COGEU

FP7 ICT-2009.1.1

COgnitive radio systems for efficient sharing of TV white spaces

in EUropean context

D6.4

System level evaluation platform and simulation results

Contractual Date of Delivery to the CEC: December 2012

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Participant(s): AEGEAN, PTIN, PUT

Work package: WP6

Est. person months: 20 MM

Security: PU

Nature: Report

Version: 1.0

Total number of pages: 66

Abstract:

This deliverable reports simulation studies for the LTE extension over TVWS aplication scenario based on the COGEU broker model. Several novel Radio Resource Management algorithms are presented and simulated. The improvement of the LTE system coverage, capacity and QoS are analysed for the Munich area with realistic TVWS data from the COGEU database. This work also analysis the business model of the COGEU spectrum broker.

Keyword list: LTE over TVWS, Radio Resource Management, TVWS Geo-location Database, Spectrum broker, Profitability Analysis

Executive Summary

This deliverable report the final work performed in Task 6.5 “Simulation tools and system level evaluation”. More specifically, T6.5 elaborates on the evaluation through simulation of cognitive radio systems that utilize TVWS to improve the overall system capacity and QoS in line with LTE COGEU scenarios specified in WP2. Using TVWS opportunities previously identified in D6.3, this task elaborates on the simulation of the cellular extension over TVWS and studies the improvement of LTE cellular coverage and QoS metrics, when extra TVWS carries are available.

Following, the key achievements of this deliverable are listed below:

- A Radio Resource Management (RRM) framework, is developed and implemented for a LTE system that exploit TVWS spectrum. The proposed RRM framework guarantees a better QoS in LTE systems, by extending their services over the TVWS. Also, by adopting the proposed RRM scheme in LTE systems, operators can be capable to cover a larger geographical area with fewer number of base stations, decreasing investment costs and providing cheaper cellular broadband services, especially to end users located in rural areas. Furthermore, it is demonstrated that TVWS could be exploited to support LTE downlink peak data traffic in urban areas such as Munich. In particular, simulation results obtained with realistic TVWS data for the Munich scenario show a decrease of the average CBR (Call block rate) from the initial value of 2.94% to 0% when extra TVWS carriers are allocated through the proposed RRM framework.
- Decision-making optimisation methods based on Backtracking, Pruning, Simulated Annealing and Genetic algorithms are utilised, in order to evaluate RRM algorithms performance in terms of maximum-possible spectrum utilisation and minimum spectrum fragmentation. A set of simulations are conducted where various secondary systems with different requirements request access to the available TVWS through the COGEU broker system. Simulation results show that the Simulated Annealing algorithm performs better in comparison to the other algorithms, obtaining the best-matching solution in a shorter simulation time.
- Potential profit of the COGEU spectrum broker is investigated, in case that a spectrum broker sells temporary licenses for small areas (e.g. 1 Km radius) in the Munich area. The broker incomes and costs are analyzed considering TVWS availability data from two COGEU geo-location databases: more restrictive and less restrictive. The results indicated that in the more restrictive case, the spectrum broker income cannot guarantee profitability. Additionally, results obtained for the less restrictive case indicated that the expected profitability of the spectrum broker income can be achieved when the average price for spectrum unit (1 MHz, one year license, 8h/day period, per site) exceeds 100€.
- Because the broker’s profitability is dependent on the DVB-T protection criteria (set by the regulator), the secondary players interests, the spatial TVWS distribution and the technology constraints (e.g. availability of LTE-A carrier aggregation), is very likely that the broker’s profitability cannot be guaranteed considering only a limited operational area. Therefore the broker is expected to expand the operational area (beyond Munich) and the frequency band (beyond TV UHF spectrum).
- It was demonstrated that an auction mechanisms that takes in consideration the carrier aggregation features of the LTE-A system, allows for better resource utilization of TVWS and for higher auction efficiency of the COGEU model.

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1- Introduction

One of the main purposes of D6.4 “System level evaluation platform and simulation results” is to evaluate the performance of COGEU LTE use case scenario, when extra TVWS carries are available and compare the performance of the RRM scheme utilizing different optimization algorithms. Furthermore, a profitability analysis is presented in this deliverable, in order to verify the viability of the COGEU broker business model.

TVWS give the opportunity to a radio access technology, such as an LTE network system to increase the available radio resources in critical moments, when the network experiences capacity limitations. This opportunity is based on the exploitation of the RRM, which makes the best decision in terms of the best carrier (legacy or TVWS) to provide the service, as well as the cell that the user should be allocated. In this context, chapter 2 addresses the issue of frequency planning, when extra carriers are needed, by improving the two algorithms proposed in D6.1. For this scope, the LTE TVWS Management System is described in detail, while the coverage and the capacity analysis are presented with the exchanges of information/messages among LTE Management System and the spectrum broker. Towards simulating the performance of the LTE over TVWS, the geo-location database of Munich (more restrictive and less restrictive cases are utilised) is exploited, in order the LTE Management System to grand information regarding the TVWS availability, the boundaries of them, as well as the area of interest. The simulation results that are presented, verify the proper functioning of all modules of the algorithm and of the TVWS Management System.

Chapter 3 reports the work performed, regarding the proposed Radio Resource Management (RRM) framework, exploiting TVWS under the “Real-time Secondary Spectrum Market - RTSSM” policy. The proposed RRM framework is applied in the second COGEU regulatory scenario and guarantees a better QoS in LTE systems, by extending their services over the TVWS. This regulatory scenario is based on a centralised CR network architecture, where a Spectrum Broker is capable to manage the increased radio spectrum demand, by orchestrating the available TVWS. Towards addressing the need for increased radio spectrum demand, the use-case scenario of LTE over TVWS is exploited, since it is capable to provide flexible deployment, in terms of high spectral efficiency, bandwidth and different modulation/coding schemes. In addition, LTE deployment over TVWS may enable cellular networks operators to cover large geographical areas with less number of base stations, decreasing investment costs and providing cheaper cellular broadband services, especially to end users located in rural areas. Furthermore, TVWS could be exploited to support peak data traffic in urban areas with increased bandwidth demands, while several schemes to share channels on a temporary basis of short or medium duration are investigated, towards providing relief of crowded cellular networks that experience peak loads. The exploitation of TVWS will allow for more network carriers to be available at lower frequencies and despite the fact that a part of VHF/UHF radio spectrum will be dedicated for digital terrestrial television and wireless microphones services, another part of it will remain under-utilized for future secondary usage. In this context, decision-making optimisation methods based on the Backtracking, the Simulated Annealing and Genetic algorithms are utilised in order to evaluate the RRM performance as a matter of maximum-possible spectrum utilisation and minimum fragmentation.

Finally, chapter 4 presents the extension of the work obtained in D2.3 of SWOT analysis, by investigating the potential profits of the spectrum broker in case of the spectrum broker sells temporary and local licenses in the Munich area. In this context, the broker incomes and costs are analysed for the Munich scenario.

2- LTE extension over TVWS

2.1- Introduction

The 3GPP LTE is a new radio access technology that is been largely deployed. The LTE is a disruptive system in the sense that do not use the 3GPP radio interface evolution based on the WCDMA technology but adopted a new approach based on Orthogonal Frequency Division Multiplexing (OFDM), characterized by its flexibility, two duplex modes (TDD and FDD), several possible bandwidths and inter-cell interference coordination mechanisms. These are important features in order to guarantee the success of the system on an overcrowded radio spectrum. It is the first cellular system that depends mainly of already used bands for its deployment, which means that the LTE deployment will be done on the spectrum released by other systems. The TV spectrum and particularly the TVWS can be an opportunity not only to deploy the LTE but also to do it into an innovative way; in the framework of a new spectrum management paradigm proposed by COGEU.

COGEU project proposes a secondary spectrum market that guarantees a better QoS in LTE systems, by extending their services over the TVWS. In order to guarantee a better QoS the exclusivity of the spectrum usage need to be ensured, with an allocation of the TVWS carriers, and minimizing interferences. In order for this to be taken into account a new Radio Resource Management (RRM) procedures should be implemented at operator's network. This was already mentioned in the D6.1, chapter 4, where the main goal was to optimize the available radio resources (RR) provided by legacy carriers and TVWS carriers.

The TVWS can be an opportunity for the most recent radio access technology, the LTE network system, giving the possibility to increase the available radio resources in critical moments when the network experiences capacity limitations. Typically the network traffic varies throughout the day creating a pattern similar to the Figure 1.

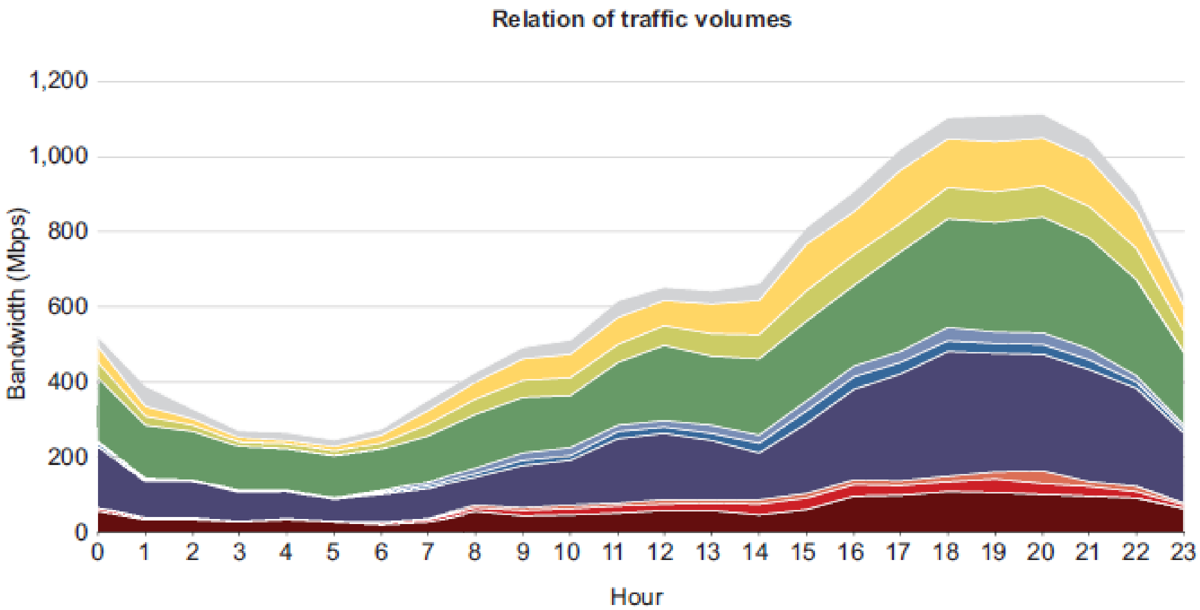


Figure 1: Typical fluctuation of traffic over a day [1]

During traffic peaks the use of the TVWS carriers can be very useful for the operator's to keep the QoS above the minimum value. The Service Level Agreement (SLA) defines the minimum quality of service that the mobile operator should provide to their customers.

To offload the network, operators can book TVWS carriers during these periods of time when the network is more loaded. This dynamic behaviour means that TVWS can be shared in the time domain by different players. For this TVWS carriers allocation the COGEU broker needs to work in a temporally basis with need to add new functionalities to the cellular system. An innovative proposal on the spectrum management was presented in the deliverable 6.1, section 4.1, having the following functionalities: network monitoring, TVWS carrier's assessment, network parameterization & configuration and RRM.

In the deliverable 6.1, chapter 4, were proposed and evaluated two algorithms for RRM on the 2GHz (legacy frequency) and 700MHz (TVWS frequency) frequencies. Using the same environments, network configurations, parameterizations and the same 5 MHz bandwidth, the results, as expected, showed that TVWS could provide higher capacity and radio coverage than legacy carriers, summing up, greater spectral efficiency.

2.2- LTE TVWS Management System

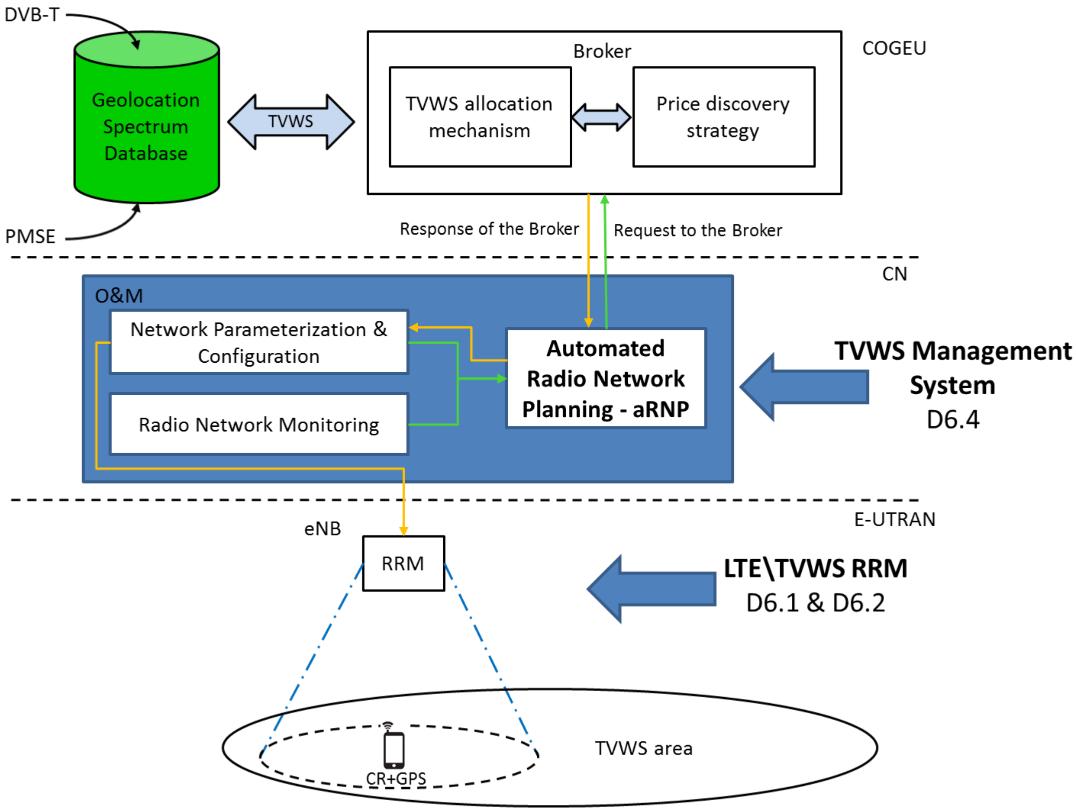


Figure 2: TVWS carrier's attribution and RRM on LTE

The Radio Resource Management (RRM) module, as it appears in the Figure 2, was firstly defined in deliverable 6.1 and 6.2. In the RRM is provided the decision of which is the best carrier (legacy or TVWS) to provide the service needed and where the user should be allocated. This way by using the algorithms proposed for the RRM in D6.1, the QoS is improved and the system capacity can be optimized. For this module a solution was presented where the user allocation or user scheduling should happen dynamically and automatically. In the deliverable 6.1, two possible algorithms were created and implemented in the LTE simulator.

With the first algorithm the TVWS carriers are only allocated to the user when legacy carriers are fully occupied. From the standpoint of the network implementation, this algorithm becomes simpler than the second algorithm because in this case there is no particular evaluation based on QoS. The user always requests the service using the legacy carrier but if it is fully occupied, the network informs the user equipment that a TVWS carrier will be used instead.

In the second algorithm the network operator will have an optimized control of the system capacity, maintaining the QoS. The User Equipment (UE) should take measurements of the Signal to Noise plus Interference (SINR) on both carriers and send this information to the network side that evaluates on which carrier less radio resource will be needed to provide de required service. The choice is made by the highest SINR and once chosen, the network provides the information for the terminal which carrier should be used. By choosing the carrier with the highest SINR, the number of radio resource blocks (RRB) needed decreases, leaving more resources available for other users. In conclusion, comparing the algorithm 1 and 2, with the algorithm 2 it is possible to optimize the RRBs and achieve higher capacity using the same RRBs.

Since the RRM was exploited in deliverable 6.1 and 6.2, now our next step will be to address the TVWS Management System. In Figure 2 an overview of the main connection between the COGEU Broker, the

TVWS Management System and the LTE\TVWS RRM is presented (the green arrows are part of a first phase of communications while the orange arrows belong to a second phase).

All the processes to control and allocate the TVWS carriers is fully automated and starts by monitoring the physical layer of the radio networks, the Radio Network Monitoring receives the measurements from the mobile terminals, the eNBs and collects network statistics data. This information is send to the module called Automated Radio Network Planning (aRNP) and is about the network status such as the provided service quality, traffic volume, equipment malfunction, etc. To provide the required QoS, the network defines a set of Key Performance Indicators (KPIs) that need to be regularly checked such as the call block rate (CBR), call drop rate (CDR) or the minimum bit rate for best effort services. If some of the KPI's doesn't meet the network operator minimum requirements, the monitoring module will trigger a request for a new TVWS carrier that will solve the non-compliance or at least improve it. When this happens all the information of the actual Network Parameterization & Configuration is send to the aRNP so that it's possible to analyse the effects of the use of TVWS in the existing network.

The KPI analysis is made in the aRNP were the system calculates how many carriers will be required for all the different cells that experience a decrease in QoS. Several cells may require a carrier at the same time, so reusing the same carriers that are already used in other cells is viable when the interference is minimal or almost absent. A request for TVWS carriers is made to the Broker. The Broker communicates with the Geo-location Spectrum Database and returns to the LTE TVWS Management System a list of channels including other parameters associated with each channel: carrier, antenna maximum transmission power, location and availability in the timeline. Then a process of analysing the best configuration and parameterization with the new TVWS carriers is initiated. The provided list of channels, given to the aRNP allows to choose the best channel for the specific case, taking in consideration the TVWS channel already deployed in the network. After selecting the best channel for the specific cell it is examined the best settings for this new TVWS antenna. The impact that this antenna causes in the network will be analysed by the aRNP. If the results of the KPI's fulfil the criteria or minimum requirements set by the operator the aRNP will try to book the identified TVWS channel in the COGEU Broker. The booking success depends on the result of the auction process, the COGEU proposed process. If the operator manages to book a channel it can be implemented in the network, the Network Parameterization & Configuration is updated and the RRM is used again.

2.2.1- *General description*

In this section the LTE TVWS Management System is presented in detail as depicted in Figure 3 and Figure 5. Since this is a rather long algorithm, it was divided into two parts. In the first stage is made a coverage analysis and in the second stage a capacity analysis.

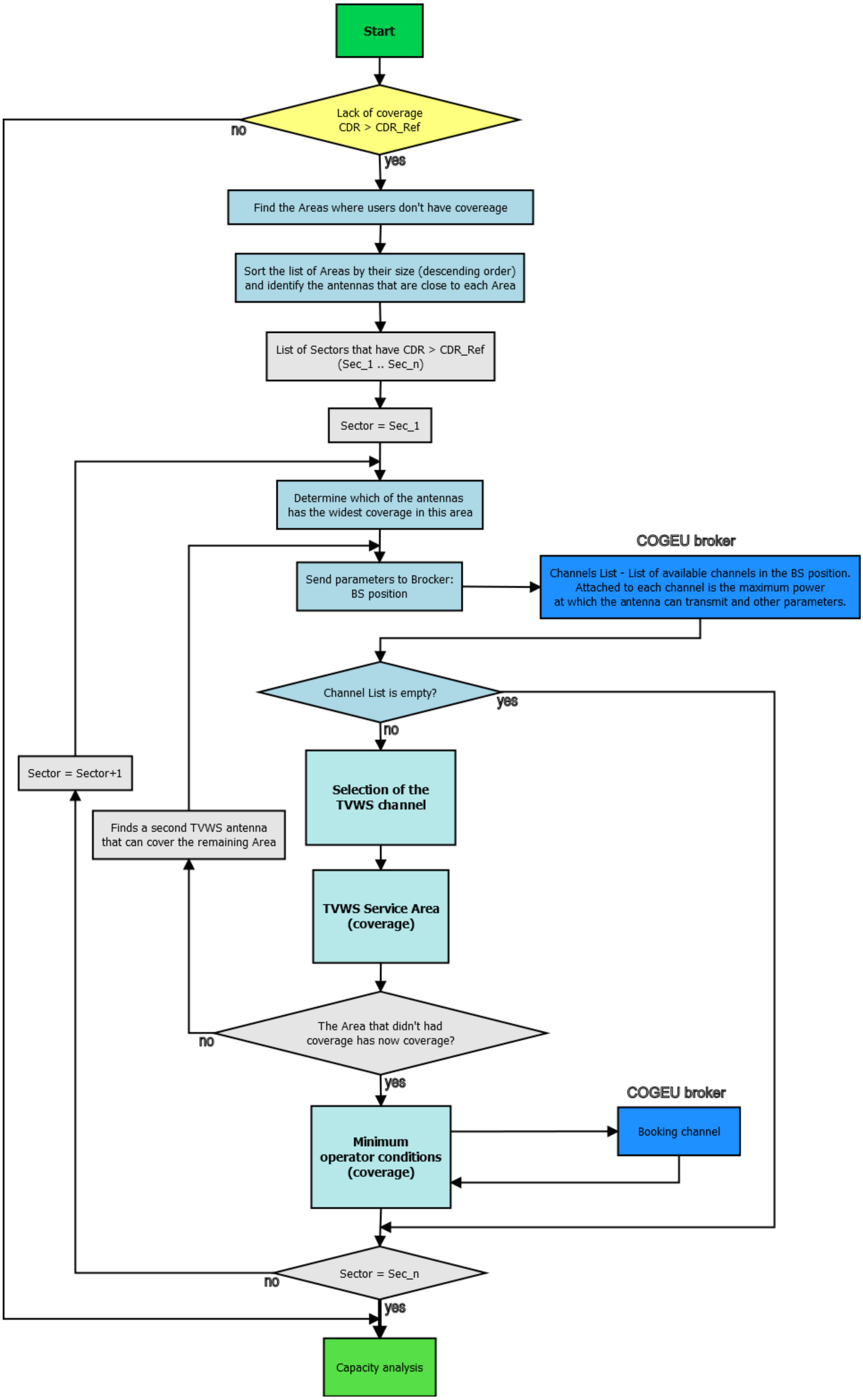


Figure 3: LTE TVWS Management System - Coverage analysis (first phase)

Leveraging one of the benefits of using lower frequencies (the possibility to obtain higher coverage using the TVWS carriers, carriers with lower frequencies) a first analysis in terms of coverage is performed. The trigger for the first part of the algorithm is comparing the CDR with a reference value defined by the network operator (CDR_Ref). The call dropping rate (CDR) and the call blocking rate (CBR) on each sector/cell are important elements for the algorithm provided by the Radio Network Monitoring. If the CDR is higher than the reference value, CDR_Ref, the process shown in Figure 3 is started. First it is necessary to discover the areas that don't present coverage through a simulation of radio network. Once we have all the areas a list is created and sorted by size in decreasing order. Each of these areas are associated with the sectors and antennas that are close to the specific area. Small areas can be neglected when compared with a reference size defined by the network operator. This list of areas will be useful forward in the algorithm, when it is necessary to check if the new TVWS antenna applied to the particular sector (sector that experienced CDR), completely covers the area (area associated to this sector) that had no coverage from the Legacy network. If the coverage of this area is incomplete the algorithm attempts, by using the same steps, to apply a second TVWS antenna in order to cover the remaining area that still don't have coverage from the network.

The Radio Network Monitoring makes a constant supervision of the network and provides information related to the CDR and CBR of each sector. Then in the Automated Radio Network Planning, a sector by sector analysis is performed by comparing the CDR of the specific sector to a CDR reference. If it is higher than the reference a process of requesting TVWS channels is triggered. A request of a TVWS channel is made by sending the BS position to the COGEU broker. The COGEU broker answer with a list of available channels and the maximum transmission power allowed for each channel on that specific location. The messages between the LTE TVWS Management System and the COGEU Broker are described in detail in the 2.2.2-.

Once received the requested Channels List, if the specific BS location doesn't have any available channels the list will be empty, some modules are skipped (a jump is performed) and it won't be assigned any channel to the current sector. But if some channels are available, what follows can be divided into three relevant phases: the Selection of the TVWS channel, the TVWS Service Area estimation and the verification of Minimum operator conditions. These three modules/blocks will be explained in detail in the following threads, respectively in 2.2.5-, 2.2.6- and 2.2.7-.

In the Selection of the TVWS channel module is performed the selection of the best TVWS channels from the available options. Once it has chosen the best channel the next step is to set some parameters of the TVWS antenna in order to cover all the area that doesn't have coverage from the Legacy network but at the same time causing the minimum possible interference with the other antennas, for such, adjustments are made to the power transmission and at the same time it's necessary to ensure that in all the area without coverage the UE has at least the minimum QoS. Within this area the farthest location from the chosen TVWS antenna needs to have at least the minimum SINR from that same antenna. If this condition is not fulfilled or if the TVWS antenna doesn't have enough range (using the maximum transmission power for the specific channel allowed by the Broker) to cover the entire area that didn't had coverage from the legacy network, the algorithm examines the possibility of activating a second TVWS antenna, in order to cover the remaining area that stills doesn't have coverage. To determine which is the best second TVWS antenna (among the closest eNB's from this area, the closest antennas have been identified in the begging of the algorithm), an average of the SINR presented in all the points of this area is calculated, for each of the antennas that are close to this area. When comparing these average SINR, the antenna that presents the higher value is chosen, antenna for which will be request a TVWS channel.

The Figure 4 is only an example of an area without coverage, where the best TVWS antenna must be chosen. All the users (red dots) which are in the area A_0 don't have coverage from the Legacy network (sectors: S_1 S_2 S_3). The base station BS_1 has a high CDR so the aRNP makes a request for a TVWS channel. If the allowed transmission power of the chosen TVWS channel is low the service area of the new TVWS antenna can be smaller than what was desired to cover (the entire area without coverage). So if the A_0 zone still doesn't have a complete coverage and some of the users still don't have QoS, a second TVWS antenna from other close BS can be used.

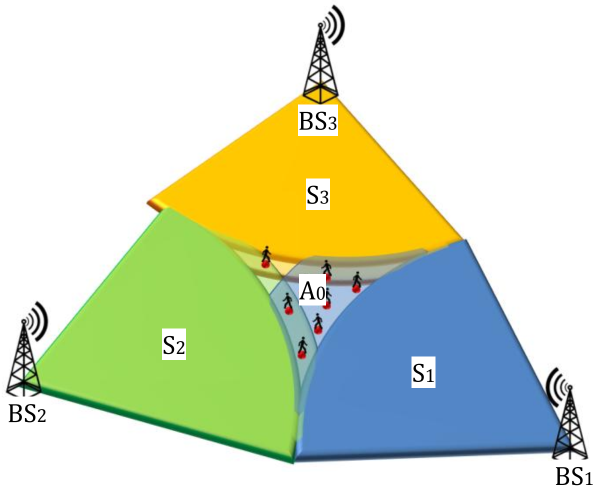


Figure 4: Zone without coverage (Z_0)

If the new TVWS antenna (from BS_1) is not able to cover the entire area A_0, a second analyse will be conducted but now only for the small area that still shows lack of coverage. A comparison between the average SINR of the remaining BS is done for this small area. For this example in Figure 4, the TVWS antenna from BS_2 would have a higher average SINR then the TVWS antenna from BS_3 so the TVWS antennas from BS_1 and BS_2 would be covering the entire area A_0.

Returning to the algorithm, one last review of the TVWS antenna along with the existing network is made. If the minimal conditions imposed by the operator are satisfied, it's worth booking the channel and the LTE TVWS Management System tries to reserve the selected channel. COGEU Broker reserves this channel for the specific date and time, sending back the booking confirmation. At this point is possible to analyse the next Sector with high CDR and all the procedures are repeated.

Once the first part of the LTE TVWS Management System algorithm ends what follows is the capacity analysis of the Legacy network (second part of the algorithm) along with the new TVWS antenna that were added to the network in the first phase of the algorithm. The CBR on each sector/cell, are compared with a reference value (CBR_Ref) defined by network operator and identifies which sectors need extra capacity. Then a request of TVWS channel, for each of these sectors, is made to the broker informing what is the BS location of the sector. The COGEU broker answer with a list of available channels and the maximum transmission power allowed for each one on that specific location.

What follows is very similar to the first part of the algorithm, divided into the same three phases but now focused on a capacity analysis: the Selection of the TVWS channel, the TVWS Service Area estimation and the verification of Minimum operator conditions. The first block is exactly the same as the applied in the coverage analysis but the other two blocks have some small differences that will be discussed later on in 2.2.6- and 2.2.7- (in the Figure 3 and Figure 5 these blocks have different labels).

Once again the selection of the best TVWS channels for the specific sector is made and the next step is to set some parameters of the TVWS antenna in order to obtain the minimum possible interference with the other antennas, for such it's necessary to approximate the service area of the new TVWS antenna to the service area offered by the Legacy antenna. If the minimal conditions imposed by the operator are satisfied the LTE TVWS Management System tries to reserve the selected channel. COGEU Broker reserves this channel for the specific date and time, sending back the booking confirmation. At this point is possible to analyse the next sector with lack of capacity and all the procedures are repeated. When the algorithm finishes analysing all sectors with lack of capacity, the Radio Resource Management is executed (the RRM isn't depicted in this Figure 5).

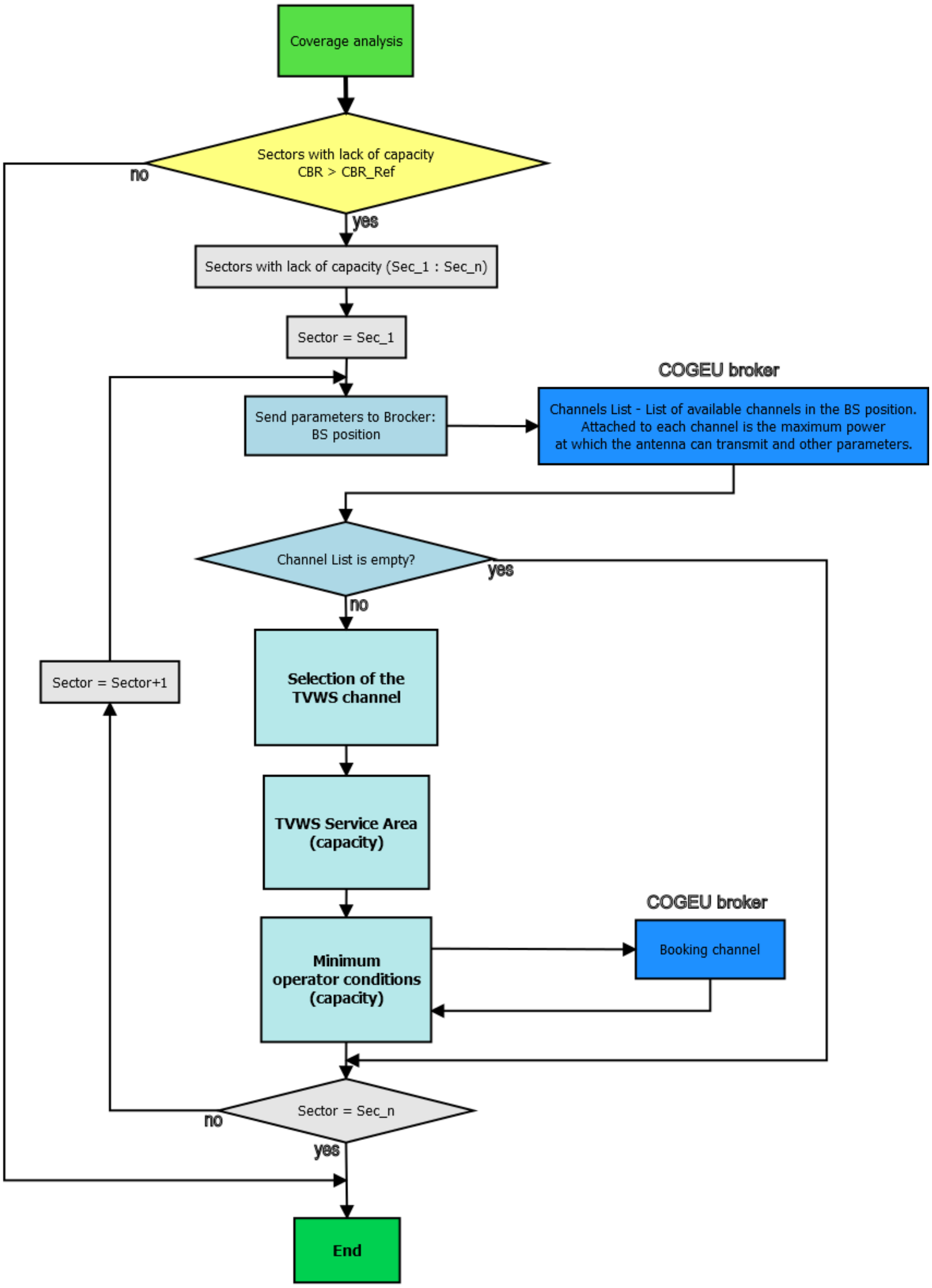


Figure 5: LTE TVWS Management System - Capacity analysis (second phase)

2.2.2- *Information exchange (between LTE - Broker)*

The next diagram (Figure 6) proposes a set of sequential messages between these “layers”: COGEU Broker, TVWS Management System and LTE\TVWS RRM. These main components were presented in Figure 2.

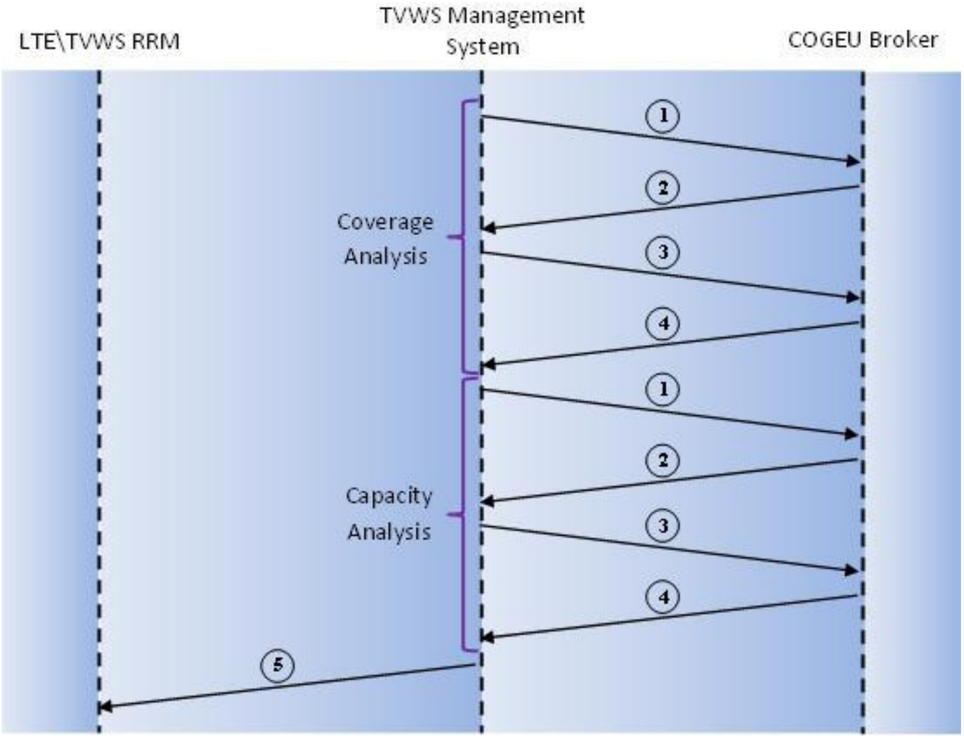


Figure 6: Sequential messaging

1- The LTE network analyses which antennas need to request TVWS channel by locating the areas without coverage or the sectors/cells that have extra capacity needs and sends the BS locations (GPS coordinates - Latitude and Longitude).
2- The Broker returns a list of available channels, Channels List (inside this list each channel has some parameters associated: carrier, antenna maximum power, available time period, etc), for each BS locations.
3- After analysing all the data in the aRNP, the TVWS Management System makes the request to book the channel that fulfil the requirements (attached to each requested channel is also sent the time slot that is desired).
4- Broker sends the confirmation that the requested channel is reserved and can be used by the operator during the time slot established.
5- TVWS Management System sends all the configuration and parameterization of the new TVWS antenna to the RRM.

2.2.3- *Broker database and the area blocks*

COGEU will adopt in TVWS a concept of spectrum pooling, which makes use of a geo-location database storing information regarding TVWS availability for possible secondary usage. The Figure 7 is the interface of the COGEU TVWS geo-location database where we have different options that anyone can exploit and use. One of those is the online spectrum broker. The interface in the figure is one way to visualize the available TVWS channels from 40 to 60, with their maximum allowed transmit power levels for the specific location, the associated maximum EIRP (Equivalent Isotropically Radiated Power). This proposed approach provides better QoS for secondary systems operation over TVWS, avoiding harmful interference with primary systems (DVB-T and PMSE systems). An overall TVWS allocation process is proposed and may be adopted by the COGEU spectrum broker entity.

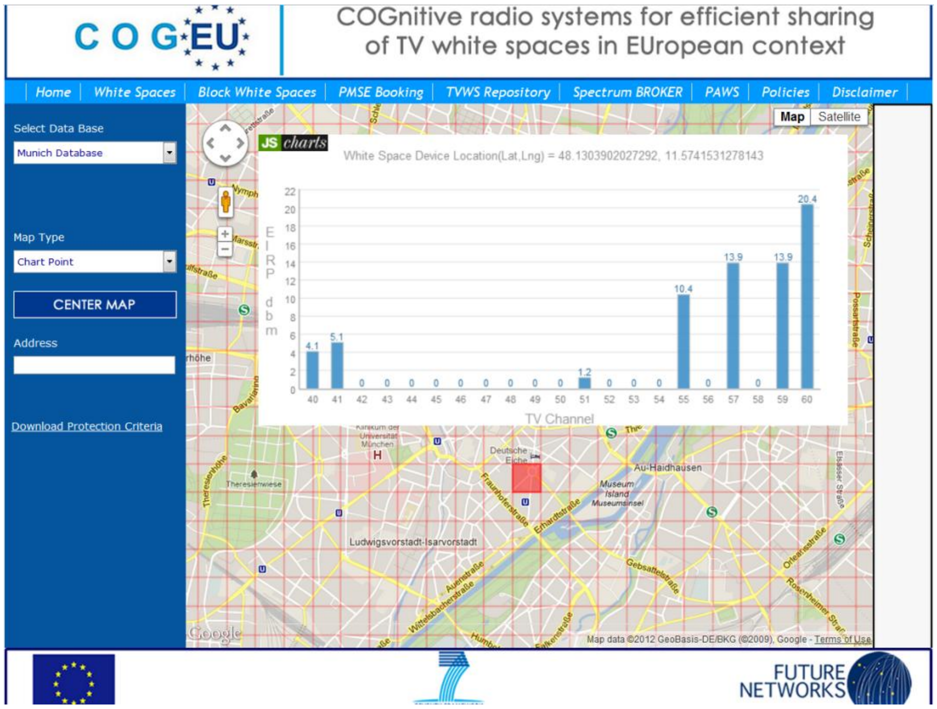


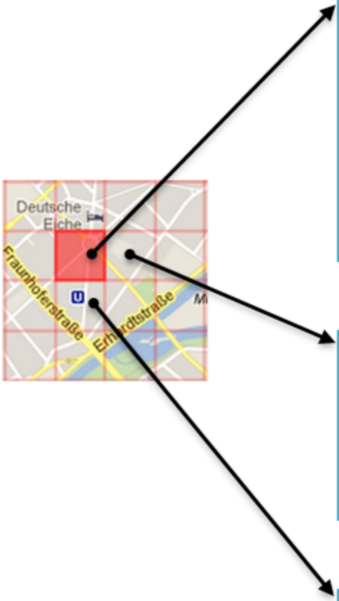
Figure 7: Interface of the COGEU TVWS geo-location database [2]

The TVWS geo-location database has the entire map divided by squares of 200x200 m, area blocks. Each block has a list of the available channels with the maximum allowed transmission power, Channels List. Basically the broker database is composed by a very large set of lists that are identified by the GPS coordinates (Latitude and Longitude). As an example, an area block was selected in the Figure 7, identified in red. Immediately above, a spectrum pool with the available TVWS resources of this specific location is presented. If an TVWS antenna is free in this area block those would be the available channels that the operator could choose.

The possibility of two different antennas with same location having the same channel is very low, it will never happen because when a channel is book the broker actualizes the list of channels so the next antenna won't have this channel available to analyse and book.

2.2.4- *Channels List*

When the network does not have enough coverage or when one or more legacy antennas exceed the limit of its capacity, the network uses the channel allocation to ensure a better QoS. After the Radio Network Monitoring identifies the new TVWS antenna that needs to be activated (to increase coverage or capacity in that sector), the BS location is send to the broker. Using the BS latitude and longitude the broker finds to witch area block the BS belong and returns the Channels List (CL) of this area block. The Channels List is closely similar to the representation provided in the next figure:



Location (Lat, Lng) = 48.13039020272292 , 11.5741531278143			
Channel	**Frequency (MHz)**	**Max EIRP (dBm)**	**Time slots occupied (h)**
40	622 – 630	4.1	*
41	630 – 638	5.1	*
51	718 – 726	1.2	*
55	742 – 750	10.4	*
57	758 – 766	13.9	16:00 – 20:30
59	774 – 782	13.9	*
60	782 – 790	20.4	14:30 – 22:00

Location (Lat, Lng) = 48.13039020272292 , 11.576863142198			
Channel	**Frequency (MHz)**	**Max EIRP (dBm)**	**Time slots occupied (h)**
55	742 – 750	12.5	*
57	758 – 766	14.6	16:00 – 20:30
59	774 – 782	14.6	*
60	782 – 790	21.6	14:30 – 22:00

Location (Lat, Lng) = 48.1285958252822 , 11.5741531278143			
Channel	**Frequency (MHz)**	**Max EIRP (dBm)**	**Time slots occupied (h)**
40	622 – 630	4	*
41	630 – 638	5	*
51	718 – 726	0.3	*
55	742 – 750	7.5	*
57	758 – 766	14.6	16:00 – 20:30
59	774 – 782	14.6	*
60	782 – 790	27.5	14:30 – 22:00

(* : available all day)

Figure 8: Three Area Blocks with their Channels List

In the Figure 8 there are represented three Channels List, from the three area blocks. The represented values were collected from the COGEU TVWS geo-location database. The frequencies are fixed for all the channels while the Max EIRP values vary greatly from place to place. For each channel available, a maximum allowed transmit power level is attached. COGEU has great concern with this to avoid interferences with neighbouring antennas that have same frequency. Some of these power values are measured on the field and the rest are estimated (using simulations), avoiding harmful interferences. The values presented in the column of Time slots occupied are not real values, they are used only for demonstration purposes and chosen as an example because for now these channels are completely available.

2.2.5- *Selection of the most appropriate TVWS channels to deploy in the LTE network*

The module Selection of the TVWS channel plays the most important role in the LTE TVWS Management System. Once verified the existence of available channels for the BS location, all these options will be analysed and compared in order to choose the best available channel to be introduced into the existing network.

This module consists in a loop that runs through the whole Channel List offered by the Broker. The cycle is presented in the Figure 9 in grey colour and each carrier represents one of the available channels. For each available channel is calculated the PathLoss, the Received Power and the Signal to Interference and Noise Ratio (SINR) in downlink for each point of the scenario. For all the calculations to be carried out for a channel, the simulation for each channel will use the maximum transmission power allowed by the Broker (max EIRP). After, the average SINR in the entire scenario is calculated and stored. When the cycle ends a comparison between the stored values from all the channels in the list is made. This way, working with the SINR DL, it’s taken into account the interference effects that would arise when using a specific carrier over an existing network that uses Legacy and TVWS bands. If there are channels which are causing interference to one of the channels being analysed, this one will present a low average SINR. The carrier with highest average SINR will be the best channel for the current network.

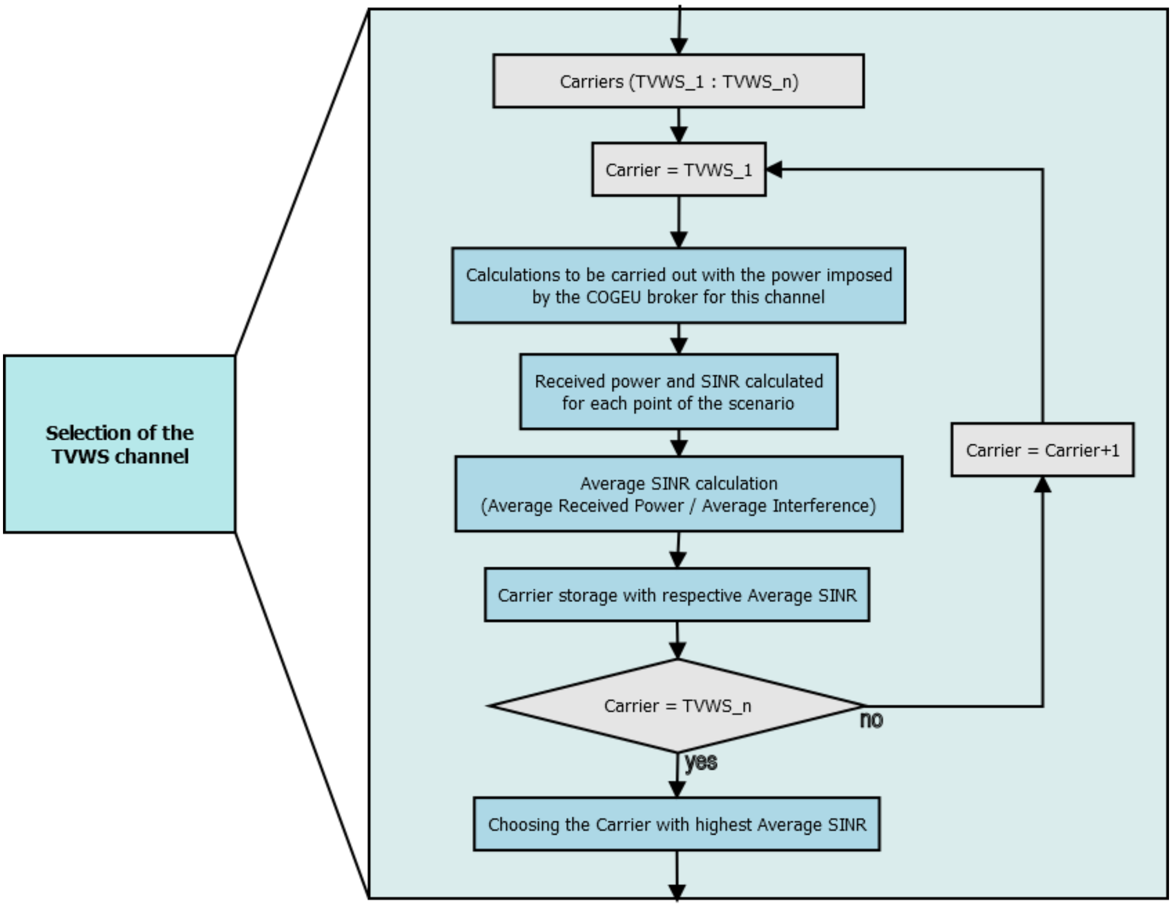


Figure 9: Selection of the best TVWS channel (for one sector/cell)

2.2.6- *TVWS Service area*

The frequencies, chosen for the antennas that will be part of the network, are one of the most relevant parameters for planning a radio network. The legacy network is planned according to the high frequencies (2.6 GHz), due to its propagation models, which translates in lower coverage comparing with lower frequencies. As known, low frequencies (700 MHz) have a much greater coverage so another type of planning for TVWS must be taken into account.

In a TVWS network the antennas will be in the same place as the antennas legacy, pointed in the same direction (same azimuth). When a network has lack of coverage, the entire area where the UE don´t have the minimum QoS is identified along with the best TVWS antenna to cover this area. After knowing this the transmission power of the TVWS antenna is adjusted so that on the site with worst SINR (worst coverage from the Legacy antenna) we have from the new TVWS antenna at least the minimum QoS in the same place. This way it is ensured to have at least the minimum QoS throughout the entire area that had no coverage, causing to the neighbouring cells minimal interference possible. An example is presented in the Figure 10 where the transmission power from the TVWS antenna was adjusted to cover the area that had no coverage from the Legacy network. Whit this parameters the TVWS service area was adjusted to cover the entire area with the least possible interference.

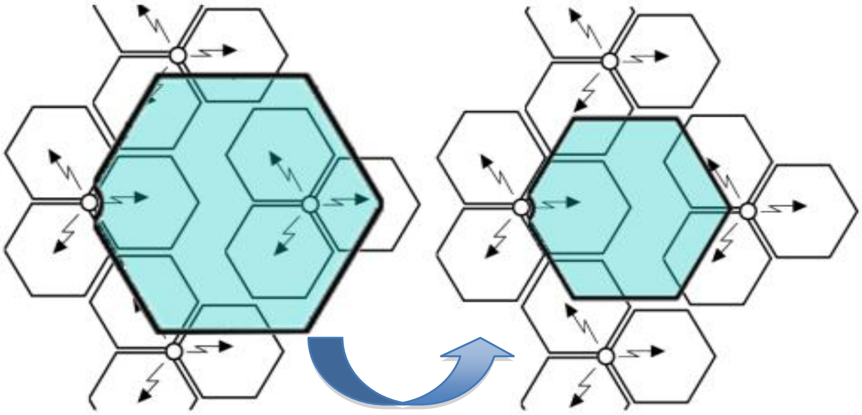


Figure 10: The TVWS service area for a better network coverage. The first case (left side) without any adjustment and the second case (right side) with transmission power adjustments. (TVWS antenna with service area at blue over a legacy network)

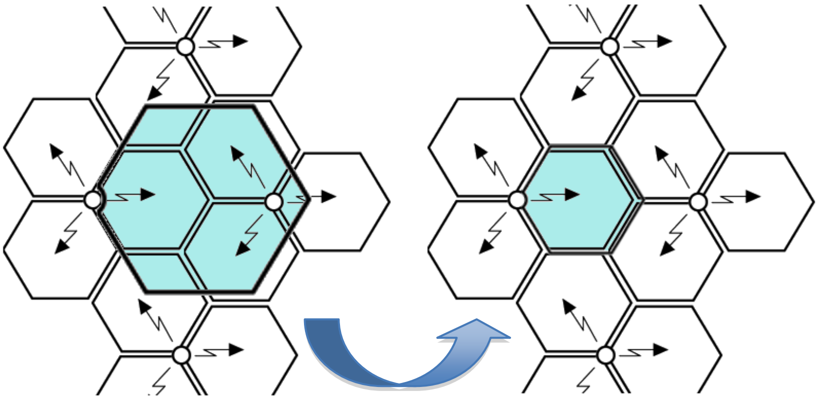


Figure 11: The TVWS service area for a better network capacity. The first case (left side) without any adjustment and the second case (right side) with transmission power adjustments. (TVWS antenna with service area at blue over a legacy network).

When analysing a sector that suffers from lack of capacity, a different approach has to be done. In this case the TVWS service area needs to be very similar to the service area from the Legacy antenna. As it's possible to view through the Figure 11, if the TVWS antenna doesn't have any adjustment it will have a very large coverage that can cause a lot of interference in neighbouring TVWS antennas if they are using the same carrier. So the aim is that the TVWS antenna has at least the same service area that offered by the Legacy antenna causing the minimum of interference possible.

The request for allocation of a TVWS channel is done when one of the legacy antennas has a lack of capacity. Once a channel is assigned to that location it must be checked the service area of that antenna legacy in order to adjust the coverage of the TVWS antenna so both antennas have the same service area or as close as possible. Depending on the situation, the new TVWS antenna will be adjusted by varying his transmission power. The Figure 12 is an example of the service areas from the Legacy and the TVWS antennas. The boundary from the coverage of the Legacy antenna is represented in green and shows a slight deformation due to the interference caused by the other antennas that have the same frequency. In red the boundary from the coverage of the TVWS antenna (in this case this is the only TVWS antenna with this frequency so there is no interference from others antennas) with the necessary adjustments in the transmission power to have almost the same coverage in both service areas.

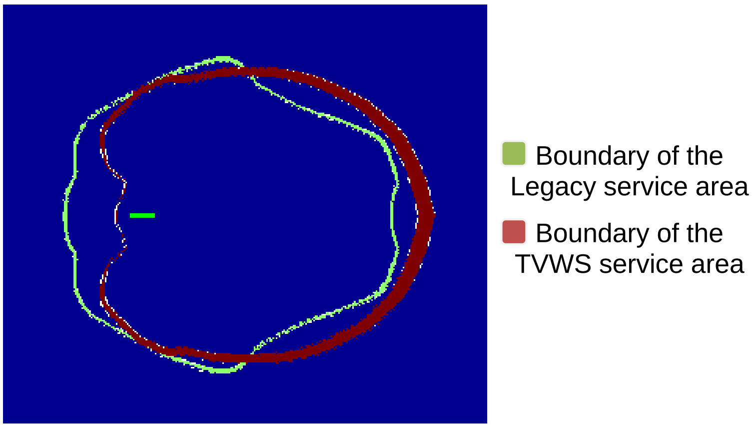


Figure 12: Service areas of the legacy antenna (green) and of the TVWS antenna with adjustments in the transmission power (red)

As mentioned previously the TVWS Service Area module will take a different approach depending on the type of analysis that is needed. Within this module there are two paths: one for the first phase of the LTE TVWS Management System, the coverage analysis, and another for the second part, the capacity analysis. Figure 13 presents the module TVWS Service Area and it is also present in the block diagram of LTE TVWS Management system, Figure 3 and Figure 5.

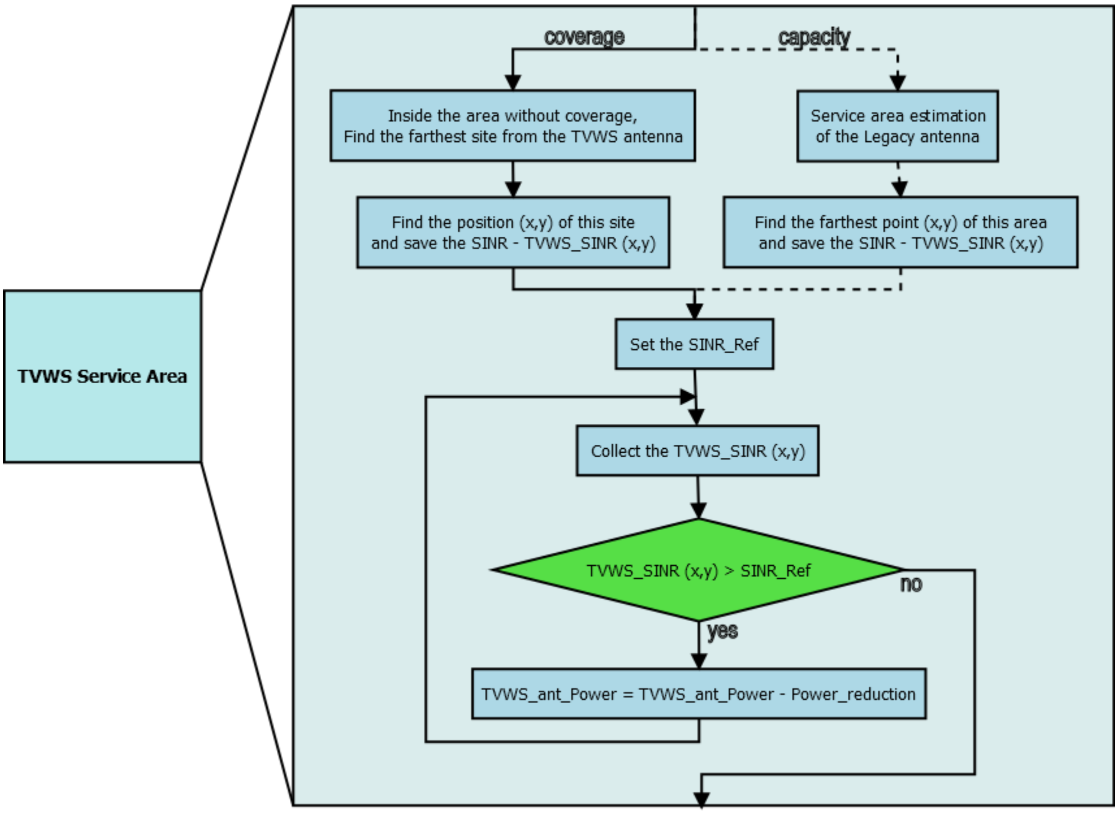


Figure 13: Service Area of the chosen TVWS channel (for one sector/cell)

If it's being made a coverage analysis, the farthest site from the TVWS antenna inside the area without coverage needs to be found. Once identified, the position x and y of that location is saved and SINR that the TVWS antenna offers for that location is also saved as the TVWS_SINR (x,y). For the capacity analysis case, the service area of the Legacy antenna needs to be found. With this the farthest point of this service area is identified and the position in x and y are saved along with the TVWS_SINR (x,y).

The following process is the same for both type of analysis. This final process aims to reduce the tarnsmission power of the antenna as much as possible without exceeding the minimum SINR, SINR_Ref(x,y). This way it is guaranteed that whole the desired area will have at least the minimum QoS. The minimum SINR value serves as a reference and is set before entering in a cycle as you can see in the Figure 13. This cycle is adjusting the TVWS antenna, decreasing the transmission power until the SINR of the TVWS channel, in the same site previously chosen, is equal or slightly greater than the SINR of reference.

It is to pay attention to when we first enter this cycle (while Legacy SINR(x,y) > TVWS SINR(x,y)) the Transmission Power DL of the TVWS antenna (TVWS ant. Trans. Power DL) starts already limited by the max EIRP of the chosen TVWS channel.

In some cases due to the fact that all TVWS channels are limited with a max EIRP, the channel chosen as the best among the possible choices from the channel list can have a low max EIRP compared to what would be desired. With a low max EIRP the service area provided by the TVWS antenna can be smaller than the service area of the legacy antenna. In these cases the minimum QoS in the entire area is not guaranteed. Nevertheless, it can be used and it lies with the operator if it is worth using this channel or not.

2.2.7- *Minimum operator conditions*

By the end of the algorithm the operator must make a final decision. This decision is made within the Minimum Operator Conditions module, presented in Figure 14. Again two different paths exist inside this module depending on which the analysis that is on going, the coverage or the capacity analysis.

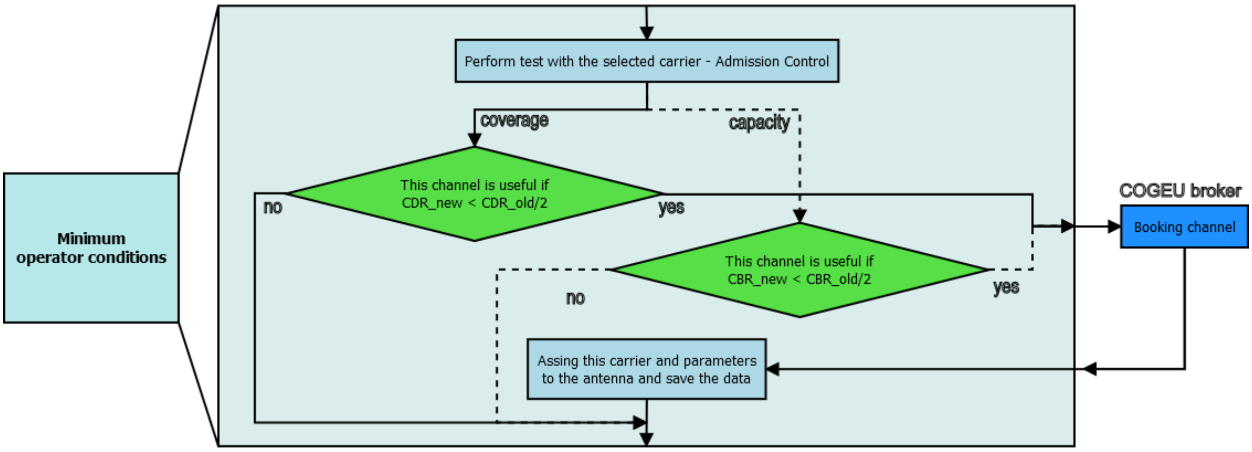


Figure 14: Minimum operator conditions and Booking channel (for one sector)

The first block to appear in this Figure 14, Perform test with the selected carrier - Admission Control, is simulating the RRM to analyse what will be the behaviour of the network when applied the new active TVWS antenna. A proper analysis of these results will be important to determine if it worth to book this channel or not. If it's worth the TVWS Management System sends a booking request, the Broker confirms that request and then the system can assign this carrier to the antenna, along with all the other parameters and configurations. If not the algorithm proceeds to the next area with lack of coverage or to the next sector with lack of capacity, leaving the antenna without any assigned channel.

For such validation we propose the following condition. For the coverage analysis, the new TVWS antenna meets the minimum requirements if the CDR (CDR_new) of the sector decreases to half of what it had without any TVWS channels, presented in the Figure 14 as CDR_old/2. Then the LTE TVWS Management System can make the reservation, otherwise no. The same goes to the capacity analysis where the CBR needs to decrease to half of what it had without TVWS channels (CBR_new < CBR_old/2). It was necessary to define these reference values, to implement the algorithm, but these can be easily changed to align with the operator preferences.

2.3- Deploying TVWS in the Munich area

2.3.1- *Identification and characterisation of the area under evaluation*

The entire algorithm presented was implemented and tested in the LTE network simulator that had already been presented in D6.1. In order to obtain results as near as possible to the reality we aim to create a scenario as realistic as possible. Munich was the city where the COGEU focused its study and where some trials have been performed. As such, it was chosen an area on the outskirts of Munich. We can see this area on the Munich map presented in the Figure 15, bordered with a black rectangle. This area belongs to Ramersdorf-Perlach and Table 1 has some more information.

Ramersdorf-Perlach	
Area (Km^2)	19,9
Population	102689
Density (population/Km^2)	5160,25

Table 1: Ramersdorf-Perlach characteristics

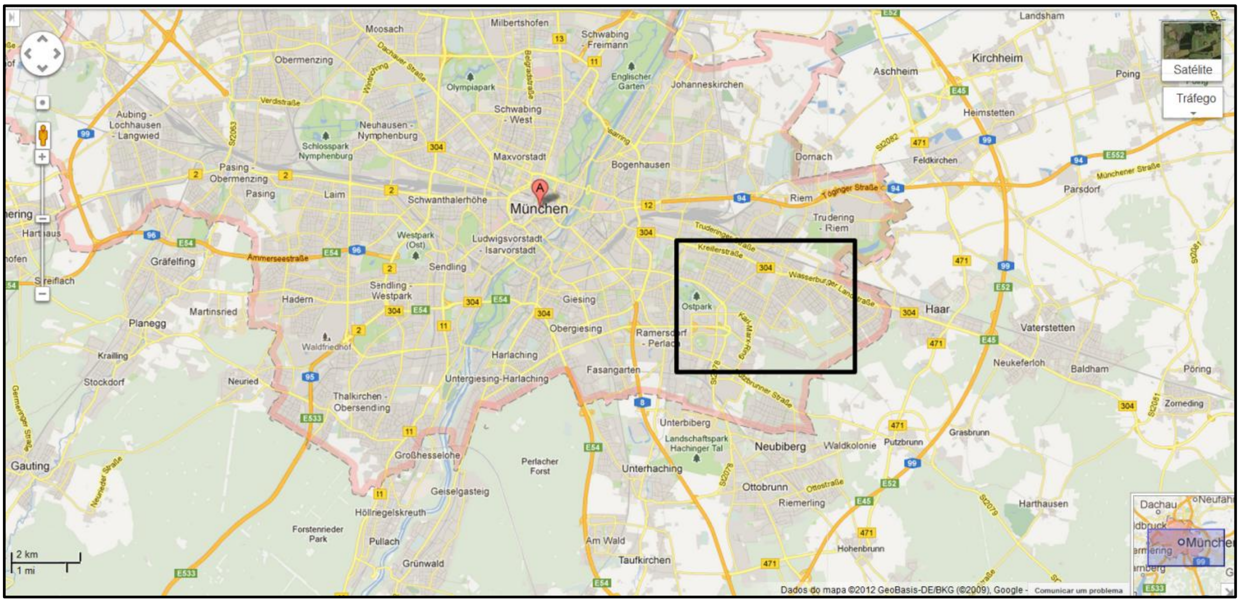


Figure 15: Chosen area of Munich

Expanding the chosen area we can see the following 4,8x3,8 Km map in Figure 16, already divided into the Area Blocks of 200x200 m. The orange triangles represent all the base stations that there exist (this information about the BS's locations comes from a Monitoring Federal Network Agency database - EMF database [3]).

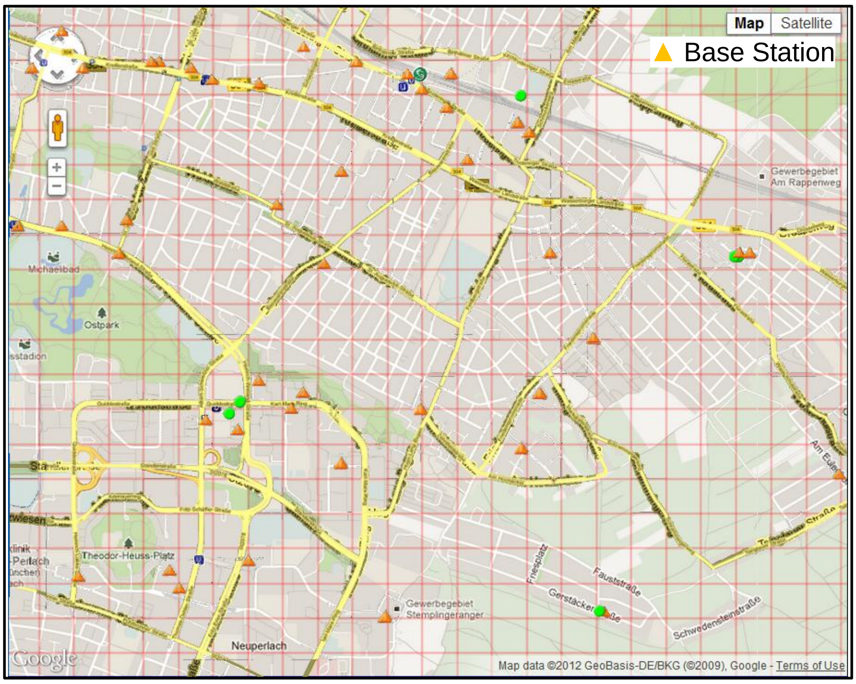


Figure 16: The chosen area with all the BS's

All these BS that appear in the Figure 16 belong to different operators, this information is also available at the EMF database but unfortunately it was a little confused and therefore not very reliable. The LTE simulator has so far been used to perform planning networks assuming only one operator, so in order to be possible to implement this scenario in the LTE simulator it was necessary to take into consideration only some of the BS depicted in Figure 16. We have overcome the complexity of the scenario that needs to be simulated maintaining it as much realistic as possible. The chosen BS's are evenly spaced and have an almost complete coverage of the scenario. In the upper right corner of the map there is a zone with lack of coverage, this is because the BS that should be covering this area isn't within the chosen area of the map. It was possible to verify this through some simulations of coverage that will be presented later on, in Figure 21. All the chosen BS's are presented in the Figure 17, a total of 21 BS's. We assume that all these BS's belong to the same operator while the neglected BS's belonged to other operators.

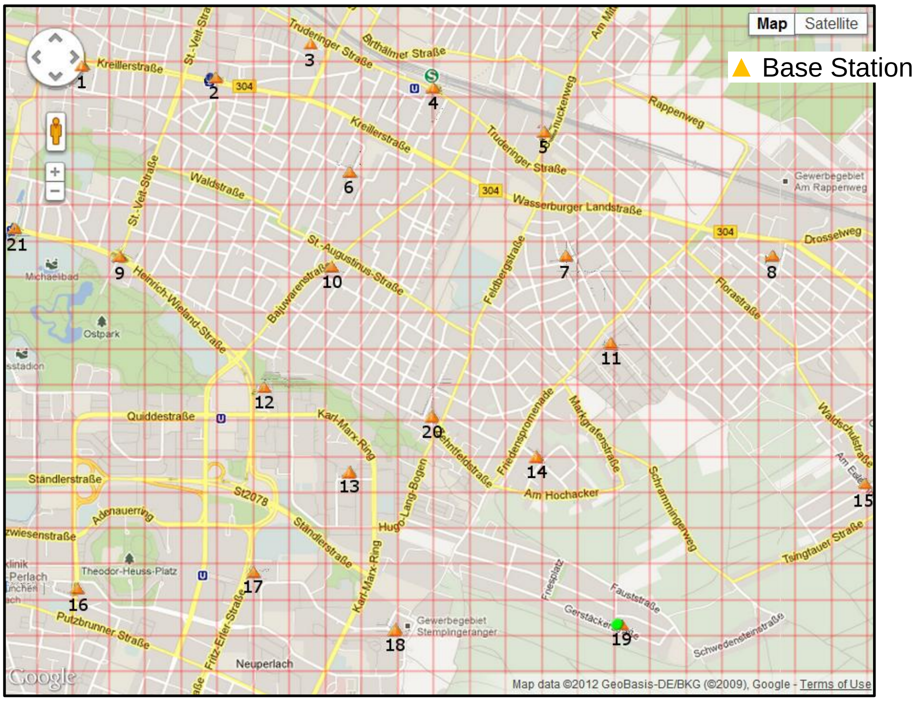


Figure 17: Chosen BS's for the simulations (numbered from 1 to 21)

2.3.1.1 Network Parameters

With the EMF database, besides being possible to collect information about the BS's locations that exist in this area, it is also possible to obtain information about the antennas azimuth of each BS's [3]. This database has a long list of antennas (with their azimuth) for each BS and some of these antennas belong to different operators. So, some of the antennas have been chosen because implementing all of them would be too complex. The chosen antennas for each BS are in the Table 2 with the associated frequency and azimuth.

BS	1	2	3	4	5	6	7	8	9	10
2600 MHz	90º	60º	0º	0º	0º	70º	80º	80º	14º	60º
2605 MHz	210º	180º	120º	120º	120º	190º	200º	200º	134º	180º
26010 MHz	330º	300º	240º	240º	240º	310º	320º	320º	314º	300º

BS	11	12	13	14	15	16	17	18	19	20	21
2600 MHz	0º	80º	0º	70º	80º	80º	80º	80º	90º	80º	60º
2605 MHz	120º	200º	120º	230º	200º	200º	200º	200º	210º	200º	180º
26010 MHz	240º	320º	240º	340º	320º	320º	320º	320º	330º	320º	300º

Table 2: Antennas azimuth [3]

Throughout this topic some BS's parameters were defined, as the BS's positions, the antennas frequencies and azimuth. In order to have a good review of the developed algorithm it is necessary to set the remaining parameters assuming a heavily overloaded urban scenario, consisting of 21 sites with

3 sectors per site and a random distribution of users. The most relevant Legacy antennas parameters are in the Table 3 and the UE (User Equipment) parameters in the Table 4.

TxPower	33 dBm
antHeight	35 m
antType	120 º
antTilt	9,5 º
Cable Losses	2 dB
Duplex mode	FDD
CarrFreqDL	2610 - 2615 - 2620 MHz
CarrFreqUL	2420 - 2425 - 2430 MHz
Bandwidth	5 MHz
PropModel	Erceg Urban
Sectors/site	3

Table 3: Legacy network parameters [4]

UE txMaxPower	23 dBm
UE antHeight	1,5 m
bit rate DL	1 Mbps
bit rate UL	256 Kbps
UE antType	Omnidirectional

Table 4: User Equipment parameters [4]

All the TVWS antennas that are in the field will have the same positions and azimuth of the Legacy antennas and are in a first stage disabled but some of the TVWS antennas parameters are constant and must be set. The remaining parameters vary depending on the situation and are defined by the aRNP: the carrier and the transmission power of the TVWS antennas. The most relevant TVWS antennas parameters are presented in the Table 5. The LTE has spectrum flexibility: 1.4, 3, 5, 10 and 20 MHz but each TVWS channel has 8 MHz so the LTE TVWS Management System will only use 5 MHz of the available channel bandwidth for Downlink.

TxPower	-
antHeight	35 m
antType	120 º
antTilt	9,5 º
Cable Losses	2 dB
Duplex mode	FDD
CarrFreqDL	-
BW	5 MHz
PropModel	Okumura-Hata
Sectors/site	3

Table 5: TVWS network parameters

2.3.1.2 TVWS channels and the geo-location database

In some cases the same channel might be reused in the neighbour antennas and therefore it's important to assign specific carrier for each channel. In the Table 6 the carriers of each channel are presented.

Channel	**40**	**41**	**42**	**43**	**44**	**45**	**46**	**47**	**48**	**49**	
CarrFreq (MHz)	622	630	638	646	654	662	670	678	686	694	
Channel	**50**	**51**	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**	**60**
CarrFreq (MHz)	702	710	718	726	734	742	750	758	766	774	782

Table 6: The carrier frequency of each channel [4]

In the LTE simulator the allocation in time was neglected. The time periods that the operators seek to reserve particular channels or the time periods in which the channels are already being used throughout the day are not taken into consideration by the LTE simulator. This means that the channel lists required by the simulator will consist only in the available channels and the maximum EIRP allowed for each channel. These values (displayed in Table 7 and Table 8 and used in the simulations) were collected from the COGEU geo-location database for each of the BS locations. The values in Table 7 and Table 8 were collected from the same database but with different characteristics. The Table 7 shows a less restrictive list where it's possible to see EIRP values much higher than those of the Table 8, a list far more restrictive. These two databases were used and the results will be analysed further ahead.

Available Channels - List less restrictive							
BS 1	Channel	41	51	55	57	59	60
	Max EIRP (dBm)	24,9	8,4	8,4	37,4	51	58
BS 2	Channel	41	51	55	57	59	60
	Max EIRP (dBm)	31,5	12,8	12,8	37,4	47,5	54,5
BS 3	Channel	41	51	55	57	59	60
	Max EIRP (dBm)	32,3	21,2	21,2	37,4	43,5	50,5
BS 4	Channel	41	51	55	57	59	60
	Max EIRP (dBm)	30,3	17	17	37,4	39,5	46,5
BS 5	Channel	41	51	55	57	59	60
	Max EIRP (dBm)	19,6	13,8	17,3	36,5	36,5	43,5
BS 6	Channel	41	55	57	59	60	
	Max EIRP (dBm)	19,7	20	36,5	36,5	43,5	
BS 7	Channel	41	51	55	57	59	60
	Max EIRP (dBm)	25,6	15,9	15,9	26,9	26,9	33,9
BS 8	Channel	41	51	55	57	59	60
	Max EIRP (dBm)	21,6	15,5	16	23,5	23,5	30,5
BS 9	Channel	41	51	55	57	59	60
	Max EIRP (dBm)	29,8	12,9	12,9	37,4	45	52
BS 10	Channel	41	57	59	60		
	Max EIRP (dBm)	29,1	32,9	32,9	39,9		
BS 11	Channel	41	51	55	57	59	60
	Max EIRP (dBm)	16,3	13,5	13,5	22,4	22,4	29,4
BS 12	Channel	41	51	55	57	59	60
	Max EIRP (dBm)	23,6	16,3	16,3	32	32	39
BS 13	Channel	41	51	55	57	59	60
	Max EIRP (dBm)	21,2	15,5	15,5	22,4	22,4	29,4
BS 14	Channel	51	55				
	Max EIRP (dBm)	13,4	28				
BS 15	Channel	55					
	Max EIRP (dBm)	16,8					
BS 16	Channel	40	41	57	59	60	
	Max EIRP (dBm)	8,2	24,6	32,3	32,3	39,3	
BS 17	Channel	51	55				
	Max EIRP (dBm)	19,5	19,5				
BS 18	Channel	51	55				
	Max EIRP (dBm)	16,3	16,3				
BS 19	Channel	51	55	57	59	60	
	Max EIRP (dBm)	22,5	23	16,1	16,1	23,1	
BS 20	Channel	41	57	59	60		
	Max EIRP (dBm)	14,2	15,2	15,2	22,2		
BS 21	Channel	41	51	55	57	59	60
	Max EIRP (dBm)	19,8	9,4	9,4	37,4	49,2	56,2

Available Channels - List more restrictive							
BS 1	Channel	41	55	57	59	60	
	Max EIRP (dBm)	10	8,4	16,4	18,4	18,4	
BS 2	Channel	41	51	55	57	59	60
	Max EIRP (dBm)	12,3	11,2	12,8	20,8	22,8	22,8
BS 3	Channel	41	57	59	60		
	Max EIRP (dBm)	8,4	14,4	16,4	16,4		
BS 4	Channel	41	51	55	57	59	60
	Max EIRP (dBm)	9,4	10	17	25	27	27
BS 5	Channel	41	51	55	57	59	60
	Max EIRP (dBm)	10,9	9,8	19,2	25	27,8	29,1
BS 6	Channel	55	57	59	60		
	Max EIRP (dBm)	11,3	15,8	19,3	24,1		
BS 7	Channel	41	51	55	57	59	60
	Max EIRP (dBm)	9,1	9	12,1	23,9	25,9	25,9
BS 8	Channel	55	57	59	60		
	Max EIRP (dBm)	16	17,6	18,6	26		
BS 9	Channel	41	51	55	57	59	60
	Max EIRP (dBm)	8	9	11	20,9	22,9	22,9
BS 10	Channel	41	57	59	60		
	Max EIRP (dBm)	10,1	15,2	17,2	17,2		
BS 11	Channel	55	57	59	60		
	Max EIRP (dBm)	13,5	14	19,2	23,5		
BS 12	Channel	41	55	57	59	60	
	Max EIRP (dBm)	7,8	16,3	20,2	21,2	26,3	
BS 13	Channel	41	55	57	59	60	
	Max EIRP (dBm)	8,4	15,5	18,4	20,6	25,5	
BS 14	Channel						
	Max EIRP (dBm)						
BS 15	Channel						
	Max EIRP (dBm)						
BS 16	Channel	40	41	57	59	60	
	Max EIRP (dBm)	8,4	8,7	14,1	16,1	16,1	
BS 17	Channel						
	Max EIRP (dBm)						
BS 18	Channel						
	Max EIRP (dBm)						
BS 19	Channel	51	55	57	59	60	
	Max EIRP (dBm)	8,2	8,2	16,1	16,1	18,2	
BS 20	Channel	57	59	60			
	Max EIRP (dBm)	14,1	15,2	16,1			
BS 21	Channel	41	51	55	57		
	Max EIRP (dBm)	9,4	16,6	17,6	19,4		

(* all the channels with a max EIRP < 7 dBm were neglected)

Table 7: The Channels List of each BS (the available channels and the respective max EIRP) with a less restrictive database [5]

Table 8: The Channels List of each BS with a more restrictive database [5]

2.3.2- ***Simulation Environment***

The LTE simulator was developed in Matlab were LTE radio behaviour could be examined in terms of radio coverage and capacity along with some statistics such as CDR and CBR. Having a scenario well defined by base station parameters, user equipment parameters, network and environmental characteristics it's possible to perform simulations were legacy frequencies and TVWS frequencies work together for a better QoS. In deliverable 6.1 the LTE simulator architecture and interface was introduced and the two RRM algorithms were proposed.

In the Figure 18 the Graphical User Interface (GUI) is presented and at the same time it's depicted the simulation scenario, of 5x4 Km, with all the BS's in the proper location and the antennas with the proper azimuth.

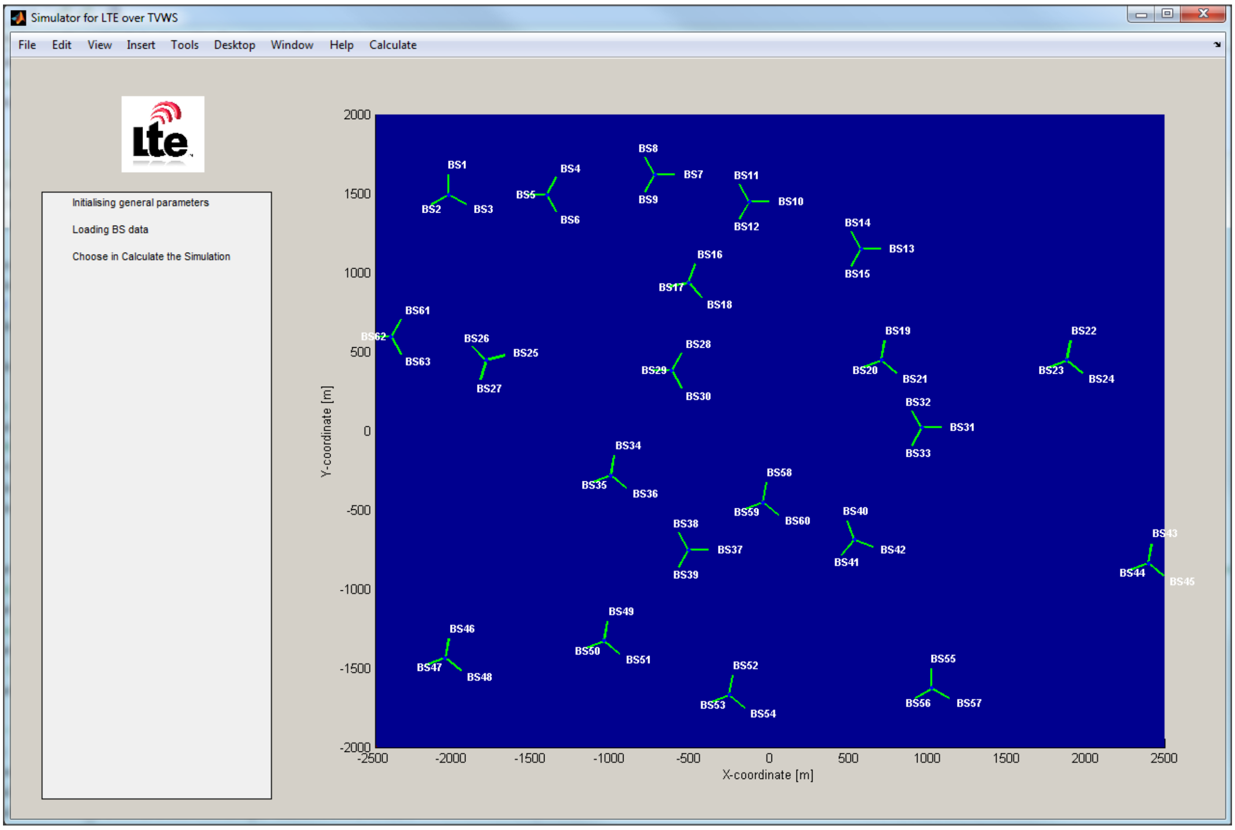


Figure 18: GUI interface of the LTE simulator and the simulation scenario with all the BS's (the green lines are the antennas)

For testing the LTE TVWS Management System the urban scenario needs a realistic number of users or user equipment's (UE). Ramersdorf-Perlach city has a density of 5160 population/Km^2 so it is assumed that the number of active clients connected to the network operator can be calculate with the next equation:

$$\text{Density x Area of the scenario x Clients of this operator x Active users} =$$

$$= 5160 \text{ population/Km}^2 \times 20 \text{ Km}^2 \times 18\% \times 5\% = 928{,}8$$

By using the equation previously defined, it was assumed that the scenario would have 925 active users and after simulating this scenario it was found that some of the sectors were overloaded. We can see all the 925 active users randomly dispersed in the Figure 19.

For each of these UE it was assigned a particular service and each service belongs to a QoS Class Identifier (QCI). The percentage of UE for each service or QCI is presented in the Table 9. These values are close to what happens in reality.

QCI	1	2	3	4	5	6	7	8	9
Percentage (%)	20	10	9	5	5	32	3	8	8

Table 9: Percentage of UE for each QCI

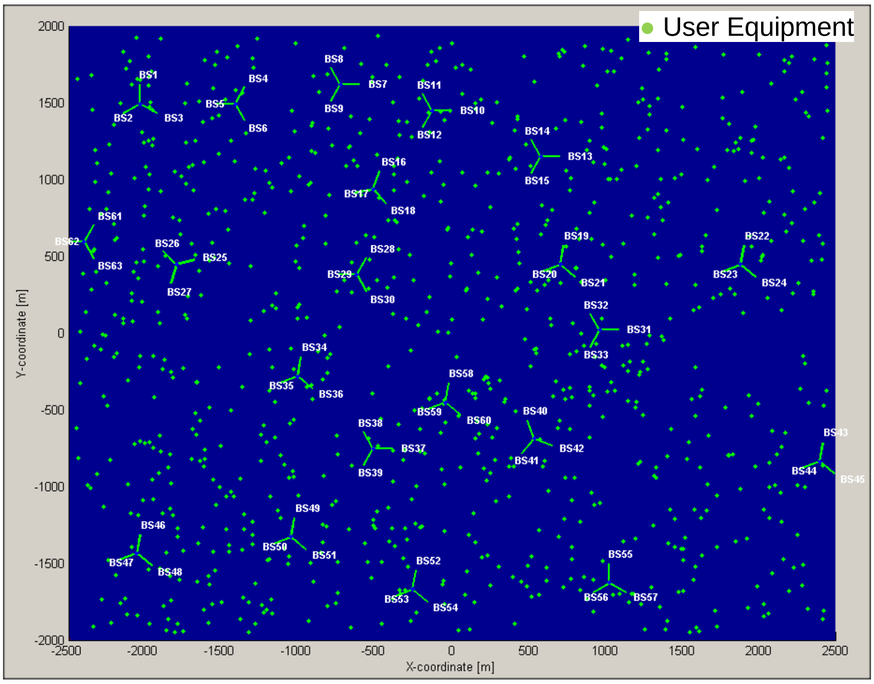


Figure 19: The BS's and all the UE's (green dots)

All the scenario characterizations had as objective to approach it to a real scenario. Each antenna has its own position, azimuth and carrier that affect through interference all the neighbouring antennas with the same carriers. As a consequence the service areas will not have a uniform coverage and each service area will have its particular coverage area. For the chosen scenario all the service areas from the Legacy antennas are depicted in Figure 20, from the antenna 1 (in blue) to the antenna 63 (in dark red). In the upper and lower right corners, the dark blue are places without coverage. As previously mentioned this happens because the antennas that cover these areas aren't within the map.

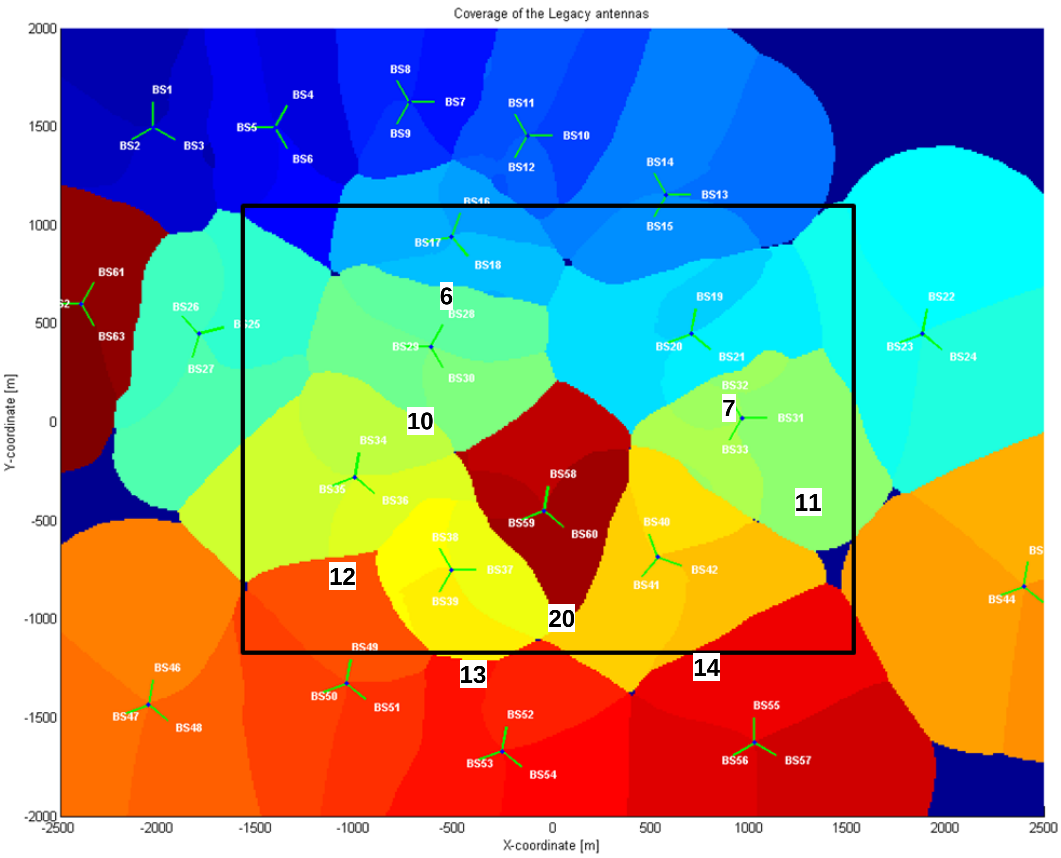


Figure 20: Service areas of the Legacy network and the area to analyse

Due to the fact that we have a scenario with area limitations, the BS's that are outside of this 5x4 Km are not taken into account and by so it's not possible to account the effects that they would cause to this network. Effects like the coverage, already mentioned above, and the interference between antennas that have same carriers. These effects are relevant and well visible around this scenario but at the center of it the BS's are already subject to interference from other antennas that are around them and have the same carriers. Having said that in order to have a more reliable analysis it was chosen only the most central area of this scenario to be analysed. The Figure 20 presents the chosen area with a black square where only the BS's and sectors that are within this area will be analysed.

Within the area of analysis chosen we have 8 BS with the sectors presented in Table 10. All this 25 sectors are going to be analysed by the LTE TVWS Management System.

BS	**6**	**7**	**10**	**11**	**12**	**13**	**14**	**20**
Sector	16-17-18	19-20-21	28-29-30	31-32-33	34-35-36	37-38-39	40-41-42	58-59-60

Table 10: Number of each Sector to analyse

2.3.3- *Simulation results*

Legacy network

The LTE simulator creates the entire legacy network, which already has all the well defined parameters, is simulated and analysed before entering in the LTE TVWS Management System. A first peek can be made by the user of this simulator to see which users have the requested service and which don't have due to lack of capacity or lack of coverage of the network. In Figure 21 the served users are displayed (in the created scenario) as green spots, the users without service by lack of capacity are in yellow rings and the users without service by lack of coverage are in red rings. While the Table 11 presents the number of users.

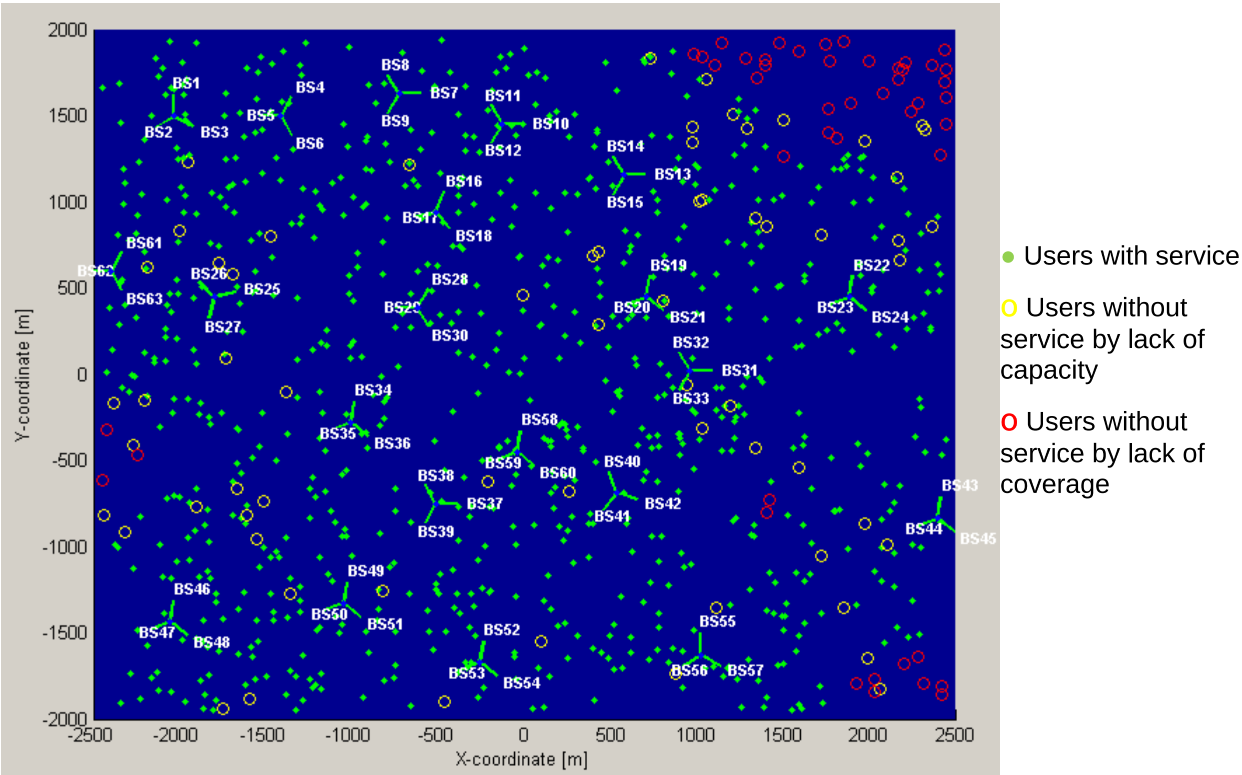


Figure 21: The legacy network with all the users (with and without service)

	Legacy network	
	All the scenario	**Area of analysis**
Total of UE	925	290
Served users	815	273
Not served users by lack of capacity	64	17
Not served users by lack of coverage	46	2

Table 11: Number of users with and without service, operating only the legacy network

In Figure 22 and Figure 23 is presented a bar graph of the CDR and CBR of each sector, respectively. By analysing the CDR and CBR we can see that this network could suffer some improvements. The dashed red line represents the criterion established by the operator in order to activate the TVWS Management System when the CDR or CBR exceed this threshold. The threshold value used in these examples was 2%. For the scenario that was presented the average CDR was 0,69% and the average CBR was 2,94%.

The equations that follow show how the CDR and CBR of each sector were calculated.

$$CDR_{Sec\,n} = \frac{UsersCov_{Sec\,n}}{UsersSer_{Sec\,n} + UsersCov_{Sec\,n}} \times 100$$

$$CBR_{Sec\,n} = \frac{UsersCap_{Sec\,n}}{UsersSer_{Sec\,n} + UsersCap_{Sec\,n}} \times 100$$

Where,

$UsersSer_{Sec\,n} = Number\ of\ users\ with\ service, in\ the\ Sector\ n$

$UsersCap_{Sec\,n} = Number$ users without service by lack of capacity, $in\ the\ Sector\ n$

$UsersCov_{Sec\,n} = Number$ users without service by lack of coverage, $in\ the\ Sector\ n$

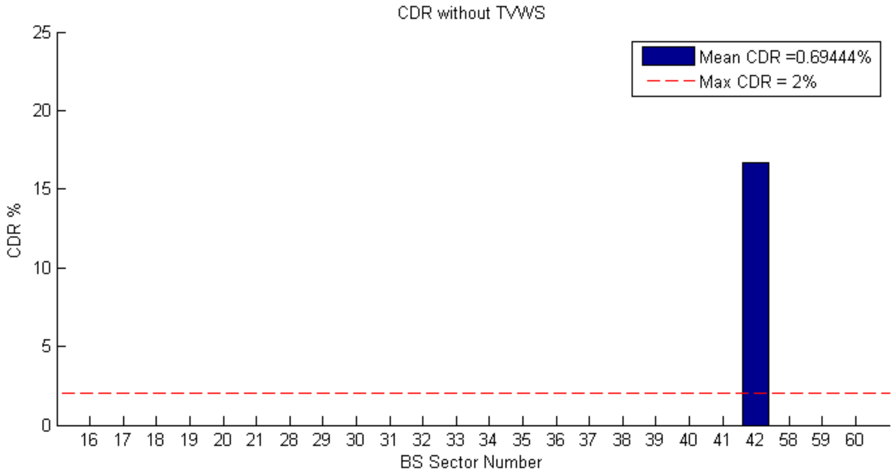


Figure 22: CDR of each sector (within the area of analysis) without any TVWS applied

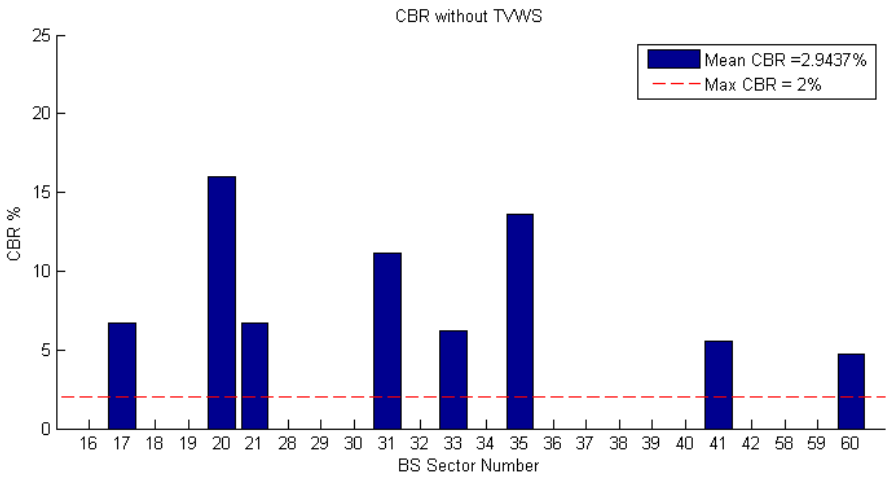


Figure 23: CBR of each sector (within the area of analysis) without any TVWS applied

With these results we know that the sectors 42, 17, 20, 21, 31, 33, 35, 41 and 60 will trigger the TVWS Management System. The first phase of the developed algorithm identifies the sector 42 and tries to find an available TVWS carrier and to activate the TVWS antenna to improve the coverage of this sector. While the remaining sectors are identified by the second phase of the algorithm, and again the system tries to find available TVWS carriers and to activate the TVWS antennas but now to improve the capacity of these sectors.

Once activated the TVWS antennas, the process that follows has to do with the Radio Resource Management (RRM). In the deliverable 6.1 two algorithms for RRM were proposed and evaluated. With the algorithm 1 the TVWS carriers are only allocated to the user when legacy carriers are fully occupied. In the algorithm 2 the user terminal should take measures on both carriers concerning the received signal quality (in particular the SINR) and send this information to the network side that evaluates on which carrier less radio resource will be needed (with high SINR the number of resource blocks decreases). This second algorithm gives the network an optimized use of the system capacity and provides the user the contracted QoS. All the results presented in this chapter were achieved using algorithm 1, due to the fact of being the simplest solution from the practical network implementation point of view. We would have even better results in the resource management if the algorithm 2 was used.

Active TVWS antennas

Different results from the TVWS Management System may be obtained depending on the availability of the TVWS in a specific location, depending on the geo-location database. As we have two databases, one less restrictive and another more restrictive, comparing the results between the two will be interesting.

In the Table 12 the results of these two different databases are presented. All the sectors that experience some extra needs, in capacity or in coverage, are shown in this Table 12, the same sectors listed above. If a TVWS antenna was activated to have better QoS in the specific sector, the parameters chosen by the aRNP for this antenna are also presented in the table (channel and transmission power). When the TVWS Management System uses the less restrictive geo-location database 9 TVWS antennas are activated, while using the more restrictive database only 7 TVWS antennas are activated.

	Sector	**17**	**20**	**21**	**31**	**33**	**35**	**41**	**42**	**60**
Less restrictive database	**TVWS Channel**	60	41	60	57	59	57	51	55	57
	Transmission Power (dBm)	14,5	19,1	21,4	20,9	13,4	23	13,4	23	15,2

More restrictive database	**TVWS Channel**	60	59	60	59	57	60		57
	Transmission Power (dBm)	15,1	21,4	21,4	19,2	14	23,3		14,1

Table 12: Configuration of the active TVWS antennas performed by the aRNP

Comparing the two geo-location databases, due to the different availability of TVWS channels for the same locations or the very different maximum transmission power allowed by the COGEU broker for the same carrier, the final results or configurations set for the new active TVWS antennas can be very different when using one database or the other.

When using the more restrictive database the TVWS antenna 41 and 42 had no available TVWS channels or if they had they didn't meet the minimum requirements established by the operator. Antennas 41 and 42 belong to BS 14 and looking to Table 8 we can see that in this BS location doesn't exist TVWS channels available.

One other case is related with the difference between the chosen channels, where, for example, for the TVWS antenna 20 it was assigned two different channels. This antenna is one of the first antennas to be analysed so when choosing the best channel the only antennas that can interfere are the antennas that already have an assigned channel (like the antenna 42 and 17 with the channel 55 and 60). Using the less restrictive database it was chosen for the TVWS antenna 20 the channel 41 but with the more restrictive database the aRNP chose the channel 59 because in this database the maximum transmission power allowed by the broker for the channel 41 is too low. In turn the antennas which follow will take in to consideration the TVWS channels chosen by the previous antennas (the interference of these TVWS antennas for the same carriers), so the chosen channels that follow can be different when comparing the results from these two geo-location databases.

Although we are using two different databases the transmission power established by the controller presented in 2.2.6- reached the same power levels. Therefore the TVWS coverage area is approximately equal in both cases. In this simulation is not visible any big limitation in the transmission power imposed by the COGEU broker, even when using the more restrictive geo-location database, but this could happen in other situations (a different scenario or a geo-location database even more restrictive). For example a limitation in the transmission power imposed by the broker is visible in the TVWS antenna 31, when using the more restrictive database the maximum transmission power for the channel 59 is 19,2 dBm but to cover all this sector 31 it needs a transmission power slightly higher than this, therefore the controller assigns this 19,2 dBm to the antenna.

Legacy and TVWS Services Areas

The correct functioning of the control on the transmission power of the TVWS antennas can be analysed with the following figures (Figure 24, Figure 25 and Figure 26), concerning to the service areas of the different Legacy and TVWS antennas. The legacy service areas of each sector that experiences some extra needs are shown in the Figure 24. In Figure 25 and Figure 26 are depicted the service areas of the TVWS antennas that were activated by the aRNP when using the less restrictive geo-location database and when using the more restrictive databases, respectively. These graphical representations of the TVWS service areas are directly related to the antenna configurations presented in Table 12.

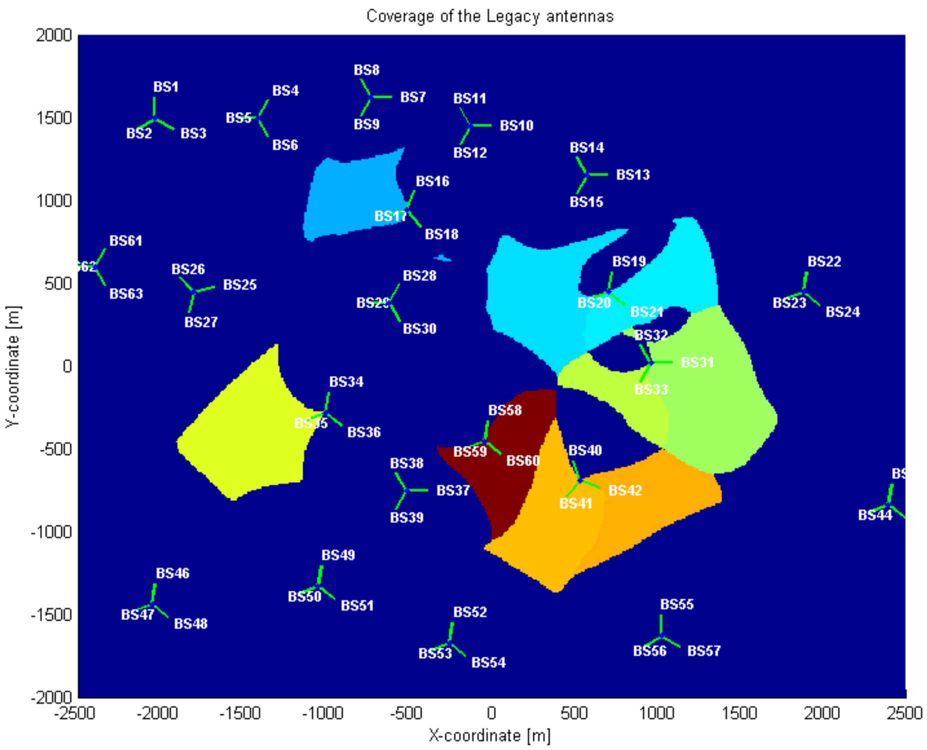


Figure 24: Legacy service areas of each sector that experiences some extra needs (capacity or coverage)

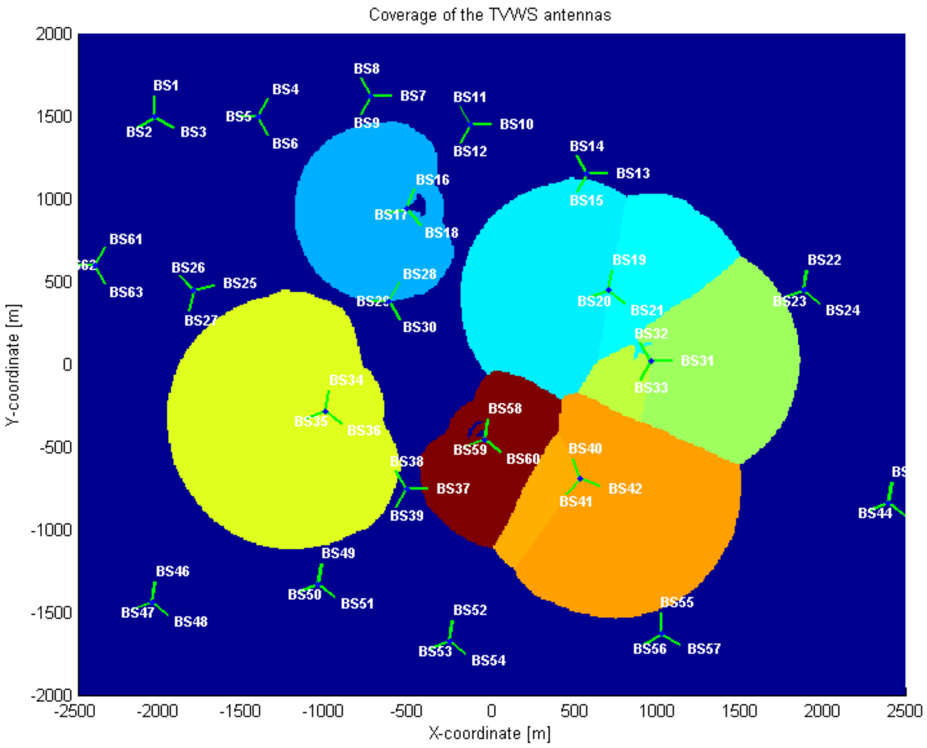


Figure 25: Service areas of the active TVWS antennas when using the less restrictive database

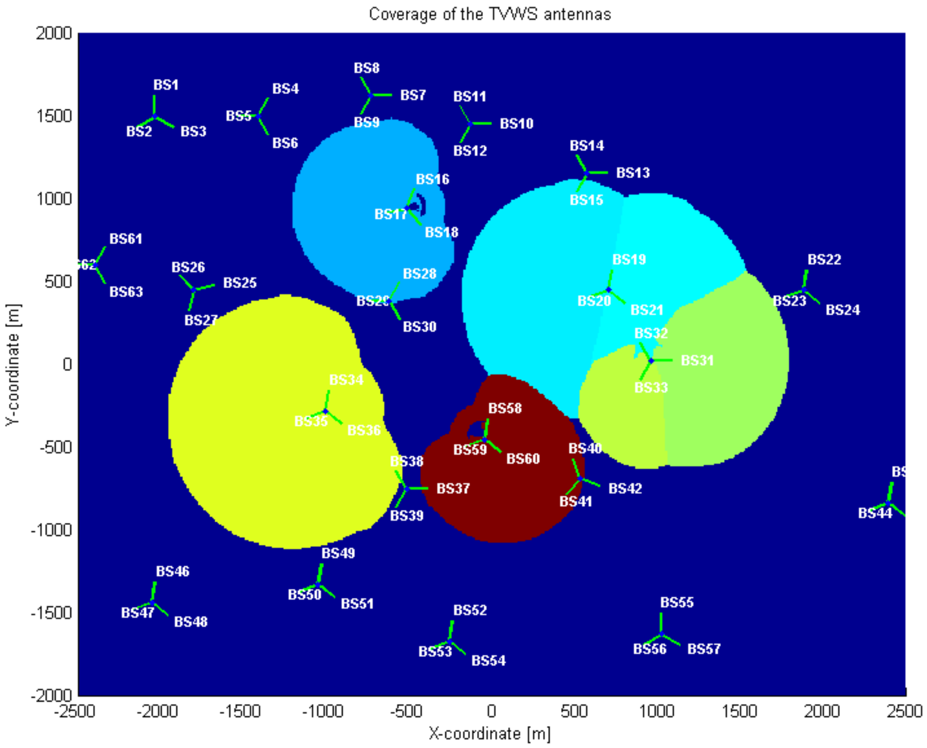


Figure 26: Service areas of the active TVWS antennas when using the more restrictive database

In these figures four specific cases were chosen due to their greater relevance: the chosen transmission power of the TVWS antennas 17, 20 and 35, the not activation of the TVWS antennas 41 and 42, the use of the TVWS antenna 42 to have a greater coverage and the difference between the service areas from the TVWS antenna 31 in the Figure 25 and in the Figure 26.

As mentioned in the topic TVWS Service Area, when a sector has lack of coverage the algorithm will try to activate a TVWS antenna and adjust the TVWS service area to cover the area that didn't have coverage from the legacy network. When a sector has lack of capacity the algorithm will try to activate a TVWS antenna and adjust the TVWS service area to cover at least the same area of the Legacy service area. Three good examples, where it is possible to verify the control of the transmission power, are the TVWS antennas 17, 20 and 35. The transmission power of the TVWS antennas were adjusted so that TVWS service area would cover at least the Legacy service area as it's possible to see comparing Figure 24 with Figure 25 or Figure 26 because in both geo-location databases the results in terms of service area are very similar.

We can see, in Figure 26, that when using the more restrictive geo-location database the TVWS antennas 41 and 42 weren't activated due to the lack of available TVWS channels at the BS location. Comparing the Figure 24 with the Figure 25 we also can see that the service area of the TVWS antenna 42 is larger than the service area from the legacy antenna 42 as we wanted, in order to cover the area that had no coverage from the legacy network. This lack of coverage can be seen in the Figure 20.

The TVWS antenna 31 displays a small difference in the service area size when using the less restrictive geo-location database in Figure 25 or when using the more restrictive database in Figure 26. With this antenna the assigned TVWS channel was different but if we didn't have any limitation on transmission power we could expect for the same transmission power using both databases because the stopping criterion of the decreasing transmission power (the SINR reference from the Legacy antenna) is the same. This doesn't happen because when using the more restrictive database the chosen channel 59 has the maximum transmission power allowed by the broker very low, and by so the TVWS antenna 31 stays from the beginning with the 19,2 dBm, as previously mentioned. While using the less restrictive database the chosen channel is the 57 and the assigned transmission power is 20,9 dBm, providing a greater coverage.

So the control of the transmission power works properly adjusting the service area of all the active TVWS antennas to the Legacy service area or to the area without coverage from the Legacy network.

Sector load

One way to verify if all the active TVWS antennas that were activated were applied to the correct sectors that experience some extra needs in capacity is by analysing the antenna load in terms of percentage of Resource Blocks (RB) occupied on each Legacy antenna. A bar graph with these values is presented in Figure 27. Two similar bar graphs are presented in Figure 28 and Figure 29 where it's possible to see the antenna load of each active TVWS antenna when using the less restrictive geo-location database and the more restrictive database, respectively. All the percentages load are calculated dividing the sum of all RB/s used of all UE with a service that are in the sector by the total number of RB/s that the sector or antenna provides.

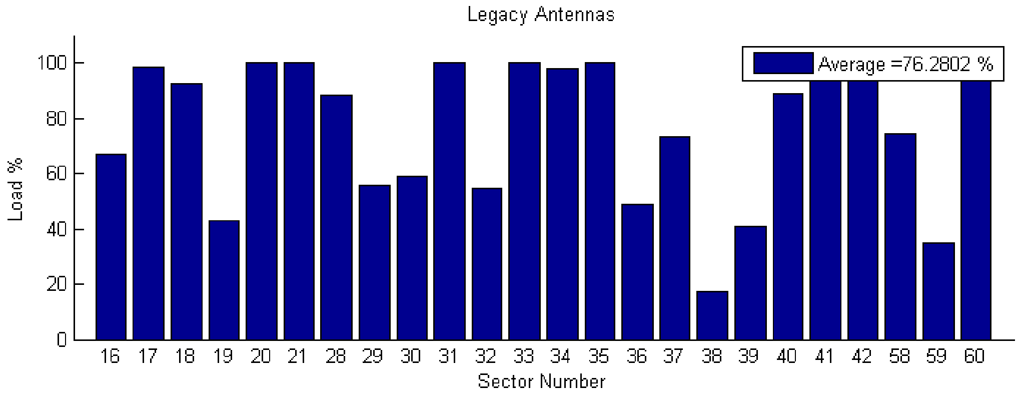


Figure 27: Antenna load in the Legacy antennas (in Downlink)

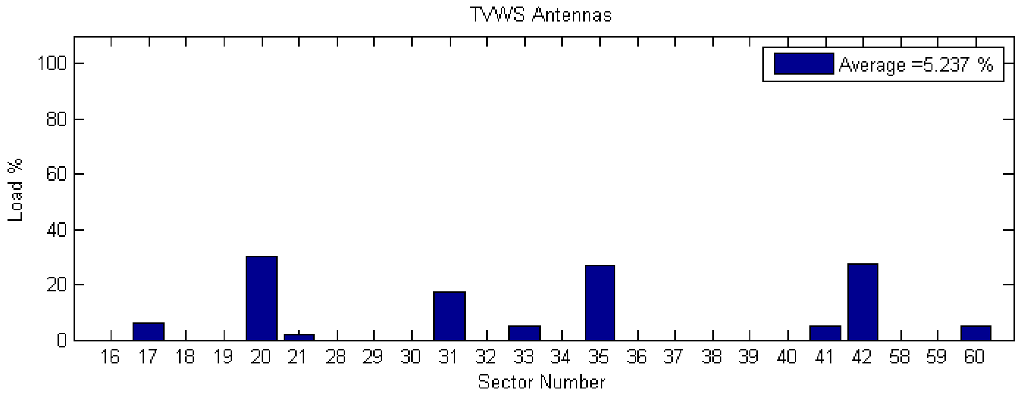


Figure 28: Antenna load in the active TVWS antennas when using the less restrictive geo-location database (in Downlink)

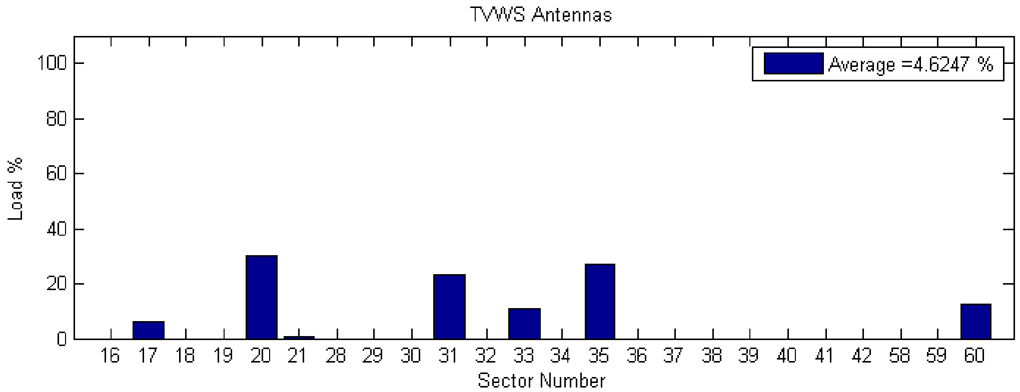


Figure 29: Antenna load in the active TVWS antennas when using the more restrictive geo-location database (in Downlink)

This analysis of sector loads is interesting to identify the sectors that felt lack of capacity but, as is obvious, the sectors that experience lack of coverage can't be identified by the load. These values help to identify only the sectors that had a CBR.

The aRNP request for TVWS channels when some sector has a CBR higher than the CBR of reference (set at 2%). This happens when the legacy antenna of this sector is completely full, not having more RB available for the remaining UE to have the required service. That said and analysing the Figure 27, we can see that all the legacy antennas that have, approximately, between 95% to 100% of the RB occupied belong to the sectors that requested TVWS channels by the aRNP. In Figure 28 and Figure 29 is viewable that the active TVWS antennas belong to these sectors. A detail worth nothing is that some of the legacy antennas have ≈95% of the RB occupied and already have a CBR higher than 2% without being completely full. It happens because the remaining RB of the legacy antenna, the ≈5% that stills could be occupied, are not enough for the remaining UE that need a guaranteed bit rate (GBR) to continue to have their service. In other cases the remaining RB are occupied by users that have a service with non-GBR.

Comparing Figure 28 with Figure 29 it's possible to verify that the average load is higher when using the less restrictive geo-location database, 5,24%, that when using the more restrictive database, 4,62%. When comparing these two we need to take into account the influence of the two TVWS antennas, 41 and 42, that are active in the Figure 28 and deactivated in the Figure 29. When active these TVWS antennas accommodate UE which were accounted in the CDR or the CBR. So using the less restrictive geo-location database a larger TVWS coverage, more UE with service and thereby an increase in the average TVWS antennas load comparing to the results in the more restrictive database.

If we look at these charts in more detail it's possible to see a general small increase in all the active TVWS antennas from the Figure 28 to the Figure 29. When using the more restrictive database the service area of each TVWS antenna are slightly small to what was obtained when using the less restrictive database. Some reasons for this to happen were already mentioned previously, like the lower transmission power chosen by the aRNP or the interference between the same TVWS carriers. All the UE are in the same place when using both geo-location databases, so when the TVWS service areas decreases, the SINR in downlink of each UE also decreases, forcing some UE to decrease there modulation or codification and leading to an increase of used RB.

RB per user

In documents like this kind, when dealing with RB, it's usual to analyse the number of RB per users or even RB per Mbit. This analyse of RB per UE will allow us to extract some more conclusions. In a simplistic way, the RB that one UE needs depends on the bit rate needed for the specific service and the quality of the signal received from the BS (speaking only for downlink). According to this SINR the modulation and codification are set which in turn give us the number of RB for this UE. Since it's not possible to analyse all the UE one by one, an average of RB is maid in each sector which results in RB per user. All the RB values presented are the number of RB in one second.

In Figure 30 is depicted the number of RB per UE in all the legacy antennas. While in Figure 31 and Figure 32 are presented the number of RB per UE in the active TVWS antennas when using the two geo-location databases.

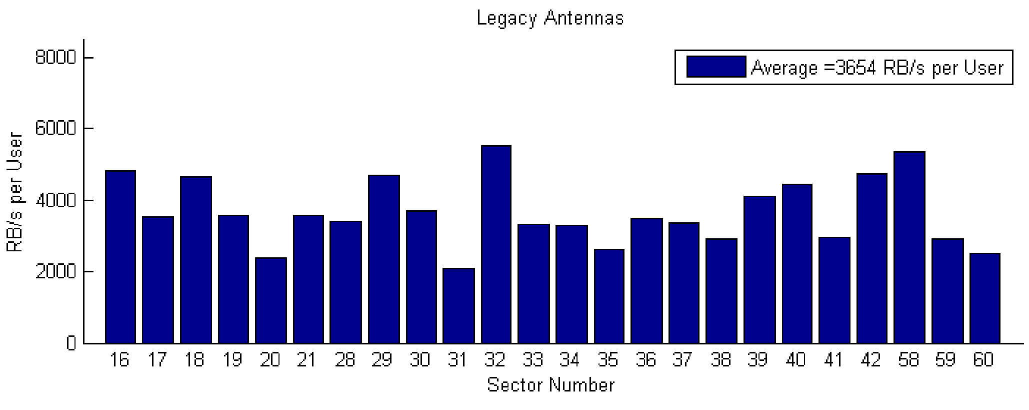


Figure 30: RB per user in the legacy antennas

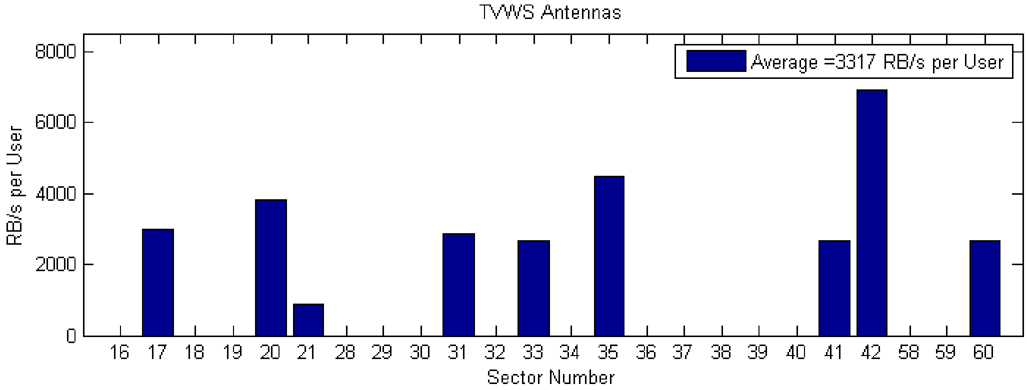


Figure 31: RB per user in the active TVWS antennas when using the less restrictive geo-location database

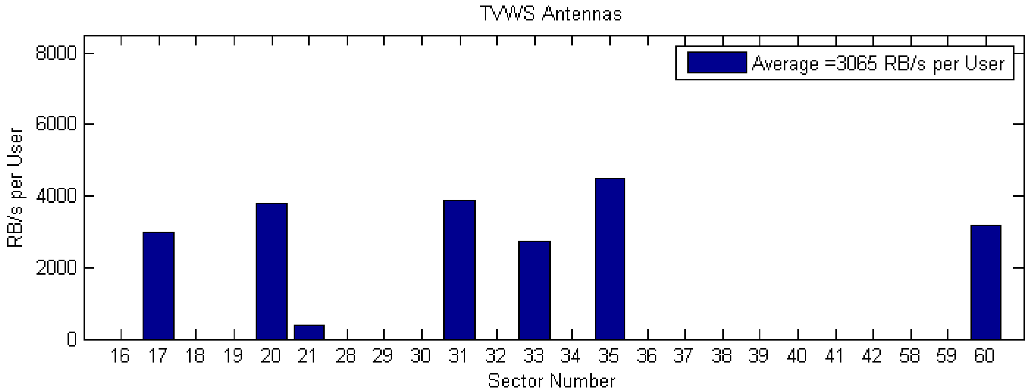


Figure 32: RB per user in the active TVWS antennas when using the more restrictive geo-location database

Comparing the results from Figure 31 and Figure 32, using the less and the more restrictive geo-location databases, it's possible to see that the values are very similar except in the sectors 41 and 42 where we have the TVWS antennas actives in Figure 31.

The most important conclusion we should draw from these three graphs is the different of RB per user in the TVWS antenna 42 in the Figure 31 comparing with all the other antennas. In the sector 42 we had a CDR without any CBR, meaning that in this specific case we had only UE without coverage from the legacy network (more specifically from the legacy antenna 42). The aRNP, when activates the TVWS antenna 42, adjusts the service area (setting the transmission power) so that this antenna provides service to all the area without coverage from the legacy network. The UE on that location are now connected to the TVWS antenna 42 but as they are far from the BS the SINR (in downlink) is low, having to deal with a low modulation and codification which results in an increase of RB needed to have the same service. As these UE that didn't had coverage are the only ones connected to the TVWS antennas 42 the average number of RB per user in this sector is very high.

CDR and CBR

In order to examine the performance of our TVWS Management System applied in a real scenario it was conducted a comparison between the CDR and CBR network without such a system (namely the absence of any TVWS antenna) and the CDR and CBR network with this system (with some active TVWS antennas). The graphs that follow (Figure 33, Figure 34, Figure 35 and Figure 36) are related directly with this, where at the same time we can compare the results of the CDR or CBR with and without the TVWS Management System (with TVWS antennas in green and without TVWS antennas in blue). These bar graphs are quite similar to the Figure 22 and Figure 23 and the CDR and CBR values of the network without TVWS antennas are the same. In the Figure 33 and Figure 34 we have the results of the CDR and CBR of each sector when using the less restrictive geo-location database and in the Figure 35 and Figure 36 the results of the CDR and CBR of each sector when using the more restrictive geo-location database. The dashed red line represents the criterion established by the operator in order to activate the TVWS Management System when the CDR or CBR of the sector exceed this threshold (max CDR and max CBR equal to 2%).

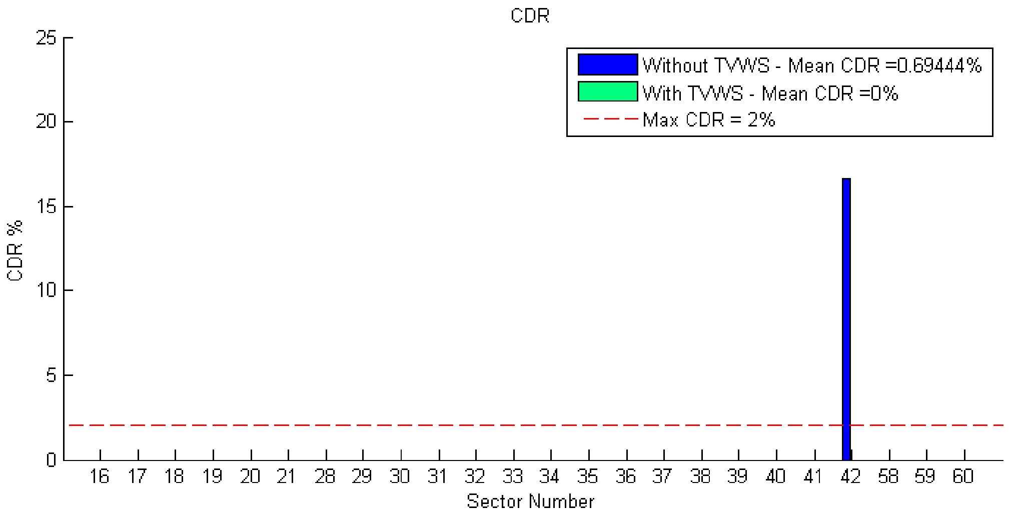


Figure 33: CDR of each sector without using the TVWS antennas (the blue bars) and using the TVWS antennas (the green bars) with the less restrictive geo-location database

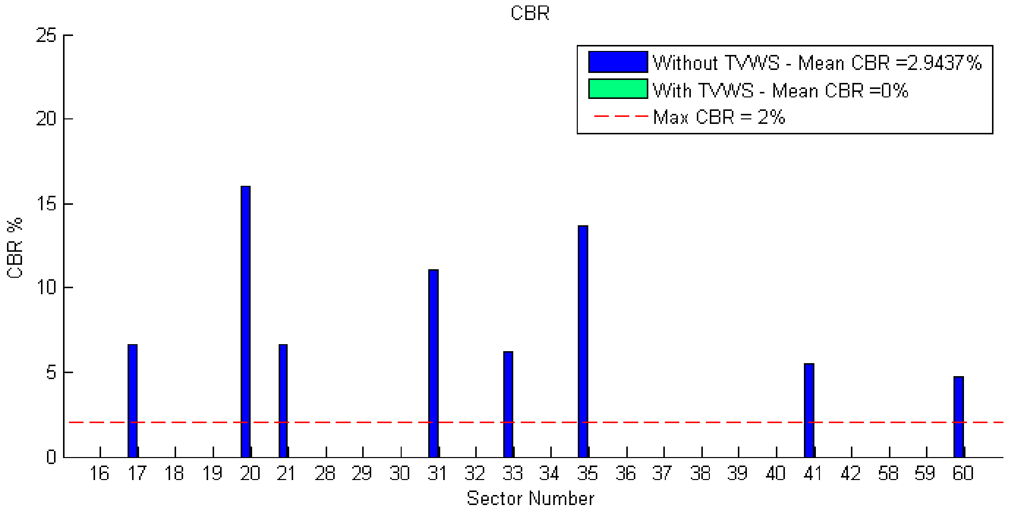


Figure 34: CBR of each sector without using the TVWS antennas (the blue bars) and using the TVWS antennas (the green bars) with the less restrictive geo-location database

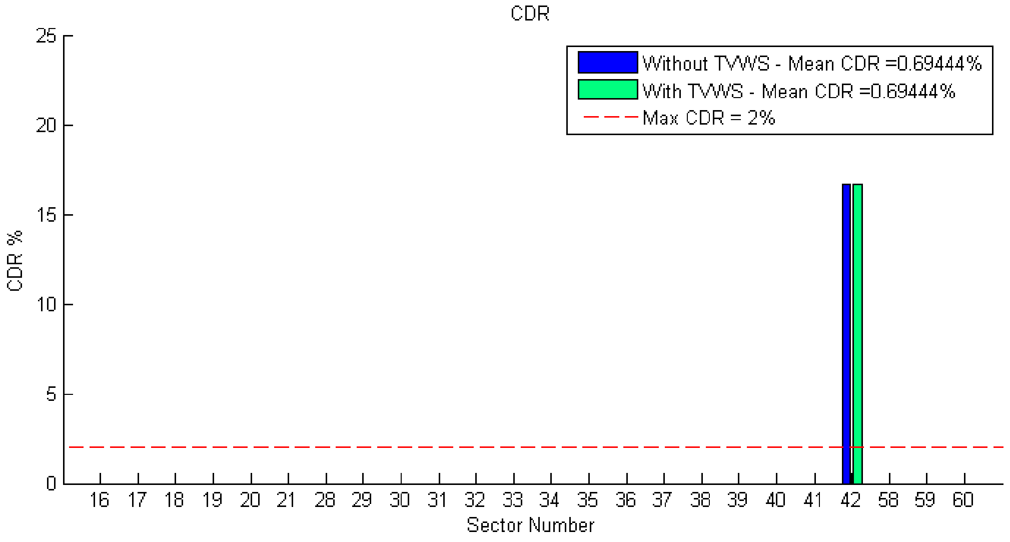


Figure 35: CDR of each sector without using the TVWS antennas (the blue bars) and using the TVWS antennas (the green bars) with the more restrictive geo-location database

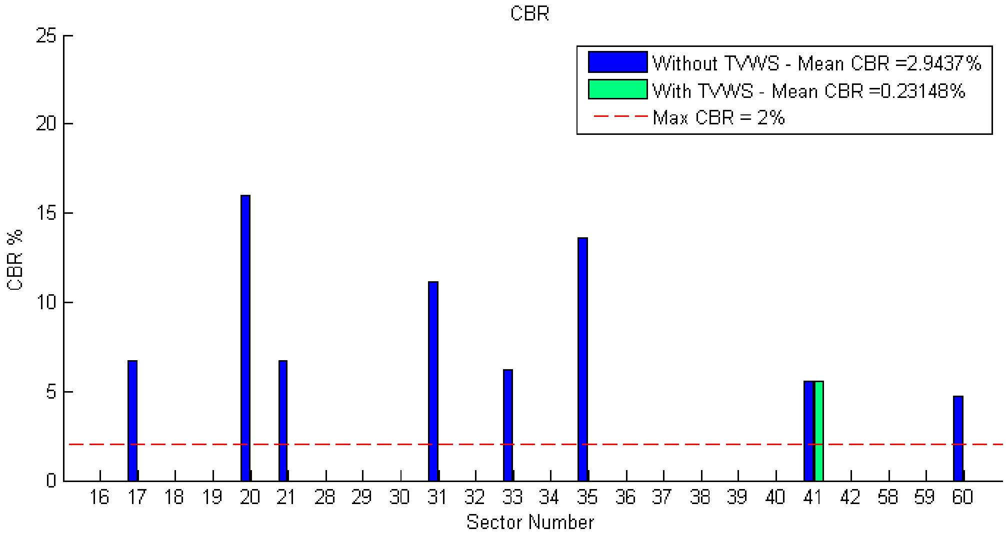


Figure 36: CBR of each sector without using the TVWS antennas (the blue bars) and using the TVWS antennas (the green bars) with the more restrictive geo-location database

The sector 42 was the only sector that presented users with lack of coverage, so looking to the Figure 33 or Figure 35 we can see the CDR higher than the reference CDR of 2%, activating the TVWS Management System to find a solution.

Without using the TVWS Management System the network would have an average CDR of 0,69% and an average CBR of 2,94%. Switching on the TVWS Management System these values decrease considerably. Using the less restrictive geo-location database we can see a complete reduction in the CDR and the CBR, in Figure 33 and Figure 34, with a final average CDR and CBR of 0%. In all the sectors that felt some extra needs, TVWS antennas were activated by the aRNP and all the UE without service (by lack of coverage or capacity of the network) that were accounted now will have the requested service. The same does not happen when using the more restrictive geo-location database because in this case the TVWS antennas 41 and 42 were not activated. As mentioned previously this database has no TVWS channels available for this BS location so they couldn't be activated. As a result the UE in these two sectors remained in the same situation, without being possible to continue having the desired service. In terms of number, the average CDR remained the same at 0,69% and the average CBR decreased to 0,23%, as it's possible to see with the Figure 35 and Figure 36.

3- Performance Evaluation of Radio Resource Management Algorithms

3.1- Introduction

This chapter elaborates on the performance evaluation of the proposed COGEU Radio Resource Management (RRM) framework for TV white spaces (TVWS) exploitation under the "Real-time Secondary Spectrum Market - RTSSM" policy. The proposed RRM framework is applied in the second COGEU regulatory scenario that guarantees a better QoS in LTE systems, by extending their services over the TVWS. This regulatory scenario is based on a centralised CR network architecture, where a Spectrum Broker is capable to manage the increased radio spectrum demand by orchestrating the available TVWS.

Towards addressing the need for increased radio spectrum demand, a potential use-case scenario for the COGEU RRM framework could be the LTE standard [6] that provides flexible deployment, in terms of high spectral efficiency, bandwidth and different modulation/coding schemes. In addition, LTE systems can be designed to operate in alternative unused spectrum bands (e.g. TVWS), when both dimensions of space and time are considered [7], as well as they can coexist with other telecommunication systems. LTE deployment over TVWS may enable cellular networks operators to cover large geographical areas with less number of base stations, decreasing investment costs and providing cheaper cellular broadband services, especially to end users located in rural areas. Furthermore, this specific part of spectrum could be exploited to support peak data traffic in urban areas with increased bandwidth demands, while several schemes to share channels on a temporary basis of short or medium duration may be investigated, towards providing relief of crowded cellular networks that experience peak loads. The exploitation of TVWS will allow for more network carriers to be available at lower frequencies and despite the fact that a part of VHF/UHF radio spectrum will be dedicated for digital terrestrial television and wireless microphones services, another part of it will remain under-utilized for future secondary usage.

The deployment of LTE systems requires a new radio spectrum management policy. Among the envisaged schemes [8], [9] the RTSSM policy is the most appropriate solution, especially for deployments that require sporadic access to radio spectrum and for which QoS guarantees are important. RTSSM policy, adopts spectrum trading, by permitting the spectrum license holder to run admission control algorithms that allow secondary systems to access radio spectrum only when QoS is adequate. Trading of secondary spectrum usage may occur through network management entities (e.g. spectrum broker), exploiting radio resource management (RRM) algorithms [8], [10], in order to efficiently allocate the available resources to secondary systems [11], [12]. Secondary systems, in this case, dynamically request access only when radio spectrum is needed, and are charged based on channel utilization basis, as a matter of types of services, access characteristics and priority level requirements. The access types may comprise a long-term lease, a scheduled lease and a short-term lease or spot markets, while the discovery mechanisms and levels of service agreement vary from one access type to another.

The enabler towards the deployment of LTE systems over TVWS, considering the RTSSM policy is Cognitive Radio (CR) technology/networks [13], [14]. CR networks enable for the dynamic access of radio spectrum from secondary systems, by avoiding the interference to primary ones. For this purpose, a centralized network architecture [15] is appropriate for LTE deployment based on RTSSM policy, rather than a distributed one, due to QoS provisioning requirements. Furthermore, the exploitation of a spectrum broker will enable for orchestrating the available network resources, by collecting information about radio spectrum access usage stemming from primary systems, as well as information about the transmission requirements/demands from secondary ones. Based on this information, an optimal solution (e.g. solution that maximises spectrum utilisation) on dynamic spectrum access can be obtained. Nevertheless, in all cases, and no matter which network architecture or radio spectrum management policy is adopted, the deployment of LTE networks over TVWS leads to another challenge, regarding the proper coexistence of primary with secondary systems, avoiding possible channel interference. Unlike current cellular networks, operating, under fixed radio spectrum allocation schemes, future LTE deployment scenarios will take into account adjacent channel interference issues with other telecommunication systems. Therefore, such a deployment results the necessity to accommodate dynamic adjacent channel interference control, as well as more sophisticated radio resources management techniques, by considering optimized solutions to allocate network resources, in order to increase network performance and provide guaranteed QoS.

A vital part of most centralized CR network architectures is the radio resource management entity (RRM), which is responsible for the radio resource allocation process, besides satisfying the Secondary System's QoS requirements and maintaining interference-free operation between Primary and Secondary Systems. To achieve these, the RRM exploits optimization methods [15], [16], among which are the decision-making ones, which are trying to reach an optimal solution through classical mathematical rationalization, i.e. by formulating an objective function so that equality and inequality constraints are not crossed [16]. Such decision-making RRMs may be implemented through a number of optimisation techniques, such as the integer/combinatorial programming (e.g. Backtracking) and the mathematical programming (e.g. Simulated Annealing, Genetic Algorithm). While the former provides a "global" optimum solution among all possible ones, the latter picks it from a smaller set of solutions that satisfy the objective function [17]. It should be noted, however, that the choice of the most appropriate decision-making RRM implementation technique constitutes an application-driven approach, based on specific use-case scenarios, and by taking into account the corresponding implementation intricacies. Thereupon, metrics such as the complexity of the RRM algorithm, the range of the possible solutions to be checked, the processing time and computational power required for obtaining the optimum solution have to be considered prior to choosing the most applicable technique. In this context, decision-making optimisation methods based on the Backtracking, the Simulated Annealing and Genetic algorithms are utilised in order to evaluate the RRM performance as a matter of maximum-possible spectrum utilisation and minimum fragmentation. Additionally, the RRM performance is evaluated taking into account Spectrum Broker benefit and secondary systems service rate. Simulationl tests that were carried-out under controlled conditions environment verified the validity of the proposed framework and presented at section 3.5.2-.

3.2- Cognitive radio network architecture for QoS provision

This section presents the COGEU broker-based CR network architecture for the efficient exploitation of TVWS under the RTSSM regime. The overall architecture of this network is depicted in Figure 37, and comprises two core subsystems: a) a Spectrum Broker responsible for coordinating TVWS access and administrating the economics of radio-spectrum exploitation, and b) a number of Secondary Systems (i.e. mobile network operators and wireless network providers), competing/requesting for TVWS utilisation. In particular, this network architecture consists of secondary systems, that provide different services classes depending on the type of service, voice data, etc.

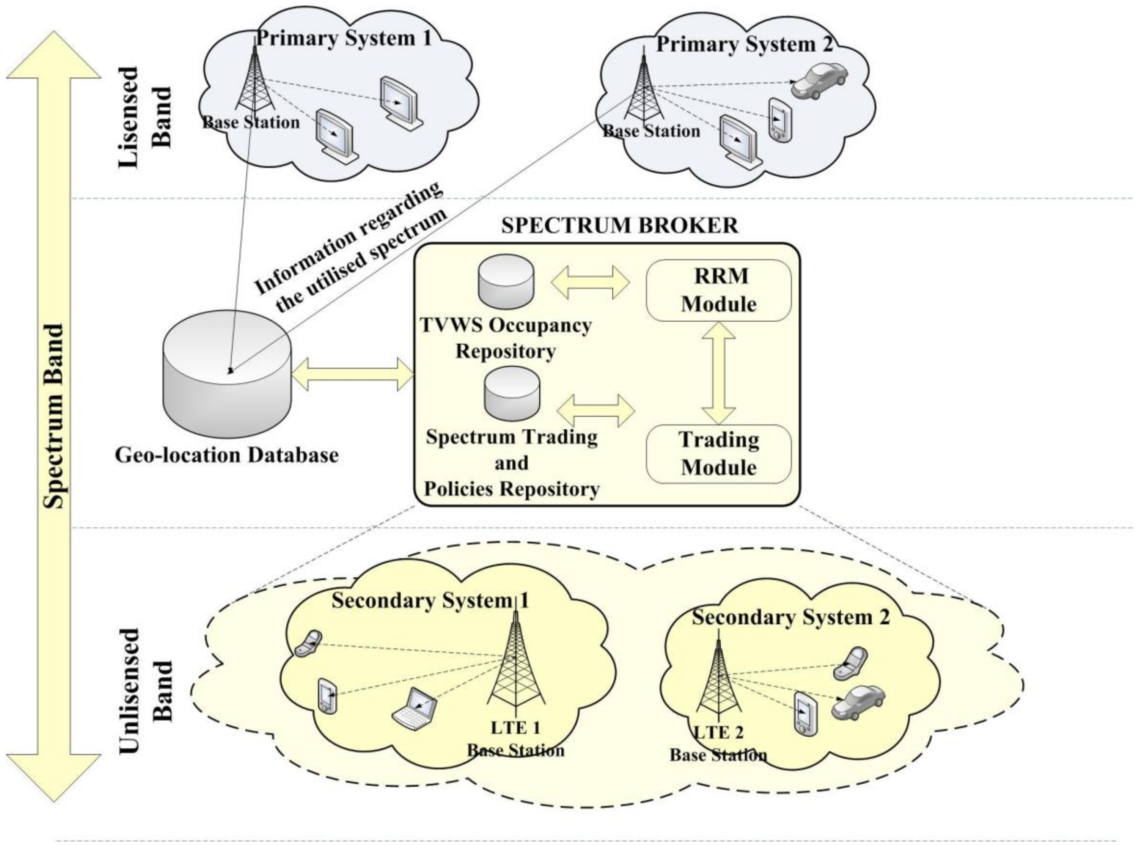


Figure 37: Architecture of the proposed CR network operating under the RTSSM regime

According to this architecture, Spectrum Broker comprised of four sub-entities, a TVWS occupancy repository, a RRM module for TVWS allocation, a spectrum trading repository and a spectrum trading module. The TVWS occupancy repository obtains information from the national database, namely as Geo-location database, which includes data regarding the available TVWS in specific locations and the maximum allowable transmission power of secondary systems per channel, in order to avoid causing interference to primary systems. The TVWS occupancy repository creates a spectrum-portfolio, including all the above mentioned information that is advertised to bidders. Moreover, the RRM module matches the secondary systems requirements with available resources and thus allocates the TVWS based on QoS requirements. The TVWS allocation mechanism implements an algorithm that uses information from the Geo-location database to determine the TVWS bands and power at which a secondary system should be allowed to operate, in order to avoid spectrum fragmentation, optimise QoS and guarantee fairness in TVWS access. Moreover, trading module is responsible to determine the revenue of Spectrum Broker, which aims to trade/lease spectrum with temporary exclusive rights to the most valuable bidder. Finally, spectrum trading repository hosts information about the TVWS selling/leasing procedure, as well as the spectrum-unit price to be exploited during the trading phase, creating a price-portfolio.

The system operation is based on three layers/entities, as depicted in Figure 38, each one denoting a significant process for the resource allocation. The layers of the system comprised of the Local Recourse Manager (LRM), the Spectrum Manager (SM) and the Spectrum Broker (SB).

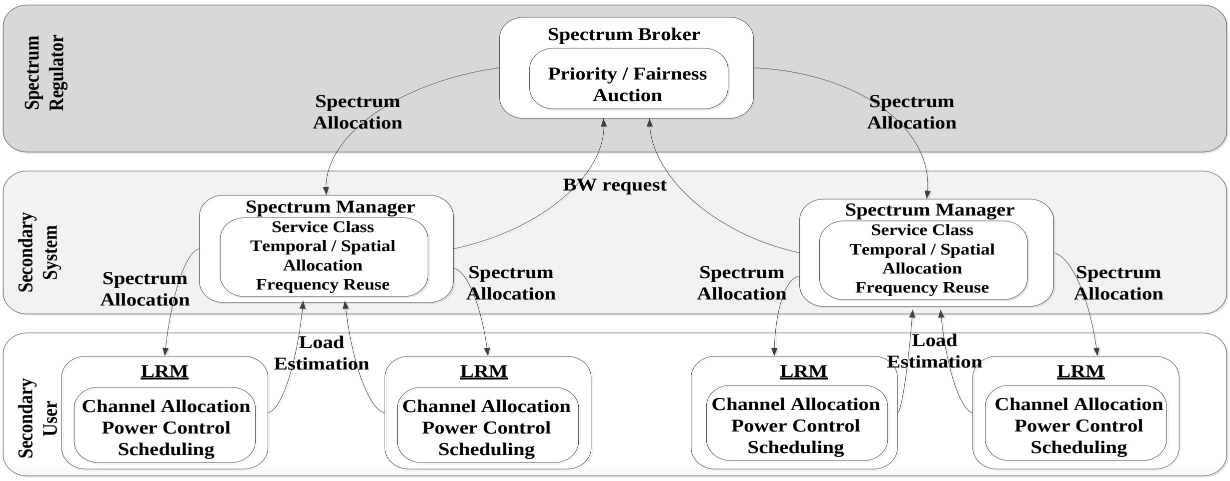


Figure 38: Layers of system operation

The LRM is responsible for the disposal/assignment of spectral resources within the area of each secondary system. More specifically, LRM calculates the required bandwidth needed for each class, taking into account the radio link operation and the traffic load. Depending on the requests sent by the secondary users through the LRMs, the spectrum manager of each secondary system assigns to them the TVWS resources. Moreover, each spectrum manager sends information to the Spectrum Broker based on the requested bandwidth of each secondary system, the load handled, and the priority of classes. It also sends a negotiation request, in case that a secondary system requests for more bandwidth than the initial needs for bandwidth. The Spectrum Broker is responsible for conducting the spectrum allocation process, either utilising a fixed-price or an auction approach, based on negotiations and requests for required bandwidth.

The Spectrum Broker of the proposed network architecture is in charge of trading the available spectrum to a number of competitive secondary systems or bidders (denoted as I) that participate in the allocation/auction process. In this case, the commodity of the allocation/auction is the spectrum, which consists of four fragments denoted as F, each one having different power requirements and sizes in MHz, denoted as Fi. The total spectrum can be leased to I allocation/auction participants, such as LTE, WiMax, UMTS, WiFi and Public Safety secondary systems with different bandwidth and transmission power requirements. The final allocation of the fragments depends on the interest/bids of all secondary systems and the profit maximization function of the Spectrum Broker.

The Spectrum Broker of this CR network architecture initially advertises data regarding spectrum portions that are available to be leased to secondary systems, as well as relevant maximum allowable transmission power thresholds. This information originated from the Geo-location database, is hosted within the TVWS Occupancy Repository. It has to be noted here that the following description of the RRM taking into account both market-driven policy (i.e. fixed-price), as well as auction-based policy. Thus, the Spectrum Broker firstly advertises the spectrum-portfolio and the price-portfolio to the secondary systems, in order to be informed for the transmission characteristics and the call price of the TVWS spectrum. After this stage, bidders (i.e. secondary systems) send/define their needs/bids for the spectrum of interest, as well as the offered price, in case of auctions. Spectrum Broker collects all interests/bids and sends them to Radio Resource Management (RRM) module. RRM module analyses and processes them as a matter of secondary systems technical requirements and the locally available TVWS channel characteristics. For each spectrum portion/fragment, Spectrum Broker creates and maintains a list with interest/bids per time period, namely as auction-portfolio, in order to choose the most valuable bidder for each specific time slot, in case of auction process, or to assign TVWS to secondary systems that causing the least spectrum fragmentation, in case of fixed-price. The auction portfolio is also analysed/elaborated by a Trading Module, taking into account a spectrum-unit price or call price (e.g. cost per MHz) that is based on spectrum-auction policies.

Finally, an optimised solution combining the RRM results and the Trading Module output is obtained, enabling Spectrum Broker to sell/assign TVWS frequencies to the corresponding secondary systems under the RTSSM regime/policy. In other words, Spectrum Broker is responsible for obtaining the best-matching solution, through an optimisation-based process, which constitutes a NP-hard problem, thus an approximation algorithm is required in order to solve either the fixed-price or the auction process.

3.3- Implementation of Decision Making Algorithms for TVWS allocation

Figure 39 illustrates the logical diagram of this decision-making approach, where a “Process Data” function is initially taking place for producing all possible combinations, and therefore a set of “Possible Allocation Solutions”. As soon as all these Possible Allocation Solutions are established, the RRM calculates the optimum ones, and creates the Spectrum Portfolio that will be used by the Broker during the trading process. This Spectrum Portfolio is the result of the iterative process namely as “IsValidSolution” in Figure 39, which examines if a Possible Allocation Solution fulfils the SS’s technical requirements. In such a case the Possible Allocation Solution is registered in the Spectrum Portfolio, otherwise it is discarded. To this extent, the selection of the best-matching solution (Optimal Solution), is the result of an optimisation process targeting either to minimise spectrum fragmentation (fixed-price policy) or to maximise the profit (auction-based trading), whichever is appropriate.

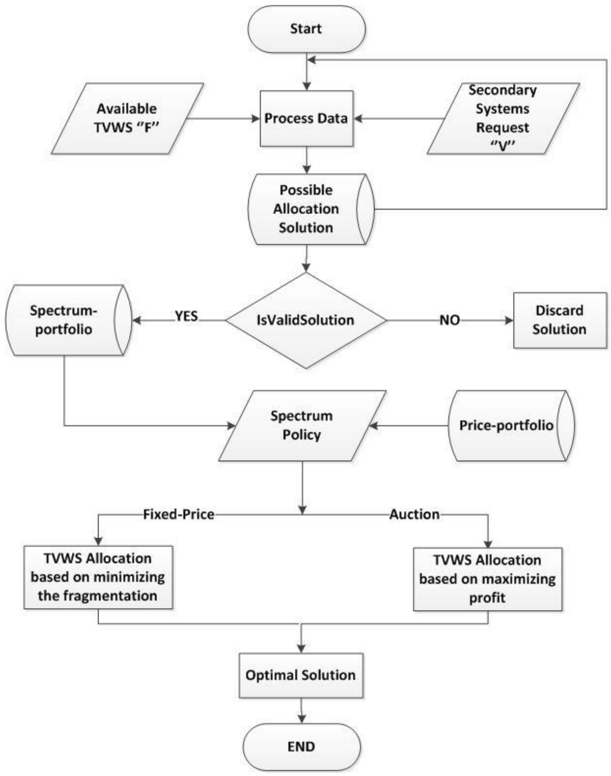


Figure 39: Logical diagram of the proposed decision-making approach towards establishing the optimal allocation solution

3.3.1- *Extension of Backtracking Algorithm with Pruning*

Based on the above, the simplest approach in order to solve an integer-programming problem, such as spectrum allocation in CR networks, is to generate all possible spectrum allocations, by performing systematic/exact search. Backtracking [17], is capable to generate each one possible spectrum allocation solution exactly once avoiding both repetitions and missing solutions. Backtracking generates all possible solutions based on the available resources and the SS request by repeatedly choosing a SS request to accommodate in an available channel. In the backtracking method, as soon as an allocation solution is generated, the validity of the constraint is checked. If an allocation solution violates any of the constraints, backtracking reject this one, thus is able to eliminate a subspace of all variable domains. The backtracking algorithm may be improved by some filtering techniques, which aim at pruning the search space in order to decrease the overall duration of the search.

```
Backtracking()
  Create initial solution S
  for i = 1 to subset of variable length do
      Generate a new solution S_i
    if (Objective_function(S) ≤ Objective_function(S_i))
        then save the new solution S_i to best found S
      else reject the S_i solution
Return S
```

Table 13: Backtracking Algorithm pseudo-code

3.3.2- *Simulated Annealing*

On the other hand, Simulated Annealing (SA) [17] is a heuristic algorithm for the global optimisation problem, which can be applied in resource allocation. SA algorithm replaces, at each step, the current allocation solution by a random "nearby" solution. This allocation solution is chosen with a probability that depends on the difference between the corresponding function values and on a global parameter T (called the temperature). The probability is large when the temperature is high so that the algorithm will not be stuck in a certain local optimum. On the other hand, the probability is low since the probability of local optima is low. When the temperature is zero, the algorithm reduces to the greedy algorithm. Typically this step is repeated until the system reaches a state that is good enough for the application, or until a given computation budget has been exhausted.

```
Simulated-Annealing()
 Create initial solution S
 Initialize temperature t
 repeat
   for i = 1 to iteration-length do
       Generate a random transition from S to Si
 if (Objective_function(S) ≤ Objective_function(S_i))
    then save the new best solution S_i to previous one S
 else
      Change state/solution with a random probability
 Reduce temperature t
 until (t=1)
 Return S
```

Table 14: Simulated Annealing Algorithm pseudo-code.

3.3.3- *Genetic Algorithms*

Finally, Genetic Algorithms (GA's) are search algorithms that work via the process of natural selection. They begin with a sample set of potential solutions, which then evolves toward a set of more optimal solutions. Within the sample set, solutions that are poor tend to die out while better solutions mate and propagate their advantageous traits, thus introducing more solutions into the set that boast greater potential (the total set size remains constant; for each new solution added, an old one is removed). A little random mutation helps guarantee that a set won't stagnate and simply fill up with numerous copies of the same solution. In general, genetic algorithms tend to work better than traditional optimization algorithms because they're less likely to be led astray by local optima. This is because they don't make use of single-point transition rules to move from one single instance in the solution space to another. Instead, GA's take advantage of an entire set of solutions spread throughout the solution space, all of which are experimenting upon many potential optima. However, in order for genetic algorithms to work effectively, a few criteria must be met:

– It must be relatively easy to evaluate how "good" a potential solution is relative to other potential solutions.

– It must be possible to break a potential solution into discrete parts that can vary independently. These parts become the "genes" in the genetic algorithm.

– Finally, genetic algorithms are best suited for situations where a "good" answer will suffice, even if it's not the absolute best answer.

Genetic()
1: Choose the population S of random initializations
2: **repeat**
3: **for** i = 1 to iteration-length **do**
4: Generate a random populations from S to Si
5: **if** (Objective_function(S) ≤ Objective_function(S_i)) //Evaluate the fitness of each chromosome
6: **then** save the new best solution S_i to previous one S
7: **else**
8: Select pairs of best-ranking chromosomes to reproduce
9: Apply crossover operation
10: Apply mutation operation
11: until the Stop criteria
12: **Return** S

Table 15: Genetic Algorithm pseudo-code

3.4- **Problem formulation and performance evaluation**

TVWS channels can be considered for leasing by Spectrum Broker, taking into account both time and frequency domains, as shown in Figure 40. More specifically, Figure 40 depicts the occupied and the available TVWS, as well as requirements of secondary systems for accessing spectrum at specific time durations. S denotes all available TVWS, while Δt and Δf denote time and frequency interval respectively. For each (Δt,Δf) an unused part of spectrum is available for specific time (i.e. slot).

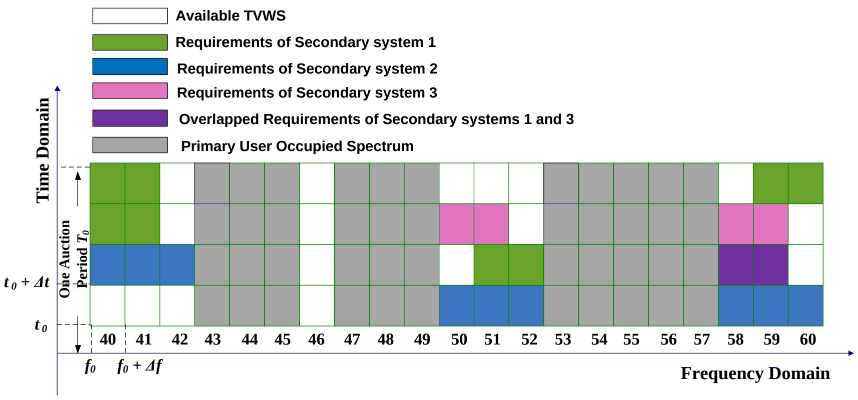


Figure 40: Time and Frequency domains for TVWS allocation

1: **Inputs:** $TVWS_{pool}$, Location(x,y), $Power_{max}$, $Demand_{SS}$

2: Update TVWS repository from Geo-location database

3: Estimate the spectrum-unit price

4: Create and advertise price-portfolio

5: Receive secondary systems request R= {R_1,…, R_l},

where R_i = {x_i, t_i}

6: **for** all Requests **do**

7: Sort R_i in descending order based on priority and update the price-portfolio

8: **end for**

9: Calculate the minimum fragmentation (Frag(i,f)) for all secondary system requests

10: Create initial solution S

11: **for** i = 1 to subset of variable length **do**

12: Generate a new solution S_i

13: **if** (Objective_function(S) ≤ Objective_function(S_i))

14: **then** save the new allocation solution S_i to best found S

15: **end if**

16: **end for**

17: **return** Best Allocation Solution

Table 16: Fixed-price Algorithm pseudo-code

1: **Inputs:** $TVWS_{pool}$, Location(x,y), $Power_{max}$, $Demand_{SS}$

2: Update TVWS repository from Geo-location database

3: Estimate the spectrum-unit price

4: Create and advertise price-portfolio

5: Receive secondary systems bids $P^{(b)}$ = {$P_1^{(b)}$,…, $P_l^{(b)}$},

where $P_i^{(b)}$ = {x_i, t_i}

6: **for** all Bids **do**

7: Sort $P_i^{(b)}$ in descending order based on price and create the auction-portfolio

8: **end for**

9: Calculate the highest valuation S[i,j] for all TVWS slots (i,j)϶ {1, 2,…, m}

10: set $S_{optimal}$ = S[i,j]

11: **for** slot =1 to m **do**

12: **if** (S[i,j]) ≤ (S[i+1, j+1])

13: **then** save the new auction solution (S[i+1, j+1]) to the best found

14: **end if**

15: **end for**

16: **return** Best Auction Solution

Table 17: Auction-based Algorithm pseudo-code

According to the proposed fixed-price allocation process (see Table 16), the Spectrum Broker obtains the optimal solution by minimising an objective function "C(A')", as a matter of allowable transmission power (P(i,f)), requested bandwidth (BW(i,f)), spectrum fragmentation (Frag(i,f)) when a secondary system "i" is assigned to a specific frequency "f" and/or secondary systems' prioritisation (Pr(i)) (e.g. in case that a number of secondary systems must be served before other ones, due to higher QoS level priority).

$$minimise: C(A') = \sum_{i \in V} \sum_{f \in F} x_{if} [P(i,f) + BW(i,f) + Frag(i,f) + \Pr(i)]$$

On the other hand, in auction process (seeTable 17), the, Spectrum Broker collects bids to lease spectrum to secondary systems and subsequently determines the allocation solution along with the price for each spectrum portion from the price portfolio, in order to maximize its profit. The auction process is then repeated, when spectrum portions are still available. Furthermore, in case of auctions, spectrum sellers are denoted as N = {1,2,…,n}, while in the proposed CR network architecture N=1 (i.e. Spectrum Broker, leasing the available TVWS S = {1,2,…,s} to I = {1,2,…,i} secondary systems). Each buyer "i" is able to purchase x_i portions of spectrum for a specific time t_i by reporting a price $P_i^{(b)} = \{x_i, t_i\}$ (i.e. Bid Price), while Spectrum Broker leases y_n portions of spectrum for a specific time t_i by reporting a price $P_n^{(s)} = \{y_n, t_i\}$ (i.e. Asking Price). Finally, $x_{i,n}$ is the quantity that "i" secondary system purchases from Spectrum Broker. Towards maximizing benefit of both Spectrum Broker and secondary systems, an optimization problem can be formulated as a linear programming problem as follows:

$$maximise: \sum_{i=1}^{i} \sum_{n=1}^{n} x_{i,n} t_i \left(P_i^{(b)} - P_n^{(s)}\right)$$

3.5- **Test-bed description and Performance Evaluation**

3.5.1- ***Test-bed Description***

Towards verifying the validity of the proposed RRM algorithms and the capacity of the CR network architecture for efficient TVWS exploitation and QoS provisioning within the RTSSM policy, a decision making process was implemented by exploiting Simulated Annealing algorithm [14]. In this context, several sets of experiments were designed and conducted under controlled-conditions (i.e. simulations) evaluating the performance of the above algorithms, as a matter of LTE secondary systems service rate and the percentage of spectrum broker benefit. The experimental test-bed consists of a TVWS Occupancy Repository, which keeps records about UHF/TV frequencies that can be utilised by LTE secondary systems. Information in this repository was built around actual/real spectrum data gathered within the framework of the COGEU project [15], concerning TVWS availability between 626MHz (Ch.40) and 752MHz (Ch.60) in Munich area, Germany [16]. It should be noted that in the simulation tests that were conducted, both fixed-price and auction-based modes were selected, based on a single spectrum-unit price that was applied for every TVWS trading process.

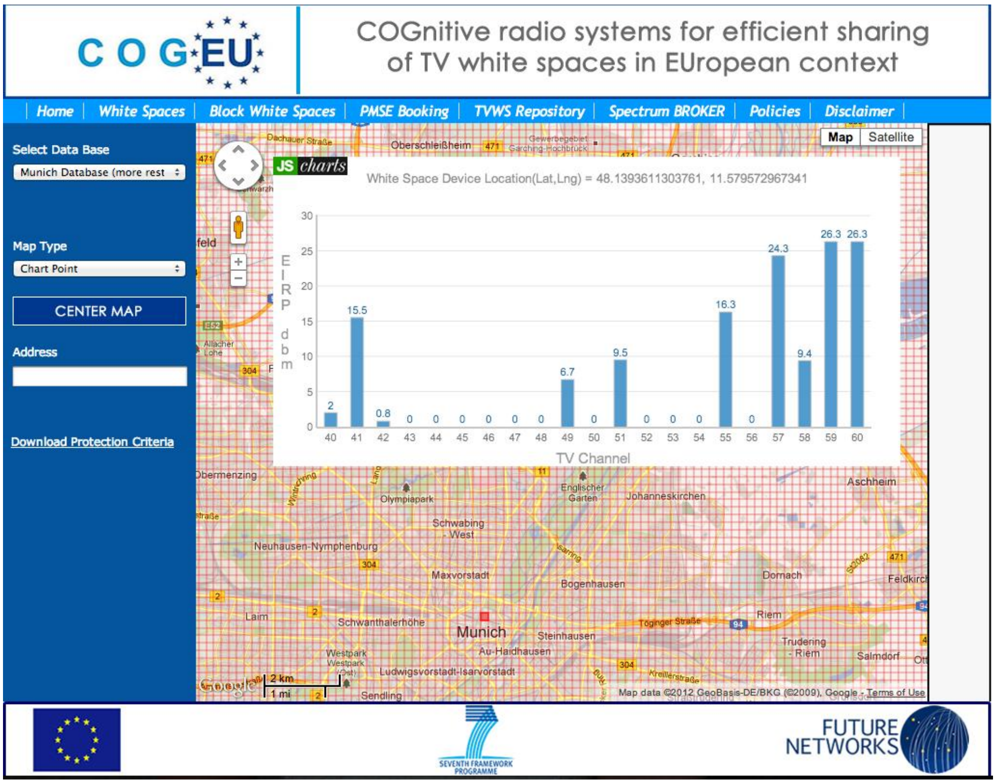


Figure 41: TVWS availability in Munich area

In this context, the simulation scenario includes seven LTE secondary systems with different radio characteristics that were simultaneously competing for the available TVWS (see Figure 42) during 4 different time periods. LTE systems operate under Time-Division-Duplexing (TDD) mode, while a different QoS level was adopted for each system, based on specific services requirements. This QoS level was respected by the optimisation algorithms for both fixed-price and auction-based mode, during spectrum allocation process. Additionally, for each new simulation period (namely as Time Period in the experimental tests) secondary systems with different QoS expectation were entering the test-bed, under a fixed schedule, requesting access to the available (at the given Time Period) TVWS. The technical specifications of such LTE secondary systems are presented in Table 18.

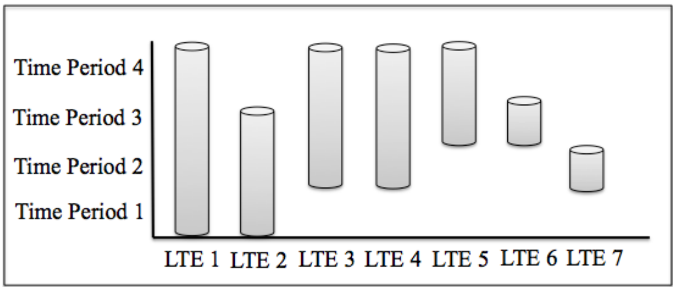


Figure 42: Time Periods of simulation scenario

From Table 18 it comes that there are two major types of services defined with guaranteed bit rate (GBR) and non-guaranteed bit rate (Non-GBR). GBR services are real-time applications, such as conversational voice and video, while Non-GBR services include P2P and Web applications. For a GBR service, a minimum amount of bandwidth is reserved by the proposed system and the network resources provision is guaranteed, by taking into account specific QoS requirements. GBR services should not experience packet losses or high latency in case of network congestion.

Secondary System	Services Provided	Bandwidth (MHz)	Priority/QoS Level
LTE 1	TCP-based services (GBR)	20	Medium
LTE 2	P2P (Non-GBR)	5	Low – Best Effort
LTE 3	Internet (Non-GBR)	20	Low – Best Effort
LTE 4	Video (GBR)	20	High
LTE 5	Video (GBR)	10	High
LTE 6	P2P (Non-GBR)	5	Low – Best Effort
LTE 7	Video (GBR)	5	Medium

Table 18: Technical Specifications of each Secondary System

On the other hand, Non-GBR services are provided under a best effort scheme and a maximum bit rate is not guaranteed on a per-service basis. Based on the above mentioned simulation scenario, four time periods were defined as it is depicted in Figure 42.

3.5.2- *Simulation results*

The performance evaluation results that were obtained after multiple simulation/experimental tests provide a quantitative and qualitative comparison of different optimization algorithms (i.e Backtracking, Pruning, Simulated Annealing and Genetic Algorithm) in terms of spectrum fragmentation and duration needed to perform the best solution. On the other hand, another set of simulation conducted for both fixed-price and auction-based mode, exploiting only the Simulated Annealing algorithm, in terms of spectrum broker benefit and secondary systems service rate. According to this simulation scenario the allocation/auctions periods are divided into 15-minutes long (i.e. four time-periods per hour) during the experimental test, as well as the available TVWS channels are 10. Therefore, the number of frequency-time slots for the competitive secondary systems are m=40.

Figure 43 depicts the performance evaluation results obtained in every time period for each RRM implementation. From the upper plot, it can be verified that all algorithms provide an acceptable fragmentation score, taking into account that: a) the value "0" represents an "un-fragmented" spectrum, while when moving towards "1" spectrum becomes more-and-more fragmented, i.e. there exist many blocks of unexploited frequencies. The lower plot represents a qualitative comparison among Backtracking (with and without Pruning technique), Simulated Annealing and Genetic Algorithm, as a matter of the duration of the simulation before obtaining the optimum solution. From this plot, it can be observed that Simulated Annealing performs slightly better in comparison to the other algorithms, obtaining faster the best-matching solution in a shorter simulation time.

More specifically, Figure 44 referred to spectrum broker benefit for both RRM algorithms (i.e. auction-based and fixed mode). It can be observed that spectrum broker benefit is increasing when the number of LTE secondary systems concurrently accessing TVWS channels, is increasing during all time periods of the above mentioned simulation scenario. Furthermore, auction-based mode provides an optimized performance, in terms of spectrum broker benefit (i.e. increased percentage), in comparison to fixed-price mode. Additionally, Figure 45 represents the service rate of all secondary systems for both allocation processes (i.e. algorithms). It can be observed that the proposed spectrum broker and RRM algorithms respect QoS requirements of secondary systems, according to the simulation scenario defined above.

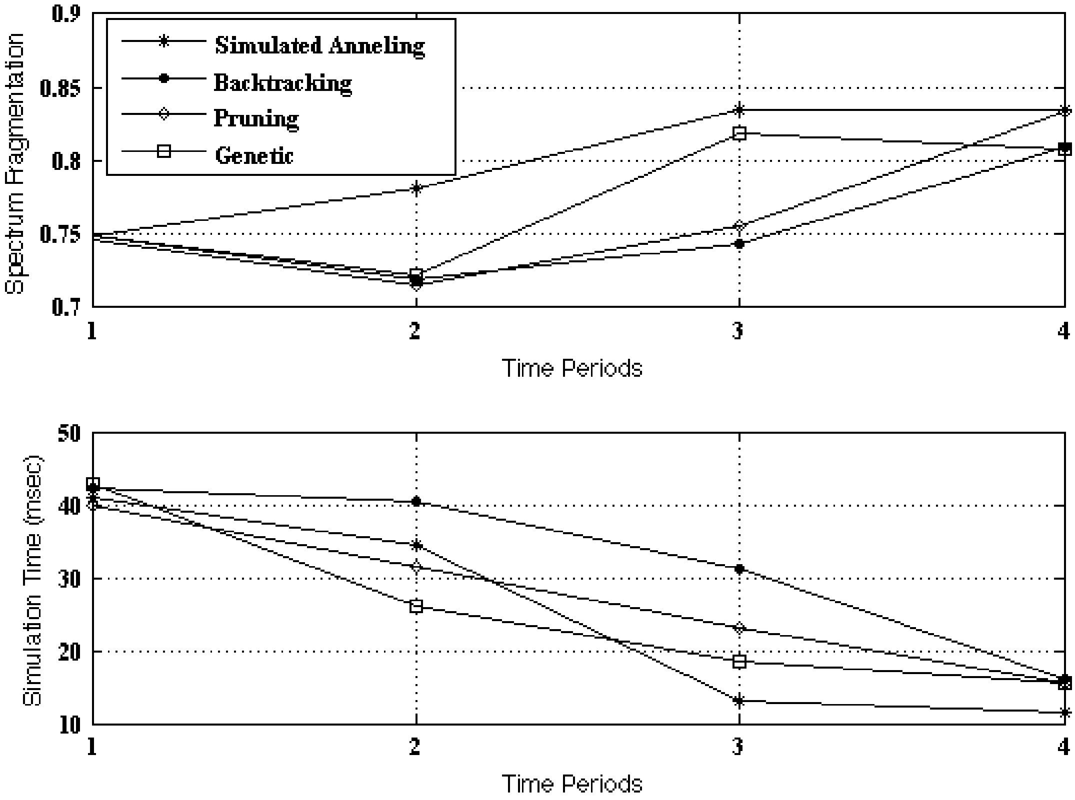


Figure 43: Compared results of algorithms performance exploiting fixed-price mode

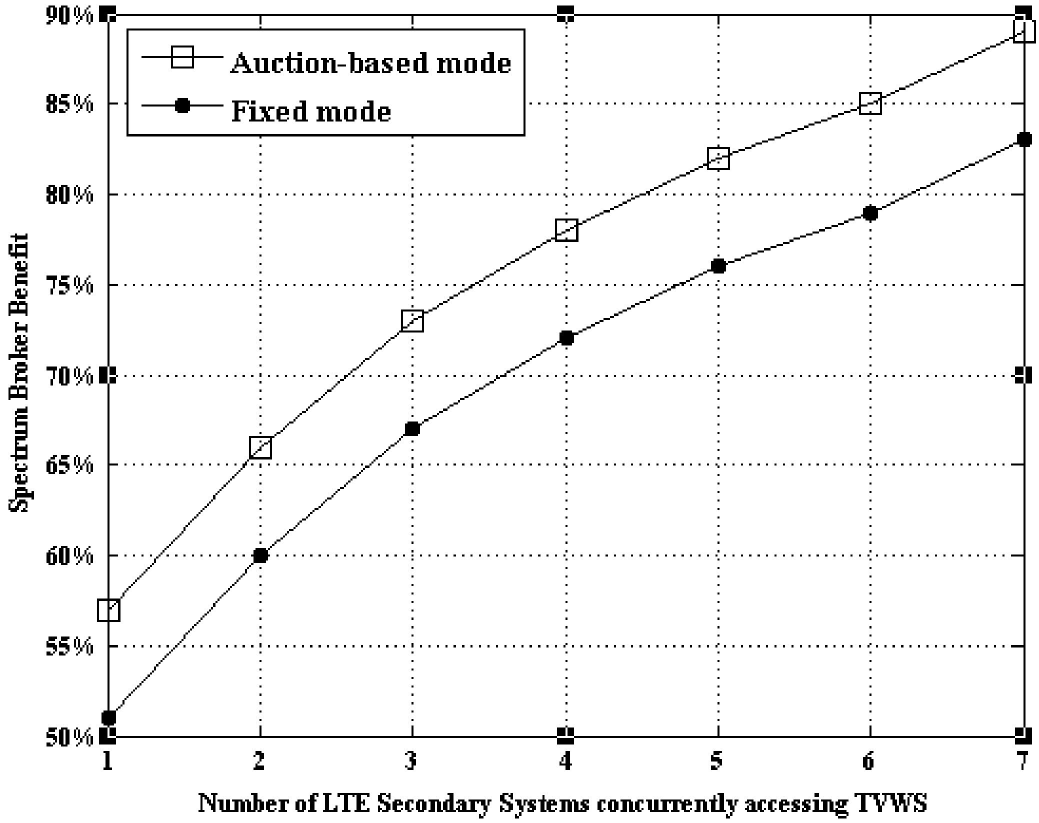


Figure 44: Spectrum Broker benefit of fixed and auctions mode exploiting simulated annealing

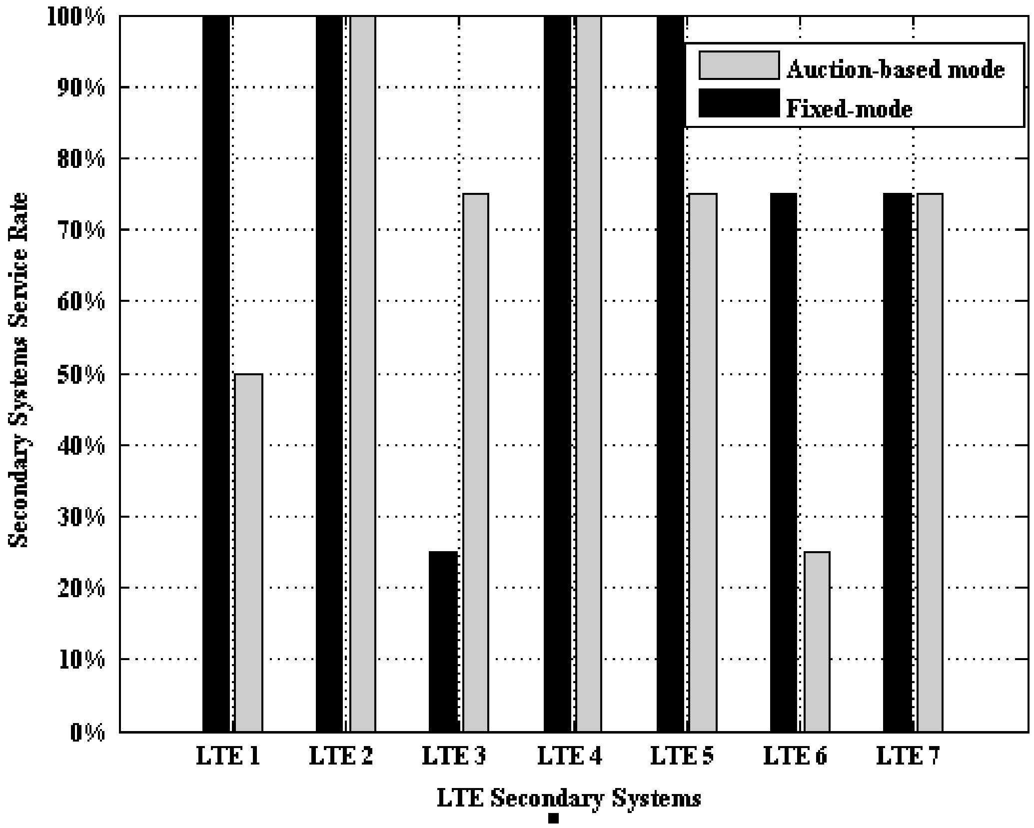


Figure 45: Secondary Systems service rate of fixed and auctions mode exploiting simulated annealing

4- Spectrum broker profitability analysis

4.1- Introduction

The major task for the broker is to sell temporary short-term licenses for the TVWS frequencies to the players which have the particular incentives to pay for the additional spectrum. These players may need the spectrum resources to serve the additional traffic or to improve their network performance. Because the broker sells the temporary licenses (e.g. 1 year for a few allocation periods) and for small areas (covered by one or by a few base stations) the payments which must be paid to the broker are expected to be lower than payments for long-term licenses. The long-term license fees are included in CAPEX, while the cost of the short-term licenses in TVWS can be transferred to OPEX as it was mentioned in the SWOT analysis in deliverable D2.3 [18]. The mentioned SWOT analysis shows the benefits of the short-term licenses for the secondary spectrum market and for the interested players. Moreover, it also seems important to show the potential profits for the spectrum broker, which may be owned by a national regulator or by the 3rd party entity. Clearly, the broker is expected to have some revenue from the assigned licenses. However, the access to a geo-location database, which the broker uses for these assignments creates some cost, too. Note, that the database will be managed most probably by some 3rd party commercial company. (In the USA, there are several potential interested companies in managing geo-location databases such as GOOGLE or Microsoft [19].)

In section 4.2- the proposal for pricing of the TVWS spectrum is presented. Then the income (revenue) model (in section 4.3) and cost model (section 4.4-) are presented. Finally the broker's profitability is discussed in section 4.5-. The income model is based on the statistical availability of TVWS and on the potential players' interest. The cost model is based on the anticipated commissions paid by the broker to the geo-location database provider and to the regulator.

In section 4.6- further discussion on the TVWS spectrum auctions is presented where the players are the LTE-operators. The work takes the carrier aggregation into account, which is the feature of the LTE-A and allows for better resource utilization and for higher auction efficiency. The simulation results confirm this fact.

4.2- Spectrum products and pricing model

4.2.1- *The auctioned spectrum products*

In this section the auctioned objects, so-called spectrum products are introduced for the market case, where the main market players are the LTE cellular systems operators. Then, the pricing model is presented, which is dependent on these offered products and on the applications and services for which they are used.

As said before, the TVWS resources are fragmented and characterized by different transmit powers. The first parameter describing the allocated spectrum is the frequency bandwidth. Here, we consider the multiple of 5 MHz, which is typical for the LTE channels. Note that 5 MHz band is a subband of the DTV 8 MHz channel. Once a single DTV channel is occupied by 5 MHz LTE transmission, it cannot be used or allocated to another LTE system, thus each auction winner should actually pay for 8 MHz. Note that in this case, the winning player may theoretically use 5 MHz and 3 MHz LTE channels in 8 MHz band if the equipment supports such an operation. In general in LTE/LTE-A systems it is possible. If there are two adjacent DVB-T channels available for one operator, he may use it for the transmission of 5, 10 or 15 MHz band, but must pay for 16 MHz.

Because the broker sells the TVWS resources to the LTE/LTE-A operators two main maximum transmit power levels are of our interest for the downlink transmission. Let us note that TVWS resources are considered mainly for the system capacity extension above the one obtained with the existing resources owned by the operators in other bands (800 MHz and 2.6 GHz bands for the LTE). Therefore the first proposed maximum transmit power is 30 dBm (1 Watt) which should allow for the signal coverage in a cell of 1 km radius. This transmit power should be useful for players having spectrum resources in 800 MHz band. The second proposed transmit power is 25 dBm which should allow for 300 m radius coverage (in a smaller cell) and should be useful for the players having spectrum resources in 2.6 GHz band. In both cases the TVWS spectrum resources will be used to serve the additional users in the downlink transmission.

Apart from the frequency bands used and the transmit power limits, the license period is important for the operators. They expect stability of the allocated resources and relatively longer-term licenses. These goals are in contradiction with flexible and very dynamic spectrum management. It has been recognized that 1 year licenses are acceptable for the operators in this regard. Such allocation time should bring enough stability and flexibility to the market. Moreover, these licenses are provided only for a particular day period. Three daily-allocation periods are considered of 8 hours each representing small-, medium- and high traffic period in a day, and one year licenses can be given to the operators to use the allocated spectrum in one of these day periods or in the combination of these periods, depending on the license term.

Because in our considerations, the LTE operators are the main secondary-spectrum-market players the spectrum portfolio (the spectrum offer) prepared by the broker should be suited to them. The so-called spectrum products available on the market are defined as the triplets of the transmission band, maximum transmit power and spectrum allocation period in a day to satisfy the following players' possible requirements:

- transmit power: 25 or 30 dBm (dependent on the TVWS availability),
- transmission mode: FDD downlink,
- license time: 8 specified hours for 1 year
  - 00:00 – 08:00 (low traffic allocation period),
  - 08:00 – 16:00 (medium or high traffic allocation period),
  - 16:00 – 00:00 (medium or high traffic allocation period),
- number of licenses: 3
- bandwidth:
  - 5 MHz (8 MHz must be paid),
  - 10 or 15 MHz (16 MHz must be paid).

4.2.2- *Spectrum pricing*

In this section, we consider the value of 1 MHz of the TVWS spectrum. This value is related to many market factors. Let us first discuss the benchmark price expressed in Euro per one MHz per person in the population in a given area (€/MHz/Pop). Note that the TVWS bands are located next to the 800 MHz band on the frequency axis, and 800 MHz band is allocated to the LTE systems. Moreover, the auction(s) for spectrum in this band were conducted lately or they are conducted nowadays. Therefore, we believe that through the appropriate scaling of the spectrum value in the 800 MHz band we can obtain the benchmark price for the TVWS spectrum.

Below, the benchmark price for the TVWS spectrum is denoted by *p*. The auctions of 800 MHz band allocate the spectrum for many years, thus the price of the TVWS spectrum one year license is decreased by the factor *l*. Then, because our considered TVWS spectrum is sold locally for the use in a single pixel-area, the population density *d* per square kilometre is considered. The number of users which will be potentially served by the operator is dependent on the allocation area *S* which is dependent on the transmit power. Moreover, the potential degree of competition is considered in a given area. The operators' market share factor is thus taken into account assuming that all big operators already have the spectrum resources in other bands. This factor is denoted by *O,* while the TVWS correction factor *x* is used taking the specific characteristic of TVWS other than 800 MHz band into account. This factor shows the incentives of operators in low/medium/high density areas. Finally the allocation period factor *t* is added. This factor is dependent on the daily spectrum allocation period for low/medium/high traffic hours.

The formula presented below is similar to Advanced Incentive Pricing and uses the most important factors to evaluate the price of spectrum (PoS). The PoS in TVWS can be thus calculated according to the following formula:

$$PoS = p * l * d * S * O * x * t \quad (1)$$

4.2.3- *Examples*

To calculate the price of spectrum in Munich area (COGEU target scenario) the following input data was used:

- *p* = 0.72286 €/MHz/pop [20],
- *l* = 0.1,

- *d* = 4359 km^{-2} – for Munich area,
- *S*
  - 3.14 km^2 for 30 dBm of transmit power and 1 km radius,
  - 0.28 km^2 for 25 dBm of transmit power and 0.3 km radius,
- *O* = 0.159 based on the operators' market share in Germany which is [21]:
  - O2 – 15.9 %,
  - T-Mobile – 31.9%,
  - Vodafone – 33.4%,
  - E-Plus – 18.8 %,
- the TVWS correction factor *x* is dependent on the area type:
  - *x* = 1 for low density areas,
  - *x* = 1.5 for medium density areas,
  - *x* = 2 for high density areas,
- the allocation period factor is dependent on the allocation period and it was inspired the analysis of the traffic in pocket data networks [22]:
  - 8 hour low traffic period *t* = 1/6 (from 00:00 to 8:00)
  - 8 hour medium traffic period *t* = 2/3 (from 8:00 to 16:00)
  - 8 hour peak traffic period *t* = 1(from 16:00 to 00:00)

The calculated price of spectrum per year may be higher than in classic 10 years auction but it is available on demand and each year may be allocated to different operator. This is the main advantage of spectrum brokering. Below, the price of spectrum for 30 dBm of transmit power is presented in the Table 19 and for 25 dBm for the considered example parameters given above. The calculated prices are dependent on the area type and the allocation period. The factors *x* and *t* may be optimized for the potential auction interest.

	Low traffic period	**Medium traffic period**	**Peak traffic period**
Low density areas	26,22	104,88	157,31
Medium density areas	39,33	157,31	235,97
High density areas	52.44	209,75	314,63

Table 19: The price of spectrum for Munich area (in €/MHz) for 30 dBm

	Low traffic period	**Medium traffic period**	**Peak traffic period**
Low density areas	2,34	9,35	14,03
Medium density areas	3,51	14,03	21,04
High density areas	4,68	18,70	28,06

Table 20: The price of spectrum for Munich area (in €/MHz) for 25 dBm

4.3- Potential broker's revenues

4.3.1- *TVWS availability in Munich area*

The spectrum broker revenue (incomes) are based on the statistical analysis of the TVWS availability and the potential interest of the market participants. The following analysis is conducted for Munich area due to the information about the TVWS availability. Such information may be found under the link given in [5] and was obtained in October 2012. The TVWS availability is dependent on the restrictive primary users' protection criteria used in the calculations, and thus, the results are different for more and less restrictive scenarios. The statistical TVWS availability is presented in Table 21 ([5]).

Channel no	Maximum transmit power	More restrictive scenario	Less restrictive scenario
40	25	---	0.1 % (62.5 px)
41	25	---	14.2 % (8875 px)
41	30	---	6.0 % (3750 px)
51	25	---	0.8 % (500 px)
55	25	---	0.4 % (250 px)
57	25	0.3 % (187.5 px)	36.8 % (23000 px)
57	30	---	31.5 % (19687.5 px)
59	25	1.6 % (1000 px)	37.8 % (23625 px)
59	30	---	33.6 % (21000 px)
60	25	6.3 % (3937.5 px)	46.0 % (28750 px)
60	30	0.5 % (312.5 px)	40.9 % (25562.5 px)

Table 21: Statistical TVWS availability in Munich area

It is worth to mention that in the more restrictive protection scenario there is only one channel available in 0.5% of the considered area for the LTE transmission with 30 dBm maximum power. In the less restrictive scenario there are four available channels for such a transmission, and in particular one of them is available in 40.9 % of places in the considered Munich area.

Note 1: The less restrictive protection criteria allow the broker to achieve reasonable profit.

Except the statistical availability of TVWS it is also important to observe the distribution of the pixels where transmission with given power may be used. In Figure 46 the TVWS availability is presented for channel 60 for 30 dBm under more restrictive criteria. In Figure 47 the TVWS availability is presented, when less restrictive criteria were used.

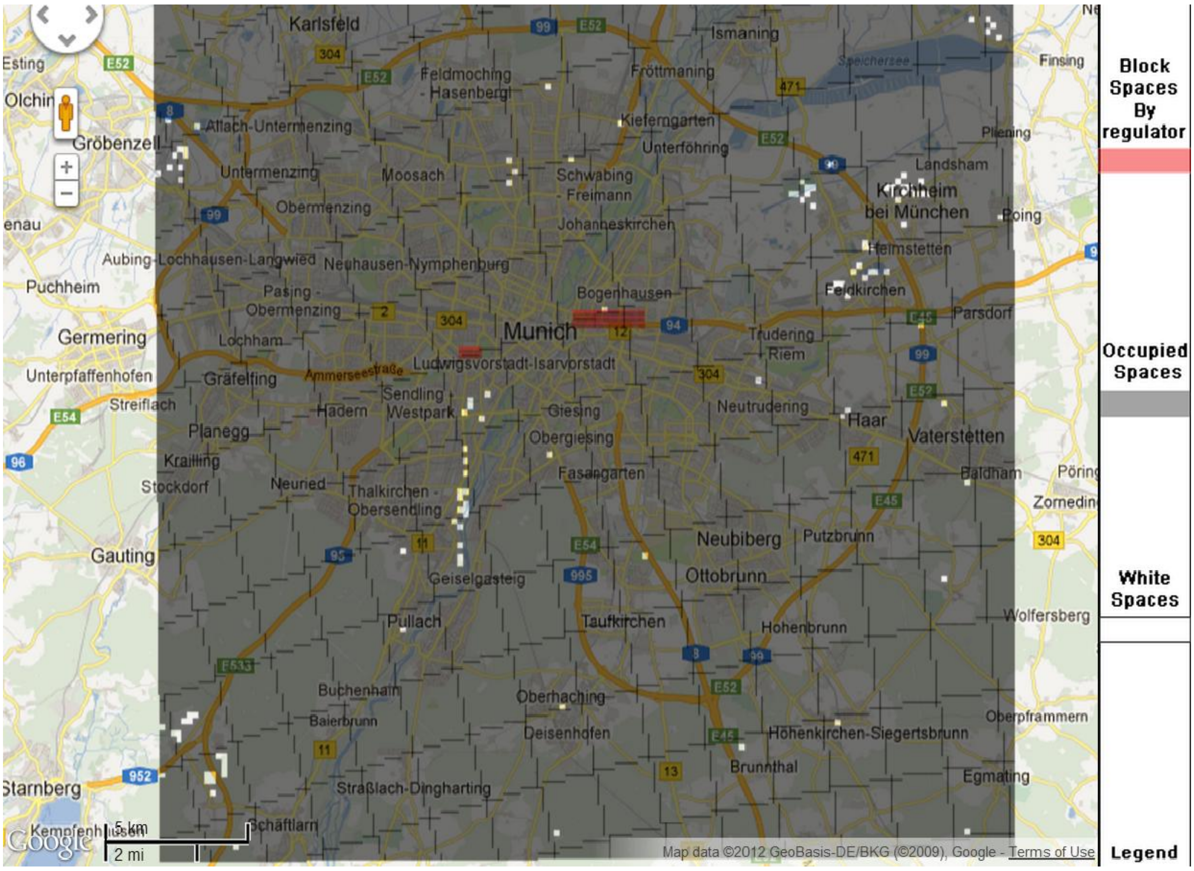


Figure 46: Channel 60 availability in Munich area (30 dBm)– more restrictive criteria [5]

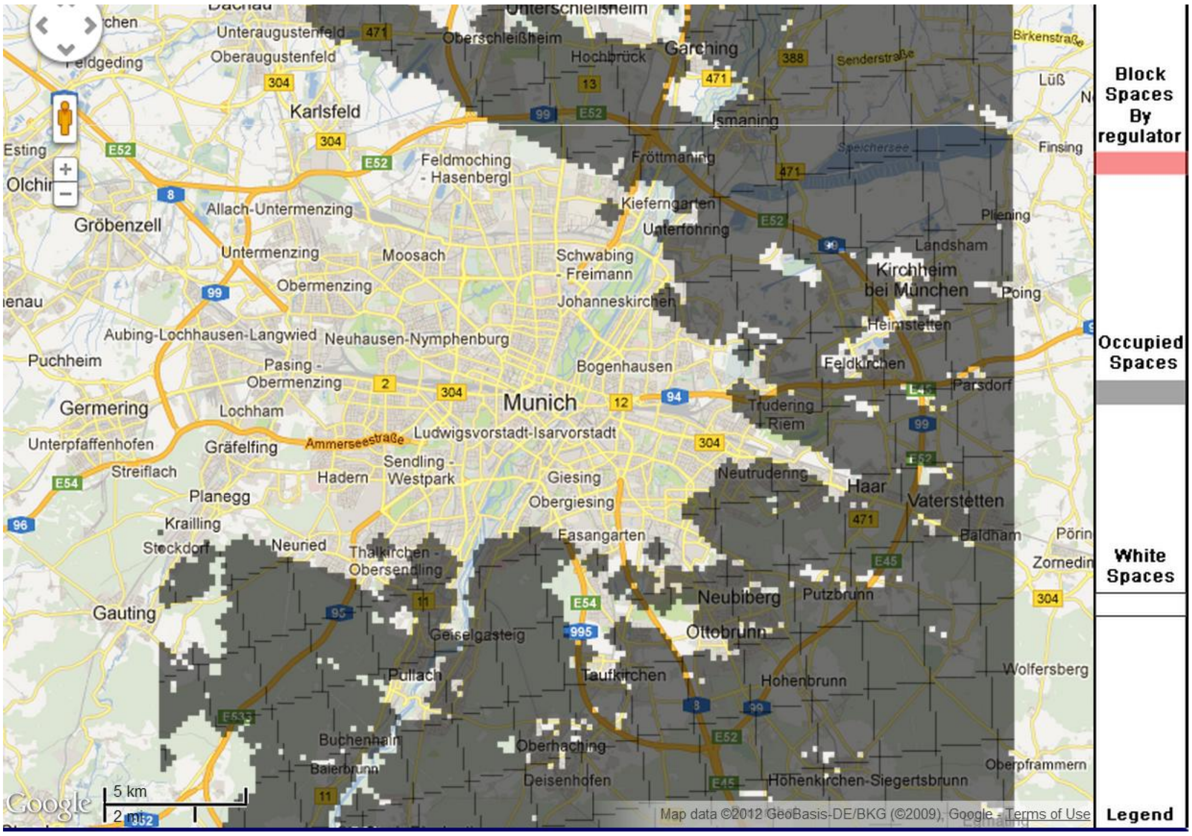


Figure 47: Channel 60 availability in Munich area (30 dBm) – less restrictive criteria [5]

Note 2: Spatial pixel distribution may influence the number of deployed base stations in TVWS band.

4.3.2- *Methodology and deployment's boundaries*

To calculate the broker's income the following methodology is used. First, the demonstrator area is calculated. It has the size of 2500 km^2 (50km x 50 km) in our test Munich area. This area was divided into single trading pixels having size 0.2km x 0.2 km (0.04 km^2), thus in the Munich area there are 62500 trading pixels. In section 4.2.1-, the spectrum products and license details were defined. The main assumption used here is that each DTV channel is sold to one operator (operator pays for 8 MHz and may use 5 MHz or 8 MHz). Moreover, 25 dBm allows for 300 m cell-radius coverage and 30 dBm allows for 1 km cell-radius coverage. Due to the interference issues between the cells and considered pixel-areas (the co-channel interference) and the protection criteria, it is assumed that no other transmission can be allowed by secondary spectrum user in radius 600 m and 2000 m respectively. Because of the assumed coverage radiuses, a single LTE base station will have coverage 3.14 km^2 (78.5 pixels) for 30 dBm and 0.28 km^2 (7 pixels) for 25 dBm. The coverage area may be given in km^2 or in pixels (when they are grouped). Using the statistical TVWS spectrum availability the possible number of base stations, which can be deployed, can be calculated what is presented in Table 22.

Channel no	Maximum transmit power	More restrictive scenario	Less restrictive scenario
40	25	---	9
41	25	---	1268
41	30	---	48
51	25	---	72
55	25	---	36

57	25	27	3286
57	30	---	251
59	25	143	3375
59	30	---	268
60	25	563	4108
60	30	4	326

Table 22: The possible number of BSs in Munich area

Note 3: The numbers presented in Table 22 allow for calculation of the maximum number of base stations which can be deployed in the whole demonstrator area.

The city-area of Munich is only 310 km^2 (12.4% of COGEU demonstrator). Thus the number of base stations which can be deployed in the city was decreased (multiplied by 0.124) because the capacity extension need by the secondary-spectrum market players is more probable in urban areas. The more realistic numbers of base stations, which can be deployed in TVWS band in the city-area of Munich are presented in Table 23.

Channel no	Maximum transmit power	More restrictive scenario	Less restrictive scenario
40	25	---	1
41	25	---	157
41	30	---	6
51	25	---	9
55	25	---	4
57	25	3	407
57	30	---	32
59	25	18	419
59	30	---	34
60	25	70	509
60	30	*1*	41

Table 23: The realistic number of BS in Munich city-area

In Table 23 the case for grouped pixels was presented (the worst case) and for the urban area only. In some particular channels (41, 57, 59 and 60) the broker must decide what is more profitable: to sell spectrum with higher or with the lower allowable power. In more restrictive scenario such situation occurs only in channel 60. The broker may sell this channel in 1 location with higher power limit or in 70 locations with lower power limit.

Note 4: For 30 dBm transmit power and 1 km radius each operator needs 796 independent base stations for full coverage in the Munich area. In a less restrictive scenario 113 independent base stations can be deployed. If it is assumed that there are 4 operators then each one can use almost 30 additional TV channels in the urban area and 200 base stations in the whole demonstrator area.

Note 5: The numbers in Table 23 are the boundaries to the numbers of possible deployed base stations in the Munich city area.

4.3.3- ***Broker's incomes from licenses with 30 dBm power limit***

In Tables 24 and 25 below the potential broker's incomes are presented which are dependent on the number of deployed base stations and the average price per MHz. In Table 24, the results for more restrictive scenario are presented, while in Table 25 the results for less restrictive scenario are given. The following formula was used for the calculation of the broker's income (revenue):

$$\Pi = B * P_{average} * N_{BS} * N_{licenses} \quad (2)$$

where Π is broker's income, B is a bandwidth of TV channel (8 MHz), $P_{average}$ is the average price for 1 MHz, N_{BS} is a number of deployed base stations, $N_{lisenses}$ (there are three licenses for one year for 8 specified hours).

	Average price 50 €/MHz	**Average price 100 €/MHz**	**Average price 150 €/MHz**	**Average price 200 €/MHz**
10 base stations	12k	24k	36k	48k

Table 24: The broker's income from licenses with 30dBm power limit in the more restrictive scenario (in €)

	Average price 50 €/MHz	**Average price 100 €/MHz**	**Average price 150 €/MHz**	**Average price 200 €/MHz**
10 base stations	12k	24k	36k	48k
25 base stations	30k	60k	90k	120k
50 base stations	60k	120k	180k	240k
100 base stations	120k	240k	360k	480k
150 base stations	180k	360k	540k	720k

Table 25: The broker's income from licenses with 30dBm power limit in the less restrictive scenario (in €)

Note 6: The main limitation in the use of TVWS is the number of base stations which can be deployed. This number depends on the potential players' interests, the protection criteria and the spatial pixel distribution with a given transmit power limit.

4.3.4- ***Broker's incomes from licenses with 25 dBm power limit***

In the tables below the potential broker's revenue is presented for the case of the maximum allowable transmit power of 25 dBm. In Table 26, the results for more restrictive scenario are presented, while in Table 27, the results for less restrictive scenario are given.

	Average price 5 €/MHz	Average price 10 €/MHz	Average price 15 €/MHz	Average price 20 €/MHz
50 base stations	6k	12k	18k	24k
100 base stations	12k	24k	36k	48k

Table 26: The broker's income from licenses with 25dBm power limit in the more restrictive scenario (in €)

	Average price 5 €/MHz	Average price 10 €/MHz	Average price 15 €/MHz	Average price 20 €/MHz
50 base stations	6k	12k	18k	24k
100 base stations	12k	24k	36k	48k
150 base stations	18k	36k	54k	72k
200 base stations	24k	48k	72k	96k
500 base stations	60k	120k	180k	240k

Table 27: The broker's income from licenses with 25dBm power limit in the less restrictive scenario (in €)

Note 7: The broker's revenue in case of the lower transmit power limit seems to be satisfaying only for a large number of deployed base stations. It is possible when all the considered players are active in the secondary spectrum market.

4.4- The broker's costs

The broker's cost model is based on the commissions, which are paid to the geo-location database provider and to the regulatory body. Further costs encompass the business-running costs and administrative costs.

It is assumed that the broker pays the commission to the geo-location database owner only for sold TVWS frequencies. The commission rate is a percent of the revenue of the traded amount of spectrum (it seems that 5-10% is a rational commission). This approach is compatible with the indirect revenue presented in [23]. It is also envisioned that the broker may also be the geo-location database provider, thus in such a case, the cost of running it can be added to the overall broker costs. This situation is more preferable by the broker only in cases when the costs of database maintenance are lower than the amount of money which should be paid in commissions. The broker must also pay the commission to the market regulator which is the owner of the unused TVWS frequencies. This commission may be from 25 – 40% of the income from the traded spectrum. Thus, the broker pays the geo-location database provider and the regulator about 30-50% of the income.

The broker has also its own costs which may be divided for CAPEX and OPEX. There are the following assumptions used in the cost model:

- No license fee is paid for the WEBID software (GNU GENERAL PUBLIC LICENSE) [25]. This software was used to create COGEU demo tools.
- Licenses from the regulator are covered in commissions paid for sold spectrum.
- The number of employees equals 3 (1 manager + 2 software engineers for the system maintenance and administration.)

- No advertising and marketing costs are envisioned because the information about the spectrum broker is available at regulators website,
- Office space equals 30 m^2 and the rent is 25 €/m^2,

The **CAPEX** costs and assumptions are the following:

- Auction system development – 30000€ (5000€ * 6 man months needed for auction system development),
- Hardware for employees - 4000€,
- Software for single employee – 3000€,
- Office equipment costs - 2000€,
- **Total costs: ~39 000 €**

The **OPEX** costs are:

- Salary to employees with tax - 180000€/year (15000€/month),
- Office rent - 9000€/year (750€/month),
- Mobile phone fees - 1800€/year (150€/month),
- Auction system hosting (business option) and hardware leasing – 500€/year,
- **Total costs: ~191 300 €**

Note 8: Total OPEX costs per year are approximately 191 300 €, thus, the minimum profit per year must be higher than this amount. It can be assumed that the auction system development may be moved to OPEX costs (if it is realized by broker's staff). Finally, all costs are approximately 200 000€ per year and if and only if the potential income will be higher the business will be profitable. Other costs may be estimated amounting to 9000€.

4.5- Profitability analysis and recommendations

For more restrictive scenario concerning the primary system protection it is assumed that the spectrum broker can sell 10 licenses for the transmission with 30 dBm and 50 licenses for the transmission with 25 dBm power limit which can guarantee the income from ~20k to 70k€, which is dependent on the operators' interests and average spectrum price. Such income cannot guarantee the profitability of the broker. Thus, the broker must try to expand the area of its operation to places with less restrictive DVB protection criteria.

For the less restrictive scenario concerning the primary system protection and for the Munich area it is assumed that spectrum broker can sell 100 licences for the transmission with 30 dBm and 200 licences for the transmission with 25 dBm power limit, which can guarantee the income from 150k to 600k€ depending on the operators interests and the average spectrum price. Such income can allow the broker to achieve profitability if the average price for the spectrum unit (1 MHz per one year license, 8h/day period, per site) exceeds 100€.

Below the amount of commissions are proposed, which must be paid to the geo-location database provider and to the regulator.

Recommendation 1: If broker achieves the income of 250k€ then the sum of commissions should be 20% to the regulator and to the geo-location database provider. If the broker achieves more than 400k€ and more than 600k€ of the income then the sum of commissions should be 30% and 40% respectively.

Finally, the following recommendations to the regulators are presented.

Recommendation 2: Because the broker's profitability is strictly dependent on the DVB-T protection criteria, the players interests (the number of deployed base stations and the price of spectrum), spatial TVWS distribution and the technology constraints (LTE and the implementation of carrier aggregation), the broker's profitability cannot be guaranteed. Therefore the broker is expected to expand the operational area, what should be envisioned by the regulator.

Recommendation 3: Before the market can guarantee the stability, it is recommended that the regulator should create the team responsible for TVWS auctions.

4.6- Single pixel auction improvement

In the previous deliverables (D6.1 [4] and D2.3 [18]) the auction modes for a single pixel-area in Munich were proposed. The auction allows for the highest resources utilization but the auction efficiency is strictly dependent on the available resources. For example if the broker sells 16 MHz (two DVB-T channels) there can be two possibilities depending on whether the TV channels are adjacent or not (fragmented). In case when TV channels are fragmented and if the LTE players are interested in 5 MHz LTE channels the maximum efficiency is 62.5% (only two 5 MHz channels may be leased). When two TV channels are adjacent the maximum efficiency is 93,75% (three 5 MHz channels may be leased). The problem of the maximum efficiency is strictly associated with the available technology. For example LTE defines the following channel sizes: 1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz and 20 MHz. In the auction design, it is assumed that the players specify the contiguous channels which they want to lease. Such requirement may be relaxed in case of the carrier aggregation mechanism applied in LTE-A. In such a case the 10 MHz channel may be obtained by two 5 MHz channels because of carrier aggregation. This means that the brokers has more flexibility in satisfying the players demands. Moreover, this carrier-aggregation mechanism is useful also within the spectrum from other bands e.g. from digital dividend (800 MHz) band, and thus, the players operating in the FDD mode may demand portions of required spectrum or only the spectrum for their downlink channels to enhance their capacity in macrocells.

The carrier aggregation is also associated with the auction complexity. In general in the combinatorial auction the broker must check 2^N combinations of players to find optimal and exact solution. N is the number of players or the independent players' bids. But there is also a cost of checking each combination of users which is B^{N+1} for B MHz of available spectrum and 1 MHz granularity. Therefore the final complexity for both NP-hard problems is $B(2B)^N$. Thus, the reduction of such cost is strongly desired especially for fragmented spectrum with different available transmit powers. Fortunately, because of LTE-A technology, the broker may use the carrier aggregation mechanism. It allows for obtaining the bandwidths higher than 3 and 5 MHz by combinations of channels of 3 and 5 MHz. Also 5 MHz may be obtained by two 3 MHz channels. Due to this assumption broker may divide each 8 MHz TV channel into 5 MHz and 3 MHz blocks (with assigned maximum transmit power) and then check if the particular set of users may be served by the available spectrum resources. Such a procedure may cause fragmentation on spectrum axis but it improves spectrum utilization and results in lower computational complexity.

Because of the carrier aggregation feature, the auction efficiency is now independent on the available resources. To prove this fact the following simulation environment was used. The broker uses the combinatorial auction in time, power and frequency dimension for LTE/LTE-A players for the following available resources (24 MHz) with given maximum transmit power (P_1, P_2, P_3) and these resources are stable in time (K is the number of spectrum blocks):

- R1 – K = 3, (B_1 =8, P_1=1), (B_2 =8, P_2=0.5), (B_3 =8, P_3=1),
- R2 – K = 2, (B_1 =16, P_1=1), (B_2 =8, P_2=0.5),
- R3 – K = 1, (B_1 =24, P_1=1).

The competitors are LTE players, having spectrum in digital dividend, demanding extra channels for the downlink transmission (this situation is equivalent to the spectrum demands in the TDD mode). For the simulations, it has been assumed that there are 12 players: 3 players demanding b_1=10MHz and p_1=1W, 3 players demanding b_2=5 and p_2=1, 3 players demanding b_3=10 and p_3=0.5 and 3 players demanding b_4=5 and p_4=0.5. The probability of participation in the auction is assumed to have uniform distribution and is 0.6 for players demanding 10 MHz and 0.9 for players demanding 5 MHz. The valuation of 1 MHz (in €) is assumed to have normal distribution G ~ (615, 123) for peak traffic period, where the first number denotes the expected value, and the second the standard deviation and it is the same for all players. The spectrum valuation is based on the analysis presented in Section 4.2.1-. The number of players, the auction-access probability and the players' valuation of the spectrum unit corresponds to the incentives of all players interested in spectrum leasing. The auction mode is time-combinatorial for 3 allocation periods. The players' valuation of the spectrum unit and the probability of participation in the auction are multiplied by respective weights for the following allocation periods:

- for low traffic period – by 1/2 and 1/3 respectively;
- for medium traffic period – by 3/4 and 2/3 respectively;
- for peak traffic allocation period – by 1 and 1 respectively.

The choice of these factors has been inspired by the analysis of traffic dynamics in cellular data networks [22]. In situations, when available spectrum is higher than players' demands the administrative price is applied which is 0.5 of the valuation of spectrum. The Monte Carlo method was used with 10000 runs for each set of parameters. To increase auction payoff and auction efficiency the spectrum fragmentation was allowed. Table 28, Table 29, Table 30 present the key metrics extracted from the simulated auction. According to assumptions the highest auction efficiency (the spectrum bandwidth sold over the available bandwidth) was achieved in the peak traffic period because the players had the most incentives to submit higher bids. Referring to the auctions results from [4] and from [18], the auction efficiency in case of the carrier-aggregation scenario is similar for peak-traffic allocation period for both time-combinatorial and time-simultaneous modes. In case of time-combinatorial auction the maximization of the auction payoff is in all allocation periods. This feature is not present in time-simultaneous mode. Due to this fact time-combinatorial auction has worse efficiency in spectrum allocation than time-simultaneous but time-combinatorial auction mode allows for consideration of players' demands in time dimension, which may be more important for them. In our previous works the maximum auction efficiency was dependent on the free resources' schemes. Because the carrier aggregation was used and fragmentation on frequency axis was allowed thus the auction efficiency is now independent on the available resources. Moreover, in R1 resource set when fragmentation is not allowed the players' demands regarding 10 MHz could not be realized. Fragmentation on frequency axis with support of LTE carrier aggregation allows for serving these users and provides better utilization of TVWS resources.

	Daily values	***Low traffic period***	***Medium traffic period***	***Peak traffic period***
Sum of players demands[MHz]	41.94	20.81	42.02	62.98
Sold spectrum [MHz]	17.57	13.38	19.34	19.99
Auction efficiency	0.73	0.56	0.81	0.83
Auction payoff [€]	9053.04	4211.60	9473.29	13474.21
Valuation of sold 1 MHz [€]	519.04	293.86	489.28	673.98

Table 28: Simulation results for R1 resource set

	Daily values	***Low traffic period***	***Medium traffic period***	***Peak traffic period***
Sum of players demands[MHz]	42.03	20.95	42.03	63.12
Sold spectrum [MHz]	17.57	13.35	19.36	19.99
Auction efficiency	0.73	0.56	0.81	0.83
Auction payoff [€]	9050.26	4214.45	9471.88	13464.44
Valuation of sold 1 MHz [€]	518.86	294.24	488.59	673.43

Table 29: Simulation results for R2 resource set

	Daily values	***Low traffic period***	***Medium traffic period***	***Peak traffic period***
Sum of players demands[MHz]	41.89	20.95	41.73	63.01
Sold spectrum [MHz]	17.67	13.61	19.41	19.99
Auction efficiency	0.74	0.57	0.81	0.83
Auction payoff [€]	9114.30	4289.54	9519.66	13533.70
Valuation of sold 1 MHz [€]	519.55	294.00	489.90	676.85

Table 30: Simulation results for R3 resource set

5- Conclusions

This deliverable, D6.4, reports research work performed in Tasks 6.5 and elaborates on different radio resource management strategies for the LTE extension over TVWS use case. The simulation analysis is performed considering the Munich scenario and realistic data from the COGEU geo-location database. This deliverable also analysis the profitability of the spectrum broker.

More specifically, chapter 2 presents the efficiency of the LTE TVWS Management Systems by utilizing the Munich scenario. The initial average CDR of 0,69% decreases to 0% if we use the less restrictive COGEU geo-location database or almost 0% if we use the more restrictive COGEU geo-location database. The average CBR decreases from 2,94% to 0% using the less restrictive database or almost 0% using the more restrictive. In both cases it was experienced a full decrease of these Key Performance Indicators (KPIs) in almost all the sector that have some extra needs in capacity or in coverage. The only sectors that didn't decrease their CDR and CBR were the sector 41 and 42 when using the more restrictive geo-location database. All the presented results endorse the proper functioning of all the modules that form the algorithm, the TVWS Management System. With the load of each legacy antenna it was verified that the sectors where it were activated TVWS antennas were the same sectors that experience some needs in capacity. The Selection of the TVWS channel was properly working and choosing the best channel from the available channel presented by the geo-location database in the TVWS Channels List. With the representation of the service areas and comparison between the legacy service area and the TVWS service area confirmed the correct adjustments done to the transmission power of all the active TVWS antennas. Using the two COGEU geo-location databases it was well visible the difference between the results. For instance, using the less restrictive database we had 9 active TVWS antennas and using the more restrictive we had 7 active TVWS antennas. Summarizing all the results were according to what was expected.

Moreover chapter 3 discusses a centralized CR network architecture that exploits TVWS under the secondary spectrum trading regime and elaborated on the design, implementation and performance evaluation of a prototype RRM framework. Towards evaluating the performance of the proposed framework, a set of simulations was conducted where various secondary systems were requesting access to the available TVWS by sending auction bids. The obtained results verified the validity of the proposed framework and compare the performance of the different optimization algorithms as a matter of maximum-possible spectrum utilisation and minimum fragmentation, as well as a matter of maximum-possible benefit of the Spectrum Broker.

In Chapter 4, this deliverable presents the extension of the work obtained in D2.3 of SWOT analysis, by investigating the potential profits of the spectrum broker in case of the spectrum broker sells temporary licenses in the Munich area. In this context, the broker incomes and costs are analysed for the Munich scenario. The results indicated that in the more restrictive case concerning the primary system protection in the Munich area, the spectrum broker income cannot guarantee the profitability. Additionally, results obtained in the less restrictive protection scenario indicated that the expected profitability of the spectrum broker income can be achieved in case when the average price for spectrum unit (1 MHz, one year license, 8h/day period, per site) exceeds 100€.

Regarding the simulation results of the spectrum auction, where the players are the LTE-A operators employing the spectrum aggregation technology, it can be concluded that the highest auction efficiency and profitability can be achieved in the peak-traffic period because the players have the most incentives to submit bids with higher valuation for higher bandwidth demands. In the peak-traffic daily period, the auction efficiency is similar for both time-combinatorial and time-simultaneous auction modes. In case of time-combinatorial auction the maximization of the auction payoff can be observed in all allocation periods of daily traffic. This is not observed in time-simultaneous auction mode. Thus, the time-combinatorial auction has worse efficiency in spectrum allocation than the time-simultaneous auction. However, the time-combinatorial auction maybe of interest for the players because it allows for completely satisfying the players' demands in time dimension based on the "all-or-nothing" rule. Finally, an improvement to the auction in the single pixel-area previously implemented was proposed, that is based on the carrier aggregation technique in LTE-A, allowing for better resource utilization and for higher auction efficiency.

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3GPP	3rd Generation Partnership Project
4G	Fourth Generation
aRNP	Automated Radio Network Planning
BS	Base station
CBR	Call block rate
CBR_Ref	Reference value of call block rate
CDR	Call drop rate
CDR_Ref	Reference value of call drop rate
CL	Channels List
CR	Cognitive Radio
EIRP	Equivalent Isotropically Radiated Power
eNBs	Evolved NodeB
FDD	Frequency Division Duplex
GBR	Guaranteed bit rate
GPS	Global Positioning System
GUI	Graphical User Interface
KPIs	Key Performance Indicators
LTE	Long Term Evolution
Non- GBR	Non guaranteed bit rate
OFDM	Orthogonal Frequency Division Multiplexing
PMSE	Programme Making and Special Events
QCI	QoS Class Identifier
QoS	Quality of Service
RF	Radio Frequency
RR	Radio resources
RRB	Radio resource blocks
RRM	Radio Resource Management
SINR	Signal to Noise plus Interference
SLA	Service Level Agreement
TDD	Time Division Duplex
TVWS	TV White Spaces
UE	User Equipment
UHF	Ultra High Frequency
WCDMA	Wideband Code Division Multiple Access
WP	Work Package
WPAN	Wireless Personal Area Network