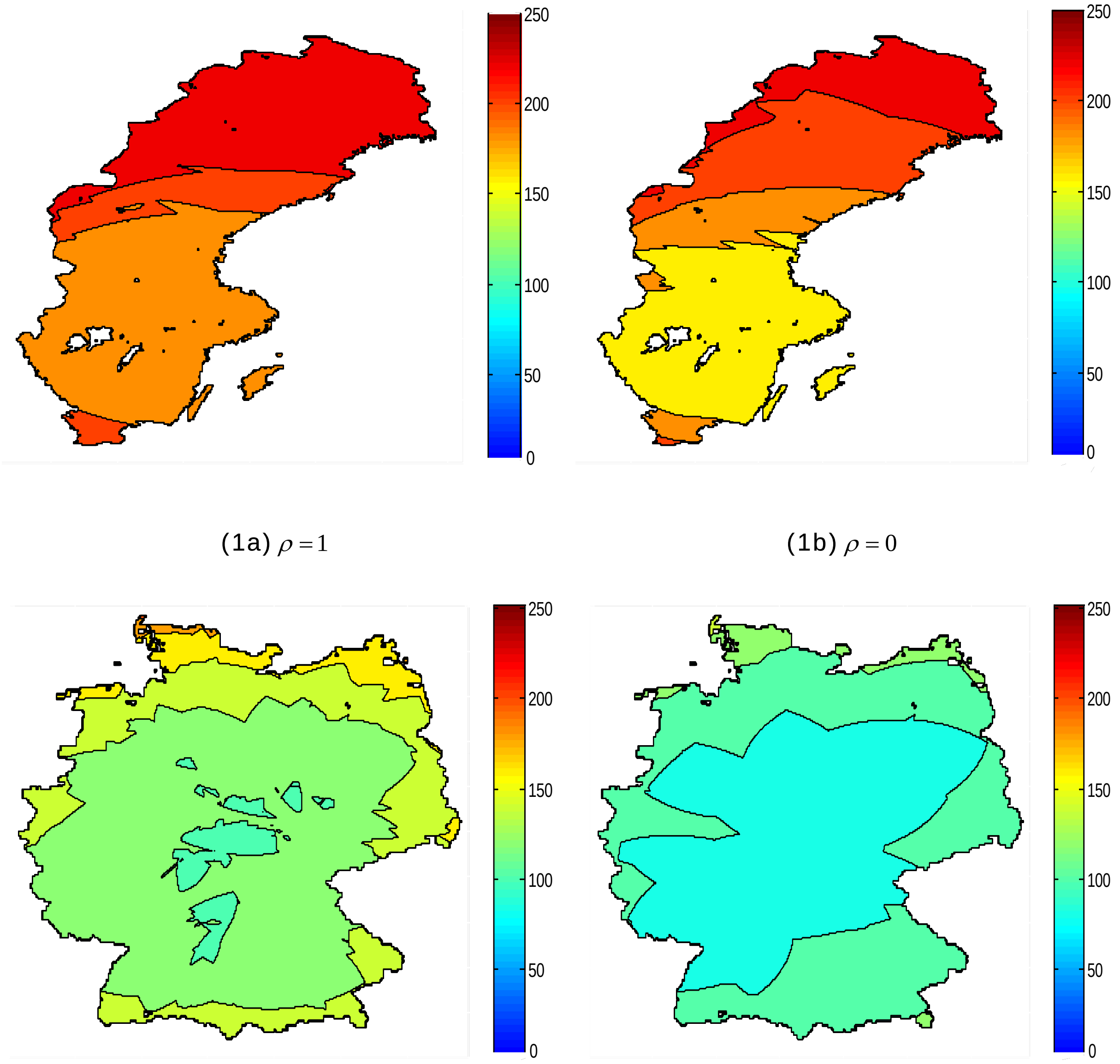
Figure 5-7: Impact of terrain elevation and heterogeneous density; $\rho = 1$ and $P_{tx,SU} = 10\text{dBm}$.

5.2.2 Multiple secondary users and multiple DME channels: Geographical Availability

For the geographical availability evaluation, we have considered two countries with different characteristics which were explained previously in Section 5.1.4. For simplicity, in our regional availability evaluation we assume homogenous density and flat terrain which can be seen a worst case scenario as it was shown in Figure 5-7.

5.2.2.1 Impact of uncertainty on the fading

In Figure 5-8, we show the availability of DME spectrum for secondary usage. A probability of SU transmission of 90% is considered as minimum requirement for channel to be available. Uncertainty on the fading reduces the number of available channels, especially for the case of Germany where population density is high in the whole territory. However, in general high availability of DME channels for low-power indoor secondary system is observed for both countries (more than 150 MHz for Sweden and more than 100MHz for Germany) even if uncertainty is present.



(1a) $\rho = 1$ (1b) $\rho = 0$

c(2a) $\rho = 1$ (2b) $\rho = 0$

Figure 5-8: Available channels for secondary usage when $P_{tx,SU} = 0\text{dBm}$ and $\Pr\left(\tilde{\xi}_j \le I_{thr}\right) \ge 90\%$; (1): Sweden and (2): Germany.

5.2.2.2 Impact of the presence of Galileo system

The upper part of the DME spectrum (1164-1215 MHz) is planned to be used by the European radio navigation satellite system (RNSS) Galileo. Secondary access to this portion of the spectrum is expected to be infeasible due to the unknown location of the potential receivers and their low sensitivity level. Figure 5-9 shows that the presence of Galileo system considerable decreases the number of available channels for low-power secondary usage.

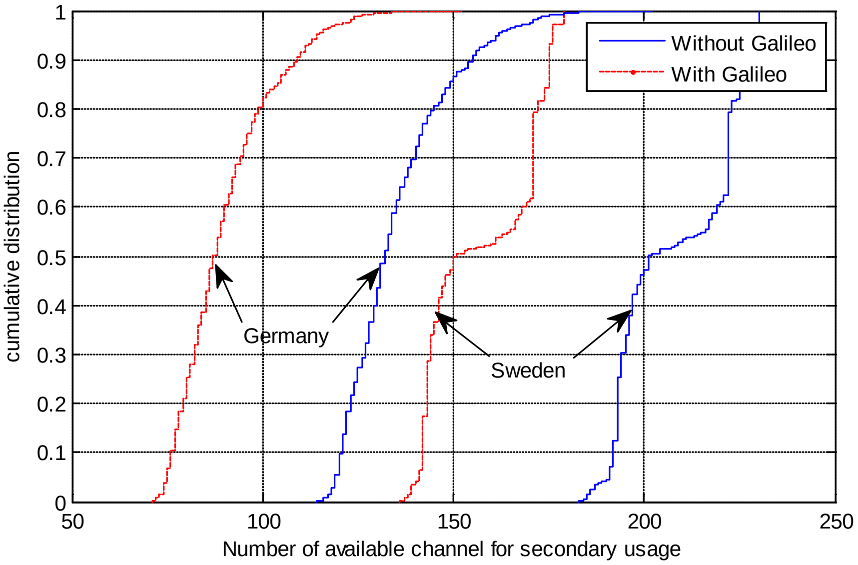


Figure 5-9: Number of available channel for secondary usage when $P_{tx,SU} = 0\text{dBm}$, $\rho = 1$ and $\Pr\left(\tilde{\xi}_j \le I_{thr}\right) \ge 90\%$.

5.2.2.3 *Impact of SU transmission power, population density and SU requirements*

We analyse the impact of different parameters of the secondary network, SU transmission power $\left(P_{tx,SU}\right)$ and minimum SU probability of transmission $\left(\min \Pr\left(\tilde{\xi}_j \le I_{thr}\right)\right)$, on the average available channels for secondary usage or white space. The average white space is calculated with respect to the geographical area and the population density of both countries [46]. Basic information about the countries considered in this study is given in Table 5-2.

Based on our results given in Table 5-3, we can observe that the average white space by population is lower than the average white space by area. Larger differences are observed for the case of Sweden where the population density has more variations compared to the case of Germany. When the secondary network requirements are stricter, higher minimum SU probability of transmission, the average white space by population and by area is smaller. However even for strict SU requirements, the average white space for low-power secondary usage in both countries is at least 50% of the total DME spectrum.

Table 5-2: Basic information of the countries of study.

Country	Population, p_o[5] [x 10^6]	Area, a_o [km^2]	Number of DME ground transponders
Sweden	8,886	431,704	30
Germany	82,250	356,027	79

[5] Population density data is an estimated based National Statistics Office (NSO) data in 2002. This can found at http://sedac.ciesin.columbia.edu/

Table 5-3: Available channels for secondary usage in Germany and Sweden, $\rho = 1$.

Country	SU parameters		White space by area		White space by population	
	$P_{tx,SU}$ (dBm)	$\min \Pr\left(\tilde{\xi}_j \leq I_{thr}\right)$	Channels	fraction	Channels	Fraction
Sweden	0	90%	207.99	85.95%	195.13	80.63%
		50%	208.56	86.18%	197.54	81.63%
	10	90%	192.44	79.52%	160.93	66.50%
		50%	196.06	81.01%	166.77	68.91%
Germany	0	90%	135.05	55.81%	133.61	55.21%
		50%	144.95	59.90%	143.16	59.16%
	10	90%	100.72	41.62%	101.03	41.75%
		50%	121.57	50.24%	121.83	50.35%

5.3 Concluding remarks

In this section, a secondary sharing scheme for low power indoor secondary system accessing the 960-1215 MHz aeronautical spectrum was investigated. We proposed an assessment methodology to evaluate the availability of DME spectrum for low-power secondary usage. Our methodology takes into account the protection of both primary victims: ground station and airborne interrogator.

Our numerical experiments show that the aggregate interference has a strong impact on the availability of DME spectrum for secondary usage. The interference margin and exclusion region needed to account for the impact of aggregate interference dramatically grows when density or transmission power of secondary user increases. Therefore, for large scale secondary deployments it is be recommendable to have low-power secondary users. The presence of uncertainty on the fading and uncertainty on the locations of airborne interrogators also affect the availability of DME spectrum. To account for these uncertainties, requirements of secondary usage need to be more strict or conservative. This considerably reduces the performance of secondary networks, especially for the secondary users located nearby the primary victim.

In spite of the impact of aggregate interference and the uncertainties, our results for the country-wide evaluation show that large portions of white spaces in the DME spectrum (more than 100MHz) are available for low-power secondary usage even with the conservative parameters for primary system protection. The average number of available channels by area or population highly depends on the secondary system parameters and requirements. For dense secondary network deployment in large scale, low transmission power is recommended to the secondary users in order to achieve high probability of successful secondary transmissions. The analysis was performed with the assumption that the secondary users can utilize all the fractions of available spectrum in 960-1215 MHz. The impact of spectrum aggregation capability remains as a further study.

6 Conclusion

This deliverable presented the results of spectrum availability assessments of selected QUASAR secondary access scenarios in the presence of multiple secondary users. The work provided here has been built upon the previous QUASAR deliverables. In D5.1 [2], the basic spectrum assessment framework was provided. Then, in D5.2 [3] the detailed secondary use scenarios were chosen and the basic framework was refined to capture the characteristics of specific scenarios under the assumption of a single secondary user in the system. As a natural but challenging extension of D5.2, this deliverable thoroughly investigated the impact of multiple secondary users on the availability of the secondary access. The examined scenarios are:

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

In Section 2, the first scenario (macro cellular use of TV white spaces) was investigated by taking Germany and Finland as examples. In Germany, it is observed that contiguous cellular coverage in TV white spaces is difficult to achieve. Capacity booster for limited local areas looks more feasible, but this does not benefit from the favourable propagation characteristics of TV white spaces. For the example in Finland, it is demonstrated that the current regulatory approaches considered by FCC and ECC are not suitable for multiple cellular-type secondary users. To improve the situation, an improved secondary power allocation scheme was proposed. The scheme provides better primary user protection under interference from multiple secondary interferers while at the same time increase the chance of achieving cellular coverage in Finland.

In Section 3, WiFi-like system was considered as the secondary users, and its performance in TV white spaces was discussed in terms of capacity and coverage. It is shown that low radio frequency of the TV white spaces is beneficial to the WiFi-like secondary usage because it enables larger coverage with limited power budget compared to existing ISM bands in 2.4 GHz and 5 GHz. This makes the use cases such as community network and outdoor hotspot promising. However, the mutual interference of secondary users under the CSMA/CA medium access control scheme significantly decreases the performance of densely deployed secondary networks. Therefore, it is a research challenge of profound importance to develop more efficient access control and channel selection mechanism for the success of the WiFi-like scenario.

In Section 4, ATC radars operating in 2.7-2.9 GHz was considered as the primary system, and low-power indoor broadband devices such as LTE HeNB were chosen as the secondary users. Spectrum sensing by individual secondary user with the radar information (e.g. location, centre frequency, EIRP, and rotation pattern) fed by a central database was considered as the opportunity detection scheme for the secondary system. An analysis was performed to investigate the impact of multiple secondary users. An increase of more than 20 dB in the minimum required separation between the radar and the secondary users is observed to be required to accommodate the densely populated secondary users. Case studies in Stockholm area and Macedonia suggest that the massive secondary use of radar spectrum is feasible particularly when the bands non-overlapping radar centre frequencies are mainly considered. Exploiting the predictable and regular rotation pattern, where applicable, of radar antennas can further provide higher secondary access availability.

In Section 5, DME devices operating in aeronautical 960-1215 MHz was taken as the primary system, while low-power devices for indoor broadband provision are considered the secondary system. The impact of aggregate interference turned out to be similar to the ATC radar scenario. The analysis suggests that co-channel access is difficult due to the large separation requirement between the primary system and the secondary users. However, it is also shown that a high density of secondary users can access adjacent channels while providing sufficient protection of the primary service. With the relatively narrow DME bandwidth (1 MHZ) and the sparse locations of DME ground stations, this scenario appears viable if the secondary users have a good capability of spectrum aggregation, as it was substantiated by the quantitative examples in Germany and Sweden. It should be noted, however, the availability of secondary access to the radar and aeronautical spectrum will hugely depend on the regulatory rules and parameters that have not been openly discussed yet.

For all of the scenarios, it is found that the aggregate interference generated by the multiple secondary users has a significant impact on the availability of the secondary use. It is thus important to stress that, results under the assumption of single secondary user can, and most likely will be overly optimistic. It is also noticeable that the current regulatory rules are not suitable to deal with the realistic scenarios with multiple secondary users. Thus, to make the best use of secondary spectrum, it is imperative to have an accurate estimate of aggregate interference and an efficient interference control scheme.

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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