Abstract:

This Deliverable, D6.2, reports the work performed in T6.2, T6.3, T6.4 and T6.5 of WP6. It firstly elaborates on the identification of the available TV white spaces in Munich area, used to populate the geo-location database of COGEU final demonstrator. Based on these results, it then deals with the simulation of LTE extension over TV white spaces and investigates the improvement of cellular coverage. D6.2 also presents the design, implementation and evaluation of networking protocols (i.e. negotiation, routing and transport layer), regarding the efficient communication and spectrum trading between secondary users in COGEU use-cases.

Keyword list: TVWS identification, LTE over TVWS, negotiation protocols, spectrum aware routing protocols, transport layer protocols.
Executive Summary

This deliverable reports preliminary work performed in Tasks, 6.2 "Spectrum-aware routing protocols", 6.3 "Cognitive transport layer protocols", 6.4 "Negotiation protocols between players for secondary spectrum trading" and 6.5 "Simulation tools and system level evaluation". More specifically, T6.2 elaborates on the design, development and evaluation of spectrum-aware routing protocols capable to efficiently operate, among COGEU secondary users. It also investigates spectrum-aware routing protocols for CR networks that are based on conventional protocols, utilized in Ad-Hoc, multi-hop wireless networks.

The research approaches proposed in this deliverable enable for the proper transition of data between secondary users with heterogeneous spectrum availability, taking into account the absence of a Common Control Channel (CCC). T6.3 deals with the implementation and evaluation of transport layer protocols that are adopted in COGEU network architectures. T6.4 elaborates on the design of a negotiation protocol, which is able to establish the efficient communication regarding trading negotiation issues, among COGEU secondary users and Spectrum Broker.

D6.2 also reports the work performed in T6.5, which elaborates on the computation of the available TVWS in Munich area and the population of COGEU geo-location database. This TVWS availability data is used in the simulation experiments, regarding LTE extension over TVWS, where three different scenarios are implemented. Following, the key achievements of this deliverable are listed below:

- Computation of the available TVWS in Munich area based on methodology proposed in D6.1. The resulted data is used to populate the geo-location database of COGEU final demonstrator.

- Data regarding the acceptable transmission power for the TVWS device, for an area 50 km x 50 km around Munich, is generated and provided in EXCEL format for integration in COGEU geo-location database.

- Investigations are performed with moderate values of parameters (i.e. protection ratios, overload threshold, etc) regarding the TVWS calculation. Results are gained with these moderate parameters approving that the operation of TVWS devices is possible in principle, in specific geographical location under a number of constraints.

- Two business cases for TVWS usage were obtained from the investigation: a) areas with portable broadcast coverage, where TVWS might be used for low power transmission systems, like WiFi, and b) rural areas / isolated residential areas, where it is possible to keep larger minimum distances between TVWS base station transmitter and closest possible broadcast receiver.

- Investigation results indicate that TVWS usage is appropriate for WiFi use in order to solve the overloading problem of ISM bands in urban and dense urban areas and could provide an affordable broadband Internet access for rural areas, which follows the call of EU parliament for equal treatment of all regions within EU.

- A LTE simulator is developed in order to obtain appropriate results of simulation, by utilizing three modes of operation (Normal, Algorithm 1 and Algorithm 2). Normal mode is possible to view useful statistics in the network planning engineering, for example, the SINR across the map and the amount of interference. The tool uses TVWS opportunities identified in Munich area.

- Simulations LTE extension in the TV white spaces are based on three areas of Munich that represent three related scenarios (urban, suburban and rural).

- Final results indicate that operators can reduce the cost of base stations installation, providing in this way services with a competitive advantage over competitors. The quality of network planning process has a direct influence on the operators’ profit. So, for an operator this parameter is very important to reduce the OPEX (Operational Expenditures) and the CAPEX (Capital Expenditures).
- Urban scenario offers higher throughput, but the difference in the number of the resource block per user in both frequencies, is small. This means that most users are close to the base station and already have high MCS for both frequencies. Also, the number of sites in urban scenario is less 18.8 % in TVWS, which represents a cost reduction.

- For the suburban scenario, the difference in the number of resource block per user in both frequencies is higher in relation of three scenarios, which means that operators in this case can provide more users per BS sector and the number of sites is less 16.7 % in TVWS, which also represents a cost reduction as in urban.

- For the rural scenario in 700 MHz, the number of sites is lowest in comparison to the other scenarios with decrease 50 % and the difference to the number of resource block between 700 MHz and 2.6 GHz is acceptable.

- A signaling protocol/interface between the Spectrum Broker and the secondary users is designed. The signaling interface is the protocol that enables for the efficient transaction of spectrum between the Spectrum Broker and the secondary users.

- Two types of negotiation protocols are developed. The first one is related with the merchant mode, where the spectrum is sold in terms of first come, first serve basis, while in the second one is associated with the auction mode, where the most valuable bidder wins the spectrum resources.

- Routing protocols in conventional wireless networks and CR networks are investigated in order to identify major problems/challenges regarding routing of data across geographical areas with heterogeneous TVWS availability. Routing in CRN is challenging and different from routing in a conventional wireless network. The secondary usage of spectrum is the key difference, since routing in CRNs could not be based on a Common Control Channel (CCC).

- Two COGEU scenarios are proposed, implemented and evaluated regarding spectrum-aware routing studies. More specifically, routing protocols are designed, developed and evaluated that can be capable to ensure the reliable data delivery across regions of different TVWS availability. The first scenario elaborates on routing studies related with secondary users, which operate under the spectrum of commons reference model of COGEU (i.e. ad-hoc network infrastructure), while the second one deals with a public safety COGEU use-case.

- A routing simulator is developed in terms of COGEU ad-hoc scenario, where the AODV protocol is modified and adapted in order to overcome the challenges regarding the absence of a CCC between the secondary users.

- Preliminary results verified the validity of the proposed routing protocol, besides identifying fields for further research in order to enhance this research approach with a coordination mechanism, towards optimizing performance of preliminary simulations.

- Transport layer protocols in CRNs have been considered in this work by THALES. A modification of transport protocols in order to operate in a cognitive radio environment; where frequent disruption is a norm and end-to-end paths are typically not available such in some secondary usage scenarios has been investigated. This modification, is however, not public so far because a pending patent issue. An introduction to the problem scope is reported in Annex 7. The work on the Transport layer protocols will be public available in Deliverable D6.4 (December 2012).
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1- Introduction

Successful deployment of Cognitive Radio Networks (CRNs) in the TV white spaces will depend on the development of appropriate networking protocols. Such work has to address the challenges in the various stages of the communication stack while considering the different approaches to access the TV white spaces, as shown in Figure 1. Therefore, the main purpose of D6.2 is to design, develop and evaluate networking protocols (i.e. routing, transport layer and negotiation ones – encircled with ellipses in the Figure), in order to overcome a number of challenges in the TV white spaces, assuming COGEU use cases and architectures as developed in WP2 and WP3 respectively.

In particular, this deliverable reports the work performed in T6.2, T6.3, T6.4 and T6.5, regarding the efficient communication and spectrum trading between secondary users. This deliverable also elaborates on the computation of the available TVWS in Munich area, towards populating the geo-location database of COGEU demonstrator. The resulted data is used to produce simulation results, regarding the LTE extension over TVWS.

Figure 2 shows the logical organization used to present the networking issues for COGEU scenarios in this deliverable. First, an investigation of the availability of the TV white spaces, specifically for Bavaria is presented in Chapter 2. Then, in Chapter 3, the results presented for the Munich area are used to assess the feasibility of TV white space usage for the LTE scenario. Moving to specific protocols, Chapter 4, presents the negotiation for the TV white spaces focusing on the Broker based secondary spectrum trading developed by COGEU in previous reports. After that, Chapter 5 addresses the issue of spectrum aware routing protocols for ad hoc scenarios, both in commercial and public safety networks under the commons scenario. Finally, Chapter 6 concludes the deliverable.
Specifically, Chapter 2 presents the procedure that is proposed for calculating the white space availability data, which in turn, is used to populate the geo-location database. IRT frequency planning tool, “FRANSY”, is utilized and serves as a basis for estimating locally available spectrum (i.e. TVWS) in the UHF bands around Munich area. Due to the lack of national and European regulation, reasonable assumptions were made in order to determine the maximum possible transmission power for a White Space Device intended to transmit at a given location in a given channel. Pmax (location, channel) is determined based on these assumptions. In a second step, a simplified zone concept is developed to estimate the total amount of TVWS over a larger area, (e.g. Bavaria, a federal state of Germany). Results are used to investigate differences in mapping the TVWS to area and mapping to population density. Based on the results, conclusions are drawn related with the WSD system (e.g. LTE or WiFi) that is appropriate for different broadcast reception area (fixed reception, portable reception).

Chapter 3 presents the performance results and evaluation procedures for LTE over TVWS validation. More specifically, by utilising TVWS opportunities previously identified in Chapter 2, this chapter simulates the cellular extension over TVWS and studies the improvement of 3G/LTE cellular coverage and QoS metrics, when extra TVWS carries are available. The idea is to redirect traffic from congested cells to TVWS carriers, achieving lower blocking probabilities. A cellular 3G planning tool is used to evaluate the amount of extra bandwidth and the duration of the spectrum leasing required for peaking support. The starting point is the traffic information/situation in the busy hour, in order to analyze, when extra spectrum is needed, as well as how much of it, is required. Different radio resource management strategies are analysed, in order to decide which systems are "moved" to the TVWS extra carriers. Simulations also illustrate how TVWS spectrum allocation changes reacting to modifications of the RF environment caused by terminal mobility.

Chapter 4 presents the negotiation protocols for the Broker based secondary spectrum trading in COGEU. Negotiation has been for decades a central subject of study in disciplines such as economy, game theory, and management. A negotiation protocol determines the flow of messages between the negotiating parties, dictating who can say what, when and acts as the rules by which the negotiating parties must abide by if they are to interact. Therefore, one of the main challenges in enabling spectrum acquisition through trading mechanism is the development of protocols to support negotiation between spectrum supplying and demanding stakeholders. COGEU Broker supports both merchant and auction modes of spectrum acquisition. Thus, in this deliverable, message sequences for the merchant and auctions modes are presented. A preliminary instantiation of the implementation of the auction mode is also presented.

Chapter 5 discusses routing challenges in a network with secondary usage of spectrum. Routing in a CR network is challenging and different from routing in a conventional wireless network. A key difference is that routing in CRNs is not based on a Common Control Channel (CCC), since it is not ensured that each secondary node can obtain the same frequency of operation. This chapter investigates multi-hop routing schemes, in order to provide efficient data delivery across regions of heterogeneous spectrum availability, even when the network connectivity is intermittent or when an end-to-end path is temporarily unavailable. In this context, two simulation scenarios are presented. The first one is related with an Ad-Hoc, multi-hop distributed network architecture, where secondary nodes are able to communicate with the use of a novel routing protocol, which is designed, implemented and evaluated. The second simulation scenario is related with a public safety COGEU use-case.

In addition to negotiation protocols and spectrum aware routing protocols, part of this work considered transport layer protocols, developed by THALES. A modification of transport protocols in order to operate in a cognitive radio environment, where frequent disruption is a norm and end-to-end paths are typically not available such in some secondary usage scenarios, has been investigated. In cognitive radio networks, many factors such as the transmission power, the bandwidth of the TVWS and the interference level can affect the packet loss rate. Similarly, RTT can be affected by the delay due to spectrum sensing and spectrum handoff, for which when the current channel becomes unusable for an unlicensed user, the unlicensed user has to search for a new channel. Therefore, the modified transport layer protocols consider these effects to optimize end-to-end rate control. Also, the impact of Service Interruption Losses, sensing and negotiations delays in Cognitive Radio networks and their influence on legacy transport protocols is investigated. The details of the developed solutions for transport layer protocols in CRNs are not yet public because pending patent issues. Annex 7 gives an introduction to the problem scope.

Finally, Chapter 6 presents the main conclusions of this deliverable and the implementation plan that will be used as a roadmap for the development and integration of the negotiation protocols in WP7.
2- Available TVWS identification

TVWS devices, according to CEPT report 24 [1], are allowed to operate on a “non-interfering, non-protected basis”. Several means were discussed (in SE43 and also within COGEU project) to cope with this non-interfering demand, among them sensing and geo location. For the geo location scenario, besides the equipment for the TVWS device to locate its own position, a database is required that provides data on acceptable transmit power for the possible channels at the requested location. This chapter describes how to calculate the data, i.e. the acceptable transmit power for the TVWS device. As these results are essential for the COGEU demonstrator, data for an area 50 km x 50 km around Munich were generated and provided in EXCEL format for integration in COGEU broker database. Knowing the acceptable transmit power for a given location is crucial for non-interfering operation of TVWS devices. Besides this requirement for the moment of operation, also an earlier information in time is required regarding the total amount of available TVWS, as a basis for decisions on system configuration and required investments, e.g. for base stations.

In the second part of this chapter estimations on available TVWS are made. Any location – even within a TV coverage area – can be considered usable for TVWS device as long as its transmit power is low enough (hence, the results will depend on the TVWS device class). In the first part of the investigation only the channel itself is considered without caring on adjacent channel occupation. In a second step also the occupation of direct adjacent channels (n±1) is taken into account being aware that for realistic treatment more adjacent channels are relevant (up to n±9, depending on protection ratios). Usually the TVWS availability is mapped to area. As there are scenarios easily imaginable where TVWS are available in unpopulated regions, mapping to population density may be a more appropriate parameter. Differences between the two variants are investigated.

2.1- Maximum transmission power for TVWS devices in the UHF bands

2.1.1- Procedure to calculate TVWS device transmit power

In order to estimate the maximum transmission power of TVWS devices in the UHF bands a methodology aspect has to be considered. The methodology that was followed is described in ECC 159 [3], (chapter 4.3.4. “EIRP limits in case of geo-location database operation”) prior to start estimating field strengths and location probabilities for a broadcasting system without TVWS devices interfere it.

Location probability describes the statistical probability that broadcast reception is possible at a given location:

\[
q = Pr(P_s > P_{s,min}) + \sum_{k=1}^{K} r_{U,k} P_{U,k} = Pr(P_s \geq U)
\]

Pr\{A\} is the probability of event A, \(P_s\) is the received power of the wanted DTT signal, \(P_{s,min}\) is the DTT receiver’s (noise limited) reference sensitivity level, \(P_{U,k}\) is the received power of the \(k^{th}\) unwanted DTT signal and \(r_{U,k}\) is the DTT-to-DTT protection ratio for the \(k^{th}\) DTT interferer [3]. \(U\) is the total nuisance field, comprising of noise plus minimum signal to noise ratio and the unwanted signal contributions from other DTT transmitters. The contributions are power-summed (i.e. summed in the linear domain):

\[
U = (N + SNR) \oplus N_{u_{DTT1}} \oplus N_{u_{DTT2}} \oplus ...
\]

If, at a given location a somewhat lower location probability \((q \rightarrow q - \Delta q)\) can be accepted, then the nuisance field can raise, giving the opportunity to operate a further interfering device:

\[
U' = (N + SNR) \oplus N_{u_{DTT1}} \oplus N_{u_{DTT2}} \oplus ... \oplus N_{u_{WSD}}
\]

So, with the knowledge of wanted signal strength \((P_s)\), location probability \((q)\) and the specification of acceptable degradation \((\Delta q)\) for each location and channel the TVWS devices nuisance field \(N_{u_{WSD}}\) can be determined. The wanted signal strengths and location probabilities can be calculated with a DTT coverage calculation software, e.g. IRT’s frequency analysis system FRANSY (Annex 1: A note on FRANSY). This software provides field strength and location probability for each location and channel.
From these data the total nuisance field \( U \) can be determined. Applying the reduced location probability \( q - \Delta q \) provides the maximum TVWS device nuisance power (see Annex 2: Procedure to calculate \( \text{IWSD}_{\text{MAX}} \)): upper ellipse in Figure 3.

![Flowchart that describes the procedure to calculate TVWS device maximum transmit power](image)

The nuisance field is at the location of broadcast antenna in channel \( \text{ch} \). This is not the location of the TVWS device and it is not necessarily the channel at which the TVWS device is transmitting. In fact, in most of the cases, the channel will be different. CEPT ECC report 148 [2] (“Measurements on the performance of DVB-T receivers in the presence of interference from the mobile service (esp. from LTE)” provides protection ratios for co channel and adjacent channel operation and overload threshold to relate TVWS device operation in channel \( \text{ch}' \) with broadcast reception in channel \( \text{ch} \). As ECC report 148 only gives ranges for some parameters, Table 1 represents the average parameters which were chosen for COGEU investigations (see Annex 3: Parameter from ECC Report 148)):

<table>
<thead>
<tr>
<th>( \text{PR}_{\text{co}} )</th>
<th>BS</th>
<th>UE</th>
<th>Oth_1</th>
<th>BS</th>
<th>UE</th>
</tr>
</thead>
<tbody>
<tr>
<td>PR_1</td>
<td>-33 dB</td>
<td>-13 dB</td>
<td>-13 dBm</td>
<td>-20 dBm</td>
<td></td>
</tr>
<tr>
<td>PR_2</td>
<td>-40 dB</td>
<td>-41 dB</td>
<td>-8 dBm</td>
<td>-18 dBm</td>
<td></td>
</tr>
<tr>
<td>PR_3</td>
<td>-39 dB</td>
<td>-42 dB</td>
<td>-19 dBm</td>
<td>-26 dBm</td>
<td></td>
</tr>
<tr>
<td>PR_4</td>
<td>-48 dB</td>
<td>-49 dB</td>
<td>-13 dBm</td>
<td>-20 dBm</td>
<td></td>
</tr>
<tr>
<td>PR_5</td>
<td>-49 dB</td>
<td>-50 dB</td>
<td>-8 dBm</td>
<td>-18 dBm</td>
<td></td>
</tr>
<tr>
<td>PR_6</td>
<td>-50 dB</td>
<td>-49 dB</td>
<td>-6 dBm</td>
<td>-18 dBm</td>
<td></td>
</tr>
<tr>
<td>PR_7</td>
<td>-50 dB</td>
<td>-52 dB</td>
<td>-5 dBm</td>
<td>-16 dBm</td>
<td></td>
</tr>
<tr>
<td>PR_8</td>
<td>-51 dB</td>
<td>-52 dB</td>
<td>-5 dBm</td>
<td>-15 dBm</td>
<td></td>
</tr>
<tr>
<td>PR_9</td>
<td>-39 dB</td>
<td>-39 dB</td>
<td>-6 dBm</td>
<td>-14 dBm</td>
<td></td>
</tr>
</tbody>
</table>

**Table 1: Parameters used for the simulations**

1 A note on notation:
- \( \text{PR}_{\text{co}} \) is the co-channel protection ratio, i.e. \( \text{ch} = \text{ch}' \)
- \( \text{PR}_n \) is the protection ratio for the \( n \)-th adjacent channel, e.g. \( n = 3 \rightarrow \text{ch} = \text{ch}' \pm 3 \). For \( n = 1 \) to 8 the protection ratios are assumed symmetrically. For \( n = 9 \) the 36 MHz intermediate frequency (IF) effect may cause a poor value (-39 dBm). If this is the case, it is only used at one side, e.g. \( n = 9 \) whereas for \( n = 9 \) the value for \( n = 8 \) is used if it is better than the value for \( n = 9 \)
- Oth_\( n \) is the overload threshold for the \( n \)-th adjacent channel
As a next step the signal propagation between the location of TVWS device and the possible location of a DTT receiver must be considered. As indicated in Figure 3 the possible scenarios describe the possible arrangements of TVWS transmitter and broadcast receiving antenna. With realistic assumptions on minimum distance and by applying appropriate propagation models the propagation loss can be determined. As the distances are usually short, typically less than a few kilometers (note: outside of coverage areas the minimum distance is the shortest distance to the edge of coverage), simple models like extended Hata or the 20/30/40dB model (described in see Annex 4: Assumptions) are appropriate. Combining propagation loss with other relevant parameters determines the coupling gain (“loss”): 

\[ \text{loss} = \text{propagation loss} + \text{antenna gain} + \text{feeder loss} + \text{polarization discrimination} \]

To estimate the maximum TVWS device maximum transmit power the contributions have to be put together:

\[ P_{\text{max,PR}}(x, y, cH) = N_{\text{max,WS}}(u, v, cH) - PR(cH - cH) - \text{loss} \]

2.1.2 - Analytical considerations

2.1.2.1 Dependence of TVWS nuisance field strength on incumbent system’s field strength

Any additional transmitter (interferer) in the vicinity of a receiver causes a degradation of the location probability. If a certain amount of degradation is acceptable, e.g. \( \Delta q = 1\% \) the acceptable TVWS nuisance field strength can be calculated (see Annex 2: Procedure to calculate \( I_{\text{WSD,MAX}} \)):

\[ N_{\text{max,WS}} = m_x + 10 \times \log_{10} \left(10^{-\sigma_{\text{eff}}(q_1 - \Delta q)/10} - 10^{-\sigma_{\text{eff}}(q_1)/10}\right) \]

The first term \( m_x \) is the mean signal strength of the incumbent signal. If this signal is equal to the nuisance field then the location probability becomes 50 %. If the mean signal strength is higher, then the location probability is higher:

\[ p_{\text{mean}} = p_{\text{mean}} + \varepsilon_x \times \sigma \]

\( \varepsilon_x \) is the confidence factor, which is related to the location probability via the error function:

\[ \varepsilon_q = \sqrt{2} \text{erfinv}(2 \times q - 1) \]

Noise limited case

A noise-limited system in a fixed reception scenario is considered:

\[ N = -98.15 \text{ dBm} \]
\[ SNR = 21 \text{ dB} \]
\[ f = 650 \text{ MHz (ch 43)} \]
\[ G = 9.15 \text{ dB (fixed rooftop: Yagi antenna)} \]
\[ \sigma = 5.5 \text{ dB (standard deviation of broadcast signal)} \]

In this case without additional interferer, if the mean broadcast signal strength \( m_x \) is \( N + SNR \), then location probability becomes \( q = 0.5 \) (50 %) and \( m_x = P_{\text{mean}} \).

At the edge of 95% coverage area the mean signal strength at the receiver input is

\[ P_{95} = (N + SNR) + \varepsilon_{95} \sigma = -68.10 \text{ dBm} \]

Corresponding field strength is:

\[ E_{95} = P_{95} + 77.21 + 20 \times \log_{10}(f) - G = 56.21 \text{ dB} \frac{\mu V}{m} \]

For other values this becomes:

<table>
<thead>
<tr>
<th>( q )</th>
<th>( \varepsilon(q) )</th>
<th>( P ) [dBm]</th>
<th>( E ) [dB( \mu )V/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 %</td>
<td>0</td>
<td>-77.15</td>
<td>47.16</td>
</tr>
<tr>
<td>70 %</td>
<td>0.5244</td>
<td>-74.27</td>
<td>50.05</td>
</tr>
</tbody>
</table>
Spectrum-aware routing, transport protocols and negotiation protocols between players for secondary spectrum trading; System level simulation tool - initial specification

<table>
<thead>
<tr>
<th>95%</th>
<th>1.6449</th>
<th>-68.10</th>
<th>56.21</th>
</tr>
</thead>
<tbody>
<tr>
<td>99%</td>
<td>2.3263</td>
<td>-64.36</td>
<td>59.96</td>
</tr>
</tbody>
</table>

Table 2: Correlation of DVB-T power/field strength with location probability in the noise limited case

For the noise limited example the nuisance signal strength can be easily expressed as a function of the incumbent signal field strength (Figure 3):

i. For each incumbent signal field strength E and location probability q₁ calculate ε₁.
ii. For q₂ = q₁ - Δq calculate ε₂
iii. Apply

\[ N_{WSO} = P_{max}^{mean} + 10 \times \log_{10} \left( 10^{-\frac{\sigma_{eff} \varepsilon(q_1-\Delta q)}{10}} - 10^{-\frac{\sigma_{eff} \varepsilon(q_1)}{10}} \right) \]

Figure 4: TVWS nuisance signal strength as a function of the incumbent signal field strength

Within a (70%) coverage area the incumbent field strength varies between 50 dBµV/m (edge of coverage) and typically 80 dBµV/m. In the vicinity of transmitters signals may reach 100 dBµV/m or even more. So, within coverage areas, where in noise limited case the broadcast signal field strength varies between 50 dBµV/m and 80 dBµV/m, the nuisance signal strength is nearly linearly related to the strength of the incumbent signal.

2.1.2 Co channel / adjacent channel operation for noise limited systems

To calculate maximum transmit TVWS device power values for protection ratios and minimum distances are required. Following Table 1 the protection ratios for estimation are rounded²:

- PRco = 22 dB
- PRn+1 = -30 dB
- PRn+2 = -40 dB
- PRn+3 = -50 dB

As fixed rooftop reception is considered, following Table 16 in Annex 4: Assumptions' for the average loss -50 dB are assumed.

With the field strength of the incumbent system and typical parameters the maximum TVWS transmission power can be estimated:

² Values are valid for 64 QAM 2/3; for 16QAM 2/3 a correction is required: -4.3 dB, see annex 3 (parameters)
protocols and negotiation protocols between players for secondary spectrum trading; System level simulation tool - initial specification

\[ P \left[ dB \frac{\mu V}{m} \right] = E [dBm] - 77.21 - 20 \times \log_{10}(f) + G \]

\[ N_{WSD}^{WSD} = (P) + 10 \times \log_{10} \left( \frac{10^{-\frac{\alpha_{eff}(\Delta q)}{10}}}{10} - 10^{-\frac{\alpha_{eff}(\Delta q)}{10}} \right) \]

- For \( f = 650 \) MHz and \( G = 9.15 \) dB: \( P [dBm] = E [dB\mu V/m] - 124.3; \)
- For \( q = 0.7 \ldots 1.0 \) and \( \Delta q = 0.01 \) the term \( 10^{\log_{10}(...) \ldots -17 \text{ dB}} \)
- Average loss: -50 dB
- \( E = 50 \ldots 80 \text{ dB} \mu V/m \)
- PR from above

So for the noise limited case this results in:

<table>
<thead>
<tr>
<th>( E [dB\mu V/m] )</th>
<th>50</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td>( PR [dB] )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>co: 22</td>
<td>-62</td>
<td>-32</td>
</tr>
<tr>
<td>nt±1: -30</td>
<td>-10</td>
<td>20</td>
</tr>
<tr>
<td>nt±2: -40</td>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td>nt±3: -50</td>
<td>10</td>
<td>40</td>
</tr>
</tbody>
</table>

Table 3: Maximum TVWS device transmit power, depending on channel separation and incumbent system’s field strength for the noise limited case (for 16 QAM2/3)

So for the co channel case from this simple model it can be concluded that maximum TVWS device transmission power is such low that a cost effective use of these channels (within coverage area) cannot be assumed. For the adjacent channels \((\pm 1, \pm 2, \pm 3, \ldots)\) maximum possible transmit power increases with increasing channel separation but also linearly depends on incumbent’s signal strength in occupied adjacent channels.

2.1.2.3 Effect of overloading: upper threshold of transmit power

Digital Terrestrial TV receivers can be tuned to any channel between 470 and 862 MHz. In order to realize high sensitivity the first step in a TV receiver is a broadband amplifier. A very strong signal on any channel between 21…69 may cause nonlinear behavior of the amplifier:

- A strong out-of-band interfering signal may deteriorate the receiver’s ability to detect a low-level wanted signal (receiver blocking). The receiver blocking response or performance level is defined as the maximum interfering signal level expressed in dBm reducing the specified receiver sensitivity by a certain number of dB’s (usually 3 dB). In this situation the receiver is still able to decode strong broadcast signals.
- If interfering signal is stronger than the overload threshold then the receiver loses its ability to decode any incumbent signal, no matter how strong this will be (overloading).

The overload threshold for the LTE base station signal according to ECC report 148 [1] is between -19 dBm and -5 dBm. Within the coverage area for fixed reception the shortest distance between TVWS device (BS) and rooftop aerial is assumed 30 m (see Annex 4: Assumptions). For this distance the coupling gain (transmitting into the cone of the antenna) for 650 MHz is -49 dB. In most of the European countries it can be assumed that there is at least one broadcast coverage within \( n\pm9 \) of each channel at any location. Under this assumption the overload threshold in combination with the shortest possible distance between TVWS device and TV antenna determines an upper limit for the possible transmission power for TVWS device according to the following equation:

\[ P_{WSD}^{WSD,0lh} = O_{lh-coupling\ gain} = -19\text{dBm} + 49\text{dB} = 30\text{dBm} \]

- This value above is the upper limit for fixed broadcast reception conditions and the advantageous values for downlink signals. For broadcast portable reception the DVB-T receiver may get closer to the BS. However due to the poorer antenna gain for dipole antenna versus fixed rooftop antenna maximum transmission power is only slightly lower.
COGEU
D6.2 - Spectrum-aware routing, transport protocols and negotiation protocols between players for secondary spectrum trading; System level simulation tool - initial specification

- For user terminal signals (UE) the overload thresholds are approximately 10 dB worse, which reduces maximum transmission power to 20 dBm.
- If portable DVB-T reception is possible then the pass loss reduces to -32 dB, which combined with TVWS UE, limits TVWS power to few dBm.

In this context and before conducting detailed simulations, it may be concluded that overload threshold defines an upper limit for transmission power.

2.1.2.4 Field strength

Formula 5 in Annex 2, indicates that $P_{WSD}^{max}$ is proportional (in dB) to the field strength of the wanted signal. At the edge of coverage $P_{WSD}^{max}$ is $\approx -60$ dBm; so if broadcast signal raises inside coverage for say 40 dB, TVWS in band use might become possible for low power applications like WiFi in areas with strong broadcast signals. However interference into TVWS applications caused by strong broadcast signals has to be considered as well.

2.1.3 Simulation results

2.1.3.1 Maximum transmission power map

The area which was investigated is a 50 km x 50 km square around Munich, in Germany (red square in Figure 5). In order to cover also rural areas, the center of investigation area is located northeast of Munich.

![Figure 5: Munich area of investigation](image)

2.1.3.2 Results of calculation

When estimating the maximum transmission power of a TVWS device at a location several parameters like strength of broadcast signal and closest distance to a broadcast receiver are relevant (see Annex 4: Assumptions). Also the occupation of adjacent channel influences maximum TVWS transmission power (see Annex 3: Parameter from ECC Report 148). Figure 6 shows the location probability (LP) for broadcast reception (fixed, 70%) for channels 36 to 44. Dark areas represent areas where broadcast reception is possible for that channel.
It can be observed (see Figure 6) in channel 40 that broadcasting reception is available in the upper right corner whereas in the lower left corner the channel is more or less unused. It could be then expected that maximum transmission power of a TVWS device (BS) should be poor in the upper right area and ‘high’ in the lower left corner. However, due to protection ratios (PR\(_n\)) and Overloading (O\(_{th}\)) maximum transmission power (\(P_{max}\)) is also limited by the adjacent channels. Figure 7 indicates that transmission power for a TVWS device within a broadcast reception area (70 % LP) is very low (dark blue). Outside the coverage area \(P_{max}\) may raise (green \(\rightarrow\) yellow \(\rightarrow\) red) with increasing distance to coverage area, but not to arbitrarily high values. This is because ch.39 has coverage in parts of this area and therefore limits \(P_{max}^{WSD}\) (green/cyan areas) by PR\(_{n+1}\). The limitations in the red and orange areas seem to be mainly caused by ch.43 (PR\(_{n+3}\)). On the right of Figure 7 a legend is shown assigning colors with transmission powers in dBm. The acceptable maximum transmission power is defined by the most restrictive value of PR and O\(_{th}\).

**Figure 6: Location probability for ch. 36 to 44 (black areas are broadcast covered)**

**Figure 7: Transmission power for a TVWS device within a broadcast reception area**

Figure 8 and Figure 9 show the limitations caused by PR and O\(_{th}\) separately. In this case DVB-T portable reception is assumed. Due to the height loss (fixed antenna is at 10m whereas portable
antenna is at 1.5 m only), in the portable broadcast reception scenario the coverage areas are
significantly smaller.

Figure 8: ch 40, TVWS base station (BS), DVB-T portable reception

Figure 9: ch 40, TVWS user equipment (UE), DVB-T portable reception

As an approximation for 95% portable reception coverage area, a 99.9% fixed reception coverage area
can be assumed (see Annex 1: A note on FRANSY). Figure 10 shows the location probability when
simulating 95% portable reception coverage area (i.e. black areas in this figure represent portable
broadcast reception areas).
Figure 10: Same area and channels like in Figure 6, but now for portable reception: Location probability fixed 99.9% (simulating portable 95%)

The left hand images of Figure 8 and Figure 9 show the limitations caused by protection ratios. Again the adjacent channel occupation limits maximum transmission power outside coverage area. As the coverage areas for portable reception are smaller than for fixed reception (also in adjacent channels), the maximum possible transmission power at some location is higher than for the fixed broadcast case.

The right hand images of Figure 8 and Figure 9 show the limitation caused by overloading. If the overload threshold was a constant value for all channel separations, this would be a homogeneous color. As this is not the case (see table 1) the right figures reflect the coverage area of channel 43 (cf. Figure 10), because Oth_3 is worse than for all other channels.

Figure 8 describe a TVWS base station scenario and Figure 9 a user equipment (UE) scenario. In this broadcast portable – TVWS UE scenario, the shortest distance between TV portable receiver and UE can be 2 m only, the effect of overloading limits maximum transmission power to 10 – 15 dBm everywhere.

Figure 11 and Figure 10 show the case for fixed broadcast reception (rooftop). More specifically, Figure 11 represents the maximum transmission power for TVWS base station (BS) and Figure 10 depicts the maximum transmission power for TVWS user terminal (UE). The significantly lower possible transmission power in the lower right corner is caused by the broadcast coverage in channel 39 and the worse protection ratio for n-1 for UE compared to BS. In the other areas the lower transmission power is due to the shorter possible distance between UE and DVB-T rooftop aerial compared to BS and DVB-T rooftop aerial (see Table 16 in Annex 4: Assumptions).
Figure 11: Ch40, TVWS BS, broadcast fixed rooftop

Figure 12: Ch40, TVWS UE, broadcast fixed rooftop

Figure 13 and Figure 12 show the maximum possible transmission power for a TVWS base station (BS) and TVWS user terminal (UE), if only portable reception is considered. Compared to Figure 11 and Figure 10 the areas where TVWS usage would be possible are larger due to the smaller broadcast portable reception coverage areas. The TVWS device maximum transmission power for portable broadcast scenario is in general smaller than for fixed broadcast reception conditions, however for some locations the distances to closest portable reception areas become larger, and so possible transmission power may be higher than for fixed broadcast scenario. For the user terminal / broadcast portable scenario the maximum transmission power is limited to 10-15 dBm due to overloading.

Figure 13: Ch40, TVWS BS, broadcast portable

Figure 14: Ch40, TVWS UE, broadcast portable

Comparing the figures above, it can be easily seen that the maximum transmission power in general decreases if TVWS UE is considered instead of TVWS BS and, in a similar way, when broadcast fixed reception is compared to portable reception. At each location where portable broadcast is possible, fixed broadcast is possible as well because it assumes antenna with better gain at higher location. Therefore the maximum possible transmission power for a TVWS device is limited by the minimum value for fixed and portable reception:

\[ P_{TVWS_{max}} = \min\{P_{fixed}^{PR}, P_{fixed}^{PR}, P_{portable}^{PR}, P_{portable}^{PR}\} \]

In order to select the most appropriate channel (e.g. the channel that allows the highest transmission power) for a given location all channels (here from channel 40 to channel 60) have to be considered. More specifically, Figure 15 and Figure 14 show all the limitations (i.e. protection ratios PR and overload thresholds \( O_{th} \) for fixed and portable broadcast reception) for TVWS base station and TVWS user equipment separately.
Higher TVWS transmission power could be enabled in a (FDD) downlink only scenario (DO). In this concept the uplink from UE to BS is realized in other bands (e.g. LTE). If the TVWS base station antenna is located at higher masts and/or outside residential areas larger minimum distances can be realized. In Figure 17 the maximum transmission power map is shown for a DO scenario where the minimum distance is set to 50m. If compared to Figure 11 it can be seen that the maximum transmission power can be some dB higher outside coverage areas.

2.2- Estimation of the available TVWS in Bavaria

In order to estimate the amount of available channels in Germany, Bavaria, which is the largest federal state, was considered. Figure 18 below shows the outline of Bavaria and the available DVB-T transmitters.
2.2.1- **Concept of protection radius (safety belt)**

In the previous sub-chapter it was shown that the acceptable TVWS device power increases with increasing distance to the closest possible DVB-T receiver antenna as the interfering signal strength reduces due to propagation path loss.

According to Table 3 at the edge of a noise limited coverage area (E = 50 dBµV/m for q = 0.7) the TVWS device transmit power must not exceed -62 dBm. This is due to the short possible distance between broadcast receiving antenna and TVWS device transmitter. Outside the coverage area the minimum separation is the closest distance \(d\) to the coverage area:

\[
P_{\text{max}}^{\text{WS}} = -62 \text{ dBm} + \text{loss}(30m, \text{fixed BS}) - \text{loss}(d)
\]

\[
= -112 \text{ dBm} - \text{loss}(d)
\]

Using a propagation model, e.g. the simple 20/30/40 dB model (see Annex 4: Assumptions) the loss and hence the maximum TVWS device transmit power can be estimated:

<table>
<thead>
<tr>
<th>(d) [km]</th>
<th>Loss [dB]</th>
<th>(P_{\text{max}}^{\text{WS}}) [dBm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.03</td>
<td>-49</td>
<td>-63</td>
</tr>
<tr>
<td>1.0</td>
<td>-90</td>
<td>-22</td>
</tr>
<tr>
<td>2.0</td>
<td>-102</td>
<td>-10</td>
</tr>
<tr>
<td>5.0</td>
<td>-118</td>
<td>5.5</td>
</tr>
<tr>
<td>10</td>
<td>-130</td>
<td>17</td>
</tr>
<tr>
<td>15</td>
<td>-137</td>
<td>25</td>
</tr>
<tr>
<td>20</td>
<td>-142</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 4: max. TVWS transmission power related to the distance to coverage area

Figure 19 shows a vertical section through the isolated location of reception in Figure 11 (ch.40 at (4466.6;5336.8)). (In the upper part of Figure 19 the corresponding detail of Figure 11 is shown.)
Figure 19: Vertical section through the isolated location of reception in channel 40 at (4466.8;5336.8)

The blue line in Figure 19 shows $P_{\text{max}}$ as a function of distance to the isolated location of reception at (4466.6;5336.8) (location moved to ‘0’). The cyan line indicates the limitation of overloading, which here in the considered case of fixed broadcast reception and TVWS base station is in the range of 30 dBm. The red circles represent the used propagation model (20/30/40 dB) [11]. For the negative direction (i.e. downward in Figure 11) for up to 6 km the maximum transmission power is not influenced by adjacent channel protection ratios or overloading. To the right (upward direction in Figure 11) the transmission power is limited due to coverage area.

At the location (4466.6;5336.8) the field strength is 51.6 dBµV/m and the location probability is 0.8375. The calculated nuisance field then is $N_u = 92 \text{dBm}$. For co channel operation the maximum transmission power becomes:

Within the pixel (coverage area) the shortest distance is 30m which corresponds to a loss of -48.8 dB, hence, $P_{\text{WSD,max}} = 92 \text{dBm} - (22 - 4.3) \text{dB} - \text{loss}$ see Figure 19. When turning the formula for a given TVWS device transmit power, the minimum distance to the coverage area can be estimated:

$$p_{\text{at Loss}} = -P_{\text{WSD,max}} - 92 \text{ dB} - 17 \text{ dB} - \text{gain}$$

$$d = \text{propagation model}^{-1}(p_{\text{at Loss}})$$
safety distance versus TVWS maximum transmission power

Figure 20 shows the results for a broadcast fixed scenario (gain = 9.15 dB). Depending on the minimum wanted transmit power of a TVWS device a minimum distance to the closest coverage area can be defined. So, a concept of different safety belts is imaginable, depending on the class of TVWS device and their maximum transmit powers. So far only the co channel was considered. To estimate maximum possible transmit power also the adjacent channel situation must be taken into account.

2.2.2 - Investigations on the availability of TVWS in Germany

Figure 21 shows location probability for channel 45 in the area of Bavaria. Black areas show broadcast coverage (>70% location probability) in all four corners of channel 45 and white areas indicate no coverage (=TVWS) in the center.

Figure 22 shows the results for the same channel 45 using colors. Dark blue areas lie outside of Bavaria and so are not considered here. The pale blue areas represent the coverage areas and are the same as the black coverage areas in Figure 21. The other colors indicate the reduction of TVWS depending on the safety distance (i.e. transmission power):
The spirit of cognition in TVWS usage lies in the idea that one of the players knows the TVWS and assigns one or more channels to a device for usage. To describe the potential given by TVWS the number of free channel for each location is a relevant parameter. COGEU considers channels 40 to 60, so up to 21 channels may theoretically be free. Again, the safety distance is relevant for the outcome as shown in Figure 24. The left picture shows the number of available channels between ch 40 and ch 60 if
the safety distance is assumed to be 0 km, whereas in the right the number of available channels for safety distance = 10 km is shown. As expected the number drops significantly.

![Figure 24: Number of available channels depending on safety distance](image)

### 2.2.3 - **TVWS mapped to area**

In Figure 25 four diagrams indicate the number of free channels in the range 40 to 60 versus the percentage of area they are available at for different safety distances:

![Safety distance = 1 km](image)

![Safety distance = 5 km](image)

![Safety distance = 10 km](image)

![Safety distance = 20 km](image)

**Figure 25: Number of free channels at different safety distances**

As already shown in Figure 22 and Figure 23 the number of available channels drops significantly with increasing safety distance. The upper left diagram shows that for a safety distance of 1 km at 50% of the locations more than 10 channels are available whereas for a safety distance of 20 km 10 free channels are available nowhere and at 50% of the locations only 6 channels are available.
2.2.4- **Mapped to population density**

In several cases TVWS are available in areas where no or only very few people are located. Therefore it is assumed that mapping the TVWS to population density should give a more reasonable indication of available TVWS.

In Bavaria the population density varies between zero (forests, fields, lakes and rivers, high mountains etc.) and up to 4000 inhabitants/ km² or even more in dense urban cities. Using the population density as the weighting function would however overestimate one or few free channels in densely populated regions towards free channels in rural areas. Therefore another weighting function is taken, following a classification used by project partner PTIN:

<table>
<thead>
<tr>
<th>Classification (inhab./km²)</th>
<th>Weight</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>0 &lt; pd ≤ 250</td>
<td>2</td>
<td>Rural</td>
</tr>
<tr>
<td>250 &lt; pd ≤ 650</td>
<td>3</td>
<td>Suburban</td>
</tr>
<tr>
<td>650 &lt; pd ≤ 2000</td>
<td>4</td>
<td>Urban</td>
</tr>
<tr>
<td>2000 &lt; pd</td>
<td>5</td>
<td>Dense urban</td>
</tr>
</tbody>
</table>

Table 5: Weighting function for mapping to population density

The weight ‘1’ for areas with zero population density was chosen because leisure activities often happen in such areas, e.g. hiking in mountainous areas, biking, walking in the nature, activities at or on the water like sailing, and users expect their communications equipment working there as well.

Figure 26 compares for safety distance 5 km TVWS “mapped to area” with “mapped to population density”:

Figure 26: Number of free channels based on area and on population density for 5 km safety distance

It seems there is only a little difference between both scenarios, i.e. in the left diagram in 50% of the location there are 8 free channels available and the right diagram indicates that for 50% of population 8 free channels are available. The situation is similar for other safety distances. The reason for this behavior can be found in Figure 25 (‘Number of available channels depending on safety distance’): there is no strong correlation between the population density and the number of free channels.

This reflects the situation for Bavaria. It cannot be excluded that in other regions or countries there is a correlation and hence mapping to population density is the more realistic variant. For our area of investigation however, it can be concluded that due to the minor differences between ‘mapping to population density’ and ‘mapping to area’ the latter one is appropriate for COGEU investigations.

2.2.5- **Considering adjacent channels**

In the considerations so far only the channel itself is taken, without any care on occupation of adjacent channels. FCC in the USA allows for white space devices a maximum transmission power of 40 mW (16
dBM) if operated in a channel adjacent to a used TV channel. In channels with at least one free channel separation to the next used TV channel up to 4 W EIRP (36 dBm) are accepted.

Figure 27 shows on the left side the percentage of free channels mapped to area for safety distance 5 km (corresponds to approx. 20 mW transmission power) where the occupation of adjacent channels is not considered. On the right hand side only channels are counted where the adjacent channels are not used, i.e. here blocks of 24 MHz contiguous bandwidth are relevant.

So, if due to transmission power the adjacent channels have to be free, then the amount of available channels drops dramatically (it even drops further as the safety distance increases when the power increases).

### 2.3 Some investigations on the compactness of TVWS

In section 2.1.3 of deliverable D4.1 the concept of compactness was introduced as it was felt that there is some relevance whether the TVWS are more contiguous or more fragmented. E.g. for LTE use of 20 MHz 3 contiguous TV channels are required whereas for FDD systems separated channels are needed.

To describe compactness the number of contiguous channels for the spectrum band under consideration is listed in descending order. As an example there could be 4 blocks of contiguous channels, one 4 channels wide, 2 blocks with 3 channels and one with 2 channels: \( b = (4, 3, 3, 2) \). In total there are 12 channels available.

Compactness then is calculated by:

\[
\text{comp} = \frac{\sum_{i=1}^{n} b(i)^2}{\left(\sum_{i=1}^{n} b(i)\right)^2}
\]

To spread compactness to the range \([0...1]\), where ‘0’ means no contiguous channels and ‘1’ means only one block of contiguous channels, a scaling is applied. Furthermore, investigations showed that using the square root of the value shows a more ‘linear’ relation to the fragmentation of channels. So, finally with \( \text{sum} = \sum_{i=1}^{n} b(i) \):

\[
\text{comp} = \sqrt{\frac{\sum_{i=1}^{n} b(i)^2}{\text{sum}^2} - \frac{1}{\text{sum}}}
\]

Compactness as defined this way is a local statistical parameter, which is derived from the channel occupation at each location. Figure 28 and Figure 29 show on the left side the number of available channels and on the right the calculated compactness for safety distance 1 km and 10 km.
The figures indicate that there might be some kind of correlation between the number of available TVWS and the compactness at that location.

Figure 30: Correlation between number of TVWS and compactness for safety distance = 1 km

Figure 30 shows that there is indeed correlation. However this is caused by the system under consideration and can easily be understood:

COGEU considers 21 channels: ch40 to ch60. If there are many TV channels occupied then the probability that the few free channels are spread over the 21 channels is high, which then means that the compactness is low. On the other hand if only few channels are occupied by TV services then there are blocks of contiguous TVWS and hence the compactness increases. In the limiting case of no TV service available at all, one block of 21 TVWS remains and compactness becomes 1.
The relevance of compactness

To clarify in a practical situation whether for a given location there is appropriate TVWS for a certain kind of application (e.g. 20 MHz LTE), compactness, being a statistical parameter, is of limited usefulness. For the secondary spectrum market as an initial parameter the value of spectrum needs to be appraised. Among other aspects the number of available TVWS in combination with the compactness is assumed to be a reasonable parameter.

2.4 Describe the interface for COGEU to access the data

In section 2.2 the maximum possible transmit power for TVWS device was calculated for an area of 50 km x 50 km around Munich. These data were generated with MATLAB software and are provided to the COGEU broker. An EXCEL sheet serves as the interface to the COGEU broker, which is described hereafter.

- For each channel 40 to 60 a separate worksheet is available, with a consistent structure.
- The names of the worksheets are ‘ch40’ to ‘ch60’
- Each worksheet covers the same 50 km x 50 km area, with a pixel size of 200m x 200m hence 251 x 251 data points
- The first line of each worksheet hosts the horizontal coordinates (East West direction) and the first column the vertical coordinates (Nort South direction). Values are given in Gauss-Krüger format. The first data point is at ‘B2’, which is the upper left corner of the area.
- The Gauss Krüger coordinates represent the center of the pixel
- The data (B2:I252) represent the maximum possible transmit power of a TVWS device for this channel at that pixel
- Used scenario: DVB-T fixed/portable TVWS device: base station

![Figure 31: Clipping of EXCEL worksheet ch40](image)

For manual use the EXCEL sheet (geo location database) has three additional worksheets:

- ‘Parameter’: lists parameters like protection ratios that were used for calculations
- ‘PMSE’: to specify locations where PMSE equipment is used. Requires to input the area of operation in Gauss Krüger format, the location (indoor/outdoor) and the time of operation
- ‘scratch’: in the yellow field coordinates can be input, either as (lat;lon) e.g. taken from Google or in Gauss-Krüger format, e.g. (4472200;5339600). After pressing the dark blue ‘convert’ button (if the specified coordinates are within the covered area) the green list of maximum acceptable transmit power is generated. In the column right to the list...
for each channel the information is given if a PMSE is registered at a location close to it. The reserved time can be seen as a comment when bringing the mouse arrow over the cell. On the right the transmit powers are shown as a diagram.

2.5- Concluding remarks

The investigations presented in this chapter were performed with moderate values for protection ratios, overload threshold, etc. Results, gained with these moderate parameters show that the operation of TVWS devices is possible in principle, however not each potential application is reasonable in every location. For example, in areas where portable broadcast reception is possible, maximum transmission power is limited to below ~20 dBm (i.e. operational range of approx. 1 km). This transmission power seems not to allow a reasonable business concept with base stations. Therefore two business cases could be viable for TVWS usage:

1. In areas with portable broadcast coverage TVWS might be used for low power transmission systems, like WiFi, which would offer several advantages towards ISM bands:
   - Better penetration characteristics allow improved in house LAN operation
   - ISM bands are overstrained especially in dense urban areas, where TVWS usage could bring a significant release
   - If –for low transmission power- operation at channels adjacent to TV used channels is possible, there is a reasonable amount of TVWS available

2. In rural areas / isolated residential areas where it is possible to keep larger minimum distances between TVWS base station transmitter and closest possible broadcast receiver, the downlink only (DO) concept could be a reasonable means to provide broadband Internet supply to area.
   - The download traffic is usually much higher than upload traffic. So using TVWS for downlink and mobile communication bands for uplink seems reasonable.
   - In rural areas wired broadband access is usually not available due to high infrastructure costs. So this TVWS usage is especially appropriate for rural areas.

The results in this chapter indicate that TVWS usage is appropriate for WiFi use to solve the problem of overload of ISM bands in urban and dense urban areas and could provide an affordable broadband Internet access for rural areas, which is in line with the call of EU parliament for equal treatment of all regions within EU.
3- RRM for LTE over TVWS

The main objective of radio network planning in a general context is to utilize the limited radio spectrum resource and radio network infrastructures as efficiently as possible. In order to approach the objective and to overcome the challenge mentioned in D2.3 [12], in terms of expenditures and NPV for a period of 5 years in a square of 50km x 50km around the Munich area. It is necessary to achieve as much coverage as possible with the optimal capacity, while reducing the costs to minimum possible. Therefore the coverage and the capacity planning are of essential importance in the whole radio network planning. The coverage planning determines the service range, and the capacity planning determines the number of to-be-used base stations and the respective capacities.

In this context, this chapter elaborates on the issues related to LTE dimensioning and description for Munich area and surroundings. With LTE dimensioning is possible to estimate the number of BSs needed to cover the Munich scenario for frequency 2.6 GHz and 700 MHz. The different between the numbers of BSs that are necessary for the two frequencies must to be evaluated to know what are the improvements and disadvantages of using the 700 MHz over the 2.6 GHz.

3.1- Radio network planning

Radio network dimensioning aims to estimate the number of required base stations in accordance with the theoretical approach, which the first step of radio network is network dimensioning. The network dimensioning process is based on the assumption of uniform distribution of subscribers, homogenous morphology and ideal site distribution. Based on this, developed a dimensioning tool made in Excel that calculates the number of BS needed. The outputs of the dimensioning phase are further used for LTE simulator. The purpose of dimensioning is to estimate the required number of radio base stations needed to support a specified traffic load in an area. This section focuses on the issues related with LTE dimensioning to use the LTE Simulator. The main objective of the LTE simulator is basically to compare the LTE frequencies and prove if the results obtained of the frequency TVWS can offer the same capacity and service regarding the frequency of 2.6 GHz with a lower number of sites.

3.1.1- Analysis and description of Munich area

The area under study for the simulation scenario is a 50 km x 50 km square around Munich (red square in Figure 32). In order to cover also rural areas, the centre of the square is located in the northeast of Munich.

So, the target of the LTE access network dimensioning is to estimate the required site density and site configurations for the area of Munich and surroundings. Initial LTE access network planning activities include the estimation of:

- Radio link budget;
- Coverage analysis;
- Cell capacity estimation;
- The final number of eNodeBs (eNBs). This value is obtained of the maximum value calculated for the capacity and coverage.

Figure 32: Munich area of consideration [19]
Dimensioning is the initial phase of network planning. It provides the first estimation on the number of necessary network element as well as the capacity of those elements.

### 3.1.1.1 Dimensioning scenario

LTE dimensioning process, as depicted in detail in Figure 33, starts with the radio link budget calculations, used to determine the maximum path loss. The maximum path loss result, in the previous step, and the propagation model (defined by the population density) are used as basis to the estimation of the cell size. This parameter is used to calculate the number of cells in the area of interest. The coverage estimation follows the above process. However, if required, a suitable number of cell sites are added to achieve the necessary capacity to serve all the intended users. If the given configuration fulfills the capacity requirements, then there is no addition to the previous plan. The assessment of eNB capacity completes the dimensioning process. In this work, the focus is targeted on radio link budget, coverage planning, cell capacity estimates and case studies for LTE dimensioning.

The purpose of LTE dimensioning that shows in Figure 33 is to estimate the required number of sites needed to support a specified traffic load in an area. As depicted in the Figure 33, the first estimated parameter was the radio link budget (1st blue block). This block has input parameters such as the criterion for cell edge definition, the system parameters and the link level result. These parameters get the maximum path loss that can support a connection between the BS and the terminal. So, with the maximum path loss value and the appropriate propagation model for deployment area, the number of BSs by coverage planning is estimated. This is only the first estimation. The next step is the verification of traffic load. Therefore, it is checked if the number of BS estimated support the capacity the operator’s to offer clients services (SLA - Service-level agreement). So, the capacity evolution has, as input parameters, the evaluation of the ability in traffic input, system simulation results and link level results, which the main goal is to obtain the number of base stations that are required to provide all customers with a guaranteed quality of service. The next step is to compare the number of BS calculated in coverage and capacity. The higher of the two is chosen for the desired area.

The following sections describe the radio link budget, estimation of coverage planning and capacity evolution in order to estimate the number of BS.
Radio link budget

In radio link budget (RLB) there are some important parameters which influence the connection between terminal and BS, for example: the transmission power, the antenna gain of the mobile equipment and the BS, the cable loss, the fade margin, etc. With these parameters is calculated the maximum allowable path loss (MAPL). For LTE, the basic RLB equation can be written as follows:

\[
\text{PathLoss}_{db} = \text{TxPower}_{dbm} + \text{TxGains}_{db} - \text{TxLosses}_{db} - \text{RequiredSINR}_{db} + \text{RxGains}_{dbi} - \text{RxLosses}_{db} - \text{RxNoise}_{db}
\]

Where,
- \( \text{PathLoss}_{db} \) = Total path loss between the transmitter signal to the receiver;
- \( \text{TxPower}_{dbm} \) = Power transmitted by the transmitter antenna;
- \( \text{TxGains}_{db} \) = Gain of transmitter antenna related equivalent isotropically radiated power (EIRP);
- \( \text{TxLosses}_{db} \) = Transmitter losses;
- \( \text{RequiredSINR}_{db} \) = Minimum required SINR for the signal to be received at the receiver with the required quality or strength;
- \( \text{RxGains}_{dbi} \) = Gain of receiver antenna related equivalent isotropically radiated power (EIRP);
- \( \text{RxLosses}_{db} \) = Gain of receiver antenna related equivalent isotropically radiated power (EIRP);
- \( \text{RxNoise}_{db} \) = Receiver noise.
In LTE, the main performance indicator is the required SINR. The required SINR is the minimum SINR to assure the same modulation and coding scheme (MCS). Therefore, a simple approach of direct SINR-MCS mapping is used to calculate the cell throughput. Maximum allowed path loss is calculated according to the condition:

\[
SINR \geq \text{RequiredSINR}
\]

\[
SINR = \frac{\text{AveRxPower}}{\text{Interference} + \text{RxNoise}} = \frac{\text{AveRxPower}}{\text{OwnCellInterference} + \text{OtherCellInterference} + \text{RxNoise}}
\]

Where

- \( SINR \) = Signal to interference and noise ratio (W);
- \( \text{AveRxPower} \) = Average received power (W);
- \( \text{Interference} \) = Interference power (W);
- \( \text{OwnCellInterference} \) = Power due to own cell interference (W);
- \( \text{OtherCellInterference} \) = Power received for neighbouring cells (W);
- \( \text{RxNoise} \) = Receiver Noise (W).

Therefore, the accurate knowledge of Required SINR is central to the authenticity of the RLB and thus the process of dimensioning. Required SINR depends up on the following factors; the Modulation and Coding Schemes (MCS) and propagation channel model. For the MCS when higher the MCS used, higher the required SINR. This means that using 16-QAM ½ will have a higher required SINR than QPSK ½. For propagation channel model it depends on the scenario that is used (urban, suburban or rural), the carrier frequency and height of the BS and terminal. So the maximum allowed path loss is calculated based on the Required SINR and it is limited mainly by the uplink direction. Because the uplink limits the establishment of communication between the terminal and the BS due to the lower terminal uplink power transmission than the BS. For this reason the analytical work will focus on MAPL in uplink, where the extent of the coverage is more critical. Table 6 shows the link budget in the uplink for LTE system. Those values from the following table are based on [16]. However due to different bandwidth and required SINR the values of maximum path loss was changed in order to reflect those changes.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Transmitter – UE</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max Tx power</td>
<td>23.0</td>
<td>dBm</td>
</tr>
<tr>
<td>Tx antenna gain</td>
<td>0.0</td>
<td>dBi</td>
</tr>
<tr>
<td>Body loss</td>
<td>0.0</td>
<td>dB</td>
</tr>
<tr>
<td>EIRP</td>
<td>23.0</td>
<td>dBm</td>
</tr>
<tr>
<td><strong>Receiver – eNode B</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>eNodeB noise figure</td>
<td>2.0</td>
<td>dB</td>
</tr>
<tr>
<td>Thermal noise</td>
<td>-107.4</td>
<td>dB</td>
</tr>
<tr>
<td>Receiver noise</td>
<td>-105.4</td>
<td>dBm</td>
</tr>
<tr>
<td>Required SINR</td>
<td>-2.75</td>
<td>dB</td>
</tr>
<tr>
<td>Receiver sensitivity</td>
<td>-108.2</td>
<td>dB</td>
</tr>
<tr>
<td>Interference margin</td>
<td>-1.0</td>
<td>dB</td>
</tr>
<tr>
<td>Cable loss</td>
<td>-0.0</td>
<td>dB</td>
</tr>
</tbody>
</table>
After determining the maximum path loss that the signal can obtain (in order for the signal to be recoverable at the receiver), the number of required BSs will be calculated for the coverage planning.

### Coverage planning

The coverage planning gives an estimation of resources needed to provide service in the deployment area with the given system parameters, without any capacity concern. Therefore, it gives an assessment of the resources needed to cover the area under consideration so that the transmitters and receivers can listen to each other. Coverage planning consists in the evaluation of DL and UL radio link budgets, but as stated above, the radio link budget is limited by the uplink to establish communication between the terminal and BS. The maximum path loss is calculated based on the required SINR level at the receiver, taking into account the extent of the interference caused by thermal noise. The maximum path loss in UL direction is converted into the cell radius, by using the appropriate propagation model to the deployment area. Radio Link Budget is the most prominent component of coverage planning exercise. The geographical information is needed in order to start the coverage dimensioning exercise. Geographical input information consists of the division of the area of interest/study to its geographical information, which is urban, sub-urban and rural, the square Kilometres of each area and their density population.

From the geographical analysis and the input information (e.g. population density or location area) the scenario selection is defined mainly based on population density. More specifically, the scenario is considered Rural, when the population density is lower than 200 people/Km², Sub-Urban when population density is between 200 and 1000, while it is considered Urban, when the population density is bigger than 1000. Furthermore, required coverage probability plays a vital role in determination of cell radius. Even a minor change in coverage probability causes a large variation in cell radius. Figure 31 depicts Munich area to be covered and the selected scenarios for each region.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rx antenna gain</td>
<td>18.0 dB</td>
</tr>
<tr>
<td>Fast fade margin</td>
<td>-0.0 dB</td>
</tr>
<tr>
<td>Soft handover gain</td>
<td>-0.0 dB</td>
</tr>
<tr>
<td>Coverage Probability (%)</td>
<td>98%</td>
</tr>
<tr>
<td>Maximum path loss</td>
<td>143.27 dB</td>
</tr>
</tbody>
</table>

Table 6: Link budget LTE in uplink
Based on radio link budget calculations, maximum allowed propagation loss is obtained. Maximum allowed propagation loss gives the attenuation of the signal as it travels from transmitted to the receiver. LTE can operate in frequency bands of 2600 MHz as well as extended band of 700MHz. Path loss models for the two possible frequency bands are incorporated in this work. Path loss is calculated into distance by using appropriate propagation models.

3.1.1.3 Calculation of number BS for Coverage

Coverage analysis fundamentally remains the most critical step on the design of any network. Appropriate selection of the propagation model the coverage analysis gives an estimation of the BS needed to provide service in the deployment area with the given system parameters. In this section the cell radius of a particular LTE sector is calculated through the maximum allowable loss, so the maxima range of coverage of a cell can be calculated. The Erceg Extended model and the Okumura Hata model is applied in this example.

For Erceg Extended models there are three morphology: Urban, Suburban and Rural. It is used in the frequency range from 1900 MHz to 3500 MHz and the basic formula for Erceg Extended propagation Path Loss is [17]

$$L = A + 10\log_{10} \left( \frac{d}{d_0} \right) + X_f + X_h + s \text{ for } d > d_0$$

where, \(d\) is the distance between the BS and the terminal in meters, the \(X_f\) and \(X_h\) is the correction factors, \(d_0 = 100\) m and \(s\) is a log normally distributed factor that is used to account for the shadow fading owing to trees and other clutter and has a value between 8.2 dB and 10.6 dB. The other parameters are defined as:

$$A = 20\log_{10} \left( \frac{4\pi d_0}{\lambda} \right)$$

$$\gamma = a - b h_b + c / h_b$$

Where the \(\lambda\) being the wavelength in m and the parameter \(h_b\) is the base station height above ground in meters and should be between 10 m and 80 m. The constants used for \(a, b\) and \(c\) are given in Table 8. The model distinguishes three types of terrain, called A, B and C. Type A presents a terrain with the highest path loss and can be used for urban areas. Type B is mainly characteristic of flat terrains with moderate or suburban areas. Type C is suitable for rural areas where path loss is the lowest.

<table>
<thead>
<tr>
<th>Model Parameter</th>
<th>Terrain A</th>
<th>Terrain B</th>
<th>Terrain C</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A)</td>
<td>4.6</td>
<td>4.0</td>
<td>3.6</td>
</tr>
<tr>
<td>(B)</td>
<td>0.0075</td>
<td>0.0065</td>
<td>0.0005</td>
</tr>
<tr>
<td>(C)</td>
<td>12.6</td>
<td>17.1</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 7 : Constants dependent on the terrain category

The correction factors for the operating frequency and for the terminal antenna height for the model are:

$$X_f = 6.0\log_{10} \left( \frac{f}{2600} \right)$$

And

$$X_h = -10.8\log_{10} \left( \frac{h_t}{2} \right) \text{ for Terrain types A and B}$$

$$X_h = -20.0\log_{10} \left( \frac{h_t}{2} \right) \text{ for Terrain type C}$$

where, \(f\) is the frequency in MHz and \(h_t\) is the terminal antenna height above ground in meters. The Erceg Extended Model is used to predict the path loss in all three environments, namely rural, suburban and urban.

For the Okumura Hata Model has the same morphology that the Erceg Estended Model: Urban, Suburban and Rural. It is used in the frequency range from 150 MHz to 1500 MHz, the distance from the BS ranges from 1 km to 20 km, the height of base station antenna \((h_b)\) ranges from 30m to 200m.
COGEU D6.2 - Spectrum-aware routing, transport protocols and negotiation protocols between players for secondary spectrum trading; System level simulation tool - initial specification

and the height of mobile antenna \((h_m)\) ranges from 1m to 10m. Hata created a number of representative path loss mathematical models for each of the urban, suburban and open country environments, as illustrated in equations (30-33), respectively and the basic formula for Okumura Hata propagation path loss in urban is [18]:

\[
L_{\text{Urban}} = 69.55 + 26.16 \log_{10}(f) - 13.82 \log_{10}(h_b) - a(h_m) + (44.9 - 6.55 \log_{10}(h_b)) \log_{10}(d)
\]

\[
a(h_m) = (1.1 \log_{10}(f) - 0.7) h_m - (1.56 \log_{10}(f) - 0.8)
\]

Path loss for suburban:

\[
L_{\text{Suburban}} = L_{\text{Urban}} - 2 \left( \log_{10} \left( \frac{f}{28} \right) \right)^2 - 5.4
\]

Path loss for open country (Rural):

\[
L_{\text{Rural}} = L_{\text{Urban}} - 4.78(\log_{10}(f))^2 + 18.33 \log_{10}(f) - 40.94
\]

The example for Schwabing-Freimann in center Munich the population density is 2.432 people/Km\(^2\), as is bigger than 1000 the scenario is Urban. The BS height \((h_b)\) is above ground 35 meters and the terminal \((h_t)\) is 1.5 meters. The range \(d_{km}\) for urban scenario can be calculated by the Erceg Urban model as follows:

\[
d_{km} = d_0 \times 10 \left( \frac{L_{\text{Urban}} - 20 \log_{10}(\frac{4\pi d_0}{3}) + 6.6 \log_{10}\left(\frac{f}{28}\right) \log_{10}(h_b)}{10 \left(4.6 - 4.0 h_b + 5.8 h_b \right)} \right)
\]

In case the Okumura Hata model the distance is calculated by following formula for urban scenario:

\[
d_{km} = 10 \left( L_{\text{Urban}} - 69.55 - 26.16 \log_{10}(f) + 13.82 \log_{10}(h_b) - a(h_m) \right)
\]

Thereby, according the Maximum path loss in Table 6, the maximum distance can be calculated as for two frequencies. The maximum range of coverage of LTE cells is shown in Table 8.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Cell radius (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban</td>
<td>3.638</td>
</tr>
<tr>
<td>700 MHz</td>
<td>2.6 GHz</td>
</tr>
<tr>
<td></td>
<td>1.134</td>
</tr>
</tbody>
</table>

Table 8 : Input parameters and calculating the maximum distance of the link LTE

Given the cell radius, the cell coverage area (that we assume to be hexagonal) depends on the site configuration in Figure 35. The use of hexagonal geometry also allows the use of the smallest possible number of cells to cover a geographic region where you want to plan a network. In addition, the hexagon closer to the most appropriate way of circular radiation pattern would occur for an omni-directional antenna to a base station in a state of propagation in free space. The area of the hexagon is given by the following expression:

\[
A_h = \frac{3\sqrt{3} \pi r^2}{2} \approx 2.6 R^2
\]

where \(R\) is the radius of the cell.

The three sites configuration the values of cell area are different.
With these three differences in the type of antenna the value of calculating the number of BS is not the same (Table 10 shows the different configurations). So the types of antennas have to be defined for the network. As the tri-sector is the most common type of antennas, it will be used for the simulations.

![Figure 35: Three different types of sites (Omni-directional, bi-sector, tri-sector)](image)

<table>
<thead>
<tr>
<th>Types of sites</th>
<th>Omni-directional</th>
<th>bi-sector</th>
<th>tri-sector</th>
</tr>
</thead>
<tbody>
<tr>
<td>CellArea ($K R^2$)</td>
<td>$2.6R^2$</td>
<td>$1.73R^2$</td>
<td>$1.95R^2$</td>
</tr>
</tbody>
</table>

Table 9: Cell area for three different types of sites

The number of sites to be deployed can be easily calculated from the CellArea, the input value of the deployment area ($DeploymentArea$).

$$NumSitesCoverage = \frac{DeploymentArea}{SitesArea}$$

For example the calculation of number of sites required for Schwabing-Freimann in center Munich network is to be designed to cover an area of 25.67 km$^2$ (see Table 11) in scenario urban. The base stations to be used are 3-sectored ($K = 1.95$). Thus, the Table 10 shows the area covered by each cell and the number of sites that is needed for coverage.

<table>
<thead>
<tr>
<th></th>
<th>700 MHz</th>
<th>2.6 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell radius (km)</td>
<td>3.638</td>
<td>1.134</td>
</tr>
<tr>
<td>Sites Areas km$^2$</td>
<td>25.8</td>
<td>2.5</td>
</tr>
<tr>
<td>Number Sites to Coverage</td>
<td>1</td>
<td>11</td>
</tr>
</tbody>
</table>

Table 10: The different the number of sites to coverage between 2.6 GHz and 700 MHz

As it is mentioned above, coverage planning gives an estimate of the resources needed to provide service in the deployment area without any capacity concern. So the next chapter the capacity is evaluator.

### 3.1.1.1.4 Capacity evolution

After calculated the number of site to a certain coverage area, the next step is analyse capacity issue. This involves selection of site and system configuration, e.g. channels used, channel elements and sectors. These elements are different for each system and the configuration is selected to fulfil the traffic requirements. In some wireless cellular systems, coverage and capacity are interrelated, e.g. in LTE. In this case, the main indicator of capacity is Required SINR distribution in the cell. This distribution is obtained by performing physical-level simulations in LTE simulator. Required SINR distribution can be directly mapped into system capacity (data rate). LTE cell capacity is impacted by several factors, for example, packet scheduler implementation, supported Modulation and Coding Schemes (MCSs), antenna configurations and interference levels.

The population density provides the basis for projecting the initial demand of subscribers, including the likely number of subscribers in different areas. By estimating the number of potential users in any area and its service fees the number of channels necessity can be estimated to guarantee the capacity and
also the scenario to be used. Table 11 shows the population density of this region of Munich, which is very important to classify areas as urban, sub-urban and urban in order to implement in the LTE simulator.

<table>
<thead>
<tr>
<th>Number</th>
<th>Name</th>
<th>Area in km²</th>
<th>Inhabitant Count</th>
<th>Inhabitants per km²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Altstadt- Lehel</td>
<td>3.16</td>
<td>18,876</td>
<td>5.973</td>
</tr>
<tr>
<td>2</td>
<td>Ludwigsvorstadt- Isarvorstadt</td>
<td>4.39</td>
<td>45,736</td>
<td>10.418</td>
</tr>
<tr>
<td>3</td>
<td>Maxvorstadt</td>
<td>4.29</td>
<td>46,058</td>
<td>10.736</td>
</tr>
<tr>
<td>4</td>
<td>Schwabing-West</td>
<td>4.37</td>
<td>59,553</td>
<td>13.628</td>
</tr>
<tr>
<td>5</td>
<td>Au-Haidhausen</td>
<td>4.22</td>
<td>54,382</td>
<td>12.887</td>
</tr>
<tr>
<td>6</td>
<td>Sendling</td>
<td>3.94</td>
<td>37,146</td>
<td>9.428</td>
</tr>
<tr>
<td>7</td>
<td>Sendling-Westpark</td>
<td>7.81</td>
<td>50,903</td>
<td>6.518</td>
</tr>
<tr>
<td>8</td>
<td>Schwantalerhöhe</td>
<td>2.07</td>
<td>26,103</td>
<td>12.61</td>
</tr>
<tr>
<td>9</td>
<td>Neuhausen-Nymphenburg</td>
<td>12.92</td>
<td>84,604</td>
<td>6.548</td>
</tr>
<tr>
<td>10</td>
<td>Moosach</td>
<td>11.09</td>
<td>47,754</td>
<td>4.306</td>
</tr>
<tr>
<td>11</td>
<td>Milbertshofen-Am Hart</td>
<td>13.37</td>
<td>66,992</td>
<td>5.011</td>
</tr>
<tr>
<td>12</td>
<td>Schwabing-Freimann</td>
<td>25.67</td>
<td>62,43</td>
<td>2.432</td>
</tr>
<tr>
<td>13</td>
<td>Bogenhausen</td>
<td>23.71</td>
<td>75,657</td>
<td>3.191</td>
</tr>
<tr>
<td>14</td>
<td>Berg am Laim</td>
<td>6.31</td>
<td>39,009</td>
<td>6.182</td>
</tr>
<tr>
<td>15</td>
<td>Trudering-Riem</td>
<td>22.45</td>
<td>53,915</td>
<td>2.401</td>
</tr>
<tr>
<td>16</td>
<td>Ramersdorf-Perlach</td>
<td>19.9</td>
<td>102,689</td>
<td>5.16</td>
</tr>
<tr>
<td>17</td>
<td>Obergiesing</td>
<td>5.71</td>
<td>47,007</td>
<td>8.232</td>
</tr>
<tr>
<td>18</td>
<td>Untergiesing-Harlaching</td>
<td>8.06</td>
<td>48,075</td>
<td>5.965</td>
</tr>
<tr>
<td>19</td>
<td>Thalkirchen-Obersending- Forstenried-Fürstenried-Solln</td>
<td>17.75</td>
<td>80,701</td>
<td>4.547</td>
</tr>
<tr>
<td>20</td>
<td>Hadern</td>
<td>9.23</td>
<td>44,993</td>
<td>4.875</td>
</tr>
<tr>
<td>21</td>
<td>Pasing-Obernzenzing</td>
<td>16.5</td>
<td>65,763</td>
<td>3.864</td>
</tr>
<tr>
<td>22</td>
<td>Aubing-Lohhausen-Langwied</td>
<td>34.06</td>
<td>37,857</td>
<td>1.111</td>
</tr>
<tr>
<td>23</td>
<td>Allach-Untermenzing</td>
<td>15.45</td>
<td>27,73</td>
<td>1.795</td>
</tr>
<tr>
<td>24</td>
<td>Feldmoching-Hasenbergl</td>
<td>28.71</td>
<td>54,245</td>
<td>1.889</td>
</tr>
<tr>
<td>25</td>
<td>Laim</td>
<td>5.29</td>
<td>50,082</td>
<td>9.457</td>
</tr>
<tr>
<td>Total</td>
<td>Munich</td>
<td>310.43</td>
<td>1,326,206</td>
<td>4.272</td>
</tr>
</tbody>
</table>

Table 11: Population density in Munich

The cell radius is based on evaluating the LTE cell capacity and the data rate that needs to provide available services (speech data, VoIP, multimedia, etc.) for all users. All the data related to the geographical properties and the estimated traffic volumes at different area. Traffic demand taking into account the use of different services at the same time. This, in turn, involves several steps:

- Estimation of the potential user population;
- Estimation of the service penetration considering dimensions such as:
  - Service class (i.e., bit rate of packet switched services)
  - Operation environment (i.e., urban, suburban, rural), etc;
- Estimation of the activity factor per service type and class;
- Estimation of equipment dimensioning;
- Estimation of CAPEX (Capital Expenditure) including network related equipment, infrastructure, etc;
- Estimation of OPEX (Operational Expenditure) including network support and maintenance, etc.

3.1.1.1.5 Calculation of number BS for capacity

For example, in order to calculate the number of BSs for the capacity concern, it was considered that the customers of a new operator in Portugal will have around 13% – 18% inhabitants in the first year. For the number of active user by a single cell was considered 5% for urban, 3% for suburban and 2% for Rural, all these values are described in [20]. On based this, the number of user for the new operator is:

\[
\text{NumberOfUser} = \text{Inhabitant} \times \text{PercentOfCustomers} \times \text{PercentOfUserActives}
\]

With the knowledge of traffic demand estimation and the factors involved in it, the overall data rate that is required can be calculated. The total data rate for the capacity calculation is:
The number of sites necessary to support the above calculated total traffic is simply:

$$\text{OverallDataRate} = \text{NumberOfUser} \times \text{ConstantDataRate}$$

The number of sites required for capacity to Schwabing-Freimann in center of Munich (Table 11) is the same scenario that was used for calculating the number of BS to coverage. It is considered the bandwidth of 5 MHz, sites of tri-sector, the operating frequency of 2.6 GHz and 700 MHz. Firstly it is need calculation of number of user is required based the formula 38:

$$\text{NumberOfUser} = 62430 \times 0.18 \times 0.5 = 561.87 \approx 562$$

Then overall data rate is calculated by the number of user multiplied by the bit rate of each user. Here it is assumed that a user has a constant bit rate with 1 Mbps for downlink.

$$\text{OverallDataRate} = 562 \times 1\text{Mbps} = 562\text{Mbps}$$

With the overall data rate of the LTE network, the number of BS to support that traffic has to be dimensioned. The capacity of the site was considered in the [15] (chapter 4.1 - RRM problem formulation). For 700 MHz the capacity is 12.83 Mbps, in case 2.6 GHz is 9.86 Mbps. The Table 12 shows the number of sites needed to support the traffic demand for all users.

<table>
<thead>
<tr>
<th></th>
<th>700 MHz</th>
<th>2.6 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site Capacity (Mbps)</td>
<td>12.83</td>
<td>9.86</td>
</tr>
<tr>
<td>Number Sites to Capacity</td>
<td>15</td>
<td>19</td>
</tr>
</tbody>
</table>

Table 12: The different the number of sites to capacity between 2.6 GHz and 700 MHz

As a result number of sites for capacity is 19 for 2.6 GHz and 15 for 700 MHz. There is significant reduction in the number of the sites. Consequently the CAPEX and OPEX is less.

**Summarising the network planning**

The goal of network planning is to achieve as much coverage as possible with the optimal capacity using the frequency TVWS, while reducing the costs as much as possible by reducing the number of sites. The coverage and the capacity planning are of essential importance in the whole radio network planning. The coverage planning determines the service range, and the capacity planning determines the number of to-be-used base stations and their respective capacities. In addition to LTE, the 3GPP is also defining IP-based, flat network architecture. This architecture is defined as part of the System Architecture Evolution (SAE) effort. The LTE–SAE architecture and concepts have been designed for efficient support of mass market usage of any IP-based service. The architecture is based on an evolution of the existing GSM/WCDMA core network, with simplified operations and smooth, cost-efficient deployment. All the quality of service requirements are to be met and cost has to be minimised. Good interface dimensioning is very important for smooth performance of the network. Quality-related inputs include average cell throughput and blocking probability. These parameters are the customer requirements to provide a certain level of service to its users. These inputs directly translate into QoS parameters.

So the network planning must have the number of sites for service quality required. To achieve the number of sites must be carefully defined. Therefore, it is considered that the total number of sites is calculated as highest value between the coverage and capacity.

$$\text{NumTotalSites} = \max(\text{NumSitesCoverage}; \text{NumSitesCapacity})$$

In this case, the highest value is 19 sites for capacity. The reason is that the number of sites is limited by the assigned service to customers. Thus the operator to provide the services requested by the terminal needs to reduce the radius of coverage and increase the number of sites.

Table 13 shows different the number of sites between the 700 MHz and 2.6 GHz in Munich. The results were obtained with a dimensioning tool made in Excel.
Therefore, the number of sites in a network planning is a very important parameter, because in addition to the equipment of each site, there are also the costs of network connection such as the use of fiber optics or the costs of renting space to put sites. The Table 13 shows that the number of sites in the 700 MHz is much lower, so it is an advantage to reduce OPEX and CAPEX. Thus, COGEU target is to easier enable the admission of new players into the market in order to be competitive with incumbents.

3.2- Implementation of LTE over TVWS for COGEU

3.2.1- LTE Simulator

The LTE Simulator was developed in Matlab™ using a tool to support the development of graphical user interface (GUI) and an object-oriented language provided by Matlab™, with the aim to obtain results of simulations for the frequency legacy and TVWS. A number of useful statistics to the network designer (e.g., SNR across the map, the value of the interference) can optimize radio network planning as well as all the statistical data that the program can provide by this process of visualization. The first image that appears in the simulator is shown in Figure 36, which pops up a window with a choice of three scenarios that are able to be simulated:

- Urban;
- Sub-urban;
- Rural.
protocols and negotiation protocols between players for secondary spectrum trading; System level simulation tool - initial specification

Table 14 below, represents the main parameters of the three scenarios for three different scenarios.

<table>
<thead>
<tr>
<th></th>
<th>Urban</th>
<th>Sub - Urban</th>
<th>Rural</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS TxPower</td>
<td>33 dBm</td>
<td>34 dBm</td>
<td>36 dBm</td>
</tr>
<tr>
<td>BS antHeight</td>
<td>35 m</td>
<td>35 m</td>
<td>56 m</td>
</tr>
<tr>
<td>PropModel</td>
<td>ErCeg, Okumura-Hata, SUI231</td>
<td>ErCeg, Okumura-Hata, SUI231</td>
<td>ErCeg, Okumura-Hata, SUI231</td>
</tr>
<tr>
<td>Cell Radius</td>
<td>0.75 Km</td>
<td>1.125 Km</td>
<td>3.5 Km</td>
</tr>
<tr>
<td>Tilt</td>
<td>9.5º</td>
<td>8º</td>
<td>0º</td>
</tr>
<tr>
<td>Antenna Gain</td>
<td>12 dBi</td>
<td>12 dBi</td>
<td>14.5 dBi</td>
</tr>
</tbody>
</table>

Table 14: Main parameters of the three scenarios

Figure 37 shows the window used to select the operating frequency (700 MHz, 2 GHz and 2.6 GHz). This choice is important to selection the propagation model.

Figure 36: Choose Scenario

Figure 37: Choice of operating frequency
As there is a generic propagation model for all types of settings, parameters and frequencies are using hybrid models that include the characteristics of empirical and theoretical models. Figure 38 illustrates all the propagation models available in the simulator LTE.

![Figure 38: Graphic representation of the propagation models](image)

In order to estimate the signal parameters accurately for mobile systems, it is necessary to estimate its propagation characteristics according with the environment. Propagation analysis provides a good initial estimate of the signal characteristics. The use of these models has certain flexibility. Thus, they can be calibrated with actual measurements performed in the specific propagation environments where they are used. Therefore, the propagation model predicts the real scenario where are considered obstacles, buildings and trees, etc. However, the application of empirical models with a component requires the classification of environments (urban, suburban and rural). This work uses the most common models in the literature and the most suitable for the new generation of mobile networks, being chosen the Okumura-Hata model, the cost231, the SUI Erceg and Extended, as is mentioned in Table 14.

At the end of the frequency selection process there is have the option of the relief of the wanted area for simulation. The simulations will be held in Munich. This option is illustrates in Figure 39.

![Figure 39: Local Simulation](image)

Figure 40 illustrates the graphical interface of the LTE simulator. The rectangle in red shows the initial parameters such as the definition of map scale, the creation of menus, the graphical displays and also the upload of parameters of the base stations. The figure also notes the coordinates XX and YY (in blue rectangle) in order to have the knowledge the positions of base stations and coverage area. Simulation has 19 sites with three sectors (base stations with 120 ° opening angle) which make a total of 57 base stations. Figure 40 illustrates also the end of the whole process of preparation for the simulation in order to choose which of the following options (enhanced in black rectangle): Normal, Algorithm 1 or Algorithm 2.

The Normal option works as a network planning tool that can analyze the coverage and capacity of an LTE network. In the case of the Algorithm 1 option, in addition to planning the network also makes a simple RRM for the two carriers (700 MHz and 2.6 GHz), the aim is to increase the ability of the operator Legacy. So, when the carrier 2.6 GHz is fully occupied the operator uses the carrier TVWS
provided by the broker. In this case, without making a previous analysis in the two carriers regarding the number of resources block consumed.

In the case of Algorithm 2 is already conducted a preliminary analysis, so of assigning a carrier to a terminal is considered the connection quality for two carriers (Legacy and TVWS), which improves the efficiency and savings resource blocks (RB) of LTE. The disadvantage of monitoring the two carriers is to increase the processing to analyze the quality of connection. This behaviour is like a Multi-RAT (Multiple - Radio Access Technology), but as it uses the same radio access technology is called Multi-band.

![GUI of the simulator LTE on TVWS](image)

**Figure 40:** GUI of the simulator LTE on TVWS

The simulation is performed in all the area considered in the above example, 19 sites with 3 sectors. But in order to avoid inaccurate measurements at the border (e.g., the corners of the simulation area) measurements are only considered in the centre of the simulation (inside the circle).

After selecting one of the options (*Normal, Algorithm 1 or Algorithm 2*) the LTE simulator is prepared to load the remaining data for the simulation presented Figure 41 such as:

- Loading antenna date;
- Loading MS date.

![Load the input parameters](image)

**Figure 41:** Load the input parameters

At the end of loading all input parameters such as the antenna data and MS data, the simulator initializes the calculations. At the end of running calculations the Figure 42 is presented.
The Figure 42 shows in the black rectangle the number of interactions, the operating frequency, the bandwidth and base station transmission power. The interest of having interactions in the simulator is to approach the values to a real scenario. For this, the terminal location is also changed in each iteration.

The Figure 42 also shows the Display User menu (enhanced in blue rectangle) with the ON option selected. It is possible to display different terminal positions as is demonstrated in the figure. Other menus can also be selected like the Propagation Model menu for the graphic display of the propagation model used, the Coverage menu to view the line of sight of each BS, the Results menu to view the various sub-menus of simulation results and finally the Exit option to exit the program. All these options are presented in a purple rectangle Figure 42.

Then it is shown one of three possible figures (Normal, Algorithm 1 or Algorithm 2), the menu display Results depends on the option selected. The Normal option shown in Figure 43 (shown in blue rectangle) has the sub-menu BS_Legacy referring to the frequency (2.6 GHz).
The algorithm 1 option shown in Figure 44 (enhanced in blue rectangle) has the menu BS_Legacy, BS_TVWS and Total_RB_Algl. The sub-menus to the BS_Legacy and the results are identical to BS_Legacy in the Normal option (Figure 43). In case of menu BS_TVWS the structure is the same but the results are based on the number of users that were blocked in BS_Legacy. Only these users are used to the new assignment of the carrier TVWS and the results are shown in the menu BS_TVWS. For menu Total_RB_Algl shows all resources blocks occupied by carrier Legacy and carrier TVWS for each base station.

The objective of the three options are designed to achieve the highest possible coverage, with the ideal capacity, reducing costs, these are issues of paramount importance in all network planning and radio. The coverage planning sets the distance between cells, number of base stations to be used and limits...
of coverage. Capacity planning determines their respective capabilities and determines the range of services.

3.2.2 - Metrics

The performance of a communication system can be described in terms of different performance parameters like Path Loss, SINR, Resource Block, throughput, Bandwidth efficiency, etc. So the evaluation of Performance Metrics for Simulator LTE is very important. In the simulator LTE the first option is selected regarding the scenario and the frequency. These two parameters are obtained by the corresponding propagation model for calculating the signal attenuation (Path Loss) in the simulation area. Figure 46 represents an example of Matlab™ code used to calculate the propagation model with Path Loss ERCEG URBAN.

![Matlab code for ERCEG URBAN propagation model](image)

Figure 46: Example of a propagation model for calculating the Pathloss

The Path Loss allows calculating the maximum range of cells to be estimated with an appropriate propagation model, such as Okumura-Hata, Erceg, etc. Accounting for all losses from the transmitter, through the medium (free space, cable, fiber, etc.) to the receiver, is calculates the Link Losses. In Figure 47 is a graphical representation of Link Losses in the simulation area.

![Graphical representation of Link Losses](image)

Figure 47: Link Losses in the simulation area
The next step is calculating the Link Budget, this parameter is responsible for the attenuation of the transmitted signal, the antenna gains and Link losses. The link budget equation is represented in the following equation [21]:

\[
\text{Received Power (dBm)} = \text{Transmit Power (dBm)} + \text{Gains (dB)} - \text{Link Losses (dB)}
\]

Figure 48 shows the function of signalLevDL (Received Power) for calculating the Link Budget, the calculation of Link Budget can also be used to compare the coverage for the different systems and gives the maximum range of cells. Therefore gives the number of sites required to cover the geographical area.

```matlab
function signalLevDL(db)
    numBSs = size(obj.RSList,1);
    for k = 1:numBSs
        % P_{tx} = P_{tx} - G_{t} - G_{r} - L
        obj.RSList(k).PowerLev = obj.RSList(k).txPowerPerSubCarrier + obj.RSList(k).antennaGain + ...
        obj.RSList(l).antGain - obj.RSList(k).linkLossDL ;
    end
end
```

**Figure 48:** Calculation of the link budget in downlink

The next step is getting the SINR as the name indicates the SINR makes the difference between the received signal level and noise of co-channel interference and thermal noise. Figure 49 visualizes the SINR the coverage area.

![Graphical representation of SINR](image)

**Figure 49:** Graphical representation of SINR

Finally, the function cellSelectionDL in Figure 50 is used to calculate the base station which connects the terminal. The selection is made as follows, each terminal receives SINR values in all base stations and the highest value is the selected. The terminal chooses the BS that has the highest Modulation and coding scheme.
All the functions that were described above were made for both Downlink and Uplink (enhanced in red rectangle in Figure 42).

After the terminal select the BS is made the admission control. This decides if a terminal will be admitted or rejected. Therefore, it is necessary to know how many resource blocks are needed for each user. The resource block depends of the throughput, Modulation and coding schemes (MCS) and the number of symbol per resource block (84 symbols - 12 sub-carrier × 7 symbol). The following equation represents the result of the number of resource blocks occupied by each user:

\[
\text{NumberRBDLPerUser} = \frac{\text{ThroughputPerUser}}{\text{modulationDL} \times \text{CodingRateDL} \times \text{sym_per_RB}}
\]

With this result, the BS decides whether it has the resources to serve the terminal. So, the number of resources block occupied by each terminal is a very important parameter. If the value is less, will be greater capacity of BS.

3.3- Preliminary Evaluation of LTE over TVWS

3.3.1- Evaluation/ Simulation results

The results of the available TVWS channels investigation in Munich area are presented and used as a case study scenario in the performance evaluation of the number of sites required. All the simulations were done without considering elevation and terminals are uniformly distributed in all area.

In each scenario have two simulations; the first simulation is based on an evaluation of throughput between two carriers (Legacy and TVWS). To further investigate the difference between the numbers of sites required to cover the same area, without losing the service, the second simulation is based on the number resource block per user in each BS sector. For all simulation it is considered that the operator has 18% of the population for the first year. Furthermore, it is considered that the percentage of the active users for urban areas is 5%, for suburban areas is 3%, while for rural ones is 2%.

3.3.1.1 Urban Scenario

In Schwabing-Freimann have 62,430 inhabitants in 25.67 km² in area, based on population density is considered urban. This parameter is important for choose which propagation model it used in the LTE simulator. Then is needed calculates the number of users for the simulation. This calculations is given by the formula (36), where is made the relationship the number of habitants in Schwabing-Freimann with the percentage of customers by operator and percentage of active users. With this relationship is obtained the value 561 users for the simulations.

The simulations were made two evaluations, the first evaluation is through the throughput and the other is the number of resource block per user in each BS. The urban simulation results (Figure 51 and Figure 52) show that the frequency TVWS can provide more throughputs and the number of resource block is less (Figure 53 and Figure 54).
Furthermore the radius the frequency 2.6 GHz is 481 meters and the 700 MHz is 541 meters. So the result for 2.6 GHz was needed 57 BS sector and the 700 MHz to coverage the same area was only need 48 BS sector. For the operator this parameter is very important to reduce the OPEX and the CAPEX.

In conclusion for the urban scenario the number of BS is lowest for 700 MHz and the service by operator is the same or better for the customers. In (Figure 53 and Figure 54) it is showed the number resource block per user in each BS sector. For the 700 MHz the number is lowest, about 65 resource block, which means that the operator can have more users per BS sector.

### 3.3.1.2 Sub-Urban Scenario

In the case for suburban scenario the simulation results (Figure 55 and Figure 56) also show a greater benefit to use the TVWS. The simulations were made for the city Erding near Munich, this city has 34,514 inhabitants in an area of 54.64 km², based on population density is considered the Suburban and active users is 161. Thus, the scenario for the 2.6 GHz is a need seven site to coverage, while for 700 MHz only needs six sites.
The number of resource block per user between the two bands is shows in Figure 57 and Figure 58. The frequency 700 MHz have 4202 resource block and the frequency 2.6 GHz have 4422. So in 700 MHz have less 221 RB that the frequency 2.6 GHz.

In conclusion for the suburban scenario the results of throughput is approximate the same for the two frequencies but with less number of BS in frequency TVWS. For the differences the number of resource block is higher in relation of three scenarios, which means that the operator in this scenario can provide a more users per BS sector.

3.3.1.3 Rural Scenario

In rural scenario is considered the city Berglern near the Munich, this city has 2568 inhabitants in an area of 19.89 km$^2$ and the active user is 10. The simulation results (Figure 59 and Figure 60) show that
use of frequency TVWS can provide greater radio coverage, because the number of BS sector reduces for the half. In the frequency 2.6 GHz is 2352 meters the radius, but in 700 MHz is higher, it is 3326 meters. This different is higher than 1 Km and the service to the customers is not degraded.

That is, with setting the probability of 2.6 GHz and 700 MHz radio coverage is 100%, but in 700 MHz the number of BS is decreases. Furthermore the throughput for 700 MHz is higher than the frequency 2.6 GHz, about 1.36 Mbps.

The number of resource block per user between the two bands is shows in Figure 61 and Figure 62. The frequency 700 MHz have 4862 resource block and the frequency 2.6 GHz have 4919. So in 700 MHz have less 57 RB that the frequency 2.6 GHz.

In conclusion for the rural scenario in 700 MHz the number of BS is lowest the three scenarios and the difference the number of resource block between 700 MHz and 2.6 GHz is acceptable, which means that the operators can provider higher coverage without losing the service.

3.4- Conclusion remarks

The of LTE simulator, developed in MATLAB, uses a tool named GUIDE to support the development of graphical user interface (GUI) and object-oriented language provided by MATLAB. With this tool is possible to obtain the results of simulation in the frequency Legacy and the frequencies freed by analogue TV. The LTE simulator uses three modes of operation (Normal, Algorithm 1 and Algorithm 2). Normal mode is possible to view useful statistics in the network planning engineering, for example, the SINR across the map and the amount of interference. The network planning is a major task for operators. Moreover, it is never an ending process, which forces a new round of work with each step in the network’s evolution and growth. Sometimes extra capacity is needed temporarily in a certain place, and network planning is needed to boost the local capacity. Poor planning results in a configuration in which some places are awash in used or underused capacity and some areas may suffer from blocked calls due to the lack of adequate capacity. Using TVWS opportunities previously identified in T6.5.1 (see
chapter 2) in Munich area. It can be usefully for the evaluation of the number of sites required. So, the simulations were chosen three parishes in the area of Munich that represent the three scenarios (urban, suburban and rural). The final results show clearly a reducing number of BS in the TVWS frequency comparatively to the legacy frequency concerning the three scenarios mentioned above. These results can be used to prove that the operator can reduce the cost of the base station installation, providing this way services with a competitive advantage over competitors. The quality of network planning process has a direct influence on the operator’s profits. So for operator this parameter is very important to reduce the OPEX and the CAPEX.

The main conclusions that can be extracted using the three scenarios above mentioned, the urban is that has higher throughput, but the difference in the number the resource block per user in both frequencies is small. This means that most users are close to the base station and they already have high MCS for both frequencies. Regarding the number of sites in the urban scenario, the number of sites is less 18.75 % in TVWS, which represents a cost reduction.

For the suburban, the different in the number of resource block per user in both frequencies is higher in relation of three scenarios, which means that the operator in this scenario can provide more users per BS sector and the number of sites is less 16.66 % in TVWS, which also represents a cost reduction as in urban.

The rural scenario in 700 MHz the number of sites is lowest the three scenarios with decrease 50 % and the difference the number of resource block between 700 MHz and 2.6 GHz is acceptable, which means that the operators can provider higher coverage without losing the service and a higher cost savings.
4- Negotiation protocols between players for secondary spectrum trading

4.1- Challenges/background and problem analysis of negotiation protocols in CRN

The increase in the demand for internet based wireless services, and technological advancements, especially in the context of software defined radio, is a clear indication that corresponding devices will be having highly-cognitive transmitters and receivers with the capability of using multiple frequency bands, variable transmission powers, modulation schemes and MAC protocols. To complement this, such devices will be able to bid for the spectrum that they require from a market entity such as a Broker, or will have ways of automatically reducing interference by negotiation with other devices [22]. Therefore, one of the main challenges in enabling spectrum acquisition through trading mechanism is the development of protocols support negotiation between spectrum supplying and demanding stakeholders.

Negotiation has been for decades a central subject of study in disciplines such as economy, game theory, and management. A negotiation protocol determines the flow of messages between the negotiating parties, dictating who can say what, when and acts as the rules by which the negotiating parties must abide by if they are to interact [24]. In the context of the TV white spaces, to the best of our knowledge, there is currently a lack of a unified protocol to allow the negotiation of spectrum for brokered mechanism for secondary spectrum trading where such trading modes as auction and merchant are supported.

This section address negotiation protocols in relation to the Broker based secondary spectrum trading mechanism for the TV white spaces developed by COGEU.

4.2- State of the Art of Negotiation Protocols in CRN

There are several works that address negotiation protocols in CRN. For example, in [22], Secretan et al propose a protocol, called PREDATOR (PRotocol for Equitable, Dynamic AllocaTion of Radio spectrum), that accommodates both brokered and ad hoc configurations. The work assumes a paradigm where, in licensed bands, nodes must talk to a coordinating central authority, while in unlicensed bands; a node can make an effort to negotiate with other nodes to achieve a mutually beneficial network configuration. While devices operate in the unlicensed portion of the spectrum, they may also voluntarily use a local, non-authoritative broker, to better optimize or prioritize access. In this paradigm, certain nodes may be capable of communicating in both unlicensed and licensed bands, potentially seeking to reduce cost or increase bandwidth. This work come close to the COGEU approach, however, it focuses on negotiation protocols to enable benign network configurations, whereas in COGEU, the focus is on the trading mechanism for efficient TV white space usage through the Broker.

In [23], the authors propose DSAP (Dynamic spectrum access protocol) which is a centralized protocol that provides dynamic allocation of wireless spectrum to network nodes. In short, the goal of DSAP is to increase performance of wireless networks by intelligently distributing segments of available radio frequency spectrum to wireless nodes to avoid congestion, minimize interference, and to adjust the clients’ wireless medium usage to fit the network administrator’s needs. Though the work addresses the reduction of interference among other aspects similar to COGEU, there is still a need to address secondary trading based negotiation protocols for the TV white spaces.

The above is a non-exhaustive list of the many works that have been done in the context of negotiation protocols for cognitive radio networks, whereas most of them focus on unlicensed usage. It is worth to mention here that, conceptually, the COGEU approach is not entirely new; however, the project has endeavored to align different research works in a holistic manner, and with a specific focus on secondary spectrum trading of the TV white spaces through the Broker. The remaining sections will provide more details on the underlying approach.
4.3 Design of COGEU network architecture enhanced with the selected negotiation protocol

In the D3.3, where the COGEU architecture is defined, one of the strong requirements taken into account is that the use of white spaces available spectrum is enabled via the capability of a device to query a database / broker and obtain information about the availability of spectrum for use at a given location. The broker is considered reachable via the internet and the devices/entity querying the broker are expected to have some form of internet connectivity wirelessly using frequencies outside the band 470-790 MHz, or via some wired connection in case of non-mobile TVWSNs on a dedicated communication channel. Figure 63 shows the interfaces for web based negotiation protocols between the players and the COGEU Broker.

![Diagram of COGEU Web-service](image)

A messaging interface between the white space devices and the broker is required for operating a network using the white space spectrum. The following text discusses various aspects of such an interface and the need for a standard.

COGEU messaging interface is considering the IETF PAWS (Protocols to Access White Space database) Working Group recommendations. The IETF PAWS Working Group expects to:

- Standardize a protocol for querying the database, which includes a location sensitive database discovery mechanism and security for the protocol, and application services.

- Standardize the data structure to be carried by the query protocol. Since the location of a user device is involved, privacy implications arise, and the protocol will have to have robust security mechanisms. Existing IETF location data structures and privacy mechanisms may be considered for use.

It states that an efficient messaging interface needs to be:

1. **Radio/air interface agnostic** - The radio/air interface technology used by the white space device in available spectrum can be 802.11af, 802.16, 802.22, LTE etc. However, the messaging interface between the white space device and the database should be agnostic to the air interface while being cognizant of the characteristics of various air-interface technologies and the need to include relevant attributes in the query to the database.
2. **Spectrum agnostic** - the spectrum used by primary and secondary users varies by country. Some spectrum has an explicit notion of a "channel" a defined swath of spectrum within a band that has some assigned identifier. Other spectrum bands may be subject to white space sharing, but only have actual frequency low/high parameters to define protected entity use. The protocol should be able to be used in any spectrum band where white space sharing is permitted.

3. **Globally applicable** - A common messaging interface between TVWSD and databases will enable the use of such spectrum for various purposes on a global basis. Devices can operate in any country where such spectrum is available and a common interface ensures uniformity in implementations and deployment. Since the White Space device must know it's geospatial location to do a query, it is possible to determine which database, and which rules, are applicable, even though they are country specific.

4. **Address regulatory requirements** - Each country will likely have regulations that are unique to that country. The messaging interface needs to be flexible to accommodate the specific needs of a regulatory body in the country where the white space device is operating and connecting to the relevant database.

These requirements are in line with the COGEU vision for the exploitation of the TV the spaces presented in COGEU D2.1 and D3.1.

In a typical implementation of Broker based access TV white space, a radio or a base station where several end users are attached to, is configured with, or has the capability to determine its location in latitude and longitude. At power-on, before the device can transmit or use any of the spectrum set aside for secondary use, the device must identify the Broker or database to query, contact the Broker, provide its geo-location and receive in return an offer with a portfolio of usable white space at the given location. In the merchant mode, for example, the device can then opt to buy one of the channels from the list, and once the negotiation procedure is concluded with the device being sold the rights to use the spectrum, only then the device can transmit and receive on the selected channel. The device must renegotiate the terms of usage once the expiry time of the rights is reached.

4.3.1 **Design of the negotiation protocol adopted in COGEU**

The COGEU broker supports merchant mode and auction mode for allocating spectrum. In the merchant mode, the price is decided by the allocation procedure which considers various factors which influence the value of TVWS in a given place. In the auction mode, the auctioned band has a benchmark price, then each demand (bid) has an associated price and the winning bid decides the final price. In this section, the interfacing signaling between the broker and the spectrum user are presented. The signaling interface is the (negotiation) protocol that enables the transaction of spectrum between the Broker and the user to take place efficiently. Through these negotiation protocols, the Broker maximizes its revenue as well as ensures fairness between players, and ultimately improves the efficiency of spectrum usage. In this case, spectrum is sold in terms of first come first serve basis in the merchant approach, or the most valuable bidder wins the band depending on the auction mechanism.

In the following subsections the negotiation sequence steps of the merchant and auction modes will be given. The modes are based on the flow charts presented Figure 64 in and Figure 65.

4.3.1.1 **Analysis and description of merchant mechanism – Definition of Simulation scenario**

The COGEU Broker could announce a set of reference prices for the available TVWS, and adjust the prices based on time, location, bandwidth required and other factors to maximize expected revenue or to clear the market periodically. This approach is generally simpler, and requires less overhead (information exchange) than an auction mechanism. However, a well-designed auction mechanism can achieve either a higher efficiency or more revenue depending on the intended objective and market conditions.

Figure 64 gives the operation sequence of the merchant mode protocol.
The sequence is as follows:

1. The broker informs the players about the available TVWS portfolio and corresponding prices,
2. Network operators and service providers buys spectrum in first come first serve basis
3. The broker authenticates the players
4. The Broker process the bill for the temporary spectrum rights for the buyer.
5. The payment systems authorizes the transaction (or payment)
6. The Broker allocates temporary spectrum rights to the buyer
7. The Broker updates the local TVWS repository and monitors market

### 4.3.1.2 Analysis and description of auction mechanism – Definition of Simulation scenario

The COGEU Broker is equipped with mechanism to determine how the TV white spaces are allocated among players, and how much each player pays for each spectrum asset. The allocation method, or mechanism, must balance efficiency with complexity. The trading mechanism could be realized through an auction mechanism in which the broker collects bids to buy from the players, bids to sell from the geo-location database, and subsequently determines the allocation along with the price for each spectrum asset. The auction would then be repeated as spectrum assets become available (i.e., as they become available)
are released by supplying players). Figure 65 illustrates the COGEU trading mechanism based on auction. Specifically, it shows an example of the English auction protocol message sequence.

The auction mode behaves differently depending on the type of auction (See COGEU D6.1 and D2.3). The following is a generic sequence of events in allocation the TVWS through the auction mode:

1. The Broker informs the players about the available spectrum.
2. Interested participants or players such as network operators and service providers send their bids for the spectrum.
3. The Broker authenticates the players for the obvious security reasons.
4. The Broker solves an auction to maximize its revenue or spectrum efficiency.
5. The Broker informs the bid results.
6. Depending on the auction mechanism, iteration (1-5) continues until the bit winner is found.
7. The Broker announces the final results
8. The winner acknowledges the results

Figure 65: English Auction Protocol
9. The Broker process the bill for the temporary spectrum rights to the auction winner.
10. The winning bidder authorizes transaction (or payment)
11. The Broker allocates the temporary spectrum rights to the auction winner.
12. The Broker updates the local TVWS repository and monitors market.
13. The winning players transmit their data.

4.3.2 - **Negotiation Data Structures**

The COGEU Broker supports different negotiation protocols, like direct trading or one-on-one bargaining protocol or the various auction types or one-on-one bargaining protocols. Each negotiation protocol that is to be conducted fully automated in a dynamic secondary spectrum market has to be clearly described. In order to achieve effective negotiation outcome, a description of a process that is complete and that can be processed by machine has to be provided that its correct application in the automated Broker based TV white space acquisition can be assured.

To specify a comprehensive set of negotiation attributes, the COGEU Broker employs negotiation taxonomies originating in e-commerce research and economics. These taxonomies present a set of parameters that allow for detailed description of specific negotiation protocols. For this framework the existing taxonomies were integrated and consolidated in order to derive the following set of attributes and corresponding domains suitable for definition of automated secondary spectrum trading negotiations between the Broker and spectrum users.

- General Negotiation Process: Basic negotiation parameters like start, termination or negotiation rounds.
- Negotiation Context: Configuration in terms of involved roles and agents.
- Negotiated Issues: temporary exclusive rights terms including to be negotiated.
- Offer Submission: Rules concerning the bidding process, like when an offer can be posed or what constraint it has to satisfy. ( Bid expressiveness is studied in COGEU D2.3.)
- Offer Allocation: Matchmaking rules for the negotiation, as reported in COGEU D6.1 and D2.3.
- Information Processing: Rules defining which information about the current negotiation and bidding history is available to which agent(s).

With these attributes a multitude of 1:1 and 1:n negotiation protocols can be defined. For a more detailed description of the identified attributes, see [25].

4.4 - **Preliminary instantiation of an auction negotiation protocol for COGEU**

The operation of the market according to the open-cry auction model establishes that initially the spectrum seller need to define a policy statement that specifies which banks they trust to provide micropayment tokens and have an account with. Figure 66 [26] presents an example that defines a contract between buyers and banks (public keys and signatures are truncated for readability). A spectrum buyer needs to have a contract with a bank that allows them to spend micropayment tokens.

```plaintext
local-constants:
    player = "rsa-hex:3048024100aa88..."
    bank_1 = "rsa-hex:3048024100bf78..."
authorizer: bank_1
licensees: player
conditions: app_domain == "spectrum market" &&
            @date <= 20111212 &&
            amount == "0.1" &&@number <= 100 -> "true";
signature: "sig-rsa-sha1-hex:26d7da6725"
```

Figure 66: Definition of the contract between players and banks
The COGEU Broker Back End specifies in a signed policy statement an offer which is sent to the Broker Front End (which acts as a clearing house). The statement specifies the terms of the offer and the signature binds the Broker to these terms. Figure 67 [26] give the details of a keynote credentials of the offered spectrum usage rights, the expiration date of the offer, and that a bid should be greater or equal to 3.0 monetary units.

When the Broker finds a bid they first need to verify that the player can indeed deliver the payment and that all market / context / technical terms are satisfied by the given bid. If the player has a valid contract with a bank that the Broker trusts and the offer terms are met by the proposed bid then the transaction can be authorized (Figure 68 [26]). Therefore, the Broker is sure that they are going to be paid for the provided spectrum usage rights.

When the Broker informs the player that they accept the bid the latter releases the required number, in the above case 30, of tokens to the former. At that point, the Broker issues a signed keynote policy statement to the player that includes the purchased spectrum usage rights as specified in the initial offer. It is called the spectrum use credential. It can be used by the player as a proof of the spectrum assignment facilitating the operation of policy schemes. The Broker collects tokens and periodically contacts the issuing bank to translate them into monetary units and deposit them to their account.

Figure 69 gives an example related to the definition of an English auction negotiation protocol as presented in subsection 4.3.1. A timeout is associated with the Auction, players involved can place bids until the timeout expires, the highest bid wins the auction; a bid is simply described by a player ID and an amount that they wants to pay. The Broker receives offers and notifies results to the participants and to the service invocator.
The Broker needs to consult the policy repository for transaction compliance as presented in COGEU D2.2. For example one compliance rule that the Broker has to check every time a new offer is submitted is that one service is not allowed to post two consequent offers. When, in fact, the last bidder is the same as the current bidder, the Broker throws an exception to signal a non-compliant behaviour; the exception handler, in this case, will be the refusal of the bid submitted.

Referring to Figure 69, the process specified in the example is considered a meta-protocol because it does not refer to a particular abstract or concrete service. Roles in the negotiation protocol are specified only by names in the partnerLinks element, the Broker obtains a specification of the actual negotiation protocol enriching the meta-specification with the information provided by participants in the negotiation initiation phase. The difference between abstract services and concrete implementations is that: in the meta specification partnerLinks are defined only from an abstract point of view, the coordination context gives a concrete binding to actual services involved in the negotiation process. The bidPT portType, for instance, will be every time substituted by the protocol specific interaction portType(depending on the
type of Auction mechanism or strategy) of the customer segment that is considered in the placing of the current bid [71]. Thus, the portType will specify different auction mechanism presented in COGEU D2.3.

4.5- Future work for the Evaluation of negotiation protocols for COGEU

The performance of the negotiation protocols will be evaluated in the forthcoming deliverables. There will be a number of evaluation categories to capture the performance of the negotiation protocol. For the case of auction based negation protocols, the performance will be measured by its revenue-raising capability and its spectrum assignment efficiency, i.e. the total amount of spectrum sold as a percentage of that available to be sold. Revenue measures the auction's ability to extract the value which it would have placed, ex ante, on the resource it was offering. Efficiency is measured by examining whether negotiation protocol resulted in the sale items to go to the bidders who place the most value on items. This can be measured by making bidders place private valuations on the spectrum lots before the auction process. These private valuations can then be compared to the values actually paid at auction when the negotiation process is concluded. Both the efficiency and revenue-raising ability of the market mechanisms can then be evaluated. The extension of this work will be complementary to the work done in COGEU D2.3 on Secondary Spectrum Market Emulation Tool and Market Dynamic Studies.
5- Spectrum-aware routing protocols

COGEU has defined a Cognitive Radio network architecture in D3.3 [28] based on spectrum of commons regime, regarding the opportunistic access of TVWS by secondary users/nodes. One research challenge that has to be investigated in such network architectures is related with the way that routing paths are established between CR nodes located in different areas. Routing is an important/core function in COGEU network architectures based on network layer design, enabling for seamless connectivity of CR nodes, as well as for the efficient data transfer between them. At the same time, routing in CR networks is crucial for other design issues such as flow control and network mobility management, which are also important and need to be addressed as future research work.

COGEU nodes located in different areas are considered to have a dynamic spectrum access capability, according to the TVWS availability in a specific location and time period. Each COGEU node seeks and uses the TVWS channels, such as a multi-radio system and should be able to forward data packets in a self-organized way. It is obvious therefore that the main research issue among the network layer functions has to be routing and the establishment of efficient paths between different nodes of such CR networks. These networks are characterized by dynamically changing TVWS channel sets at each node, under a multi-hop and ad-hoc mode of operation. They also operate as a cooperative network, in which cognitive secondary nodes take help of their neighboring nodes in order to forward data to the destination based on TVWS availability. Such an opportunistic usage of TVWS introduces challenges like the creation and maintenance of wireless multi-hop paths among secondary nodes by deciding both the relay nodes and the spectrum/TVWS channels to be used on each link of the path.

Routing in a network with secondary usage of spectrum is challenging and different from routing in a conventional wireless network. A key difference is that routing is not based on a Common Control Channel since it is not ensured that each secondary node can obtain the same frequency. Therefore, multi-hop routing schemes in COGEU use cases have to be investigated, in order to provide reliable data delivery across regions of different TVWS availability, even when the network connectivity is intermittent or when an end-to-end path is temporarily unavailable. Figure 70 illustrates the challenge addressed in this part of the deliverable. More specifically, Figure 70 depicts three areas (i.e. Area A, B and C) where primary systems have produced three locations with heterogeneous spectrum availability. In order to set up multi-hop connections among node pairs with different spectrum, intermittent bridge nodes have to switch between multiple channels. In such a case, links on each path need to be established on different TVWS channels according to the spectrum availability in a specific area and time period.

![Figure 70: Routing across regions with heterogeneous spectrum availability.](image-url)

In a general context, routing in COGEU network use cases constitutes a rather important but yet unexplored problem, especially when a multi-hop wireless network architecture is considered. The design of a new routing protocol is therefore required that is based on a conventional routing protocol, modified accordingly in order to overcome the challenges defined above and establish/maintain optimal...
Before proceeding to get into routing in COGEU use cases, a review was firstly performed regarding the state-of-the-art on routing (e.g. conventional routing protocols) in ad-hoc and multi-hop networks since there is a strong similarity to the CR networks. Conventional routing protocols are based on either link-state or distance vector algorithms aimed at identifying optimal routes to every node in the multi-hop network. Topological changes often encountered in network are reflected through propagation of periodic updates. To update and maintain the routing consumes tremendous bandwidth and is not practical. For IP-based multi-hop networks, routing protocols can be generally categorized as proactive or reactive, depending on whether the protocol continuously updates the routes or reacts on demand.

Proactive protocols, also known as table-driven protocols, continuously determine the network connectivity and already-available routes to forward a packet. This kind of routing protocol is obviously infeasible to frequently re-configurable networks such as CR networks, due to the extreme dynamics of links. Reactive protocols, also known as on-demand protocols, invoke determination of routes only when it is needed (i.e., on-demand). There are two well-known reactive protocols: Dynamic Source Routing (DSR) and Ad-hoc on demand Distance Vector (AODV). When a route is needed, reactive protocols conduct some sort of global search such as flooding, at the price of delay to determine a route, but reflecting the most updated network topology (i.e., availability of links).

5.1- State-of-the-Art on Routing Protocols in conventional and CR networks

In wireless networks two types of routing protocols can be utilized for the reliable data delivery, the so called a) proactive (known as table driven) and b) the reactive (also called on-demand) protocols as defined above. The former is feasible when the routes can be stored and maintained in routing tables, which means that nodes periodically register changes in the topology and update routing information. The latter protocol can be utilized, when the routes are first discovered on demand, which is possible to happen when data needs to be transmitted to a node where no route has yet been discovered. In the proactive approach the advantage is little latency since routes are already available, while the disadvantage includes the increase of the routing traffic, since the routes require nodes to periodically update routing tables. On the opposite approach, the reactive protocols is capable to save bandwidth because it limits the routing overhead, however is adding latency at the beginning of transmission to nodes when no route, has yet been discovered.

Another crucial issue that categorizes the routing protocols depends on the information that is stored in the packet header. Thus, the routing protocols can be separated in two categories, a) source and b) hop-by-hop. The former, include the entire route in the packet header, while the latter include information about the destination in the header and use local tables to determine the next hop on the route. On source routing protocols it is not required any intermediate node to update the routing paths in order to forward the packets, but the packet size can easily grow, especially in large networks. On the
other hand, in hop-by-hop routing protocols the advantage is the small packet size, but it is inevitable the usage of intermediate nodes in order to maintain and exchange routing information.

Based on the literature [31], the most widespread routing protocols for the conventional networks are the Ad-hoc On-demand Distance Vector (AODV) and the Dynamic Source Routing protocol (DSR). The former belongs to reactive and hop-by-hop categories while the latter to reactive and source categories. More specifically, AODV uses a route discovery process and makes hop-by-hop routing, by broadcasting discovery packets only when necessary. AODV forwards information concerning changes in local connectivity to neighbor nodes that are likely to need it. Also, AODV supports the exchange of routing messages (RREQ, RREP) between source and destination node. Alternatively, DSR consists of two mechanisms, the Route Discovery, which handles establishment of routes and the Route Maintenance, which keeps route information updated. DSR operates on demand in order to establish the data path, while it is exchange signaling information between source and destination nodes via RREQ (Route Request) and RREP (Route Replay) messages.

5.1.2 Routing in CRN

A multi-hop Cognitive Radio network is, in many ways, similar to a multi-channel network. In both cases, each node has a set of channels available for communication. When two nodes wish to communicate, they negotiate to select a communicating channel. However, two are the major differences in such network environments. Firstly, in a multi-channel network, the number of channels available at each node is fixed and the channels have equal transmission ranges and bandwidths. On the other hand, in a multi-hop Cognitive Radio network, the number of channels available at each node is a variable and the environment is heterogeneous. Thus, it is possible that a secondary node do not have available channel at all, due to the complete occupancy of the spectrum by primary systems.

In this context, this subsection presents the most recent approaches that have been proposed in literature, regarding routing protocols, which can be utilized in CR networks. In the next table (see Table 15), a sort description about these routing protocols is listed. Most of such approaches utilize an AODV-style message for the route discovery and route reply. In the route discovery step, a RREQ (route request) message is sent by a source node to acquire the possible route to the destination. Also, the channel information (i.e. spectrum opportunities) is piggybacked with this RREQ message. Once the destination receives the RREQ message, it will have a full knowledge about the channel availability along the route from a source node. The destination then chooses the route with the lowest delay and also assigns a channel to each node along the route. Then, the destination node sends back a RREP (route reply) message to the source. This message also contains the information on channel assignment so that the nodes along the route can adjust the channel allocation accordingly. Once a source node receives this RREP, it starts data transmission.

Table 15 below presents the most up-to-dated approaches, which propose either multi-flow or multi-frequency scheduling schemes aiming to evaluate routing protocols for CRN.

Table 15 Routing Protocols for Cognitive Radio Networks

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPEAR [32]</td>
<td>- Integrates spectrum discovery with route discovery to cope with spectrum heterogeneity, and obtain optimal usage of available channels.</td>
</tr>
<tr>
<td></td>
<td>- Coordinates channel usage explicitly across nodes to optimize channel assignment on a per-flow basis, and to minimize inter-flow interference.</td>
</tr>
<tr>
<td></td>
<td>- Starts the route set-up by broadcasting and AODV-style route discovery, which accumulates information about each node’s available channels and their quality.</td>
</tr>
<tr>
<td></td>
<td>- Exploits local spectrum heterogeneity and assigns different channels to links on the same flow to minimize intra-flow interference.</td>
</tr>
<tr>
<td></td>
<td>- Is distributed and incurs low computational and communication complexity.</td>
</tr>
<tr>
<td></td>
<td>- Utilizing spectrum heterogeneity, SPEAR can attain near-optimal end-to-end throughput that does not degrade with additional hops.</td>
</tr>
<tr>
<td>SEARCH [33]</td>
<td>- It is a routing protocol that jointly undertakes path and channel selection to avoid regions of PU activity during route formation.</td>
</tr>
</tbody>
</table>
AODV routing protocol is modified to include the list of preferred channels by a given node as the route request (RREQ) is forwarded through the channel. The optimal paths found by geographic forwarding on each channel, are combined at the destination with an aim to minimize the hop count. By binding the route to regions found free of PU activity, rather than particular CR users, the effect of the PU activity is mitigated.

**SAMER [34]**
- Utilizes the available spectrum blocks by routing data traffic over paths with higher spectrum availability.
- Routes with highest spectrum availability are selected as candidates.
- Tries to balance between long-term route stability and short-term route performance via building a runtime forwarding route mesh.
- Can effectively utilize the available spectrum and achieve high end-to-end throughput.

**ROPCORN [35]**
- ROCORN was designed for data transportation by making use of link modeling.
- The key idea was to design a link cost metric that is based on its spectrum usage history as opposed to its instantaneous state.
- The proposed approach also incorporates a cost metric that accounts the load of the available bands.
- It has the advantage of capturing any spatial and/or temporal locality of link disconnection and leveraging it for optimal route selection for CRNs.

**SORP-DORP [36]**
- SORP provides an on demand routing approach, while DORD is an enhancement.
- A metric is defined that evaluates the effectiveness of candidate route in SORP taking into account the path delay and node delay, considering:
  - The switching delay between channels and
  - The backoff delay within the channel
- Also DORP defines an additional metric:
  - The queuing delay in order to count the end-to-end delay.
- AODV was modified (in both protocols) to form a mechanism on the control channel for exchanging spectrum availability information among network nodes.

**CRP [37]**
- The route-setup in the CRP protocol is composed in two stages
  - The spectrum selection stage, and the
  - Next hop selection stage.
- The source node broadcasts the RREQ over the control channel, and this packet is propagated to the destination.
- Each intermediate forwarder identifies the best possible spectrum band, and the preferred channels within that band during spectrum selection.
- To enable this, several CR metrics are proposed, that are weighted appropriately in an optimization framework for choosing the spectrum.

**SAOR [38]**
- SAOR is suited for CRN under wireless fading channels.
- SAOR employs a cooperative scheme to enable multi-path transmissions and maintains the statistical QoS guaranteed throughput for practical applications.
- Results in performance evaluation confirm that SAOR enjoys less delay with guaranteed throughput in CRN.

**MRSA [39]**
- To minimize the effect of “onset” of primary users, use of multi-path routing is
proposed, assuming that multiple radios are equipped at each station.
- Using multi-path and multi-radio in wireless mesh networks shows that the performance (e.g. end-to-end throughput) is substantially more resilient to the dynamic behavior of primary users than other choices.
- The proposed routing and spectrum access framework seeks to reduce the contention and interference among stations in perspective of traffic load balancing.

5.2. COGEU reference model scenario based on distributed CR infrastructure

5.2.1 Analysis and description – Definition of Simulation scenario

This sub chapter elaborates on the description of a scenario based on spectrum of commons COGEU reference model to act as a basis for designing, developing and evaluating a routing protocol to overcome research challenges described above. In this context, Figure 71 depicts a simulation scenario, where secondary users are scattered in three geographical areas (i.e. A, B and C in Figure 71) with different TVWS availability. Secondary users located in the first geographical area opportunistically operate using channels from 52 up to 60, while remaining channels are dedicated for usage by primary users. Also, secondary users located in the second and third geographical areas are able to transmit on channels 41-47 and 49-60, respectively. In this simulation scenario, secondary users located outside these areas, are able to operate on all the available channels (i.e. channels 40-60) and act as coordinator nodes (intermediate secondary nodes in Figure 71). These nodes are enhanced with a coordination mechanism that enables to determine routing paths between secondary users with different TVWS availability in areas A, B and C. Coordination nodes have sensing capabilities and are connected with a Geo-location database that includes TVWS availability for all geographical locations.

This simulation scenario includes three source secondary users (i.e. S1, S2 and S3 users in Figure 71) that wish to deliver data flows to corresponding destination secondary users (i.e. D1, D2 and D3 users in Figure 71) located in geographical areas with heterogeneous TVWS availability. The main challenge in such an ad-hoc CR network architecture is the spectrum heterogeneity of the available TVWS between neighbouring areas, prohibiting secondary users to communicate since there is no CCC. In such a case, coordination nodes will act as intermediate/bridge nodes between source and destination secondary users, coordinating data flows and deciding the most optimum routing path that has to be followed. According to the simulation scenario depicted in Figure 71, when secondary user S1 wishes to transmit data flows to secondary user D1, it firstly communicates with coordination node 2 on channel 52, which is in charge to route data flows to D1 by switching to channel 43. Additionally, secondary user S2 wishes, at the same time to transmit data flows to secondary user D2 (see Figure 71). In this case, coordinator node 3 located between geographical areas B and C is not able to process data flows from S2, since it serves at the same time data flows originated from secondary user S3 targeted to...
secondary user D3. In such a case, data flows are redirected to coordination node 2, which is then in charge to communicate with D2 on channel 60. It has to be noted here that all coordination nodes are connected to a TVWS Geo-location database, through a CCC (i.e. channel 40).

5.2.2 - **Design of a routing protocol adopted in COGEU**

Towards enabling for an efficient data transition between source and destination users of the above-mentioned simulation scenario, a novel routing protocol was designed, implemented and evaluated under controlled simulation conditions. This routing protocol is based on the exchange of AODV-style messages [40] between secondary users, including two major steps (route discovery and route reply). During the route discovery step, a RREQ (route request) message, including TVWS availability of nodes, is sent by the source user to acquire a possible route up to the destination user. Once the destination user receives the RREQ message, it is fully aware about the spectrum availability along the route from the source user. The destination user then chooses the optimum routing path, according to a number of performance metrics (e.g. backoff delay, switching delay, queuing delay, number of hops, throughput) and assigns a channel to each secondary user along the route. It has to be noted here, that the evaluation of performance metrics is conducted, by each intermediate node during the routing path of the RREQ message. In the next step, destination user sends back a RREP (route reply) message to the source user that includes information regarding channel assignment so that each node along the route can adjust the channel allocation accordingly. Once this RREP is received by the source user, it initiates useful data transmission.

Figure 72 presents the detailed process of the proposed routing protocol for handling both RREQ and RREP messages. The source user initiates a flow (i.e. New Flow in Figure 72), transmitting a RREQ message to an intermediate node located in a neighbouring location. The intermediate node is updated by Geo-location database about TVWS availability of its neighbouring nodes and determines if it is capable or not to accommodate the incoming flow from source user. If it is capable, it then evaluates the performance metrics, accommodates it and finally forwards it to the next hop or to the destination user, by forwarding the RREQ message. Once the destination user receives RREQ message, it is fully aware of channel availability along the route from the source node. Destination user sends then back a RREP message to the source user. This message contains information regarding channel assignment so that secondary users along the route can adjust the channel allocation accordingly. Once the source user receives the RREP, the routing path has been established and useful data transmission is initiated.

In the case when the intermediate node is not capable to accommodate the incoming flow (i.e. New Flow in Figure 73), a coordination mechanism (redirection process in Figure 73) is in charge of informing the source user, about the neighboring node, which could possibly act as an alternative intermediate node. In such a case, the intermediate node sends a RREP message to the source user, including redirection information. As soon as the source user receives this message, it broadcasts a
Redirecting RREQ message to the next possible intermediate node, which is then in charge to decide if it is feasible to accommodate the data flow, evaluate the performance metrics and forward it to the next hop. The proposed routing protocol determines a route only when a source user wishes to send a data flow to a destination user. Routes are maintained as long as they are needed by the source user and the exploitation of sequence numbers in the exchange messages guarantee a loop-free routing process. Furthermore, the proposed routing protocol as a reactive one, creates and maintains routes only if it is necessary, on a demand basis. The routes are maintained in routing tables, where each entry contains information, regarding destination user, next hop, number of hops, destination sequence number, active neighbouring nodes for this route and expiration time of the flow. The number of RREQ messages that a source user can send per second is limited, while each RREQ message carries a time to live (TTL) value that specifies the number of times this message should be re-broadcasted. This value is set to a predefined value at the first transmission and increased during retransmissions, which occur if no replies are received.

Figure 73: Message exchange process in routing protocol, including redirection

5.2.3- Metrics for COGEU routing protocol

Towards verifying the validity of the proposed routing protocol, several experimental tests were conducted, under controlled conditions (i.e. simulations), utilising NS-2 simulator [41]. More specifically, in such scenario intermediate nodes are receiving concurrent data flows, stemming from other secondary users, resulting to increased delays. According to this specific simulation scenario, a number of data flows are contending to pass through the same intermediate node, thus evaluation of delays is crucial regarding the efficient performance of the proposed routing protocol. In this context, a number of delay [42], [43], [44], [45] metrics, are evaluated, such as switching delay ($D_{\text{switching}}$), medium access delay ($D_{\text{backoff}}$) and queuing delay ($D_{\text{queuing}}$). Switching delay occurs when a secondary user during the routing path switches from one channel to another, while the medium access delay, namely backoff delay, is based on the MAC access schemes used in a given frequency band. Backoff delay is defined as the time from the moment that a data flow is ready to be transmitted up to the moment the data transmission is successfully initiated. Queuing Delay is based on the output transmission capacity of a secondary user on a given channel. More specifically, queuing delay represents the time needed for a data flow to wait in a queue until it can be processed.

According to the simulation scenario a queuing system was set up, exploiting a $M/M/1/K$ Kendall model [46], utilising an inter-arrival time (i.e. first M of the $M/M/1/K$ model), as well as an accommodation/serveing time (i.e. second M of the $M/M/1/K$ model) following exponential distributions based on the load/service rate (i.e. $\rho$). The system capacity (or number of flows can be served) was set to $K = 1$, while the service rate $\mu$ depends on the parameters $\lambda$ and $\mu$. $\lambda$ denotes the number of data flows, arriving every second and $\mu$ denotes the number of data flows that are accommodated every second. Load/service rate is equal to $\lambda/\mu$ and during the simulation test load was varied from 0.05 to
0.45, towards evaluating the node queue under different loads [47]. The formulation of mean queuing delay $D_{\text{queuing}}$ and losses rate $P_{\text{block}}$ [48], [49] are depicted below:

$$D_{\text{queuing}} = \frac{\rho}{\mu - \lambda}$$

$$P_{\text{block}} = \frac{(1 - \rho)\rho^k}{1 - \rho^{k-1}}$$

Additionally, the evaluation of $D_{\text{switching}}$ and $D_{\text{baccoff}}$ [43], [44] is crucial in such simulation scenario. Then, cumulative delay at an intermediate node $i$ is based on them and is computed as follows:

$$ND = \sum_i (D_{\text{switching}} + D_{\text{baccoff}})$$

Finally, end-to-end delay from the source user up to the destination one is computed as the overall sum of $D_{\text{queuing}}$ and $ND$:

$$D_{\text{End-to-End}} = D_{\text{queuing}} = ND$$

In Figure 74 different routing delays are presented. More specifically, switching delay is related with the time needed for node B to switch from channel 40 to channel 41 in order to act as an intermittent node enabling the efficient routing of data from node A to node F.

Moreover, the channel availability in such multi-hop CR networks is significantly different than in traditional wireless multi-channel multi-hop networks. Indeed, nodes in multi-hop CR networks potentially have partially overlapping or non-overlapping sets of available channels, and the available channel set at a secondary user is of time-varying nature and changes in correlated or uncorrelated manner with respect to sets of other nodes. Consequently, network layer solutions in multi-hop CR networks should be able to cope with the necessity of re-routing in case specific portions of the currently active path are “impaired” by the presence of an activating primary user. Figure 75 shows a case where re-routing is needed due to a primary user becoming active. The two-hop portion of the path (dashed lines in the right side of the figure) needs to be replaced with the three-hop segment as it is shown in the left side of the figure. The cost involved in the rerouting phase contributes to the overall maintenance cost.
The maintenance cost [52] represents the effort needed or penalty paid to maintaining end-to-end connectivity in such a dynamic multi-hop CR network. The maintenance of a route may involve link switching and channel switching operations as a primary user become active. In the former case, one or more links along the route must be replaced by other ones not interfered with by primary user, whereas in the latter case, the same link can be maintained, but the transmission must be carried over to another spectrum portion. In either case, signaling is required to coordinate with other primary user, which translates to a cost in terms of consumed power, and service interruption time while switching routes.

5.2.4 - Graphical User Interface of COGEU routing simulator

The simulator for COGEU routing protocol was developed in NetBeans 6.9, while a Graphical User Interface (GUI) was developed in order to create a user-friendly application. Figures 36-38 illustrate the GUI of the routing protocol simulator. More specifically, the user can define the simulation scenario, by selecting the “New Row” button in Figure 77 (a). Then a dialog with a number of parameters will appear. The user can define the number of areas, according to the simulation scenario, the TVWS availability and the secondary nodes inside each area Figure 77 (b). It is also able to define either if a node is a “coordinator node” or a simple secondary user. Finally, the application enable for the definition if the source and destination secondary nodes Figure 78. When the simulation scenario is fully defined, then a graphical representation of it appears in the application.
5.2.5 - Preliminary Evaluation/ Simulation results of a routing protocol for COGEU

Based on the metrics defined above the performance evaluation results below represent number of packets in queues (see Figure 39), losses rate (see Figure 80) and mean queuing delay (see Figure 81), for differed service rate values (i.e. load). It can be observed that both losses rate and queuing delay are increasing when service rate is varied from 0.05 up to 0.45, validating the proper operation of intermediate nodes buffers when the $M/M/1/K$ Kendall model is adopted.
Furthermore, Figure 82 represents end-to-end delay and node delay for three different data flows of the simulation scenario defined above (see Figure 71). It can be observed that end-to-end delay and node delay for data flow 2 is higher in comparison to delays of data flows 1 and 3, since the routing path from S2 secondary user to D2 secondary user (see Figure 71), includes a higher number of hops, as well as a redirection process is occurred.
5.2.6 - **Future work on routing for COGEU distributed network use-cases**

The research work that was performed in the framework of this deliverable will be enhanced during next year (in D6.3). Figure 83 shows enhancement of the COGEU routing protocol. More specifically, the coordination mechanism adapted to every intermediate node will be further able to determine if a neighbor node performs better in the routing path. For this scope, the message exchange process of COGEU routing protocol will be modified in order to consider the new feature of the coordination mechanism. When a source node initializes a new flow by sending a RREQ, the intermediate node is informed regarding the neighborhood status from the geo-location database through the CCC. Then, the intermediate node evaluates the new flow (i.e. throughout performance metrics) and encapsulates the evaluation result in a message that it will be forwarded to all neighboring nodes. This message is the Redirecting request signal in Figure 83. Once the neighbouring nodes receive a Redirecting request, they check its validity with the corresponding flow, ensuring that they are not the source/destination nodes or next-hop nodes of that flow. Then the neighboring nodes initiate a process, in order to evaluate the flow and they send to the intermediate node the result of the evaluation through a Redirecting replay message. Once the intermediate node receives the Redirecting reply from several of its neighbouring nodes, it then selects the optimum one in order to serve/accommodate the incoming flow. Finally, the intermediate node generates a RREP message in order to inform the source node regarding the new candidate intermediate node, while it also sends a confirmation message to the new intermediate node informing that it is chosen to handle the flow. On the side of the source node, once receiving the RREP, it changes the next-hop node and starts data transmission.

### 5.3 - Public Safety Scenario for Cognitive Radio Ad-Hoc Networks

The flexibility of cognitive radio Ad-Hoc networks capabilities appears to have the potential to enhance Public Safety operations. Firstly, cognitive radio operating in the TVWS can facilitate multi-organisational (e.g. fire-brigade and police) interventions at operational level, which would not be based on the need for dedicated and harmonised spectrum assignment to Public Safety systems at the European level. Instead, systems could collectively use possible TVWS spectrum that is available in an open access manner. More details on this scenario are provided in COGEU Deliverable D3.3 of WP3. Secondly, cognitive radio technologies have the potential to address interoperability issues of emergency communications systems, through two different means. A TVWS gateway could be used to link two different radio communications systems on different frequencies or the cognitive radio system could be used to minimize mutual interference between two communications systems deployed in the same operational crisis site.

One of the challenging features of the TVWS for public safety operation is its variation across space and time. More specifically the available channels are not contiguous and vary from one location to another.
In addition the white space available in a given location can vary with time if one or more of the TV band primary users start/stop their operation. This requires frequency agile architectures to map to the available white space spectrum, retune to a new operating channel, or tune-away to perform sensing measurements. Another major challenge that faces reliable operation in the white space is interference among peer TV band devices given the unlicensed nature of operation in this band. Managing interference between nodes in the same network is generally a difficult problem, and the problem becomes more challenging when these devices belong to heterogeneous networks using different air interfaces.

5.3.1 - Analysis and description

5.3.1.1 Dissemination of GPS information for Public Safety Application

Within this study, we investigate a Public Safety well known service called “Situation Awareness applications” or Common Operational Picture. It consists in sharing periodically some GPS information between all Public Safety Workers during an intervention. Those GPS information can be enriched by other information such as health reporting, environmental data, incident reports, or any data that could provide a better knowledge of the Crisis Theatre. This service is not stringent in terms of Quality of Service requirements and the key objective of this study is to investigate the viability of this service under Cognitive Radio Network applied to the COGEU architecture definition. The contributions are twofold:

- Proposition of one GPS information sharing protocol for Situation Awareness service support in Public Safety Network.
- Performance assessments under Cognitive Radio Network assumptions to evaluate the viability of this service.

5.3.1.2 How to route all-to-all communications

All-to-all communication in Wireless Ad-hoc Networks is a multicast routing inter-flow communication subcase. Two main approaches emerged in the literature when one strives to either minimize the number of transmissions or the time needed to achieve successful all-to-all communications. The first one consists in selecting a subset of router that will be in charge of routing native messages (Connected Dominating Set based approaches) [60], [61]. The second one consists in combining native messages either deterministically or randomly (Network Coding based approaches). Those two approaches are in relation with the Situation Awareness Service support in wireless network since the traffic resulting of such an application is all-to-all.

5.3.1.2.1 Connected Dominating Set based approaches for all-to-all communications

A Connected Dominated Set (CDS) of a graph G is a set D of nodes with the two following properties:

- The subgraph of G induced by D is connected.
- The set D is a dominating set of G, i.e. a node either belongs to D or is adjacent to a node in D.

Connected Dominated Set based approaches [60] consist in selecting nodes to form a CDS and activating forwarding only for this subset. The leaves of the tree do not forward any message. Reducing the number of nodes in the CDS means reducing the number of transmissions required to achieve successful message delivery.

However, finding the CDS with the smallest cardinality is NP-Complete. In the depths of difficulty, building the CDS in ad hoc networks has to be distributed. Many heuristics exist such as the one implemented in OLSR -called MPR (Multi Point Relay) [61] or Dominant Pruning based and Total Dominant Pruning solutions [60].

Figure 84 depicts an example of CDS developed within the framework of OLSR routing protocol. This example emphasizes on the gain of selecting a subset of nodes for forwarding activity and benefiting of the broadcast nature of the channel.
A main drawback of such solutions is the consequent over-head to build the CDS. Moreover, when one strive to tackle mobility issues, very lossy environment issues or unavailability of links in Cognitive Radio Network, CDS based all-to-all communications can become rapidly not efficient. As a key consequence, needed signalling delivery for CDS maintenance does not support packet loss that creates immediately incoherency within CDS building. For this concern, even if performance of CDS based solutions are relevant, they are not suitable with Public Safety Networks deployed in particular environments identified under the scope of the COGEU use cases.

5.3.1.2.2 Network Coding based approaches for all-to-all communications

Network Coding based approaches aim at reducing number of transmissions by benefiting of the broadcast nature of the wireless medium. In contrary to the flooding tree based solutions, Network Coding techniques do not exclude any nodes from the routing/forwarding activity. Deciding which messages are encoded can be done either deterministically or randomly.

- Determinist Network Coding: Determinist Network Coding consists in selecting deterministically a subset of messages to be encoded. In [62], messages are encoded in order to maximize the number of neighbours that will be able to immediately decode it. To do so, nodes need to know the list of messages that have all of their neighbour nodes. This can be achieved by an additional protocol [62].

- Random Network Coding: Random Network Coding consists in combining messages randomly without any knowledge of what have the nodes in the neighbourhood. Crisostomo et al. [63] performed a comparison between MPR diffusion and network coding technique. As a main conclusion, the study shows that network coding clearly outperforms MPR in most of the cases. Those solutions are compared in [64]. A main conclusion is that Random Network Coding outperforms Determinist Network Coding for All-to-All communication traffic patterns. Moreover, the benefit of using a combined solution including tree-based and Network Coding based approaches is not interesting if we also consider the over-head needed for tree-based approaches. This leads us to consider only the Random Network Coding technique (Annex 6) for Cognitive Radio Networks.

5.3.2 Definition of Simulation scenario: Situation Awareness Service over cognitive radio Ad-Hoc networks

Within this sub-section, we detail the Situation Awareness Service requirements and the main two targeted goals. Then, we present the solution based on Random Network Coding technique for which performance assessments have been performed and reported in the following sub-section.

First, Situation Awareness Service offers a standard overview of an incident. This standard overview aims at providing intervention information as refreshed as possible to facilitate Incident Commander/Unified Command (e.g. in the case of a European cooperative intervention that involves different Operations Center). Then, collected information about the intervention deployment has to be conveyed towards the Mission Control Centre that can often reach by using a couple of gateways.
Figure 85: Level of Public Safety Situation Aware service usage. At the top the local view of a Public Safety Worker and at the bottom the global view needed for the Mission Control Centre.

The second main goal for Situation Awareness Service is to provide an overview of the intervention deployment for all Public Safety Workers. The goal is crucial to prevent incoherent decisions and can dramatically improve cooperative work on the field. This overview can be incremental in the sense that relevancy of situation information decreases with the distance between two Public Safety Workers. Those two goals come into variety performance criterion forms. The first goal is measured in terms of time for all GPS information to reach the gateways towards Mission Control Centre(s). The second one is evaluated in terms of time needed to have all global overview of the intervention for all workers and also how evolve the knowledge of Public Safety Workers in time. This last criterion is related to the point mentioned before: relevancy of situation information decreases with the distance between two Public Safety Workers.

5.3.3- Preliminary implementation of an all-to-all routing protocol model for COGEU

5.3.3.1 Adapted Random Network Coding Protocol

According to the results from literature and especially those from [64], Random Network Coding technique is considered to be the most adapted to the Situation Awareness Service support in Cognitive Radio Networks. GPS information are periodically collected by each node. The concept is quite simple to implement and only requires two buffer within each node: i) one formative packets; ii) one for encoded packets. Adapted Random Network Coding Protocol consists in combining native packets picked up randomly from the native packet buffer before sending them to other nodes in the network. We call it adapted, because the according to the acceptable computation time -that depends on the used device- the maximum number of encoded packets can be dynamically increased or decreased.

5.3.4- Preliminary Evaluation/ Simulation results

5.3.4.1 Simulation Environment

An ad hoc network is deployed within a 3000 × 3000 m² area. This network can be considered to be relatively static since the time needed to achieve a successful dissemination for a given generation is lower than the operational mobility within the intervention field. Number of nodes in the topology varies from 20 to 80. We consider that PHY/MAC layers does not ensure a perfect collision avoidance for transmissions and we quantify those collisions in terms of Packet Loss ratio. Moreover, under the COGEU Public Safety use case assumptions, we consider a link to be not available when a primary user needs to use spectrum resource. Herein, we do not distinguish if a transmission fails because of a PHY/MAC collision or a PMSE user arrival since the result is similar, we consider the transmission just impossible. Each point on the following curves is the average result of a hundred simulations of the
same scenario (number of nodes and diffusion technique). We evaluate here the required amount of data so that each node GPS coordinate information are received by all nodes in the network and required delay to disseminate data over the entire network.

5.3.4.2 Situation Awareness Service Support in function of TVWS Spectrum availability

Spectrum availability at end-user level clearly depends on the primary users spectrum usage. Herein, we assume that secondary systems are aware of the primary user existence thanks to the COGEU geo-location database and is able to pre-empt its own transmission when notified by it or when sensing reports incumbent presence in the area. In Figure 85, we present a study in which we model the primary user spectrum usage in terms of radio resource availability. The spectrum availability (x-coord) evolves from fully available spectrum to a 20% spectrum usage opportunity. We compare basic routing schemes like Pure flooding protocol to Random Network Coding ones in terms of time needed to provide the service to operational users. Network Coding approach improves clearly the Pure Flooding one and provides the service 5 times faster. Situation Awareness Service benefits of Network Coding based routing dissemination in terms of refresh rate of GPS information updates.

5.3.4.3 Network Coding design for Radio Resource usage optimization

The point that we deal with herein, is how Random Network Coding has to be designed to provide the most efficient radio spectrum usage. This is measured in terms of radio resources needed to support the Situation Awareness Service. By using less amount of resources, the protocol ensures to be less impacted by a primary user unexpected arrival and on the other hand reduces the radio resource waste and enables other services to coexist within the network.

Figure 86: Impact of spectrum unavailability on overall delay required a successful information delivery (expressed in milliseconds)

Public Safety networks often operate in very hostile environment. Providing robust radio communication links for node transmission is very challenging. Figure 86 depicts the impact of spectrum unavailability on time spent for successful information delivery.
Figure 87: Situation Awareness Service robustness in function of maximum Number of Encoded Packets.

Figure 87 illustrates Radio Resource usage to support Situation Awareness Service. Maximizing the number of encoded packets provides redundancy and diversity during the dissemination that improves clearly the performance of the solution.

We observe a significant benefit of increasing the maximum number to be encoded randomly for dissemination. However, this implies more computation time and the need to have largest buffer to be able to store encoded packets that cannot be decoded immediately when they are received. Then, the maximum number able to encode depends clearly on equipment requirements that is not dealt within this study. Results dramatically encourage to increase this value to its maximum to reach the best performance gains for the Situation Awareness Service.

5.3.4.4 Evolution of the knowledge of a Public Safety Worker within the field

Figure 88 depicts the evolution of the knowledge of a Public Safety worker within the field. The x-coordinate indicates the coverage range of its knowledge and y-coordinate the time needed to achieve an entire view of the considered area. Once again, performance assessment shows that Network Coding technique is more efficient for Situation Awareness Service.
6- Conclusions and future work

This Deliverable, D6.2, reported the results of Tasks 6.2, 6.3, 6.4 and 6.5. “FreqScan” software was utilised in order to identify the available TVWS in Munich area. Wave propagation models for broadcasting to short-distance applications were studied in order to cope with the interference situation encountered between short-range systems and the medium-range/long-range broadcasting service. The maximum transmission power for each location on a 200m x 200m grid was calculated for UHF channels 40 to 60. Also, a statistical investigation of TVWS availability in Bavaria, based on a zone model was made. Furthermore, a comparison was performed between mapping of TVWS-to-area and mapping of TVWS-to-population density. In the next step, analysis and network planning for extension of LTE over TVWS was conducted. More specifically, an LTE simulator was developed, where the data calculated from “FreqScan” tool was used as an input to the LTE simulator. The simulator produced evaluation results for qualitative comparison among the three LTE modes of operation (Normal, Algorithm 1 and Algorithm 2).

This deliverable also elaborated on the design, development and implementation of negotiation protocols, spectrum-aware routing protocols and transport layer protocols, capable to efficiently operate in COGEU network architectures, overcoming the challenges of using the TV white spaces in the networking aspect. More specifically, the design and initial substantiation of a negotiation protocol was presented, in order to determine the communication/trading among secondary systems and the Spectrum Broker of COGEU demonstrator. The signaling protocol/interface between the Spectrum Broker and the secondary user was designed in order to enable the proper transaction among them. This signaling included two types of negotiation, one for merchant mode and the second for the auctioning mode.

On the routing layer, protocols in conventional networks and CRNs were investigated to deal with the two major problems/challenges of routing in CRN (i.e spectrum awareness and spectrum heterogeneity). Two COGEU scenarios were proposed in order to design, implement and evaluate routing protocols which are capable to ensure that multi-hop routing schemes can provide reliable data delivery across regions of different TVWS availability. The first scenario discussed routing issues, by utilizing the spectrum of commons COGEU reference model (i.e. ad-hoc network infrastructure), while the second one elaborated on a public safety COGEU use-case. A routing simulator was developed in terms of COGEU ad-hoc scenario, where the AODV protocol was modified accordingly to the cognitive radio network challenges. Preliminary results verified the validity of the proposed protocol, besides identifying fields for further research by enhancing the proposed routing protocol with a coordination mechanism in order to optimize the preliminary performance.

In Annex 7, consideration for the implementation of transport layer protocols that are adopted in COGEU network architectures has been introduced. The complete version of the work address problems related with communication disruption between secondary systems due to the opportunistic nature of TVWS availability. However, this output is not yet public because a pending patent submitted by THALES. In D6.3 we except to report more details regarding the COGEU transport layer protocol.

In the future, the work reported in this deliverable will be further extended in D6.3 (“Spectrum-aware routing, transport protocols and negotiation protocols between players for secondary spectrum trading – final”) and D6.4 (“System level evaluation platform and simulation results”), where research work will be conducted, regarding the enhancement and optimization of the proposed networking protocols. In order to ensure the efficient exploitation of the protocols, new metrics and simulation results will be obtained. In the context of LTE over TVWS, a number of simulation scenarios will be carried out, in order to obtain more qualitative comparison among urban/suburban and rural scenarios. Furthermore, the basic framework developed in this deliverable, regarding negotiation protocols (T6.4), as well as the results from TVWS identifications (T6.5) will be further enhanced in D8.3 and be used in T7.2 (“COGEU demonstrator, development and integration”) for the COGEU final demonstrator.
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[8] ITU-R SM.2028-1 ‘Monte Carlo simulation methodology for the use in sharing and compatibility studies between different radio services or systems’, Appendix 1 to Annex 2: Propagation Model, 2002 (Extended Hata)


D6.2 - Spectrum-aware routing, transport protocols and negotiation protocols between players for secondary spectrum trading; System level simulation tool - initial specification


NS-2 Simulator, http://isi.edu/nsnam/ns/


S. Rousseau, F. Benbadis, D. Lavaux, L. San, Overview and Optimization of flooding Techniques in OLSR HotMESH 2011, third IEEE International Workshop on Hot Topics in Mesh Networking, June 2011, Lucca, Italy


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<tbody>
<tr>
<td>ATSC</td>
<td>Advanced Television Systems Committee</td>
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<tr>
<td>3GPP</td>
<td>3rd Generation Partnership Project</td>
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<td>4G</td>
<td>Fourth Generation</td>
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<td>CEPT</td>
<td>Conference of European Postal &amp; Telecommunications</td>
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<td>CR</td>
<td>Cognitive Radio</td>
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<td>DSM</td>
<td>Dynamic System Management</td>
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<td>FPGA</td>
<td>Field-Programmable Gate Arrays</td>
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<td>GSM</td>
<td>Groupe Spécial Mobile (also, Global System for Mobile communication)</td>
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<td>IEEE</td>
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<td>ICT</td>
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<td>IPR</td>
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<td>LAN</td>
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<td>OFCOM</td>
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<td>OFDM</td>
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<td>PAPR</td>
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<td>SAP</td>
<td>Services Ancillar to Programme making</td>
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D6.2 - Spectrum-aware routing, transport protocols and negotiation protocols between players for secondary spectrum trading; System level simulation tool - initial specification

<table>
<thead>
<tr>
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<th>Description</th>
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<td>SDR</td>
<td>Software Defined Radio</td>
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<tr>
<td>TV</td>
<td>Television</td>
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<td>TVWS</td>
<td>TV White Spaces</td>
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<td>TVWS-OR</td>
<td>TVWS Occupancy Repository</td>
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<tr>
<td>UHF</td>
<td>Ultra High Frequency</td>
</tr>
<tr>
<td>UMTS</td>
<td>Universal Mobile Telecommunications System</td>
</tr>
<tr>
<td>US</td>
<td>Unites States of America</td>
</tr>
<tr>
<td>USRP</td>
<td>Universal Software Radio Peripheral</td>
</tr>
<tr>
<td>VHF</td>
<td>Very High Frequency</td>
</tr>
<tr>
<td>WCDMA</td>
<td>Wideband Code Division Multiple Access</td>
</tr>
<tr>
<td>WiMAX</td>
<td>Worldwide Interoperability for Microwave Access</td>
</tr>
<tr>
<td>WiFi</td>
<td>IEEE 802.11</td>
</tr>
<tr>
<td>WLAN</td>
<td>Wireless Local Area Network</td>
</tr>
<tr>
<td>WP</td>
<td>Work Package</td>
</tr>
<tr>
<td>WPAN</td>
<td>Wireless Personal Area Network</td>
</tr>
<tr>
<td>WWRF</td>
<td>Wireless World Research Forum</td>
</tr>
</tbody>
</table>
Annex 1: A note on FRANSY

Coverage calculations and calculated field strength values for fixed scenario, generated with IRT's frequency planning tool FRANSY, serve as the database for ongoing considerations. These calculations provide field strength $E$ and location probability $LP \ (q \equiv LP)$ for channels 31 to 60 and locations in Bavaria. A 200 m grid is used.

FRANSYs data pool is provided by BNetzA’s open and closed user group’s data, where the open user group’s data contain planning data for Germany and neighboring countries and the closed user group provides assigned transmitters within Germany (i.e. transmitters in operation).

Coverage calculations and calculated field strength values for fixed scenario, generated with IRT’s frequency planning tool FRANSY, serve as the database for ongoing considerations. These calculations provide field strength $E$ and location probability $LP \ (q \equiv LP)$ for channels 31 to 60 and locations in Bavaria. A 200 m grid is used.

FRANSY only considers primary users (i.e. broadcast transmission); possible interference caused e.g. by PMSE or TVWS devices is not taken into account.

FRANSY data are available for fixed broadcast scenario. To get an impression on the situation for portable scenario, the field strength values were reduced by 16 dB (height loss) and the location probability calculated with these values but for the same nuisance field strengths.

Figure 89 shows the result. The red areas are locations with $LP \geq 95\%$ (portable). In Figure 90 the fixed scenario is shown, where areas with $LP \geq 99.9\%$ are red.

Red colored areas look quite similar in both diagrams, so for portable reception (95%) fixed reception data with location probability 99.9% seem to be a reasonable approximation.

---

Figure 89: Location probability channel 45 portable, areas with $LP \geq 95\%$ are colored red
Figure 90: Location probability channel 45 fixed, areas with LP ≥ 99.9% are colored red.
Annex 2: Procedure to calculate $I_{WSD,MAX}$

Formula 4.3-4 of [ECC report 159] [3] describes the situation of a broadcast system with unwanted DTT signals:

$$q_1 = \Pr \left\{ P_S \geq P_{San} + \sum_{i=1}^{K} r_{U,i} P_{U,i} \right\} = \Pr \left\{ P_S - U \right\}$$

Solving eqn. (1) provides field strength (equivalent to $P_S$) of the wanted DTT signal and the location probability. Available tools like IRT’s frequency planning system FRANSY can be used to solve this task.

Additional interference caused by a TVWS device can be included by an additional term in formula (50):

$$q_2 = \Pr \left\{ P_S \geq P_{S,min} + \sum_{i=1}^{K} r_{U,i} P_{U,i} + U_{WSD}^{MAX}(u,v) \right\}$$

As any additional system operating in the UHF bands will deteriorate reception conditions for DTT reception, an acceptable degradation for the location probability has to be fixed. With the results from FRANSY, formula (2) and an assumption for acceptable degradation we can calculate the maximum acceptable interference caused by a TVWS device at the location of a broadcast receiving antenna.

From ECC 159 formula 4.3-5 we have:

$$q_1 = 1 - \frac{1}{2} \text{erfc} \left\{ \frac{1}{\sqrt{2}} \frac{m_S(dBm) - m_{U1(dBm)}}{\sqrt{\sigma_S^2(dB) + \sigma_U^2(dB)}} \right\}$$

We use $m_{U1(dB)}$ to describe the median value for the nuisance field. From the data we get from FRANSY $(E,q)$ we can determine: $m_{U1(dBm)}$

$$m_{U1(dBm)} = m_s - \sigma_s \cdot \text{erfcinv}(2(1-q_1))$$

$m_{U1(dBm)}$ is the nuisance signal strength:

$$m_{U1(dBm)} = (N \oplus I) + PR = (N + PR) \oplus (I + PR)$$

Here PR is the protection ratio for DVB-T interfered with DVB-T (17.9 dB).

For a reduced location probability $q_2 = q_1 - \text{degradation}$ a higher interference $m_{U2(dB)}$ is acceptable, where $m_{U2(dB)} = m_{U1(dB)} \oplus (I_{WSD} + PR_{WSD})$.

$$\frac{m_{U2}}{10} = \frac{m_{U1}}{10} + 10 \frac{I_{WSD} + PR_{WSD}}{10}$$

and hence:

$$I_{WSD} = (m_{U2(dBm)} \oplus m_{U1(dBm)}) - PR_{WSD}$$

Now with (4) $I_{WSD}^{MAX}$ can be determined:

$$I_{WSD}^{MAX} = m_s - PR_{WSD} + 10 \log_{10} \left( e^{\sigma_{eff,c}(q_2)} - e^{\sigma_{eff,c}(q_1)} \right)$$

With the calculations described so far, we reach the upper ellipse $I_{WSD}^{MAX}(u,v)$, describing the maximum acceptable interference level of the TVWS device at the location of a broadcast reception antenna.
Annex 3: Parameter from ECC Report 148

Values for protection ratios (PR) and overload thresholds \(O_{th}\) are taken from ECC report 148 [2] where:

- For protection ratios the values for 90th percentile are taken.
- For overload thresholds the values for 10th percentile are taken (which means that 10% of the receivers are interfered at the given levels).
- Silicon USB receivers are not taken into account.
- As some values cover a wide range, the average value from the given ranges were taken, e.g. PR for user equipment for \(n+2\): \([-45...-42]\) and \([-46...-32]\) \(\rightarrow\) -(45+42+46+32)/4 = -41 dB\(^3\)
- RP-values need correction according to table 4 in ECC 148
  - 64 QAM 2/3 Gaussian \(\rightarrow\) 16 QAM 2/3 fixed: -4.3 dB
  - 64 QAM 2/3 Gaussian \(\rightarrow\) 16 QAM 2/3 portable: 1.0 dB (following the note below the table the value for mobile reception is used)

\(^3\) Averaging the dB values provides lower mean values than averaging the linear values. Hence averaging dB values causes ‘better’ protection ratios and ‘worse’ overload thresholds.
Antenna gain
- Yagi antenna: 9.15 dBi (12 dB - 5 dB feeder loss + 2.15 dBi)
  Outside the cone antenna discrimination of -16 dB is assumed [ITU-R BT.419-3] [5]
- Dipole antenna: 2.15 dBi
**Annex 4: Assumptions**

**Acceptable degradation**
For the calculations an acceptable degradation of 1% is assumed.

**Protection of DVB-T receivers only within coverage area**
Signal propagation is a statistical process and field strength values are log normal distributed. So there is no clear border, which separates areas with broadcast coverage from areas where broadcast reception is not possible. Therefore ITU GE06 [4] defined pixels with

- Location probability ≥ 95 %: good reception
- Location probability ≥ 70 %: acceptable reception.

For the subsequent considerations it is assumed that (fixed) broadcast reception is only possible within 70 % coverage area, so TV receivers outside that coverage area are not protected. For demonstration purposes it is assumed that in 99.9% (fixed) coverage areas portable reception (95% location probability) should be possible, see Annex 1.

**Considered channels**
Channels 40 to 60 are investigated where data from Oct. 2010 are used. Occupation of adjacent channels has to be considered, however after DSO the occupation above channel 60 is not known, so for the simulations channels above 60 are considered free.

**Distance between TVWS transmitter and DVB-T receiver (antenna)**
Broadcast scenarios: a) fixed rooftop reception (FR), b) portable reception (PO)

<table>
<thead>
<tr>
<th>TVWS-systems: a) base station (BS), b) user equipment (UE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>In this scenario at each location where a base station is available, also UE may be found. There is however an additional option – downlink only- (DO) where the UE uses different frequency bands to transmit (e.g. LTE bands). In this case UE needs not to be considered.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fixed (FR)</th>
<th>Portable (PO)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Base station (BS)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>d&lt;sub&gt;min&lt;/sub&gt; = 30 m</td>
<td></td>
<td>d&lt;sub&gt;min&lt;/sub&gt; = 10 m</td>
</tr>
<tr>
<td>Yagi antenna</td>
<td>Dipole antenna</td>
<td></td>
</tr>
<tr>
<td><strong>User equipment (UE)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>d&lt;sub&gt;min&lt;/sub&gt; = 20 m</td>
<td></td>
<td>d&lt;sub&gt;min&lt;/sub&gt; = 2 m</td>
</tr>
<tr>
<td>Yagi antenna</td>
<td>Dipole antenna</td>
<td></td>
</tr>
<tr>
<td><strong>Downlink only (DO)</strong></td>
<td>Higher BS antenna</td>
<td>Higher BS antenna</td>
</tr>
<tr>
<td>d&lt;sub&gt;min&lt;/sub&gt; = 50 m</td>
<td>d&lt;sub&gt;min&lt;/sub&gt; = 50 m</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 16: Geometrical parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>o In scenarios where UE is active, due to the poorer protection ratios (PR) UE operation is more restrictive.</td>
</tr>
<tr>
<td>o In DO scenario fixed rooftop is more restrictive condition than portable.</td>
</tr>
<tr>
<td>o So there remain three scenarios:</td>
</tr>
<tr>
<td>o scen&lt;sub&gt;1&lt;/sub&gt;: fixed / portable broadcast with BS-PR and O&lt;sub&gt;in&lt;/sub&gt; for P&lt;sub&gt;BS&lt;/sub&gt;&lt;sup&gt;max&lt;/sup&gt;</td>
</tr>
<tr>
<td>o scen&lt;sub&gt;2&lt;/sub&gt;: fixed / portable broadcast with UE-PR and O&lt;sub&gt;in&lt;/sub&gt; for P&lt;sub&gt;ue&lt;/sub&gt;&lt;sup&gt;max&lt;/sup&gt;</td>
</tr>
<tr>
<td>o scen&lt;sub&gt;3&lt;/sub&gt;: fixed broadcast with BS-PR and O&lt;sub&gt;in&lt;/sub&gt; for P&lt;sub&gt;DO&lt;/sub&gt;&lt;sup&gt;max&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

For fixed reception it might be assumed that the rooftop antenna directs to the broadcast transmitter and so TVWS devices outside coverage area could not radiate into the cone of a TV directional aerial:
But due to the ragged structure of coverage area it may be possible that WSD outside fixed coverage area is within the cone of a Yagi antenna. So only for dist > 10 km an antenna discrimination of 16 dB, recommended in [ITU-R BT.419-3] is assumed. The figure below shows areas with no coverage (here: gray and black) within the TV coverage area (here: red and white).

Figure 91: location probability for ch 44: terrain profile causes ragged structure

**Propagation model**

For TVWS devices the maximum transmit power will be in the range of up to few Watts. With this, the max range of interference will be limited to few kilometers. To calculate propagation loss for TVWS systems, simple propagation models like [ITU-R P.1546-4] or [8] that do not take into account topology can be used. For distances from 10 m to 10 km these models are compared with an even more simple model 20/30/40dB [11] and it was found that this 20/30/40dB model is appropriate for the considered accuracy:

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>Propagation Loss (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>d &lt; 100 m</td>
<td>20 dB/decade</td>
</tr>
<tr>
<td>100 m ≤ d &lt; 1000 m</td>
<td>30 dB/decade</td>
</tr>
<tr>
<td>1000 m ≤ d:</td>
<td>40 dB/decade</td>
</tr>
</tbody>
</table>
Operational data vs. plan data

For the investigations operational data were used. This is reasonable because to determine the possible transmit power the actual occupation of TV channels is required.

On the other side, the TVWS statistics, e.g. how much bandwidth is available for TVWS use in a considered area, is relevant for business decisions. For such decisions however the operational data are inappropriate because they do not consider those situations where channels are assigned to broadcast operators but the operators have not started transmission so far, though it could be the case at any time.

Figure 93 shows the situation of channel 51 in Bavaria. The left picture shows that this channel is actually not used in Bavaria, whereas the picture on the right indicates that there are some assignments which would, if switched on, reduce the available TVWS significantly. So for decisions that require a long term stable situation, e.g. concerning investments for establishing a TVWS network, the plan data are the appropriate data pool.

Figure 93: Comparison of actual use of ch 51 with plan entries
Annex 5: Comparison of spectrum occupation measurement in the Munich area with simulation results

Accuracy of the propagation models [24]

According to SE43(11)11 [10] for terrain based prediction models the standard deviation of the error is 6...9 dB. For the edge of a 70% coverage area this means ($\sigma = 5.5$ dB):

$Cf(70\%) \times \sigma = 2.8842 \, \text{dB} \pm 6 \, \text{dB} \rightarrow LP = 28...95 \%$

$Cf(70\%) \times \sigma = 2.8842 \, \text{dB} \pm 10 \, \text{dB} \rightarrow LP = 10...99 \%$

Measurements made in August 2010:

![Freising, 10-m-height](chart.png)

Figure 94: broadcast signal strength for fixed rooftop situation in Freising, north of Munich

In Figure 94 the values contain the gain of the measurement antenna (-7dB).

<table>
<thead>
<tr>
<th></th>
<th>Measurement</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ch 48</td>
<td>-54 dBm</td>
<td>-47 dBm</td>
</tr>
<tr>
<td>Ch 54</td>
<td>-53 dBm</td>
<td>-47 dBm</td>
</tr>
<tr>
<td>Ch 56</td>
<td>-54 dBm</td>
<td>-47 dBm</td>
</tr>
</tbody>
</table>

Note:

For the simulations FRANSY assumed the antenna to be at least at rooftop height whereas for the measurements the antenna height was 10m in all cases. So for the measurements line of sight was not possible for all locations (measurements from 20 different locations at Freising site were averaged for the above diagram) and hence measured signals are weaker than results from the simulations.
Annex 6: Network Coding principle

Basically, network coding consists in coding information at Network layer. Routers can combine information to be routed either from a single flow, we talk about intra-flow network coding [65] (see Figure 95) or from more than one - we talk then about inter-flow network coding [66] (see Figure 96). By definition, we call native packet a non-coded packet and coded packet a packet resulting from a combination of at least two native ones. At first, network coding technique was introduced for wired network by Ahlswede et al. [67]. In their study, authors show that classical network switch forwarding efficiency can be notably improved by ingeniously combining packets before sending. They consider the well-known Max-flow min-cut theorem that states the maximum value of an \( s - t \) cut is equal to the minimum capacity of an \( s - t \) cut, where \( s \) and \( t \) are both network nodes. Figure 95, extracted from [63] illustrates the benefits of using network coding in wired network for a multicast communication between a source router \( S \) and three sinks, \( t_1 \), \( t_2 \) and \( t_3 \). The source router \( S \) is physically connected to three routers 1, 2, 3 with links of capacity equal to 1 (one bit per time can be sent onto each link). Those intermediate routers are connected to the sinks such as a link exists between 1 and \( t_1 \), and \( t_2 \); between 2 and \( t_1 \), and \( t_3 \) and finally between 3 and \( t_2 \) and \( t_3 \). The link capacities are also equal to 1. The source router has to transmit two bits \( \{b_1, b_2\} \) to each sink, see Figure 95a.

In order to ensure that all sinks will receive the two bits from \( S \), at least 10 transmissions are needed, see Figure 95b, one transmission on each link and 2 for the link \((S, 3)\). Figure 95 b introduces the network coding. Instead of sending \( b_1 \), and \( b_2 \) independently on link \((S, 3)\), the source router \( S \) combines both \( b_1 \), and \( b_2 \) (exclusive OR (XOR) is one of the most popular algebraic expression combination for network coding). Then, router 3 forwards to sinks \( t_2 \) and \( t_3 \) that decode it to obtain respectively \( b_2 \) and \( b_1 \).

Figure 95: Network Coding techniques out-performs multicast communications in wired / wireless Networks

Clearly, multicast communications take advantage of network coding in wired networks and this breakthrough leads further studies to apply the same concept within the context of Wireless Networks. Indeed, network coding is not confined anymore to multicast communications in wired networks but this technique has been extended to wireless ones by benefiting of the broadcast nature of wireless transmissions. In order to emphasize this gain, let us consider the example given in Figure 96. First, a depicts the natural forwarding scheme in wireless network without network coding. Two nodes \( S_1 \) and \( S_2 \) are both source node and destination, and this one for the other. Let us consider that those two nodes are within the transmission range of a common node \( R \) that plays the role of relay node for communication between \( S_1 \) and \( S_2 \). Finally, let us assume that each transmission link has a capacity of one bit per time unit. To send one bit from \( S_1 \) to \( S_2 \) and vice versa from \( S_2 \) to \( S_1 \), at least 4 transmissions are needed.

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Network Coding technique can reduce amount of radio resources and time by 25%.

Figure 96 b depicts the network coding based solution. At first step, both $S_1$ and $S_2$ send a bit respectively $b_1$ and $b_2$ to $R$. Instead of relaying the two native information, $R$ first encodes them into an encoded one ($b_1Lb_2$) and broadcasts it using only one transmission. As a main result, the number of needed transmissions is reduced by 1 (that represents a 25% reduction) and the time to deliver the two bits is also reduced by 1.

To make a mapping of this example and the previous definitions Figure 97 deals with multicast intra-flow applied network coding and Figure 96 with unicast inter-flow network coding. To end with illustration use case, Figure 97 depicts a multicast inter-flow applied network coding in wireless network. This example is the closest one from the Common Operational Picture service application.

Many different criteria can be considered to evaluate the performance gains of a solution. Here above, number of transmissions and time are pointed. Another important feature of network coding is the robustness assurance in the context of lossy environment. Network Coding provides an efficient redundancy in order to guarantee reliability [68], [69], [70]. This feature is particularly relevant in the COGEU context of Cognitive Radio Networks wherein radio resources can be pre-empted by a primary user (PMSE, DVB-T).

Here, only linear Network Coding is examined. Let us consider a set of N messages $M = \{m_1, ..., m_N\}$ all composed of B bits (e.g. $m_i = \{b_i 1, ..., b_i B\}$). Let $V = \{v_1, ..., v_N\}$ a set of N vectors of B coefficients such as $8v_i 2 V, v_i = \{c_i 1, ..., c_i b\}$. We define encoded message $M_{enc}$ built from messages from $M$, see Equation 1.

$$M_{enc} = \bigoplus_{i=1}^{N} v_i, m_i$$
Decoding process consists applying the XOR function onto $M_{enc}$ by using native messages. According to the definition given in [68], let $d$ be the number of native messages that have been encoded to compute $M_{enc}$ also called degree. In order to decode the message $M_{enc}$, at least $d - 1$ native messages are required.
Annex 7: Cognitive transport layer protocols – Cross layer with routing protocol in CRN

Task T6.3 of COGEU project will use output from previous WP6 work in order to assess legacy transport protocols and proposed enhancements to transport protocols. The methodology adopted is illustrated in Figure 98 below. The Network topology is presented using real TVWS map provided by T6.5.1. The routing algorithms will be simulated across Munich areas with heterogeneous TVWS availability (different TVWS pools available in different areas). The outputs from the routing simulations as a form of Packet error rate and delays will be used to emulate a CRAHN. Transports protocols studies will then take place on top of this Cognitive Radio Ad-Hoc Network in order to define strategies and algorithms for efficient congestion control mechanisms.

In the transport layer, modifications have to be made to TCP and UDP working in a cognitive radio environment to avoid performance degradation. Congestion control in TCP depends on the packet loss rate and the round-trip-time (RTT). With a wireless link, a TCP sender could mis-interpret packet loss due to wireless error as a sign of congestion. As a result, congestion avoidance and slow start mechanisms would be invoked. Some variants of TCP were proposed to cope with this problem in a wireless environment. For example, an indirect-TCP (I-TCP) splits a connection of wireless link from the wired link, so that each TCP connection can be optimized for wireless and wired networks, respectively.

In cognitive radio networks, many factors such as the transmit power, the bandwidth of the spectrum hole, and the interference level can affect the packet loss rate. Similarly, RTT can be affected by the delay due to spectrum sensing and spectrum handoff, for which when the current channel becomes unusable for an unlicensed user, the unlicensed user has to search for a new channel. Therefore, the transport layer protocol has to consider these effects to optimize end-to-end rate control.

Figure 98: COGEU Task 6.3 methodology