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Interference Management in Cognitive Radio Systems

Faculty of Electronics, Communications and Automation

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Currently, the radio spectrum is beginning to be crowded due to the rapid growth of wireless technologies this century. However, many studies show that the major licensed bands, such as those allocated for television broadcasting, amateur radio, paging, etc. are underutilized and some of the remaining bands are heavily used. This fact leads to spectrum wastage. Therefore, new techniques are needed to take advantage of the spectrum opportunities causing a reasonable level of interference in the licensed bands. Hence, cognitive radio has become an important research topic in these last years since it tries to take advantage of the unused spectrum by the licensed users. In addition to spectrum sensing algorithms, sharing protocols, policies, among other things, the interference management has become an important topic in cognitive radio in order to manage and fulfil the regulatory constraints. The management of interference is, unquestionably, required to treat and quantify all the interference produced by the unlicensed users at the licensed receivers. In order to manage this interference, the secondary users must be able to adjust their parameters to fulfil these constraints. In the current work is presented an overview of cognitive radio and interference management. Several quantitative and performance criteria are studied as well, in order to illustrate the effect that the different parameters produce on the interference in the licensed bands.
Acknowledgments

This Master’s thesis has been carried out in the Signal Processing Laboratory, which belongs to the Faculty of Electronics, Communications and Automation of Aalto University School of Science and Technology (TKK), during the year 2010. This research was done for the Master’s degree in Telecommunication Engineering.

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Finally, but not least, I would like to thank all my friends living in Finland and abroad, for their friendship and for giving me those great moments during one of the finest and exciting periods of my life, it was a pleasure to share it with you all.

I dedicate my Master’s degree to my mother and to the memory of my father.

Espoo, December 2010.

Ivan Pardina Garcia
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<tr>
<td>AMTPL</td>
<td>Allowable Maximum Transmit Power Level</td>
</tr>
<tr>
<td>AoA</td>
<td>Angle of Arrival</td>
</tr>
<tr>
<td>AoD</td>
<td>Angle of Departure</td>
</tr>
<tr>
<td>ATPC</td>
<td>Average Transmit-Power Constraint</td>
</tr>
<tr>
<td>AWGN</td>
<td>Additive White Gaussian Noise</td>
</tr>
<tr>
<td>AWMTM</td>
<td>Adaptative Weighting Multitaper Method</td>
</tr>
<tr>
<td>CAF</td>
<td>Cyclic Autocorrelation Function</td>
</tr>
<tr>
<td>CBS</td>
<td>Cellular Base Station</td>
</tr>
<tr>
<td>CDF</td>
<td>Cumulative Distribution Function</td>
</tr>
<tr>
<td>CDMA</td>
<td>Code Division Multiple Access</td>
</tr>
<tr>
<td>CR</td>
<td>Cognitive Radio</td>
</tr>
<tr>
<td>CSCC</td>
<td>Common Signalling Control Channel</td>
</tr>
<tr>
<td>CSI</td>
<td>Channel State Information</td>
</tr>
<tr>
<td>DARPA</td>
<td>Defence Advanced Research Projects Agency</td>
</tr>
<tr>
<td>DCM</td>
<td>Directional Channel Modelling</td>
</tr>
<tr>
<td>DDCM</td>
<td>Double Directional Channel Model</td>
</tr>
<tr>
<td>DoA</td>
<td>Direction of Arrival</td>
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<tr>
<td>DoD</td>
<td>Direction of Departure</td>
</tr>
<tr>
<td>DSA</td>
<td>Dynamic Spectrum Access</td>
</tr>
<tr>
<td>DSP</td>
<td>Digital Signal Processor</td>
</tr>
<tr>
<td>DSSS</td>
<td>Direct-Sequence Spread Spectrum</td>
</tr>
<tr>
<td>DySPAN</td>
<td>Dynamic Spectrum Access Networks</td>
</tr>
<tr>
<td>FCC</td>
<td>Federal Communications Commission</td>
</tr>
<tr>
<td>FDD</td>
<td>Frequency Division Duplex</td>
</tr>
<tr>
<td>GC</td>
<td>Graph Colouring</td>
</tr>
<tr>
<td>GP</td>
<td>Global Parameters</td>
</tr>
<tr>
<td>GSCM</td>
<td>Geometry-based Stochastic Channel Model</td>
</tr>
<tr>
<td>HMM</td>
<td>Hidden Markov Model</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
</tr>
<tr>
<td>INSR</td>
<td>Interference-Noise Signal Ratio</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
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</tr>
<tr>
<td>ITL</td>
<td>Interference Temperature Level</td>
</tr>
<tr>
<td>ITMA</td>
<td>Interference Temperature Multiple Access</td>
</tr>
<tr>
<td>IWFA</td>
<td>Iterative Waterfilling Algorithm</td>
</tr>
<tr>
<td>LOS</td>
<td>Line-Of-Sight</td>
</tr>
<tr>
<td>MAC</td>
<td>Medium Access Control</td>
</tr>
<tr>
<td>MIMO</td>
<td>Multiple-Input Multiple-Output</td>
</tr>
<tr>
<td>MMDS</td>
<td>Multichannel Multipoint Distribution Service</td>
</tr>
<tr>
<td>MPC</td>
<td>Multiple Path Channels</td>
</tr>
<tr>
<td>MTM</td>
<td>Multitaper Method</td>
</tr>
<tr>
<td>NE</td>
<td>Nash Equilibrium</td>
</tr>
<tr>
<td>NLOS</td>
<td>No Line-Of-Sight</td>
</tr>
<tr>
<td>OFDM</td>
<td>Orthogonal Frequency Division Multiplex</td>
</tr>
<tr>
<td>OSA</td>
<td>Opportunistic Spectrum Access</td>
</tr>
<tr>
<td>PBN</td>
<td>Packet Based Network</td>
</tr>
<tr>
<td>PFA</td>
<td>Probability of False Alarm</td>
</tr>
<tr>
<td>PITC</td>
<td>Peak Interference Temperature Constraint</td>
</tr>
<tr>
<td>PMD</td>
<td>Probability of Miss Detection</td>
</tr>
<tr>
<td>PN</td>
<td>Pseudo random Number</td>
</tr>
<tr>
<td>PN</td>
<td>Pseudo Noise</td>
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<tr>
<td>POMDP</td>
<td>Partially Observable Markov Decision Process</td>
</tr>
<tr>
<td>PR</td>
<td>Primary Receiver</td>
</tr>
<tr>
<td>PT</td>
<td>Primary transmitter</td>
</tr>
<tr>
<td>PU</td>
<td>Primary User</td>
</tr>
<tr>
<td>QoS</td>
<td>Quality of Service</td>
</tr>
<tr>
<td>RE</td>
<td>Radio Environment</td>
</tr>
<tr>
<td>ROC</td>
<td>Receiver Operating Characteristic curves</td>
</tr>
<tr>
<td>SCF</td>
<td>Spectrum Correlation Function</td>
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<tr>
<td>SCM</td>
<td>Spatial Channel Model</td>
</tr>
<tr>
<td>SCME</td>
<td>Spatial Channel Model Extended</td>
</tr>
<tr>
<td>SD</td>
<td>Sequential Detection</td>
</tr>
<tr>
<td>SDR</td>
<td>Software-Defined Radio</td>
</tr>
<tr>
<td>SINR</td>
<td>Signal to Interference-Noise Ratio</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
</tr>
<tr>
<td>SR</td>
<td>Secondary Receiver</td>
</tr>
<tr>
<td>SSA</td>
<td>Statistic Spectrum Access</td>
</tr>
<tr>
<td>ST</td>
<td>Secondary Transmitter</td>
</tr>
<tr>
<td>SU</td>
<td>Secondary User</td>
</tr>
<tr>
<td>SUI</td>
<td>Standford University Interim</td>
</tr>
<tr>
<td>SVD</td>
<td>Singular Value Decomposition</td>
</tr>
<tr>
<td>TDD</td>
<td>Time Division Duplex</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<td>--------------</td>
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</tr>
<tr>
<td>TDMA</td>
<td>Time Division Multiple Access</td>
</tr>
<tr>
<td>TDoA</td>
<td>Time Delay of Arrival</td>
</tr>
<tr>
<td>TM</td>
<td>Transmit Margin</td>
</tr>
<tr>
<td>WIM</td>
<td>WINNER Phase I Channel Model</td>
</tr>
<tr>
<td>WPAR</td>
<td>Weighted Probability of Area Recovered</td>
</tr>
<tr>
<td>WPTR</td>
<td>Weighted Probability of Time Recovered</td>
</tr>
<tr>
<td>XG</td>
<td>Next Generation</td>
</tr>
<tr>
<td>ZDSC</td>
<td>Zero Delay Spread Cluster</td>
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# List of Symbols

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<th>Symbol</th>
<th>Description</th>
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<tr>
<td>$A_{pcov}$</td>
<td>Coverage area of the PTs</td>
</tr>
<tr>
<td>$A_{prot}$</td>
<td>Protected radius area of the PTs</td>
</tr>
<tr>
<td>$I_0 (\cdot)$</td>
<td>Bessel function of first kind and zero-order</td>
</tr>
<tr>
<td>$K$</td>
<td>Ratio between specular component and multipath mean power</td>
</tr>
<tr>
<td>$L_{pcov}$</td>
<td>Attenuation between the PT and the coverage radius in decibels</td>
</tr>
<tr>
<td>$L_{spi}$</td>
<td>Received power after first order shadowing</td>
</tr>
<tr>
<td>$L_{sp}$</td>
<td>Received power after shadowing calculation with spatial correlation</td>
</tr>
<tr>
<td>$L_{time}$</td>
<td>Received power after shadowing calculation with temporal correlation</td>
</tr>
<tr>
<td>$P_n$</td>
<td>Noise power in decibels</td>
</tr>
<tr>
<td>$P_{t1}$</td>
<td>Power transmitted by PTs in decibels</td>
</tr>
<tr>
<td>$\cap$</td>
<td>Set-theoretic intersection</td>
</tr>
<tr>
<td>$\cup$</td>
<td>Set-theoretic union</td>
</tr>
<tr>
<td>$\gamma_{pcov}$</td>
<td>SNR at the at the edge of the coverage radius for the PUs</td>
</tr>
<tr>
<td>$\gamma_{prot}$</td>
<td>SNR at the at the edge of the protected radius for the PUs</td>
</tr>
<tr>
<td>$P_{FH}$</td>
<td>Probability of finding a spectrum hole</td>
</tr>
<tr>
<td>$P_{fr}$</td>
<td>Probability of interference</td>
</tr>
<tr>
<td>$P_{nFH}$</td>
<td>Probability of no finding a spectrum hole</td>
</tr>
<tr>
<td>$P_{nfr}$</td>
<td>Probability of no interference</td>
</tr>
<tr>
<td>$S_{HI}$</td>
<td>Safety of no harmful interference</td>
</tr>
<tr>
<td>$r_{max}$</td>
<td>Maximum distance used in the simulations</td>
</tr>
<tr>
<td>$A$</td>
<td>Amplitude of a signal</td>
</tr>
<tr>
<td>$A (\cdot)$</td>
<td>Mean squared magnitude of different channel impulse responses</td>
</tr>
<tr>
<td>$B$</td>
<td>Signal bandwidth</td>
</tr>
<tr>
<td>$B_c$</td>
<td>Coherence bandwidth</td>
</tr>
<tr>
<td>$B_k^i$</td>
<td>Maximum interference power at the user $i$th in the subcarrier $k$th calculated over all the users</td>
</tr>
<tr>
<td>$B_{max}$</td>
<td>Maximum bandwidth</td>
</tr>
<tr>
<td>$C$</td>
<td>Capacity in bits per second</td>
</tr>
<tr>
<td>$E (\cdot)$</td>
<td>Mathematical expectation or first moment</td>
</tr>
<tr>
<td>$F (x)$</td>
<td>Prechange density function</td>
</tr>
</tbody>
</table>
$F_0(x)$  
Postchange density function

$F_{HI}$  
Fear of harmful interference

$F_r$  
Distribution probability function of the combined multipath and shadowing-induced fading at a distance $r$

$G_r$  
Gain of the receiver

$G_t$  
Gain of the transmitter

$I_k^i$  
Interference power inserted by the user $i$th in the subcarrier $k$th

$K$  
Ratio between specular component and multipath averaged power

$L$  
Attenuation value in decibels

$L_{rep}$  
Number of replicas of a transmitted signal

$M$  
Parameter for fast fading uncertainty in decibels

$M_h$  
Channel attenuation parameter combining fading and path loss in linear units

$P$  
Received power in decibels

$PS$  
Subset of used subcarriers by licensed users that can not be used by the unlicensed one

$P_t$  
Transmitted power in decibels

$R(\cdot)$  
Correlation function

$S(\cdot)$  
Parameter for shadowing uncertainty in decibels

$S(\cdot)$  
Defines the Doppler spectrum

$T$  
Temperature in Kelvins

$T_I$  
Interference temperature

$T_L$  
Interference temperature limit

$T_N$  
Gaussian noise temperature

$T_c$  
Coherence time

$T_s$  
Symbol period

$U_i$  
Utility function of the user $i$th

$Y_{k}^m$  
$k$th eigenspectrum computed by the $m$th sensor

$\Delta$  
Defines an increment

$\Gamma(\cdot)$  
Gamma function

$\alpha$  
Attenuation constant of path loss

$\beta$  
Number defining a set of probability distributions $F_r$

$\text{mod}(\cdot)$  
Modulus operation

$\delta(\cdot)$  
Dirac delta function or unit impulse function

$\eta$  
Maximum interference level allowed by a primary receiver

$\gamma(d, \beta)$  
Received power taking into account the distribution $\beta$

$\gamma_k^i$  
SNR at the user $i$th in the subcarrier $k$th

$\hat{\cdot}$  
Estimation of some quantity

$\lambda$  
Propagation wavelength

$\lambda_{th}$  
Detection threshold in spectrum sensing

$(\cdot)^T$  
Transpose matrix
\((\cdot)^\dagger\) Conjugate transpose matrix
\(F\) Set of center frequencies
\(F_r\) Set of possible density distributions for a received signal
\(A\) Matrix of elements
\(a\) Vector of elements
\(u_k\) Left singular vectors
\(v_k\) Right singular vectors
\(\mathcal{H}_0\) Defines the binary detection 0
\(\mathcal{H}_1\) Defines the binary detection 1
\(\mathcal{N}(\cdot)\) Normal o Gaussian probability distribution
\(\mathcal{P}\) Denotes probability
\(\mathcal{P}_{FH}\) Probability of finding a spectrum hole
\(\mathcal{P}_{pb}\) Collision probability for PU
\(\mathcal{P}_p\) Probability of overlapping time for SU
\(\mathcal{P}_{sc}\) Collision probability for SU
\(Q^{-1}\) Inverse Gaussian probability function
\(WF^k_q\) Waterfilling algorithm over the \(k\)th subcarriers for \(q\)th link
\(\text{insr}_q(k)\) Inverse of the signal to noise ratio over the \(k\)th subcarriers for \(q\)th link
\(\mu(d)\) Received power considering the effect of fading
\(\mu_L\) Mean of the attenuation Lin decibels
\(\mu_\alpha\) Mean of the path loss exponent \(\alpha\)
\(\mu_{\sigma_s}\) Mean of the variance of channel distribution \(\sigma_s\) produced by fading
\(\mu_q\) Level of water for Waterfilling algorithm
\(\mu_s\) Mean of the channel distribution produced by fading
\(\nu\) Frequency in Doppler spectrum
\(\omega_m\) Weights for different sensor locations in multitaper method
\(\rho_{SU}\) Density of secondary users in users/Km\(^2\)
\(\sigma^2\) General term of statistical variance
\(\sigma_L\) Standard deviation of the attenuation Lin decibels
\(\sigma_\alpha\) Standard deviation of the path loss exponent \(\alpha\)
\(\sigma_{\sigma_s}\) Variance of the variance of channel distribution \(\sigma_s\) produced by fading
\(\sigma_k\) \(k\)th singular value
\(\sigma_{ss}^2\) Mean power of the scattered multipath signals in fast fading channels
\(\sigma_s^2\) Variance of channel distribution produced by fading
\(\tau\) Variable of continuous time for replicas of a transmitted signal
\(\tau_i\) Time of arrival of replicas of a transmitted signal \(i\)
\(\tau_{rms}\) Root mean square of a channel
\(\theta_R\) Reception angle in directional channel impulse responses
\(\theta_T\) Transmission angle in directional channel impulse responses
\(v\) Velocity in \(m/s^2\)
\( \varepsilon_D \) Correlation between two points separated by distance \( D \)

\( \xi \) Maximum allowed probability of error detecting the presence of the primary signal

\( \zeta \) Parameter for fast fading in linear units

\( a \) Adjustment parameter

\( a_i \) Time-varying complex amplitude of the \( i \)th replica of a transmitted signal

\( b_k \) Maximum interference power at the user \( i \)th in the subcarrier \( k \)th

\( d \) Distance in metres

\( d_0 \) Reference distance

\( d_{\text{corr}} \) Correlation distance for shadowing

\( f \) Frequency in Hertz

\( f_X \) Probability density function

\( f_\Delta \) Frequency increment

\( f_\varepsilon \) Frequency security margin for the spectrum lateral lobes

\( f_c \) Centre frequency

\( f_d \) Maximum Doppler frequency

\( f_{\text{max}} \) Maximum frequency

\( f_{\text{min}} \) Minimum frequency

\( h \) Channel transfer function

\( h_i \) Channel transfer function of the user \( i \)th

\( i(t) \) Function of interference as a function of time \( t \)

\( k \) Boltzmann constant \( 1.3806503 \times 10^{-23} \text{ m}^2\text{kg}^{-1}\text{s}^{-2}\text{K}^{-1} \)

\( k_d \) Separation distance in meters between for shadowing

\( l \) Attenuation value in linear units

\( l_{\text{max}} \) Maximum attenuation

\( n(t) \) Function of additive Gaussian white noise as a function of time \( t \)

\( p \) Received power in linear units

\( p_i \) Power transmitted by the user \( i \)th

\( p_{i\text{max}} \) Maximum transmission power of the user \( i \)th

\( p_{k\text{max}} \) Maximum allowed power in the channel \( k \)th

\( p_{1\text{rp}} \) Power of the PTs received at the edge of the \( r_{\text{prot}} \)

\( p_{1\text{min}} \) Minimum power at PR for error free reception

\( p_{2\text{rp}} \) Power of the STs received at the edge of the \( r_{\text{prot}} \)

\( p_{2\text{min}} \) Minimum power at SR for error free reception

\( p_I \) Interference power

\( p_i \) Power transmitted by the user \( i \)th

\( p_{i\text{max}} \) Maximum transmission power of the user \( i \)th

\( p_k \) Power transmitted by the user \( i \)th in the subcarrier \( k \)th

\( p_l \) Power limit in linear units

\( p_n \) Noise power

\( p_{1\text{t}} \) Transmitted power by the PT in linear units

\( p_{2\text{t}} \) Transmitted power by the ST in linear units
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<tr>
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<td>No interference radius between STs and PRs</td>
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<tr>
<td>$r_{SR}$</td>
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<tr>
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<td>Non-talk radius for SUs</td>
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Chapter 1

Introduction

Due to the huge growth of all wireless technologies since about 2000, the radio spectrum is beginning to be crowded. Nevertheless, it has been found that the major licensed bands, such as those allocated for television broadcasting, amateur radio, paging, etc. are under-utilized and some of the remaining bands are heavily used. This fact leads to a wastage of spectrum. Therefore, new techniques are needed to take advantage of the spectrum opportunities causing a reasonable level of interference in the licensed system. In addition to spectrum sensing algorithms, sharing protocols, policies, among other things, interference management has also become an important topic in cognitive radio in order to manage and fulfil the regulatory constraints.

The most common operation ways for a cognitive radio system are the overlay and the underlay approach, as it will be explained in Chapter 2. In the overlay operation the cognitive system tries to take advantage of the frequency and temporal holes, operating in the spectrum bands of the primary user by using the same features as bandwidth, transmission power, etc. as the licensed users. In this case, the unlicensed users should be aware of the technology used by the licensed users. In regard to the underlay approach, the method tries to take advantage mainly of the spatial holes.

An important issue to deal with the interference are the quantitative criteria. Quantitative criteria may be defined as a reference point or quantity with which other parameters can be evaluated. In order to allow the unlicensed operation, the licensed system should sacrifice as well some of its features. Some examples of quantitative criteria can be the protection radius $r_{prot}$ for the primary system, which is the radius where the decodability of the signal is guaranteed, the non-talk radius $r_n$, where the secondary users are not allowed to transmit, and others. All of these criteria will be presented in Section 5.2. Indeed, the goal of these criteria is to avoid harmful interference experienced by licensed users.

In order to evaluate the performance of the coexistence between the licensed and the unlicensed system, performance criteria will be used. Performance criteria may be defined as a reference point in order to evaluate the behaviour of the other parameters of the same kind.
Nowadays, several performance criteria have already been studied, as Section 5.3 will show. For instance, some of them are the well-known probability of miss detection (PMD) and probability of false alarm (PFA), which are widely used to determine the performance of the unlicensed system under system-level uncertainties. These last performance quantities are used as well in the receiver operating characteristic curves (ROC), which are a widely used tool to test and check the performance of any spectrum sensing detector. Other performance criteria which have already been studied are the sensitivity, the detector overhead, SNR wall, probability of interference ($P_{fr}$), probability of fear of harmful interference ($F_{HI}$), probability of finding a spectrum hole ($P_{FH}$) and weighted probability of area recovered (WPAR). In the overlay approach other measurements can be found. These include the probability of collision ($P_c$), the probability of overlapping time ($P_{rp}$), as well as the weighted probability of time recovered (WPTR), which measures the burden of sensing time relative to OFF times of the primary transmitter. Notice that these performance criteria could be divided into three types: the ones in order to evaluate the behaviour of the unlicensed system over the licensed one, the ones which evaluate purely the performance of the unlicensed system and, finally, the criteria which evaluate both performances.

Another interesting issue in interference management, which will be studied in Section 5.4, is the interference temperature technique. This technique uses the knowledge of the level of interference power limit at the primary receivers in order to compute the interference level that the secondary users can generate at them. This technique was introduced by the FCC, although it was abandoned by the same commission as unworkable in 2007, due to the problem of locating the primary receivers. Nevertheless, there are some techniques which can be used to identify where the primary receivers could be located. In spite of dismissing this approach, it is still researched.

Therefore, in Chapter 2 an overview will be given about cognitive radio systems which includes the definition of important concepts such as spectrum holes, dynamic spectrum access (DSA) and others. A brief survey about the propagation models used in cognitive radio will be explained in Chapter 3. In Chapter 5 the current different techniques and methods to manage the interference are described. Different optimal power control techniques in cognitive radio will be presented in Chapter 6. A brief survey of different spectrum sensing techniques is shown in Chapter 4. Finally, Chapter 7 will show the evaluation of some criteria explained in the work and, Chapter 8, finishes the work with conclusions and recommendations for further study.

1.1 Scope of the thesis

The management of interference is, unquestionably, required to treat and quantify all the interference produced by the unlicensed users. In order to manage this interference, these users must be able to adapt it to the constraints established by the policies of the regulatory
bodies. In the current work, several quantitative criteria and performance criteria are combined to identify the performance of a real cognitive system operation and to illustrate what is the effect on the licensed system.

So that, given some fixed quantitative criteria as the protected radius $r_{prot}$ of the primary system, the probabilities of miss detection, false alarm, harmful interference, collision, etc. the unlicensed system should be capable of respecting these constraints by modifying other parameters as the transmission properties of the unlicensed users, computing the "non-talk" radius, changing the density of unlicensed users, etc. An interesting experiment then, is to see and check what is the real produced interference in the primary system, as well as the performance criteria quantities. Another interesting study to do is how to find the optimal secondary user parameters to optimize the performance criteria quantities. The power control algorithms, using techniques such as Waterfilling, have been studied as well to manage the interference produced by the unlicensed users and reduce the non-talk radius. However, in an ideal case, the knowledge of the level of current interference at the primary receivers is needed.

Therefore, the scope of the thesis is to give the reader an overview of cognitive radio systems and study how the interference management is done. The analysis and the evaluation of some performance and quantitative criteria is studied as well, in order to see what is the behaviour of the cognitive system and analyse the produced interference in the unlicensed one. The SNR of the unlicensed users will be evaluated as well as some power control algorithms.
Chapter 2

Overview of cognitive radio systems

In order to have a general idea about the current state and the main concepts of cognitive radio, some basic concepts, definitions, standardization and regulatory issues will be explained in this section. Notice that, throughout the thesis, the licensed users can be referred to primary users as well. Likewise, the cognitive users can be called unlicensed and secondary users. The first section defines the concept of a cognitive radio system. Different proposed definitions will be given as well as the addressed problems [1, 3, 23, 24]. In the second section are explained the current approaches about Dynamic Spectrum Access (DSA) taking into account the regulatory policies [3, 25–30]. The third section explains the spectrum hole concept [1, 2, 7, 30, 31], which will be really important since one of the main goals of cognitive radio systems is based on finding the spectrum holes in space, frequency as well as in time and exploiting its advantages. Finally, a brief overview of the status in the standardization and current work groups will be presented [32–37].

2.1 Introduction

The cognitive radio approach has been introduced as a paradigm to solve, where many aspects of communication can be improved through cognition by using the underutilized licensed spectrum. Before cognitive radio, the concept of software-defined radio (SDR) was introduced by Mitola in 1991 [23]. It is defined as a multiband radio supporting multiple air interfaces and protocols being reconfigurable through software run on DSP or general-purpose microprocessors [3]. The concept of cognitive radio was also introduced by Mitola in 1998 [38] and it was defined as [24] a radio that employs model based reasoning to achieve a specific level of competence in radio-related domains. Although many definitions of cognitive radio can be found, another important one has been released by Simon Haykin. Thus, in [1] it is defined as an intelligent wireless communication system that is aware of its surrounding environment (i.e., outside world), and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the
incoming RF stimuli by making corresponding changes in certain operating parameters (e.g., transmit-power, carrier frequency, and modulation strategy) in real-time, with two primary objectives in mind:

- **Highly reliable communications whenever and wherever needed.**
- **Efficient utilization of the radio spectrum.**

In other words, cognitive radio is a context-aware smart radio, built on an SDR platform, capable of autonomous reconfiguration by learning from adapting to the communication environment [3]. Thus, cognitive radio has many applications in the radio communications area. One of the most important applications of cognitive radio has become the Dynamic Spectrum Access (DSA), where radios learn from the radio communication environment which features and at what moment cognitive radios can use licensed channels. The goal of this application, as explained above, is to take advantage of free channels in time, space and frequency used by the licensed users, avoiding the harmful interference at them and the degradation of its quality of service (QoS). The main problem of this application is how to avoid the harmful interference caused to licensed users. This leads to other open problems such as reliable signal sensing, medium access control (MAC) among cognitive radios, positioning, etc. There are many challenges that should be solved before any functional cognitive radio system can be deployed.

Once all the problems have been overcome, any functional deployed cognitive radio system should have at least the following features [7]:

- A cross-layer cognitive network architecture capable of managing different QoS requirements.
- Efficient spectrum sensing techniques which provide continuous monitoring of the spectrum with lower sensing time.
- DSA methods able to adapt to the fluctuating nature of the cognitive radio system and allocate the bandwidth accordingly.
- Adaptive spectrum sculpting at the transmitter end that causes minimal or no interference to the primary users occupying adjacent bands.

In any cognitive radio system, the main cognitive tasks should work according to the cognitive cycle shown in Figure 2.1. The cognitive cycle can be defined by the next features: Radio-scene analysis, channel identification and transmit-power control. The radio-scene analysis works on the estimation of interference temperature of the radio environment and the detection of spectrum holes, realized in the cognitive receivers. Channel identification encompasses the estimation of channel-state information (CSI) and the prediction of the
used channel capacity. It is also realized in the cognitive receivers. The transmit-power control works on the optimum transmission power at the secondary users in order to keep the constraints, taking place in the cognitive transmitter. Finally, the dynamic spectrum management, which is the responsible of managing the spectrum access, takes place in the cognitive transmitter as well.

![Cognitive device](image)

Figure 2.1: Cognitive cycle shows the different states that any cognitive radio device must be able to follow by sensing the radio environment. In this flowchart two kinds of cognitive devices can be distinguished, the receiver and the transmitter [1].

### 2.2 Spectrum holes

As it was explained in 2.1, the electromagnetic spectrum is underutilized. This leads to the concept of a spectrum hole which can be defined as [1]: a band of frequencies assigned to a primary user, but at a particular time and specific geographic location, the band is not being utilized by that user. In order to improve the spectrum utilization it is possible to allow secondary users to access a spectrum hole unoccupied by the primary system at the right location and the time in question. Cognitive radio has been suggested to promote the efficient use of the spectrum by exploiting the existence of spectrum holes. Any kind of spectrum hole enables the term of Opportunistic Spectrum Access (OSA) (Section 5.1) [39], which defines the opportunistic access of the unlicensed system to the resources of the licensed users when there is some possibility to do it. The term will be explained in greater
2.2 Spectrum holes

The spectrum holes can be identified and vary over time, space and frequency, which are defined below [2, 7].

**Temporal spectrum holes** mean that there is no signal coming from primary users over the band of interest during the sensing time. So that, the secondary users can use that spectrum band while the primary signal is absent. In such a case, the secondary users are located inside the coverage area of the primary transmitters.

**Spatial spectrum holes** mean that spectrum band of interest is busy by the primary transmitter but only in a restricted area. In other words, this spectrum band will be able to be used by secondary users being outside of this restricted area. Nevertheless, the secondary transmission is only allowed if the signal does not interfere with the primary receivers inside the coverage area.

**Frequency spectrum holes** are defined as a frequency band in which a secondary user can transmit without interfering with any primary receivers across all frequencies.

The secondary network need to identify when, where and in which band it is possible to transmit information without causing harmful interference to primary receivers. The secondary users should identify the OFF-times of the primary transmitter as well as where the secondary device can always transmit without problems and, afterwards, in which band. While detecting a frequency spectrum hole, it is not enough to detect one free band to consider that it is in reality a spectrum hole. The secondary user can still interfere with a primary system transmitting in an adjacent band due to imperfect filters [31].

It is possible to identify three different types of spectrum holes in space, which are defined as the following [1]:

- **Black spaces** are occupied by high-power local interferers most of the time.
- **Grey spaces** are partially occupied by low-power interferers.
- **White spaces** are free of radio interferences (excluding ambient noise), which is generated by natural and artificial forms of noise. The artificial form of noise noise can be generated as broadband thermal noise, transient reflections or impulsive noise.

In the classification of spatial spectrum holes shown above, the unlicensed users are only allowed to transmit when the grey and white spaces are detected.

An example of a spatial spectrum hole is shown in Figure 2.2. The $r_{pcov}$ is the maximum radius where the primary receivers can decode properly the signal from the primary transmitter. Another parameter is $r_{prot}$, defined as the protection radius where all the primary receivers have guaranteed a specific QoS and a error free reception. In order for all the primary receivers inside the $r_{prot}$ radius to have a guaranteed QoS, it is necessary to specify
2.2 Spectrum holes

Overview of cognitive radio systems

Figure 2.2: A spectrum hole in space is shown in the figure, where $r_{pcov}$ is the coverage radius of the primary transmitter, $r_{prot}$ is the radius where the primary receiver must decode the signal with a minimum service level and $r_n$ is the non-talk radius needed to ensure some level of service at the edge of the $r_{prot}$. Therefore, all the area outside $r_n$ radius can be recovered [2].

another security radius called the non-talk radius $r_n$, which depends on the transmit power of the secondary users. The non-talk radius establishes a security distance in order to give all the users inside the protection radius the desired QoS, while avoiding the harmful interference coming from the unlicensed users. On the other hand, all the primary receivers located in the area $r_{pcov} - r_{prot}$ can experience some interference when the secondary system turns on. This area is called the sacrificial zone [2]. Some primary users should accept some kind of interference to allow the secondary system to operate.

In Figure 2.2.b, the non-talk radius is considered as the worst case, where the primary receivers are considered to be at the edge of the protected radius $r_{prot}$ assuming that all the secondary users are transmitting at their maximum power. It is a more realistic case since the location of the primary receivers is unknown. In other words, if the secondary system knows exactly the location of the primary receivers, and by taking into account the transmission power of each secondary transmitter, it is possible to know where the real spectrum hole is and its shape, as it is shown in Figure 2.3.a.

Figure 2.4 shows one example of a spectrum hole in time. In this example, the primary system starts the transmission and when the channel becomes free, the secondary system needs a period of time to detect the spectrum hole. Consequently, there is a period of time when the transmission opportunity is lost. The same occurs when the primary systems transmits again. In this case, the secondary system needs a period of time to detect that the channel becomes occupied. In this period of time, the secondary system is interfering with the primary receivers but, because of the non-talk radius, only the primary receivers
2.2 Spectrum holes

Figure 2.3: Picture A shows a spatial spectrum hole knowing the real location of the primary receivers and the transmitted power by secondary transmitters. On the other hand, picture B considers the worst case, where all the secondary transmitters have the same transmission power. In the pictures the parameter $r_{PR}$ is the no interference radius between secondary transmitters and primary receivers.

located inside the sacrificial area encounter interference during this time. As a result, all the protected users maintain the same QoS. Finally, whole the area outside the non-talk $r_n$ of each primary transmitter, represents the recovered area in space.

In order to take even more advantage of the secondary network, power control would be a good solution to decrease the non-talk radius and to make a larger useful area for the unlicensed users. Figure 2.3.b shows the case where all the closest secondary nodes to the coverage radius $r_{pcov}$ a could transmit at the needed power to make the non-talk radius $r_n$ the same as the coverage radius $r_{pcov}$. In Chapter 6 can be found further details about power control in cognitive radio.

Figure 2.4: This temporal slot shows the spectrum hole in time, where the time needed by the sensing unit to detect the presence of the signal can be seen. The interference that the unlicensed users can generate due to the same sensing time is also shown in the point where the arrow is [2].

9
2.3 Dynamic Spectrum Access (DSA)

Nowadays, the spectrum management relays on Static Spectrum Access (SSA), therefore, all the spectrum bands need an owner with license to use the band. This strategy has some disadvantages as the long time that getting spectrum resources can take since it depends on the regulation bodies. Furthermore, with this spectrum policy the spectrum is used in a very inefficient way and it becomes underutilized. This underutilization is an important fact because the overall availability of spectrum resources is very limited.

On the other hand, cognitive radio systems use Dynamic Spectrum Access (DSA) technology to manage the access to empty spaces in the licensed spectrum in a dynamic way. The DSA depends on time, space and frequency. The term dynamic spectrum access has wide connotations that encompass various approaches to spectrum reform [3]. Several different ideas have been suggest to extend the DSA concept. Thus, the suggested DSA strategies are divided into three models which are shown in Figure 2.5 [3]. Below, the basis of these models are explained [3,25,26].

**Dynamic exclusive use model**

The model is similar to the current spectrum management or SSA, where all the users need a license to use the spectrum resources. It is possible to identify two approaches, as seen in Figure 2.5. Spectrum property rights allows to the users with property right to have different flexibilities. In other words, the users could use the spectrum bands with any service and technology or they just could use a specific service and technology. When the users are working using this approach, it is possible to get licenses for a long time or just for temporary usage. Thus, the licensees could sell, lease and trade the assigned spectrum and use it with any technology. On the other hand, dynamic spectrum allocation allows sharing the spectrum between different services according to the observed traffic statistics.
This approach helps to improve the spectrum efficiency. Most of the used services have some peak hours and hours when the utilisation is very low as well. So then, depending on the region and on the time, some services are unused and the spectrum becomes free. This system, for example, can take advantage of the people who are moving from residential to business areas, or other variations as holidays, important events, etc.

**Open sharing model**

This model works with a shared spectrum among devices. All the devices have the same priority to access communication services and they must share the spectrum through techniques such as cooperation or just co-existing. According to the sharing technique it is necessary for a protocol to manage the spectrum.

**Hierarchical Access Model**

This model establishes a hierarchical structure between the primary system, the license owner and the unlicensed system which tries to access the licensed spectrum without harmful interference. The interference constraints should be imposed by the licensed owner to avoid the reduction of QoS by the transmitted signals of the secondary system. In this access model, there are three important suggestions explained below: spectrum underlay, spectrum overlay and interwave.

Regarding the spectrum underlay approach, this technique has important restrictions on the transmitted power by secondary users. When the primary system signal is present in the licensed band, the transmitted power by unlicensed users should be zero in that bands or below the noise floor allowed by primary users. There is another concept proposed by the FCC Spectrum Policy Task Force called interference temperature [27] explained in Section 5.4. This strategy is based on the interference (interference temperature limit) that the primary receivers are able to allow without causing an important loss of QoS. In this concept it is necessary that the regulatory bodies choose an interference temperature limit. So that, it is possible to produce interference up to the noise floor of the primary receivers. It could use some techniques such as Direct Sequence Spread Spectrum (DSSS), in order to spread the unlicensed transmitted power at the level of the noise at the primary receivers. So that, the unlicensed does not need to know necessarily the technology used by the licensed users. In that sense, using the DSSS technique, different spreading sequences might be used in each unlicensed transmitter, as it is used in cellular mobile networks. Thus each unlicensed receiver would be able to distinguish the several unlicensed transmissions and decode just the right one. For further information about the interference temperature approach see Section 5.4.

The second approach, called spectrum overlay, is based on detecting the presence of the primary signal in order to find out white spaces (see Section 2.2) in the licensed spectrum.
The availability will depend on the location, on the time when the secondary device is sensing and on the frequency band. Once one white space has been detected, the secondary device tries to exploit it without causing harmful interference to the primary receivers. With this methodology it is not necessary to set hard constraints to the transmission power of the secondary devices. This last approach is one of the most studied in cognitive radio topics. It has been studied by DARPA Next Generation (XG) and called Opportunistic Spectrum Access (see Section 5.1).

2.4 Status in standardization

Currently, there are some organizations which are already working on the standardization of a cognitive system [32]. The IEEE 802 community [34] is developing two standards which are strongly related to the use of cognitive radio technology, the 802.22 and 802.11h. The group 802.11k is working on new techniques to add radio resource management information in WLAN by using data about the environment and the radios. The 802.22 group is trying to achieve spectral efficiencies of up to 3 bits/sec/Hz, corresponding to peak download rates at coverage edge at 1.5 Mbps up to 100 Km in coverage [33]. The fact that the working group 802.11h is not considered as a cognitive radio standard, the dynamic frequency selection has been defined as a cognitive function. This cognitive function is based on observation, orientation, decision and action in the 802.11h case. Other different entities have started to work on different cognitive radio initiatives, for example DARPA [35], the SDR Forum [36], the FCC [37] and some more initiatives in different working groups of IEEE. The DARPA organization is currently studying several issues of cognitive radio as part of the next generation programme technologies and others. The SDR forum has developed two groups in 2004 in order to research cognitive radio. One of the groups is the Cognitive Radio Working Group which is working on standardizing a definition of cognitive radio and identifying the enabling technologies. The other SDR group, the special interest group, is working on identifying commercial applications. In the case of IEEE, the IEEE 1900 group has been started to study the issue of cognitive radio and has been divided into some different subgroups [32,40]:


**1900.2** Working Group on Recommended Practice for the Analysis of In-Band and Adjacent Band Interference and Coexistence Between Radio Systems.

**1900.3** Working Group on Recommended Practice for Conformance Evaluation of Software Defined Radio (SDR) Software Modules.
2.4 Status in standardization


1900.6 Working Group on Spectrum Sensing Interfaces and Data Structures for Dynamic Spectrum Access and other Advanced Radio Communication Systems.

The IEEE organization has created as well the Dynamic Spectrum Access Networks (DySPAN) in November 2005. This is based on cognitive radio issues such as: technologies and techniques needed to implement any cognitive radio system, regulatory issues, opportunities in the market and first implementation of cognitive radio systems and its initial performance. On the other hand, the FCC has conveyed a workshop to study the impact of cognitive radio on spectrum utilization and the regulatory issues.
Chapter 3

Propagation models for cognitive radio

A propagation model is the physical medium electromagnetic wave propagation between the transmitter and receiver antennas, and includes all the external physical objects which can modify or produce influences in the propagation way between these two antennas. Indeed, it will affect the detection of the primary signal as well as the detection of spectrum holes in space, time and frequency. Other factors where the propagation model has an important impact are the probability of false alarm (PFA), the probability of miss detection (PMD) and the majority of performance criteria.

There exists the standardization IEEE 802.22 working group which is nowadays working on how to enable rural broadband wireless access using cognitive radio technology in TV whitespaces [41]. This working group is also developing and studying possible suitable models and parameters to use in these kinds of environments, as well as different other working groups in different wireless technologies.

Thus in this section will be explained different channels used in cognitive radio systems, to study the behaviour in these systems facing different kinds of propagation models. The generalized path loss and fading models [4,19,42] will be presented in this section as well as some standardized propagation and double directional models, distinguishing then between radio channel (considering the antenna effects) and propagation channel (excluding the antenna effects) [43,44]. For further information about propagation models see [45,46].

3.1 Generalized models

First of all, it is important to give some details about some generalized models and the factors having an effect on the received power. This generalized formula, which will be called the nominal model, should take into account at least the path lost, fading, shadowing effect,
3.1 Generalized models

Propagation models for cognitive radio

the additive white Gaussian noise and the antenna gains. So that, the proposed nominal model in decibels is [2,31]:

\[ P = P_t + G_t + G_r - (L(d) + S + M), \] (3.1)

where \( S \) is the parameter for the shadowing, \( M \) is the parameter for fading, \( L(d) \) is the path loss defined by \( L(d) = 10 \log (d^\alpha) \), \( G_t \) and \( G_r \) are the gain of the transmitter and receiver antenna respectively and \( P_t \) is the transmitted power. Using, for example, this generalized model in order to compute the weighted probability of area recovered (WPAR)(Section 5.3), several assumptions are proposed. The parameters \( S \) and \( M \) are considered to be independent of \( d \) and \( S + M \) is assumed to be Gaussian, therefore \( S + M \sim N(\mu_s, \sigma_s^2) \). Given this assumption, by considering the path loss the receiver power is approximated by \( P \sim (\mu(d), \sigma_s^2) \) where \( \mu(d) = P_t - (L(d) + \mu_s) \). According to IEEE 802.22 [47], the value of the mean \( \mu_s \) and the standard deviation \( \sigma_s \) can be chosen \( \mu_s = 0 \) dB and \( \sigma_s = 5.5 \) dB.

In the literature can be found another approach called the quantile model [31]. These kinds of models use a quantized version of the fading distribution, which tries to model the fact that the primary transmitter does not trust completely the nominal model [2,31]. Thus, to compute some quantitative performance measurements as the fear of harmful interference \( F_{HI} \) (see Section 5.3), it is more realistic to use this kind of model. As explained before, with these models the primary users do not trust completely in the nominal model, but they only trust in a coarse histogram of the fading distribution. So then, given a set of distributions for the received signal \( F_r \) defined by a single number \( 0 \leq \beta \leq 1 \), it is possible to define the function \( \gamma(d, \beta) \), as a function of the distance \( d \) and some distribution \( \beta \). If the function \( F_r \) is the real distribution then \( F_r \in F_r \) and it is if and only if [31]:

\[ P_{F_r} (P < \gamma(d, \beta)) = \beta. \] (3.2)

Thereby, the k-quantile model is the quantification of the previous expression. Given a set of distributions \( F_r \), the possible distribution is defined by discrete parameters. Therefore, the \( \gamma \) function is defined as \( \gamma(d, \beta_1), \ldots, \gamma_k(d, \beta_k) \). By rewriting Equation (3.2) it is obtained \( P_{F_r} (P < \gamma_k(d, \beta_k)) = \beta_k \). The k-quantile models are chosen taking into account that the nominal Gaussian model can be a possible distribution for the receiver power \( P \). Hence, it is possible to obtain the expression for \( \gamma \), which is \( \gamma(d, \beta) = \mathcal{Q}^{-1}(1 - \beta) \sigma_s + \mu(d) \) where \( \mathcal{Q}^{-1} \) is the inverse Gaussian probability function [2,31].
3.2 Models of path Loss

3.2.1 Path-Loss model

The simplest model of a propagation channel is directly the free-space path loss formula. This model can be really useful to study the ideal performance of the cognitive radio system, all this without taking into account the fading effect in the channel. The path loss expression in linear units can be expressed as:

\[ l = \left( \frac{4\pi d}{\lambda} \right)^\alpha, \]  

(3.3)

where \( \alpha \) is the attenuation constant, \( d \) is the distance in metres and \( \lambda \) is the signal wavelength. The values for \( \alpha \) can be chosen in the range \( 2 < \alpha < 4 \) depending on the application, but normally it is selected \( \alpha = 2 \). The same expression in decibels can be expressed as:

\[ L = 32.4 + 20 \log_{10} (fd_{Km}), \]  

(3.4)

where \( f \) is the frequency in hertz and \( d_{Km} \) the distance in kilometres.

3.2.2 Median Path-Loss model

This model of path loss is important for modelling the signal propagation in suburban environments [19]. It is expressed in linear units and defined as following:

\[ p = p_t \left[ a \left( \frac{d}{d_0} \right)^{-\alpha} \zeta s \right], \]  

(3.5)

where \( p_t \) is the transmitted power, \( a \) is the adjustment parameter which depends on physical factors and on parameters like the operation frequency. The parameter \( \alpha \) is the attenuation constant, \( d \) and \( d_0 \) are the distance and the reference distance respectively. The most significant parameters in this last expression are the \( \zeta \) and \( s \). The parameter \( \zeta \) represent the adjustment due to the small-scale fading or fast fading because of multipath propagation in linear units. It changes according to the location and its average is one. The parameter \( s \) represents the adjustment due to large-scale fading or shadowing produced by hills, buildings, vehicles and other factors. It changes according to the distance as the previous parameter does, and its average value is also one. Assuming that the antennas at the transmitter and the receiver are omnidirectional, in this case the term \( a \) depends just on the nature of the environment. So that, in this case it is possible to consider that the quantity \( \langle p \rangle / p_t = \left( a \left( d/d_0 \right)^{-\alpha} s \right) \) is the path loss and \( \left( a \left( d/d_0 \right)^{-\alpha} \right) \) is the median path loss. The last considerations depend on the path geometry and on the surrounding environment.
Taking the same expression in dB units, $A$ and $S$ having the same meaning as in Equation (3.5), the expression can be formalized in dBs as [17]:

$$L = A + 10\alpha \log \left( \frac{d}{d_0} \right) + S \quad d \geq d_0. \quad (3.6)$$

In Equation (3.6) there are three important parts: the median path loss, the path loss exponent and fading effects. The first one, the $A$ parameter, is the median path loss defined by $A = 20 \log \left( \frac{4\pi d_0}{\lambda} \right)$ where $d_0 = 100m$ is the reference distance and $\lambda$ is the wavelength of the signal in metres. So that, this part of this equation defines the constant median attenuation caused by the wavelength and the reference distance. The path loss exponent $\alpha$ can be considered as a random variable following a Gaussian distribution over different macrocells. Hence, the $\alpha$ exponent can be written as $\alpha = \mu_\alpha + x \sigma_\alpha$, where the parameter $\mu_\alpha$ represents the mean of the path loss exponent, which is defined by $\mu_\alpha = a - bh_b + \frac{c}{h_b}$ for antenna heights $10m \geq h_b \geq 80m$. The $a, b$ and $c$ parameters depend on the kind of terrain. Table 3.1 shows some numerical values for different environments. The terrain category $A$ defines a heavy/hilly tree density, $B$ defines a medium/hilly tree density and $C$ defines light tree density. At last, the parameter $\sigma_\alpha$ is the standard deviation of the path loss exponent $\alpha$ (it can be seen also in Table 3.1 for different terrains categories) and $x$ is a Gaussian random variable defined by $x \sim N(0,1)$.

Table 3.1: Numerical values of different parameters for different terrain categories in the median path-loss model. The terrain category $A$ defines a heavy/hilly tree density, $B$ defines a medium/hilly tree density and $C$ defines light tree density [17].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Terrain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
</tr>
<tr>
<td>$a$</td>
<td>4.6</td>
</tr>
<tr>
<td>$b$ (in $m^{-1}$)</td>
<td>0.0075</td>
</tr>
<tr>
<td>$c$ (in $m$)</td>
<td>12.6</td>
</tr>
<tr>
<td>$\sigma_\alpha$</td>
<td>0.57</td>
</tr>
<tr>
<td>$\mu_\sigma_s$</td>
<td>10.6</td>
</tr>
<tr>
<td>$\sigma_\sigma_s$</td>
<td>2.3</td>
</tr>
</tbody>
</table>

This model takes into account the effect of the shadowing as well. The parameter $S$ in Equation (3.6) can be defined as $S = y\sigma_s$ where $y$ is a Gaussian random variable $y \sim N(0,1)$. The parameter $\sigma_s$ is the standard deviation of $S$ and it is itself a Gaussian random variable depending on the location and on the terrain category. By taking into account these assumptions, the $\sigma_s$ parameter can be written as $\sigma_s = \mu_\sigma_s + z\sigma_\sigma_s$ where $z$ is a Gaussian variable $N(0,1)$. The remaining parameters can be found as well in the Table 3.1.
3.3 Fading models

In a real environment, the signal is not only attenuated by path loss, other factors, for instance, fast fading and slow fading (shadowing) can be found. Figure 3.1 shows the different fading manifestations of a propagation channel [4]. The fading manifestations can be divided into two kinds, the large-scale (shadowing) fading and the small-scale fading (fast fading). With regard to shadowing, it is possible to find two basic principles. The first is the mean attenuation as a function of the distance and, the second is the variations about the mean attenuation. Regarding fast fading, it is possible to find two groups of fast fading, the time spreading of the signal and the time variance of the channel. Under these two principles, several kinds of channel can be modelled.

Figure 3.1: Types of fading propagation channels. As it can be seen in the diagram, the fading manifestations can be divided into two kinds, the large-scale (shadowing) fading and the small-scale fading (fast fading). Regarding shadowing, it is possible to find two basic principles. The first one is the mean attenuation as a function of the distance and, the second one, are the variations about the mean attenuation. Regarding fast fading it is possible to find two groups, the time spreading of the signal and the time variance of the channel. Under these two principles, several kinds of channel can be modelled [4].

Any signal received from any wireless channel is made of combinations of many replicas of the original signal coming from many different paths. These different signals can add to one another in a constructive or destructive way. When the transmitter, receiver or the environment is moving, the propagation is time varying. In other words, the scatterers in the environment can be seen as a function of time and space and, in this case, the fading phenomenon can occur.
The received signal can be written as the convolution of the transmitted signal and the time-variant impulse response. Hence, since wireless links are multiple path channels (MPC), the temporal transfer function of the channel can be written as [19]:

\[ h(t, \tau) = \sum_{i=1}^{L_{rep}} a_i(t) \delta(\tau - \tau_i), \]

(3.7)

where \( a_i \) is the time-varying complex amplitude of the \( i \)th MPC, \( \delta(\cdot) \) is the Dirac delta function or unit impulse function, \( \tau_i \) is the time of arrival of replicas of the transmitted signal. Finally, \( t \) and \( \tau \) are the continuous time of the signal and of the arrival signals respectively.

Depending on multipath propagation, the received signal can change and, indeed, the duration of the channel impulse responses are different. So that, if the mean squared magnitude of different channel impulse responses are calculated, it is possible to obtain the Power Delay Profile (PDP), which can be calculated as Equation (3.8) shows. This last function \( A \) defines the mean channel transfer expression as a function of the propagation delay. The root mean square (RMS) is the delay spread in time and can be calculated with Equation (3.9).

\[ A(\tau) = E\{|h(t, \tau)|^2\} \]

(3.8)

\[ \tau_{rms} = \sqrt{\frac{\int_{-\infty}^{\infty} A(\tau) \tau^2 d\tau}{\int_{-\infty}^{\infty} A(\tau) d\tau} - \left(\frac{\int_{-\infty}^{\infty} A(\tau) \tau d\tau}{\int_{-\infty}^{\infty} A(\tau) d\tau}\right)^2} \]

(3.9)

For the interpretation in the frequency domain, once the RMS or delay spread is calculated, it is possible to obtain the coherence bandwidth by using Equation (3.10). In literature is proposed to use \( k_{B_c} = 0.5 \) as a good approximation of \( B_c \) [19].

\[ B_c \geq \frac{\text{arccos}(k_{B_c})}{2\pi \tau_{rms}} \]

(3.10)

According to this coherence bandwidth \( B_c \), it is possible to find several kinds of small-scale fading. In order to model the delay dispersion, one of the most used models is the exponential one. So then, this model follows the expression \( A(\tau) = \exp[-\gamma \tau] \), where \( \tau > 0 \) and \( \frac{1}{\gamma} \) is the decay time constant which is the same value as \( \tau_{rms} \). The delay spread \( \tau_{rms} \) can be also calculated approximately as follows [19]:

\[ \tau_{rms} = T_1 d^\epsilon y, \]

(3.11)

where the parameter \( d \) is the distance in kilometres, \( y \) is a lognormal parameter in dB with zero mean and standard deviation \( \sigma_y \) and, finally, \( T_1 \) is the delay spread at \( d = 1 \).
km. Table 3.2 shows several values for these parameters according to different kinds of environment. Regarding the parameter $\varepsilon$, for urban, suburban and rural areas $\varepsilon = 0.5$ is used. In the case of mountainous areas $\varepsilon = 1.0$ is chosen [18].

So then, the reception of any received narrowband signal can experience three kinds of spatial variation. They are fast fading, slow fading and range dependence as well as temporal variations and polarization problems [42]. The fast fading is manifested as quick fluctuations of the signal over small areas. In this case, the signals arrive from all directions on the plane and it will be observed in all directions of motion. When some receiver is moving, it is proved that the autocorrelation of the channel is around 0.5 different when the user is located in places separated $\lambda/2$. This is known as spatial diversity.

When the receiver is situated among buildings, hills, etc. the signal will experience a change in its average depending on the location of the receiver. These signal variations will be on the order of the buildings, hills dimensions, etc. This phenomenon can be known as slow fading, shadowing or log-normal fading. It is possible to find as well another kind of fading called flat fading (non-frequency selective), which depends on the bandwidth of the transmitted signal and on the coherence bandwidth of the channel $B_c$.

Table 3.2: Parameters for the model of delay dispersion. The table shows different values for urban, suburban, rural and mountainous scenarios [18].

<table>
<thead>
<tr>
<th></th>
<th>$T_1$ ((\mu s))</th>
<th>$\sigma_y$ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Urban</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.94</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td>0.77</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>0.92</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>0.41</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>0.34</td>
<td>2.3</td>
</tr>
<tr>
<td><strong>Suburban</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.28</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>0.27</td>
<td>2.0</td>
</tr>
<tr>
<td><strong>Rural</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.076</td>
<td>5.3</td>
</tr>
<tr>
<td></td>
<td>0.071</td>
<td>4.0</td>
</tr>
<tr>
<td><strong>Mountains</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.45</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>0.45</td>
<td>2.4</td>
</tr>
</tbody>
</table>

It is possible to obtain another kind of representation for the time-variant impulse response by applying Fourier theory. The new representation is called the spreading function or delay-Doppler spread transformation $s(\nu, \tau)$, where $\nu$ is the frequency in Doppler spectrum and $\tau$ is the variable continuous of time for the different signal replicas. Averaging all the samples it is possible to obtain the Doppler spectrum $S(\nu) = E[|s(\nu, \tau)|]^2$. One of the most used Doppler spectrum in wireless communication is the Jakes Spectrum [19,46]. For
3.3 Fading models

Fading models for cognitive radio

A particular case when the scatterers are uniformly distributed in \([0, 2\pi]\), the next expression is obtained [46]:

\[
S(\nu) = \begin{cases} 
\frac{P}{2\pi f_d} \frac{1}{\sqrt{1-(\frac{\nu-f_c}{f_d})^2}} & |\nu - f_c| \leq f_d \\
0 & \text{otherwise},
\end{cases}
\]

where \(P\) is the total received power, \(f_d\) is the maximum Doppler frequency given by \(v/\lambda\) and \(f_c\) is the centre frequency.

When the communication environment is fixed, it is better to approximate the model by a Gaussian distribution with mean equal to zero. In this case, the power density spectrum about the centre frequency is proportional to the truncated equation:

\[
S(\nu) = \begin{cases} 
1 - 1.72 \left(\frac{\nu}{f_m}\right)^2 + 0.785 \left(\frac{\nu}{f_m}\right)^4 & |\nu| < f_m \\
0 & \text{otherwise},
\end{cases}
\]

where \(f_m\) scales linearly with the centre frequency and it is about 3.6Hz at \(f_c = 2.5\text{GHz}\) [19].

### 3.3.1 Flat fading and frequency selective fading

The flat fading can be experienced in any channel that has, approximately, constant gain and a linear phase response over some bandwidth, which is larger than the bandwidth used by the transmitted signal. In other words, flat fading appears when the coherence bandwidth \(B_c\) of the channel is larger than the signal bandwidth \(B\). So that, the whole transmitted signal experiences the same interference both in gain and in phase. The flat fading channels can be also called amplitude varying channels and narrowband channels.

On the other hand, frequency selective fading is when the \(B_c\) of the channel is narrower than the bandwidth of the signal. For that reason, the fading of the signal becomes different depending on the frequency. Figure 3.2 shows graphically an example of these last fading cases.

### 3.3.2 Fast fading

As it has been explained before, when the channel impulse response experiences fast changes within the symbol duration \(T_s\), it is known as fast fading. The scattered signals can be added in a constructive or destructive way, depending on the relative phase shift of the signals. Likewise, the phase shift depends on the motion speed, frequency and relative path lengths. So then, any channel can experience fast fading when the coherence time \(T_c\) of the channel is smaller than the symbol period \(T_s\). Due to this fast temporal changes within \(T_s\),
3.3 Fading models

Propagation models for cognitive radio

Figure 3.2: In picture A is shown the frequency selective fading, where the signal bandwidth $B_s$ is higher than the coherence bandwidth of the channel $B_c$. In picture B is shown the flat fading, where the signal bandwidth $B_s$ is lower than the coherence bandwidth of the channel $B_c$ [4,5].

The signal will experience as well frequency dispersion and time selective fading because of the Doppler spreading effect.

The fast fading or small scale fading can be modelled and distinguished among several types depending on the mathematical model. Hence, some distribution functions and models will be presented in this section. The most common studied fast fading distributions are Rayleigh, Ricean, Nakagami and Weibull [48, 49]. The Rayleigh distribution is considered the worst fading channel case, because is when there is no direct ray NLOS (No Line-Of-Sight). In this case, the power is exponentially distributed. The phase and the power are independent but, as a difference, the phase is uniformly distributed. When there is LOS the signal has a Ricean distribution, and it is characterized by two parameters. The first one is the power of the main ray (specular component) and the other one is the spatial power average of all the weak scattered signals. This is because there is a random multipath component arriving at different angles which is superimposed on the specular component of the signal. Notice that when the specular component is weaker or null, the probability density function of the received signal becomes Rayleigh [50]. The expression of the Ricean probability density function is defined as:

$$f_X(x) = \begin{cases} \frac{x}{\sigma^2} \exp \left[ -\frac{x^2 + A^2}{2\sigma^2} \right] I_0 \left( \frac{A x}{\sigma \sigma_s} \right) & \text{for } x \geq 0 \\ 0 & \text{otherwise,} \end{cases}$$

(3.14)
3.3 Fading models

where the parameter $A^2$ is the mean received power of the specular component (coherent power), the parameter $\sigma^2_{ss}$ is the average power of the scattered multipath signals (incoherent signals) and $I_0(\cdot)$ is the modified Bessel function of first kind and zero-order [50]. The Ricean model is many times described by the parameter $K$, which is a quantity of the fading effect over the specular component. Hence, the parameter $K$ is defined as the ratio between the specular component power (line of sight) and the multipath mean power and it can be defined as:

$$K(\text{dB}) = 10 \log \left( \frac{A^2}{2\sigma^2_{ss}} \right).$$ (3.15)

In [19] is studied the value of the $K$ parameter as a function of the distance, in the case when the measurements are done at $f_c = 5\text{GHz}$, the bandwidth $B = 100\text{MHz}$ and in decibels units. The results are the set of functions for different environments given by:

$$K(\text{dB}) = \begin{cases} 
8.7 + 0.051d & \text{Indoor Environments} \\
3.7 + 0.019d & \text{Rural Environments} \\
3.0 + 0.014d & \text{Urban Microcells},
\end{cases}$$ (3.16)

where the $K$ parameter is considered as a lognormal random variable, when the mean is as a function of the distance. So then, Equations (3.16) show the mean of the lognormal distribution of $K$. In [51] it is possible to find further information about this model.

When the transmitter or receiver are moving, this variation over the space produces temporal fading. When both transmitter and receiver are fixed, the variation of the received signal is because the external objects are moving; cars, trees because the windblown and so on. Hence, the fixed scattered objects cause the constant part in the received power and, the moving scattered objects, produce the variable part. In this case, the $K$ parameter can be defined as [19]:

$$K = F_s F_h F_b K_0 d^\gamma u,$$ (3.17)

where $K_0 = 10$, $\gamma = -0.5$, $d$ is the transmitter-receiver distance in kilometres, $u$ is a lognormal variable in dB such that $\mathcal{N}(0,0.8)$. The remaining parameters are assigned according to the values shown in Table 3.3, where $h$ is the height of the user antenna in metres and $b$ is the base antenna beamwidth in degrees. Notice that the values in Table 3.3 are given for both summer and winter seasons.

As explained before, it is possible to find at least two more kinds of channel fading distributions, Nakagami’s and Weibull’s distribution. Nakagami’s distribution was developed empirically based on measurements and it is defined by [49]:

$$f_X(x) = \frac{2}{\Gamma(k_r)} \left( \frac{k_r}{2\sigma^2} \right)^{k_r} x^{2k_r-1} e^{-\frac{k_r x^2}{2\sigma^2}} x \geq 0,$$ (3.18)
Table 3.3: Parameters for fixed links in fading environments in order to compute the $K$ parameter. Parameter $h$ defines the height of the user antenna in metres and, parameter $b$ defines the base antenna beamwidth in degrees. The values are given for summer and winter cases [19].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Summer</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_s$</td>
<td>1.0</td>
<td>2.5</td>
</tr>
<tr>
<td>$F_h$</td>
<td>$(\frac{h}{7})^{-0.36}$</td>
<td></td>
</tr>
<tr>
<td>$F_b$</td>
<td>$(\frac{b}{17})^{-0.62}$</td>
<td></td>
</tr>
</tbody>
</table>

where $2\sigma^2 = E\{x^2\}$, $\Gamma(\cdot)$ is the Gamma function and $k_r \geq \frac{1}{2}$ is the fading figure related to the number of added Gaussian random variables. When $k_r = 1$, the Nakagami’s distribution is similar to Rayleigh. Finally, the Weibull distribution takes as an envelope the expression $R = (X^2 + Y^2)^{\psi}$. When the parameter $\psi = \frac{1}{2}$ the function is Rayleigh distributed again, but when $\psi = \frac{1}{k_r}$ the Weibull’s distribution is given by [49]:

$$f_X(x) = \frac{k_r x^{k_r - 1}}{2\sigma^2} e^{-\frac{x^{k_r}}{2\sigma^2}},$$

(3.19)

where $2\sigma^2 = E\{x^2\}$.

### 3.3.3 Slow fading

In literature [19,42,52–54] it is possible to find at least two kinds of slow fading or shadowing. The first kind is the first-order shadowing and the second one is called second-order shadowing. Both of them are explained below.

#### First-order shadowing

In this model the received power follows a log-normal distribution in decibel units. A model of path loss that includes the shadow fading is shown in [17] and [19]. So then, the received power can be written as $P \sim \mathcal{N}(L(d), \sigma)$ where $\sigma$ is the standard deviation of the shadowing which takes usually in values from 3 dB (in indoor environments) to 12 dB (in outdoor environments) and $L(d)$ is the path loss in decibels. One of the most used values for the standard deviation is $\sigma = 8$ dB. In this case, the log-normal probability density function is expressed as:

$$f_X(L) = \frac{1}{\sigma_L \sqrt{2\pi}} e^{-\frac{(L - \mu_L)^2}{2\sigma_L^2}},$$

(3.20)

where $\sigma_L$ is the standard deviation, $\mu_L$ is the mean value and $L$ is the attenuation in
3.3 Fading models

Decibel units.

**Second-order shadowing**

As explained before, the shadowing is produced by hills, buildings, vehicles and other factors, therefore the nearest received power samples are correlated, since the elements that produce this effect are large objects. In [54] the author proposes one method to model the second-order statistic fading. It is realized by adding spatial correlation to the first-order shadowing received samples. Hence, the correlation is modelled as:

\[
R(k_d) = \sigma^2 a |k_d|, \quad (3.21)
\]

\[
a = \varepsilon v T / D, \quad (3.22)
\]

where \(\sigma^2\) is usually in the range between 3 and 10 dB and \(k_d\) is the separation distance in metres. The correlation coefficient \(a\) in Equation (3.21) is defined in Equation (3.22), where the parameter \(\varepsilon D\) is the correlation between two points separated by a distance \(D\) in metres, \(v\) is the mobile velocity in \(m/s^2\) and \(T\) defines time in seconds. This model can be expressed also as [52]:

\[
R(\Delta x) = e^{-|\Delta x|/d_{corr}}, \quad (3.23)
\]

where the parameter \(d_{corr}\) is the decorrelation factor and \(\Delta x\) is the increment in distance. For urban vehicular environments, \(d_{corr}\) is proposed to be 20 metres and it works properly within distances up to 500 metres [52].

In order to apply this model, in [52] can be found one way to realize the spatial correlation for shadowing based on the two-dimensional correlation. Let \(L\) be the matrix with first-order shadowing values spread over a discrete spatial area, and \(R\) the matrix containing the correlation coefficients obtained by using Equation (3.23). Thus, the second-order correlated shadowing will be obtained by calculating the two-dimensional correlation between the matrices \(L\) and \(R\). The expression of the two-dimensional correlation is given in this case by [52]:

\[
L_{sp}(x, y) = \sum_{i=1}^{N_x} \sum_{j=1}^{N_y} L_{spi}(i, j) R(x - i + 1, y - j + 1), \quad (3.24)
\]

where \((x, y)\) are the coordinates in space, \(N_x\) and \(N_y\) are the maximum number of discrete points in the space coordinates.

In [52] can be found two more kinds of correlation as the angular and temporal correlation. Once the second-order shadowing map is obtained, the angular correlation can be generated by considering the help of neighbouring tiles. In other words, it is possible
to obtain the neighbouring shadow fading value existent in that direction instead of the actual value that the user has in that location. The final angular autocorrelation function is obtained stepwise with a resolution of $2\pi/9$. Finally, the temporal correlation adds correlation in all the points as a function of the time. To achieve that, the base values of the tiles have to be interpolated in a smooth way.

Likewise, if some value of the shadowing is achieved at some $\kappa$ time $L_{\text{time}}(t_\kappa)$, the expression to achieve the next temporal value of the shadowing $\kappa + 1$ is given by:

$$L_{\text{time}}(t_{\kappa+1}) = L_{\text{time}}(t_\kappa) + \frac{\kappa \mod n}{2n - (\kappa \mod n)} (L_{\text{timenew}} - L_{\text{time}}(t_\kappa)),$$  \hspace{1cm} (3.25)

where the parameter $L_{\text{timenew}}$ is the shadow fading value at the position of interest. Once the updating interval of $n$ measurements cycles is realized, the shadow fading value must be calculated again. The updating interval depends on the measurement cycle, the velocity $v$ of the user and the resolution $\Delta s$ of the shadowing map, which is the minimum distance between points over the discrete space. The number of measurement cycles can be found by using Equation (3.26), where $t_{\text{meas}}$ is the measurement time. For further information about these models see [19,42,52–54].

$$n = \frac{\Delta s}{vt_{\text{meas}}}$$  \hspace{1cm} (3.26)

Notice that, one of the most important problems in cognitive radio is the hidden terminal problem, which appears with shadowing channels. It occurs when the device of interest is shadowed in a severe fading or inside buildings with a high losses. Hence, when the primary signal is activated, these users will not be able to detect its presence. Many authors, for example see [55], have been trying to solve this problem.

### 3.4 Standardized propagation models

#### 3.4.1 Okumura-Hata model

The model of Okumura-Hata is one of the most used models in large coverage cells within distances of up to 100 Km. Furthermore, it is workable up to the 2GHz band. This model has logarithmic dependence on the distance and on other parameters such as the antennas height, frequency, etc. The model of Okumura-Hata includes different approaches for urban, suburban and open areas propagation losses. The Okumura-Hata equation in urban areas is given in decibel units by [43,56]:

$$L = 69.55 + 26.16 \log (f) - 13.82 \log (h_b) - a (h_m) + (44.9 - 6.55 \log (h_b)) \log (d),$$  \hspace{1cm} (3.27)
where $h_b$ and $h_m$ are the transmitter antenna and the receiver device antenna heights in metres respectively, $f$ is the frequency in MHz. The function $a(h_m)$ is the correction factor for the antenna height of the receiver device and, in the case of medium to small cities, it is defined by:

$$a(h_m) = (1.1 \log(f) - 0.7) h_m - (1.56 \log(f) - 0.8).$$  

(3.28)

The adjustment in the Okumura-Hata’s expression for suburban areas is:

$$L_{asub} = L(urban\ area) - 2 (\log(f/28))^2 - 5.4.$$  

(3.29)

The adjustment for open areas is given by:

$$L_{aopen} = L(urban\ area) - 4.78 (\log(f))^2 + 18.33 \log(f) - 40.94.$$  

(3.30)

### 3.4.2 Stanford University Interim (SUI) model

The University of Stanford proposed the channel standards called Stanford University Interim (SUI) models, which are developed to work within the frequency bands below 11 GHz. The following model is defined for the MMDS bands in the USA, which is the range from 2.5 GHz to 2.7 GHz. The applicability in other bands has not been totally established.

The SUI models are divided into three kinds A, B and C. The type A is suitable for a high path loss for hilly terrains and with heavy tree densities. The type B is for flat terrains with from moderate to heavy tree densities and, the type C, is applied for flat terrains with light tree densities. Table 3.4 shows different values for the parameters in the path loss equation depending on the different kinds of terrain.

Table 3.4: Parameter values for SUI propagation model. Type A is suitable for a high path loss for hilly terrains and with heavy tree densities. Type B is for flat terrains with from moderate to heavy tree densities and, Type C, is applied for flat terrains with light tree densities [20].

<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>$b(m-1)$</td>
<td>0.0075</td>
<td>0.0065</td>
<td>0.005</td>
</tr>
<tr>
<td>$c(m)$</td>
<td>12.6</td>
<td>17.1</td>
<td>20</td>
</tr>
</tbody>
</table>

Therefore, the equation of the SUI path loss model is given by [20]:

$$L = A + 10\gamma \log \left( \frac{d}{d_0} \right) + X_f + X_h + S \quad for \quad d > d_0$$

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

$$\gamma = a - bh_b + c/h_b,$$

(3.31)
where $d$ is the distance in metres, $d_0$ is the reference distance equal to 100 metres and $S$ is a lognormal distributed factor which takes into account the shadowing effect with common values between 8.2 dB and 10.6 dB. In Equation (3.31), the parameters $X_f$ and $X_h$ are the correction factors for the operation frequency and for the antenna heights respectively. Hence, in Equations (3.32) are shown these corrections where $f$ is the frequency in MHz and $h_r$ is the receiver antenna height in metres. In the correction factor for the antenna heights it is possible to find two different corrections depending on the type of used terrain.

$$X_f = 6.0 \log \left( \frac{f}{2000} \right)$$
$$X_h^{A,B} = -10.8 \log \left( \frac{h_r}{2000} \right)$$
$$X_h^C = -20 \log \left( \frac{h_r}{2000} \right)$$

(3.32)

### 3.4.3 COST-231 Hata model

The COST-231 model is designed as an extension to the Okamura-Hata model. This model is suitable for the frequency band between 500 MHz and 2000 MHz. This model, as the previous ones, has as well some corrections depending if the model is used in urban, suburban or rural environments. In this case, the expression is given by:

$$L = 46.3 + 33.9 \log (f) - 13.82 \log (h_b) ah_m + (44.9 - 6.55 \log (h_b)) \log d + c_m,$$

(3.33)

where $f$ is the frequency in MHz, $d$ is the distance and $h_b$ is the antenna height in metres. The parameter $c_m$ is considered to be equal to 0 dB for suburban areas or open environments, and to 3 dB for urban environments. For the parameter $ah_m$, some different expression depending on the type of terrain are used. Thus, for urban environments:

$$ah_m = 3.20 \left( \log (11.75 h_r) \right)^2 - 4.97 \quad \text{for } f > 400 \text{ MHz},$$

(3.34)

and for suburban or rural environments:

$$ah_m = (1.1 \log (f) - 0.7) h_r - (1.56 \log (f) - 0.8).$$

(3.35)

### 3.4.4 ECC-33 Path Loss model

The ECC-33 is more suitable for using in European cities, since Okumura-Hata’s models were taken in cities as Tokyo, where the environment can be quite different to typical European cities. Hence, it is possible to find a large cities model and medium cities model, where the medium model is more suitable for European cities and the large model is more probably for cities with many tall buildings. The ECC-33 path loss is defined then by [20]:

$$L = A_{fs} + A_{bm} - G_t - G_r,$$

(3.36)
where $A_{fs}$ is the free space attenuation, $A_{bm}$ is the basic median path loss, $G_t$ is the gain factor of the transmitter and $G_r$ is the receiver gain factor. For a large cities model, this parameters can be defined by:

\[
\begin{align*}
A_{fs} &= 92.4 + 20 \log (d) + 20 \log (f) \\
A_{bm} &= 20.41 + 9.83 \log (d) + 7.894 \log (f) + 9.56 [\log (f)]^2 \\
G_t &= (13.958 + 5.8 [\log (d)^2]) \log (h_b/200),
\end{align*}
\]

where $f$ is the frequency in GHz, $d$ in the distance in km, $h_b$ is the transmitter antenna height and $h_r$ is the receiver antenna height in metres. Finally, as an adjustment, for medium city environments the gain of the receiver antenna is:

\[
G_r = (42.57 + 13.7 \log (f)) (\log (h_r) - 0.585).
\]

### 3.5 Standardized double-directional models

It is possible to find a lot of channel characterizations, but most of them take into account some specific antennas at both ends (at least at the transmitter). This means that the information extracted from the channel by the system will not be useful if the antennas are replaced. The same occurs when the cognitive radios use the MIMO technology, where the model for different antennas locations and different ray paths should be taken into account. Nowadays, MIMO systems are receiving a lot of interest from research and technology manufacturers, since these kinds of system can achieve much higher channel capacities (for further details about MIMO see [57, 58]). So that, in order to separate the effect of the antennas in the estimation of the propagation model, some model is needed to distinguish between the radio channel (considering the antennas) and the propagation channel (without considering the antennas). The Double Directional Channel Model (DDCM) has been proposed [44], which is based on Directional Channel Modelling (DCM). The channel coefficients are computed as a sum of rays, but the Direction of Departure (DoD), Time Delay of Arrival (TDoA), Direction of Arrival (DoA), path-strength and other kind of parameters of each ray, come from realizations of random processes [22]. The DCM is able to estimate the propagation channel excluding the effect of the antennas by using the double directional channel response.

There exist several models of channel impulse response according to how many variables are taken. First of all, the non-directional channel impulse response $h(t, \tau)$ can be found, which is the angle-integrated directional channel impulse response $h(t, \tau, \theta)$. Notice that all of the radio channels presented in the previous sections are based on the non-directional channel impulse response. The angle-integrated directional response, at once, is the angle-integrated double directional channel impulse response $h(t, \tau, \theta_R, \theta_T)$. So that, the
generalized channel impulse response which defines the double directional channel response is [22, 44]:

\[ h(n, m, r, \tau, \theta_R, \theta_T) = \sum_{l=1}^{L(r)} h_l(n, m, r, \tau, \theta_R, \theta_T), \] (3.39)

where \( n \) and \( m \) are the \( n \)th receiver and the \( m \)th transmitter antennas, \( r \) is a vector containing the relative location of the receiver from the transmitter, \( \tau \) is the ray delay time and the parameters \( \theta_T \) and \( \theta_R \) are the Angle of Departure (AoD) and the Angle of Arrival (AoA) respectively. Thus, \( h_l(\cdot) \) is the impulse response of the \( l \)th ray and \( L(r) \) represents the set of different ray ways. So that, the double directional channel can be separated in several functional parts as the transmission antenna, double directional channel and the reception antenna. The transmission antenna distribute the signal in the desired direction of departure according to the physical channel inputs offered by the double directional channel. The double directional channel includes all \( N \) propagation paths between the transmitter and the receiver, each one of this paths has connected the DoD with the DoA. Finally, the reception antenna obtains all the signal components from the DoA and combine them by weighted combination.

Below, some of the standardized channel models using the double directional channel response are explained briefly. The most common are the COST 259 Geometry-based Stochastic Channel Model (GSCM), the 3GPP Spatial Channel Model (SCM), the WINNER Spatial Channel Model Extended (SCME) and the WINNER Phase I Channel Model (WIM) [22, 57].

### 3.5.1 COST 259-GSCM

The COST 259 directional channel model is a physical model which gives a model for the delay and angle dispersion at the transmitter and receiver, for different radio environments [57]. This model is based on three levels. The first one shows three different cell types with which it is possible to work: macro, micro and pico cells. The main difference between them is the distance between the transmitter and the receiver. The second level shows several radio environments (RE) for each cell type. In each RE there exist also different propagation conditions characterized by the global parameters (GP). These last parameters are defined statistically. The third and the last level defines the propagation scenarios obtained by generating realizations of the GP’s for some specific RE. Table A1 in Appendix A shows the structure of this standardized model.

### 3.5.2 3GPP-SCM

The model SCM was developed by the 3GPP/3GPP2 organization to be a common reference for evaluating different MIMO concepts in outdoor environments, at a centre frequency of
2 GHz and a system bandwidth of 5 MHz. This model, as the GSCM explained above, is based on three environments: suburban macro, urban macro and urban micro. The last environment, urban micro, is divided into Line-of-Sight (LOS) and no Line-of-Sight (NLOS) propagation. In this case, each scenario has a fixed number of 6 paths each one represented by a Dirac function in delay domain. Each one of these 6 paths is built of 20 spatially separated sub-paths. These 20 sub-paths constitute a Zero Delay Spread Cluster (ZDSC) since all of these subpaths arrive in the same TDoA. The remaining parameters such as path power, path delay, angles, etc. are modelled as random variables.

3.5.3 WINNER-SCME

The channel models developed in the IST-WINNER project are related to both the COST 259 and 3GPP SCM models. So that, this model is developed as an extension to the model explained above 3GPP-SCM. In reality the model is called the Channel Model for Beyond-3G Systems but considered as an SCM extension. While the SCM is defined for a 5 MHz bandwidth CDMA system in the 2 GHz band, the WINNER uses 100MHz bandwidth in both the 2 and 5 GHz frequency range. In this case, the 20 sub-paths of the original SCM will be divided into mid-paths, thereby each mid-path will be able to have different TDoA. This division is needed to achieve the required effect in a larger bandwidth. This produces an intra-cluster delay spread. The model implements as well the drifting of the TDoA, AoA, AoD and the shadowing in order to obtain a more realistic time variant channel.

3.5.4 WINNER-WIM

This model is defined for seven specific scenarios and it uses a similar approach as 3GPP-SCM. In each scenario are defined a set of parameters called bulk parameters. In each channel segment, these bulk parameters are obtained from statistical processes. The channel is generated as a sum of rays organized in a specific number of ZDSC, where the delays and the angles properties are produced using statistical distributions. In this case, the number of rays in a ZDSC is 10, each one of them with the same delay and power.

3.6 Locating primary receivers problem

In order to make the cognitive radio functionalities easier, it would be interesting to know the locations of the primary receivers. As explained before, the primary receivers are considered to be passive so that the cognitive radio users are not able to know their location and, therefore, the level of interference that they are experiencing is also unknown. In the literature has been proposed some ways to estimate the location of the primary receivers and avoid the secondary transmissions when some primary receivers are detected to be close by.
3.6 Locating primary receivers problem

In [59] is proposed a method to detect the presence of these primary receivers by sensing the local oscillator leakage power which all the radio frequency receivers emit. These receivers use the local oscillator to convert the incoming signal to an intermediate frequency, by using a superheterodyne receiver. This kind of receiver has an inevitable reverse leakage and, hence, some of the local oscillator power couples back through the input port and radiates out of the antenna. This method may offer the possibility to guarantee that a cognitive user will not interfere with any primary receiver by detecting this leakage. To carry it out, low cost sensor nodes can be placed in the proximities of the primary receivers.

Instead of techniques to detect and to locate primary receivers, nowadays the most certainly feasible approach is to detect the protection region where the existence of primary receivers is probable. A strategy between cognitive users and a cognitive base station is proposed in [6] to work in a cooperative way, in order to detect the location of primary transmitters and to estimate where is the protection radius $r_{prot}$ for the primary receivers. This protection region tries to avoid the hidden node problem and the interference with the primary users. The use of the cognitive base station is justified by the minimization of the complexity in the common cognitive users. Otherwise, these users should know what the distance and the direction of the primary transmitter are, which requires probably more complicated hardware in the cognitive users. Therefore, the base station is used to estimate the distance and the direction of the cognitive users from this cognitive base station. In that case, the cognitive users just need to know what is the distance of the primary transmitter, not the direction.

![Figure 3.3: Geometrical model problem to search the protected radius $r_{prot}$ for the licensed system. This geometrical model is proposed in [6] as a new technique to solve problem of locating primary receivers.](image)

The system model is shown in Figure 3.3. Taking into account that the cognitive base
station is located at the coordinates $(0,0)$, the position of the rest of nodes is defined by
$(x_p, y_p)$ for the primary transmitter and, $(x_{s1}, x_{s2})$ and $(x_{s2}, y_{s2})$ for the
cognitive users. Once the position of the cognitive users is obtained, with the help of the
cognitive base station, it is possible to know the distance between the secondary users by calculating the
module following the expression of the simple euclidean distance $d_{s12} = \sqrt{(x_{s1} - x_{s2})^2 + (y_{s1} - y_{s2})^2}$.
At this point, when the distances $d_{p1}$, $d_{p2}$ and $d_{s12}$ are known, the position of the PU $(x_p, y_p)$
can be calculated using common geometrical theorems. Finally, considering that the minimum
power at any primary receiver for a error free reception is $p_{1r}^{\text{min}}$, the distance from
the primary transmitter to the edge of the coverage radius $r_{pcov}$ can be calculated taking
into account the transmitted power $p_{t1}$ of the primary transmitter. At this point, it is
also important to take into account the effect of the different propagation models (Chapter
3). On the other hand, the coverage radius of the secondary transmitters $r_{scov}$ can also be
calculated taking again also the transmitted power $p_{t2}(\text{dB})$ of the secondary users and the
minimum reception power at the secondary receivers $p_{2r}^{\text{min}}$. So that, the non-talk radius can
be defined as $r_n = r_{pcov} + r_{scov}$. Thus, the protection radius can be obtained as a function
of the parameters $(x_p, y_p, r_n)$.
Chapter 4

Spectrum sensing techniques

One of the most important technologies in cognitive radio systems is spectrum sensing, since it allows the detection of different spectrum holes and the Opportunistic Spectrum Access (OSA), which is described in Section 5.1. This ensures that the sensing techniques are used to offer the ability to be aware of the changes in the state of the licensed spectrum and identify the spectrum opportunities. As this topic is not the goal of this work, in this chapter are only presented briefly some common spectrum sensing techniques which can be used in cognitive radio systems as well as in other kind of wireless networks. Further details about the spectrum sensing topic can be found in [7,10,60–62]. In [63] can be found as well an interesting comparison among the different techniques explained in this chapter and which are their advantages and disadvantages.

4.1 Single user spectrum sensing techniques

As it has already been presented, the primary signal must be detected in order to identify the spectrum holes. Since the primary receivers are assumed to be completely passive, another necessity is to know where the primary receivers are located in order to avoid any harmful interference. The easiest way to solve this problem is to detect the presence of the primary signal individually in each secondary user. Furthermore, an estimation of the signal could be done as well in order to locate the primary receivers, by trusting in the estimation and by applying some other techniques as explained in Section 3.6. With this technique, it is possible to make a rough estimation of the areas where the primary receivers may be located.

The basic spectrum sensing principle is to try to detect the presence of the primary signal as a binary individual detection. So that, the detection of the primary signal is made by the secondary transmitters through local observations and it follows the binary hypothesis testing scheme shown below [10]:

\[
\text{H}_0: \text{signal is not present} \\
\text{H}_1: \text{signal is present}
\]

\[
\text{Decision:} \quad \begin{cases} \text{reject } H_0 & \text{if } P > \alpha \\ \text{accept } H_0 & \text{otherwise} \end{cases}
\]

\[
P = \frac{1}{2} \left[ 1 + \frac{\text{SNR}}{1 + \text{SNR}} \right]
\]
4.1 Single user spectrum sensing techniques

\begin{equation}
  x(t) = \begin{cases}
    n(t) + i(t), & H_0, \\
    hs(t) + n(t) + i(t), & H_1,
  \end{cases}
\end{equation}

where \( x(t) \) is the received signal at the secondary user, \( s(t) \) is the transmitted signal of the primary user, \( n(t) \) is the AWGN, \( h \) is the channel transfer function and \( i(t) \) is the interference function. When the device detects the presence of the primary signal \( s(t) \), it will decide the state \( H_1 \), otherwise it will choose \( H_0 \). Below, some common non-cooperative spectrum sensing techniques used in cognitive systems are presented.

**Matched filter detection**

If the secondary network knows the primary signal, the optimal detector is a matched filter which maximizes the detection SNR (it finds the signal in noise). One of the advantages of the matched filter detection is the time required for achieving high processing gain, which is smaller due to the coherent detection. For a good performance of this method, it would require some knowledge about the modulation type, the kind of pulse shape and the packet format. Otherwise, the performance will not be as good as desired. Therefore, one disadvantage is that different dedicated detectors would be required in order to make a good detection for any type of primary signal. However, since most of the wireless signals have pilot frequencies, preambles, synchronization word, etc. the detector could use them to realize the coherent detection [10,60].

**Energy detection**

![Figure 4.1: Schematic of energy detection technique [7].](image)

When the sensing device does not have enough knowledge about the features of the primary signal, the optimal detection method in this case is the energy detection (which finds random signal in noise). To detect the energy of the received signal, the sensed signal is treated through the functional blocks shown in Figure 4.1. First of all, the signal is filtered by using a bandpass filter to selected the bandwidth of interest and, afterwards, the obtained signal is squared and integrated over some observation interval. Finally, the output of the integrator \( Y \) is compared with a threshold \( \lambda_{th} \) to decide whether the primary user signal is there or not. In Equation (4.2) can be seen the signal \( Y \) where \( W(m) \) represents the noise and \( T(m) \) the required signal to detect averaging over \( M \) samples. The final decision strategy is shown in Equation (4.3), where \( \hat{\theta} \) defines the final decision of the estimation and \( \lambda_{th} \) the chosen threshold which depends on the variance of the noise [7,10,60].

35
4.2 Cooperative spectrum sensing techniques

\[
Y = \begin{cases} 
\sum_{m=1}^{M} |W(m)|^2, & H_0 \\
\sum_{m=1}^{M} |T(m) + W(m)|^2, & H_1 
\end{cases} 
\] (4.2)

The energy detector treats the energy as noise and decides the presence of the primary user signal depending on the level of energy observed. So that, it does not need any prior knowledge about the primary signal and, therefore, the method is robust to changes in the type of the primary signal, achieving a low processing complexity.

\[
\hat{\theta} = \begin{cases} 
H_1, & \text{if } Y > \lambda_{th} \\
H_0, & \text{if } Y < \lambda_{th} 
\end{cases} 
\] (4.3)

Nevertheless, the energy detection method has some drawbacks. For instance, the technique has low performance under a low SNR situation, since the noise variance at a low SNR level is not accurately known. Hence, the threshold \(\lambda_{th}\) depends directly on the noise variance, so that the variance of this noise can generate important performance losses (i.e. hard to maintain false alarm constraint). Another trouble is how to distinguish the interference coming from other secondary users using the same frequency channel.

In [64] an energy detection technique on OFDM using MIMO technology is presented. For further information see [7,10,60,65].

In the literature can be found many different detection techniques. Some of the most important techniques are cyclostationarity detection [7,10,60], wavelet detection [60,61,66] and covariance detection [60,61].

4.2 Cooperative spectrum sensing techniques

The non-cooperative spectrum sensing techniques have some drawbacks when the primary signal is under shadowing or multipath fading, since these typical techniques are not able to avoid, for instance, the hidden terminal problem. In this case, the secondary users sensing the primary signal are not able to detect its presence, which may produce interference in the primary system. Therefore, the cooperative spectrum sensing is the set of techniques where the information from multiple cognitive users is combined for primary user detection. This approach can improve significantly the sensing performance of the secondary users by using the spatial diversity and statistical advantages that the cooperation offers. By using cooperative techniques, for instance, the channel uncertainty can be minimized. The cooperative spectrum sensing can be divided into two types: centralized and decentralized cooperative methods. In Figure 4.2 are shown some examples the centralized (a) and the decentralized cooperative sensing technique (b) schemes. Some common cooperative spectrum sensing techniques are shown below.
4.2 Cooperative spectrum sensing techniques

Figure 4.2: In picture A is shown an example of centralized cooperative sensing using a star topology. On the other hand, in picture B is shown a decentralized cooperative sensing using a mesh topology.

Centralized cooperative sensing

In centralized techniques (Figure 4.2a) all the cognitive users send the information gathered by themselves to another cognitive radio user, which operates as the information fusion centre to make the final decision about the presence of the primary signal. In [62] an interesting centralized sensing spectrum algorithm is suggested for multiuser cognitive radio environments, which reduces the detection time and increases the agility. However, the most common techniques will be shown below.

Decision fusion

The decision fusion or hard combination combines the individual binary decisions, by using the individual strategy explained in Section 4.1. Nevertheless, in this case all the involved cognitive radios send the data to some centre fusion node, which will make a final decision about the state of the channel. Several methods to make the last decision in the fusion centre can be found. Some of them are the OR or 1-out-of-M rule, the AND rule and the Majority or K-out-of-M rule [67].

Data Fusion

In the data fusion or soft combination strategy, the fusion centre combines by averaging the estimates of the primary signal coming from all the involved secondary users. Afterwards, the final decision is made by comparing the result with some threshold $\lambda_{th}$. However, this approach requires a higher bandwidth and overhead for the transmission of the data to the fusion centre. In this field, the likelihood ratios are commonly used.
Decentralized cooperative sensing

In decentralized techniques (Figure 4.2b) all the cognitive radios exchange information with one another and then they decide whether the primary user is present or not. In order to exchange the information among users the AF (Amplify and Forward) protocol can be used [68]. The protocol amplifies and relays the received data from the other cognitive users. Therefore, the secondary nodes share the information with one another but they make their own decision taking into account the gathered data of the other secondary nodes. In the case of the decentralized approach, there is no need for any backbone infrastructure because there is no fusion centre node. In [62] is proposed an interesting decentralized detection algorithm based on a multi-user cognitive system. In decentralized cooperative sensing the Ad-hoc configuration plays an important role.
Chapter 5

Interference in cognitive radio systems

As it was explained in Chapter 1, the spectrum has become crowded and underutilized. A cognitive radio system would be able to solve this problem by taking advantage of the free spectrum. However, the cognitive users must be aware of the interference generated at primary receivers. Depending on the level of the generated interference, the performance of the primary system can be negatively affected. Therefore, the harmful interference should be controlled by the secondary users using different techniques and taking into account the effects of the propagation channel (Chapter 3). As the performance of the primary system must fulfill always the requirements of the policies and regulatory bodies, the interference management in cognitive systems has become an important issue. The interference management tries to avoid the harmful interference in the primary system by using quantitative criteria and performance criteria of the coexistence between the licensed and unlicensed systems. The interference generated among unlicensed users, when they are sharing the same resources, must be managed as well.

In Section 5.1 is explained the key issues of the concept Opportunistic Spectrum Access (OSA) [3, 6, 8, 59, 69–75]. In this section some techniques are given for sharing resources among cognitive users [10]. Different quantitative criteria in order to manage the produced interference and to quantify the level of harmful interference at the primary system, are presented in Section 5.2 [2, 8, 76]. Some typical and recent performance criteria are also presented in Section 5.3 [2, 31, 39]. The interference temperature model, which has been studied thoroughly, will be introduced in Section 5.4 [10, 11, 27]. Finally, some techniques to know approximately the location of the primary receivers, to apply successfully the interference temperature technique, are also presented in Section 3.6 [6, 59].
5.1 Opportunistic Spectrum Access (OSA)

The current use of the radio frequency spectrum is pushing researchers and designers to use higher frequencies with more demanding propagation properties. Since the licensed frequencies are not used all the time, the use of this unused spectrum will be interesting for secondary unlicensed users. Therefore, when there exists some access opportunity in the spectrum resources of the licensed system, the cognitive users should be able to use it. Thus, in cognitive radio the term Opportunistic Spectrum Access (OSA) is adopted. This solution can be defined as the technique which allows cognitive radio users to share the licensed spectrum in space and time, whether the licensed users are using the spectrum or not, since the constraints can be based on generated interference \[8,69\]. In this approach it is possible to find at least three basic components called spectrum opportunity identification, spectrum opportunity exploitation and regulatory policy \[3\]. These different components will be described below.

A channel opportunity can be figured out as the opportunity of the secondary users to transmit when a channel is not being used by primary users. In other words, take advantage of the spectrum holes (Section 2.2). Indeed, when the primary and secondary users are geographically distributed over some area, the spectrum opportunities can be also identified when some pair of secondary users can transmit successfully without causing harmful interference at the primary users. Whether the primary signal is present or not. Thus, the secondary network should be able to identify where and when it is possible to transmit respecting interference thresholds at the primary system given by the regulatory policy. In Figure 5.1, A and B denote a transmitter and a receiver of the secondary system respectively. The straight radius is the minimum distance between the secondary transmitter and any primary receiver to avoid interference. If the primary receiver is out of this radius, the produced interference in the primary node is allowed. In fact, this radius depends on the power transmitted by the secondary transmitters and the interference margin of the primary receivers. On the other hand, the dotted radius is the required distance between a secondary receiver and a primary transmitter for a some interference level at the secondary receivers. When there is some primary transmitter inside this radius, the interference produced in the secondary receiver is higher than the allowed one at this node. In this case, this last radius depends on the power transmitted by primary users and on the interference margin of the secondary receivers.

The spectrum opportunity is defined in any specific pair of secondary users (secondary transmitter and receiver). Hence, the failed communications among secondary users because of collisions among them, are still considered as access opportunity. Multicast and broadcast opportunities are still an open issue \[3\].

In order to avoid the loss of performance below limits established by the regulatory policies, some threshold parameters are defined. This means that in these scenarios \(\eta\) can be defined as the maximum interference level allowed by a primary receiver \[8\]. When the
level of interference is higher than this threshold, the harmful interference at the primary system coming from the secondary system occurs. Since the sensing algorithms used to detect the presence of the primary signals are not completely reliable, it is necessary to define another parameter to quantify this probability of error. The parameter $\xi$ is then the maximum allowed probability of error detecting the presence of the primary signal. This is directly related to the probability of miss detection (PMD) and the probability of false alarm (PFA), which will be presented in Section 5.3. Inside the radius where the transmission is not allowed for the secondary transmitters, the probability of miss detection will be considered as probability of error. On the other hand, outside this radius the probability of false alarm will be considered as the probability of error.

In order to achieve transmissions without any interference problems between a pair of secondary nodes (transmitter and receiver), the receiver should detect the presence of primary transmitters, and the transmitter should detect the presence of primary receivers. All of this following the approach shown in Figure 5.1. Each cognitive radio user, assuming its current operation status (as a transmitter/receiver), should detect the presence of primary users who can interfere or can be interfered with. Currently, there is no simple solution to the problem of locating primary users, but it is possible to find some solutions in literature [6, 59]. In Section 3.6 some existing methods are explained for locating primary receivers. A simple way to suspect the presence of the primary receivers is explained in [3]. This scenario is depicted in Figure 5.2 and is based on using the worst, or conservative, case assumption. In other words, the technique transforms the problem of detecting primary receivers into detecting the presence of primary transmitters in distances higher or equal to $r_{pcov} + r_{PR}$. The parameter $r_{pcov}$ defines the coverage radius of the primary transmitters

![Figure 5.1: The dotted line in the figure shows the required distance between the secondary receiver and some primary transmitters $r_{SR}$ to fulfill with some allowed interference level. The straight line shows the minimum distance between the secondary transmitters and the primary receivers $r_{PR}$ to achieve some allowed interference level at these receivers [8].](image-url)
5.1 Opportunistic Spectrum Access (OSA)

Interference in cognitive radio systems

Figure 5.2: Proposed scenario for the detection problem of the primary receivers [8]. The technique changes the problem of detecting primary receivers into detecting the presence of primary transmitters within distances higher or equal to \( r_{pcov} + r_{PR} \). The \( r_{pcov} \) defines the coverage radius of the primary transmitters and \( r_{PR} \) the distance of the unlicensed transmitters to avoid the interference at the licensed receivers.

and \( r_{PR} \) is the radius of the interference range of the secondary transmitters to avoid interference with the licensed receivers. This technique is based on the idea that if the coverage radius of the primary transmitter is inside the interference range of the secondary transmitter, the presence of the primary receivers is probable. Indeed, within the area calculated with this technique, in some cases there will not be primary receivers. So that, in this case one transmission opportunity is lost and it leads to overlooked opportunities.

Since the cognitive devices are not able to sense all the \( N \) channels at the same time due to hardware limitations, a sensing strategy for intelligent channel selection is necessary to track the quick variation of spectrum opportunities. This strategy should be able to find a free channel to immediate access and obtain some statistical information, in order to use it in the future to make decisions about the spectrum occupancy [3]. The optimal sensing strategy is based on some sequential decision, by making the best tradeoff between the gaining immediate access in the current temporal slot and the gaining information about the future states of the system. For instance, in [70] can be found a technique which introduces a simple and computationally efficient spectrum sensing scheme for OFDM in cognitive radio. It uses a sequential detection (SD) scheme where many secondary users cooperate to detect the same primary user. In [71] is proposed a design of optimal sensing strategies within the framework of Partially Observable Markov Decision Process (POMDP).

Commonly, the used spectrum sensing techniques do not offer a total reliability. Hence, the access strategy should depend as well on how much and when the secondary users should trust in the sensing device. In this case, it is important to take into account its receiver...
5.1 Opportunistic Spectrum Access (OSA)

Opportunistic Spectrum Access (OSA) (Section 5.3). A tradeoff between minimizing overlooked spectrum opportunities and avoiding the collisions with primary users should be made. The detector can work with two different approaches, conservative or aggressive, depending on the probability of miss detection (PMD) and false alarm (PFA), which will be explained in Section 5.3. When PMD is higher than PFA, the system is working in a conservative way to avoid the collisions with the primary system. On the other hand, if the PFA is higher than PMD, the system is working in an aggressive way which is suitable to reduce the number of overlooked spectrum opportunities. In [3] is proved that the optimal performance point of the sensing detector is when it is working in the transition point between the conservative and aggressive region. This point is achieved when the device trusts directly in the decision of the detector. Therefore, the device should access the licensed resource just if the channel is detected to be available.

When the secondary users detect the spectrum opportunity, it is necessary to know how to exploit this opportunity, in other words, which modulation, transmission power and which sharing technique among secondary users should be used. For instance, in an OFDM cognitive system, the subcarriers spacing and symbol intervals need to be equal to the spectral and temporal duration of the spectrum opportunity. Adjacent subcarriers to channels occupied by primary users may be null or allocated with low power to achieve the interference constraints. Hence, power control plays an important role in terms of interference management (Chapter 6). Once the secondary users are able to transmit individually without causing harmful interference at the primary receivers, the secondary users must avoid collisions with one another. It can be solved for example, by using a statistical method in a hidden Markov model as proposed in [73]. Some other way is to use distributed or centralized approaches in order to allocate the free subcarriers among the secondary users without causing collisions (Section 5.1.1). In [72] and [3] is shown a spatial opportunity allocation as graph colouring (Section 5.4.5). Some techniques using game theories are also applied in order to make the spatial opportunity allocation, as shown in [3, 75]. Finally, a spectrum shaping technique for interference management in DSA has been proposed in [74].

5.1.1 Spectrum sharing techniques among cognitive users

As explained above, when the secondary users are trying to access the primary resources they should choose which channel, QoS and which scheme to use. All the cognitive users must follow some procedures to determine whether the access to some spectrum resource is feasible or not. These users must avoid and manage the interference produced among them either in an intra-network or in a inter-network way [10]. An intra-network way refers to the interference among cognitive radio users inside some cognitive system, while the inter-network way refers to the interference which is made among several different cognitive radio systems.
A cognitive user should sense the spectrum in order to identify available spectrum opportunities. Some of the commonest studied spectrum sensing techniques are presented in Chapter 4. Once the spectrum opportunities has been found, the user should make a spectrum allocation which will depend on the internal different (cognitive system itself) spectrum allocation policies as well as external (licensed service). If the secondary user has been able to allocate some part of the spectrum to transmit its data, then the next step to follow will be the spectrum access. At this point, there are some important challenges in avoiding collisions among secondary users since some of them may be trying to access the same spectrum resource. There must be some protocol able to manage this spectrum allocation. When some resource of the spectrum has been allocated to some cognitive user, all the cognitive users must know it as well as the data receiver, in order to know which will be the used spectrum resource. Finally, the allocated spectrum is only available for some specific time, until the licensed system needs that spectrum resource. The capability of changing the used spectrum resource quickly must be available as well, it means using another free spectrum resource preserving a minimum QoS for the unlicensed system.

The current spectrum sharing techniques can be divided into three different classes, according to the architecture of the cognitive system, the spectrum allocation behaviour and the spectrum access technique. These different approaches are explained below [10]:

**Architecture**

**Centralized spectrum sharing** A centralized entity controls the allocation and access procedures. The cognitive users send the information about sensing to the main entity and it constructs a spectrum allocation map [77].

**Distributed spectrum sharing** When the centralized approach is not feasible, the users decide by themselves when they can access the spectrum according to the policies.

**Spectrum allocation behaviour**

**Cooperative spectrum sharing** In this solution the users share all the information about the interference that the nodes are receiving from the others. This information will be also taken into account in the allocation algorithms.

**Non-cooperative spectrum sharing** These kinds of solutions are considered as selfish, since the users consider only their own information about the surroundings to realize the resources allocation.

**Spectrum access technique**

**Overlay spectrum sharing** In this approach the secondary users access the primary spectrum resources when they are not used by the licensed system. In this
class two different approaches can be found. The first one is based on the use of different primary system subcarriers in each secondary transmitter [78]. The second one is based on estimating the time that the resource can be allocated to some user using prediction models [79].

**Underlay spectrum sharing** Once the spectrum allocation has been made, spread spectrum techniques can be used in order to spread the transmitted power under the noise floor at primary receivers, avoiding then their harmful interference.

## 5.2 Quantitative criteria

A quantitative criterion is used in order to evaluate and study different schemes to make possible the coexistence of a primary and secondary system, while evaluating the quantity of interference at primary receivers and different metric as the non-talk radius $r_n$ or the protected radius $r_{prot}$. A more formal definition for quantitative criteria could be as reference points or quantities with which other parameters of the same kind can be evaluated. Finally, quantitative criterion measures can be defined, which denotes the value of any quantitative criterion, as an example the value of the $r_n$ in metres.

In [2] are shown different criteria and models which will be presented. One of the models is merely to use the received power from the primary transmitter to determine if the secondary user is inside the recovered area or not. The received power $P$ from primary transmitter to the secondary user, using a path loss model (Chapter 3), can be written as follows:

$$P = P_t - 10 \log_{10} (r_n^\alpha),$$

where $P_t$ is the transmitted power by the primary transmitter, $r_n$ is the non-talk radius and $\alpha$ is the attenuation constant. Indeed, when the power received by the secondary user is higher than $P$, it means that the user is inside the non-talk radius $r_n$, where the transmission is not allowed. Otherwise, when the received power is lower or equal to $P$, the secondary user is out of $r_n$, so that the unlicensed user transmissions are allowed.

In an ideal channel, where only path loss is considered, Equation (5.1) is enough to calculate the distance from the primary transmitter to secondary one. In reality, the channel will experience fast fading due to multipath, shadowing and other channel effects (Chapter 3). Thus, the uncertainties produced by fading channels need to be taken into account, since the probability of interference $P_{fr}$ at the licensed system could be too high. It is necessary to add some security margins to protect the primary system from the channel uncertainties. Therefore, by adding this new parameter to Equation (5.1), it gives:

$$P = P_t - 10 \log_{10} (r_n^\alpha + \Delta),$$

45
where the Δ parameter changes according to the chosen security level for the primary system. It is possible to obtain some trade-off between the probability of interference $P_{fr}$ and the lost distance due to the values of Δ between the conservative ($Δ \uparrow \uparrow \Rightarrow P_i \downarrow \downarrow$) and optimistic case ($Δ \downarrow \downarrow \Rightarrow P_i \uparrow \uparrow$).

Since the devices are measuring directly the level of received power, it would be useful to convert the distance approach into a SNR approach to manage with margins of protection. Figure 5.3 shows the scheme of the model. If the primary system does not have any source of interference coming from secondary users, the primary receivers will be able to decode the signal up to the $r_{pcov}$ radius. The primary receiver has there the minimum required SNR to decode the signal successfully at some specific rate. When the secondary users are operating outside the $r_{pcov}$ radius, it is necessary define two more protection radius. The first one is defined as the protected radius $r_{prot}$. The primary receiver within this radius can ensure that the SINR will be high enough to achieve some QoS, taking into account the no-talk radius $r_n$. Within the $r_n$ radius, the secondary transmitters should not realize any transmission. The secondary transmitters are only able to transmit when they are outside $r_n$, otherwise they should be silent to avoid any harmful interference at primary receivers. Ideally, the $r_n$ radius should be centred on each primary receiver. However, taking into account that it is complicated to know where the primary receivers are, in this approach is considered the worst case where the edge of the protected radius $r_{prot}$ is plenty of primary users.

Figure 5.3: The figure shows the SNR margins corresponding to the protected radius $r_{prot}$, the coverage radius $r_{dec}$ and the non-talk radius $r_n$. So that, $ϕ$ defines the SNR at any user within $r_p$, $φ$ defines the SNR at any user outside $r_n$, $ω$ and $Λ$ represent the differences between the SNR at the radii defined before [8].

Hence, in this model, all the metrics will be computed directly using SNR. Thus, it is defined the SNR value $γ_{pcov}$ and $γ_{prot}$, which are the values at the edge of the coverage.
5.2 Quantitative criteria

Interference in cognitive radio systems

radius $r_{pcov}$ and at the edge of the protection radius $r_{prot}$ respectively. These levels of SNR are established by the primary receivers. The parameter $\gamma_n$ defines the SNR at the edge of the non-talk radius $r_n$ and it is established by the secondary transmitters. Likewise, these parameters, which are shown in Figure 5.3, can be defined by [76]:

\[
\begin{align*}
\phi &\triangleq 10 \log \left( \frac{p_{t1}}{p_n} \right) - \gamma_{pcov} \\
\omega &\triangleq \gamma_{prot} - \gamma_{pcov} \\
\Lambda &\triangleq \gamma_{pcov} - \gamma_n,
\end{align*}
\]

(5.3)

where the $\phi$ denotes the SNR between the primary transmitter and some primary receiver within the $r_{pcov}$ radius, $\omega$ is the difference between the SNR at $r_{prot}$ and $r_{pcov}$ radii, $\Lambda$ is the difference between the SNR at $r_n$ and $r_{pcov}$ radii. Finally, $\varphi$ denotes the SNR between the edge of the $r_{pcov}$ radius and some secondary user outside $r_n$. The remaining parameters are $p_{t1}$ and $p_n$ which are the transmitted power by the primary user and the noise power in linear units respectively. The maximum transmitted power allocated to the secondary users should guarantee the decodability of the primary signal within the edge of $r_{prot}$. In order to guarantee it, the SNR at primary receivers should satisfy:

\[
\begin{align*}
\frac{p_{1rp}}{p_{2rp} + p_n} &\geq \text{SINR}_{pcov} = 10^{\frac{\gamma_{pcov}}{10}} \\
p_{2rp} &\leq p_{1rp} 10^{-\frac{\gamma_{pcov}}{10}} - p_n,
\end{align*}
\]

(5.4)

where the parameters $p_{1rp}$, $p_{2rp}$ and $p_n$ are the primary received power at the edge of $r_{prot}$, the interference power received at $r_{prot}$ and the noise power respectively. By expressing the primary received power at the edge of the $r_{prot}$ in terms of SNR, it is possible to obtain the following constraint for the secondary system:

\[
p_{2rp} \leq (10^{\frac{\omega}{10}} - 1) p_n,
\]

(5.5)

where $\omega$ is the difference between the SNR at $r_{prot}$ and $r_{pcov}$ radii. Assuming that there is a primary receiver located at the edge of $r_{prot}$, the transmitted power of some secondary user located at the edge of $r_n$ radius should be:

\[
p_{t2} \leq \frac{(10^{\frac{\omega}{10}} - 1) p_n}{g_{21} (r_n - r_{prot})},
\]

(5.6)

where $g_{21} = d^{\alpha_2}$ is the channel gain between the secondary and primary user. When the transmitted power of the secondary users is variable, the distance of $r_n$ radius can be reduced. Hence, rewriting Equation (5.6), the SNR in decibels at the secondary transmitter should satisfy [76]:

\[
\left( \frac{p_{t2}}{p_n} \right)_{dB} \leq \frac{\alpha_2}{\alpha_p} \phi + 10 \log (10^{\frac{\omega}{10}} - 1) + 10 \alpha_2 \log \left( \frac{1}{\alpha_p} \left(10^{\frac{\Lambda}{10}} \right)^{1/\alpha_p} \left(10^{-\frac{\omega}{10}} \right)^{1/\alpha_p} \right),
\]

(5.7)
5.3 Performance criteria

The performance criteria are needed to quantify the performance of the coexistence between the primary and the secondary systems, as well as to get to know what is the effect of the channel uncertainties and the secondary system over the licensed system. A performance criterion can be defined as any reference point or quantity in order to evaluate the behaviour of other parameters of the same kind. An example of performance criterion could be the well-known probability of miss detection (PMD) and the probability of false alarm (PFA), which will be presented below. Likewise, a performance criterion quantity can be defined as the value of any performance criterion.

Some of the performance criteria that will be studied use a binary hypothesis, where $H_0$ indicates the absence of the primary signal in a specific channel and $H_1$, indicates the presence of the primary signal. This kind of hypothesis are directly related to type I and type II errors, which Table 5.1 shows. Finally, the definition of different performance criteria involved in cognitive radio are presented below.

Table 5.1: Definition of Type I and Type II errors. As it can be seen in the table, the probability $P$ of obtaining a Type I error is defined by $\alpha$. On the other hand, Type II error probability $P$ is defined by the parameter $\beta$ [21].

<table>
<thead>
<tr>
<th>Condition</th>
<th>$H_0$ is true</th>
<th>$H_1$ is true</th>
</tr>
</thead>
<tbody>
<tr>
<td>Do not reject $H_0$</td>
<td>Correct decision $P = 1 - \alpha$</td>
<td>Type II error $P = \beta$</td>
</tr>
<tr>
<td>Reject $H_0$</td>
<td>Type I error $P = \alpha$</td>
<td>Correct decision $P = 1 - \beta$</td>
</tr>
</tbody>
</table>
**5.3 Performance criteria**

**Probability of miss detection (PMD)** measures the probability that some secondary user does not detect the presence of the primary signal while this is present. Considering it as a binary hypothesis, if the detector mistakes $H_1$ for $H_0$, there will be a miss detection error which leads to a collision with primary users. This criterion has the most significance within the non-talk radius $r_n$ because it shows the probability of interference at the primary system.

**Probability of false alarm (PFA)** defines the probability of detecting the primary signal when the signal is not present. As a binary hypothesis, if the detector mistakes $H_0$ for $H_1$, there will be a false alarm and a spectrum opportunity is overlooked by the detector. Thus, a high PFA leads to high overlooking of spectral opportunities and conservative spectrum use outside the $r_n$ radius, where this criterion gains the most significance.

**Receiver Operating Characteristic curve (ROC)** describes the performance of the detector in spectrum sensing and it is specified at given SNR. This curve is basically the complementary of the PMD (1-PMD) or probability of detecting the primary signal as a function of PFA.

**Sensitivity** is the minimum value of SNR needed to achieve a specific PMD and PFA.

**Detector overhead** is sensing time needed to achieve a specific PMD and PFA value at a given SNR. This is directly related to sample complexity because if the detector is sensing a longer time, the number of samples will be higher.

**SNR Wall** is the minimum SNR level needed to detect the primary signal properly. Thus, the SNR Wall is the SNR which below robust detection is not feasible for a given spectrum sensing detector. This occurs when the mean of the probability density functions are very close or begin to overlap under the two hypothesis $H_0$ and $H_1$ as Figure 5.4 shows [9]. The energy detection (Section 4.1) is subject to this performance criterion.

In Figure 5.4 can be seen that the probabilities of miss detection and false alarm are different depending on the position of the detection threshold in the case of energy detector. Indeed, when the variance of the probability density functions is low, the error probabilities are also lower.

**Collision probability** occurs when some cognitive user detects that the primary channel is idle and it decides to transmit data. The primary system may use that channel again or it may allow a successful cognitive transmission. Thus, in the case where the primary user uses the channel again, a collision will take place. The collision probability can be given by [39]:

$$P_{coll} = f(SNR)$$
5.3 Performance criteria

Figure 5.4: Probability density functions of the received power in energy detection technique, when the primary signal is $\mathcal{H}_1$ and is not present $\mathcal{H}_0$. The probabilities of miss detection and false alarm are different depending on the position of the detection threshold. The figure is used to illustrate the SNR Wall [9].

\[
\mathcal{P}^c_{pb} = \lim_{t \to \infty} \frac{\# \text{ of collisions in } [0,t]}{\# \text{ of busy periods of PU in } [0,t]} \tag{5.8}
\]

The same performance criterion can be considered for the secondary users. In this case, the probability of collision can be defined as:

\[
\mathcal{P}^c_s = \lim_{t \to \infty} \frac{\# \text{ of collisions in } [0,t]}{\# \text{ of packet transmitted for SU in } [0,t]} \tag{5.9}
\]

**Overlapping time** is used to compute the percentage of time that the secondary user is colliding with the primary user signal. The percentage of overlapping time can be easily defined by [39]:

\[
\mathcal{P}^r_p = \lim_{t \to \infty} \frac{\text{Length of overlapping time in } [0,t]}{t} \tag{5.10}
\]

**Peak Interference-Temperature Constraint (PITC)** gives the maximum interference temperature at the primary receivers, when the used channel is under fading propagation effects [80].
5.3 Performance criteria

**Average of Transmit-Power Constraint (ATPC)**
gives the maximum interference power on average at the primary receivers, when the used channel is under fading propagation effects [80].

**Transmit Margin (TM)**
defined as the allowable maximum secondary transmission power which does not degrade the primary network QoS beyond a small tolerable predeclared limit [81] (Section 5.4.5).

In a cognitive radio system it is possible to find two kinds of uncertainties. One of them is the device-level uncertainties, which are caused by the thermal noise in the device. The second one, the system-level uncertainties, are caused by the propagation environment (shadowing, fading, etc.). It is shown in [2] that under device-level uncertainties it is important to consider as a performance criteria both the sensitivity and the SNR wall, since it was proved that the detectors have fundamental SNR thresholds. The performance criteria proposed in [2] try to characterize the system-level uncertainties. One of these performance criteria is the primary fear of harmful interference $F_{HI}$.

The probability of interference can be defined as $P_{Fr}(H_0 | r_{actual} = r)$, when the radius $r$ is lower or equal to $r_n$ (no-talk zone radius). The parameter $H$ is the binary decision of the spectrum sensing algorithm (for $H_1$ the primary signal is detected, otherwise $H_0$) and the function $F_r$ is the probability distribution of the combined multipath and shadowing-induced fading at a distance $r$ from the primary transmitter [2]. Since the distribution $F_r$ is not exactly known, the general expression to calculate the fear of harmful interference may be written as [2]:

$$ F_{HI} = \sup_{0 \leq r \leq r_n} \sup_{F_r \in \mathbb{F}_r} P_{Fr}(H_0 | r_{actual} = r), r < r_n, $$ (5.11)

where $F_r$ is be chosen among a set of distributions $\mathbb{F}_r$ taking into account the worst propagation model case. The $F_{HI}$ will be calculated at $r_n$, by considering it as a supremum. Therefore, this performance criterion will offer the maximum probability of interference at the border of the $H_0$ and $H_1$ decisions. The opposite to $F_{HI}$ which is defined as $S_{HI} = 1 - F_{HI}$ is called the safety of non-harmful interference. Another performance criterion, related to the secondary user performance, is the probability of detecting spectrum opportunities. This is the probability of finding a spectrum hole $P_{FH}$ and it is given by [2,31]:

$$ P_{FH} = P_{Fr}(H_0 | r_{actual} = r), r > r_n. $$ (5.12)

In order to characterize the amount of recovered area for the unlicensed users, a weighted probability of area recovered (WPAR) may be used as a criterion. It is given by the expression [2,31]:

$$ \text{WPAR} = \int_{r_n}^{\infty} P_{FH}(r) w(r) r dr, $$ (5.13)
where the weights \( w(r) \) must satisfy \( \int_{r_0}^{\infty} w(r) \, dr = 1 \). One commonly used weighting function is \( w(r) = A \exp(-\kappa r) \) where \( \kappa = 2 \times 10^{-5} \, m^{-1} \) and \( A \) is a scalar quantity. If the primary transmitter is intermittent, in other words, it is not transmitting continuously all the time, then it is possible to try to recover the holes in time. The goal is to use the OFF times of the primary transmitter while minimizing the sensing time [31]. There is another analogous to WPAR criterion called weighted probability of time recovered (WPTR), in order to illustrate the relative burden of the sensing time.

### 5.4 Interference temperature method

The interference temperature method has been studied by FCC [82] and is based on the interference that the primary receivers are able to allow, all this without causing an important loss of QoS in the primary system. It measures the power and the bandwidth of the interference signal. Hence, interference temperature is defined as the temperature of RF signals existing at the receiver antenna of some primary receiver from other sources as emitters and noise [27]. The unlicensed users can produce interference up to a specific limit called the interference temperature limit \( T_I \). This limit is established by regulators and it depends on the used technology by the primary system as well as the sensing location. In other words, depending on the location of the secondary nodes there will be different \( T_I \) levels. These established levels can take into account that the secondary node is not sensing at the same place where the primary receivers are located. This means that the interference sensed by the cognitive radios is not the real one supported by the licensed receivers. However, in some cases when the density of secondary users is high, the sensed interference by the secondary users could be approximately the same that the primary receivers are supporting. The equation defining the calculation of the temperature interference level is given by [11]:

\[
p = kTB \implies T_I(f_c, B) = \frac{p_i(f_c, B)}{kB},
\]

where \( k \) is the Boltzmann constant \( 1.3806503 \times 10^{-23} \, m^2 kgs^{-2} K^{-1} \), \( T \) is the temperature in Kelvins, \( B \) is the signal bandwidth in Hertz, \( f_c \) is the central frequency in Hertz, \( T_I \) and \( p_i \) are the temperature and the power of interference respectively.

The interference is typically managed in the transmitters, which means that it can be controlled at the secondary transmitters by modifying the transmitted power, out-of-band transmissions and changing the location of the them [10]. Figure 5.5 shows how the interference at the primary receiver takes place. This method has some limitations in measuring the real interference temperature in the primary receivers. The main problem comes from the secondary users that are unaware of the location of the primary receivers, because the
primary receivers are usually passive devices. It is a really challenging issue to know what is the actual level of interference in them [10]. However, the interference temperature approach would be an interesting concept if the location of the primary receivers were known with the help of some positioning system [83–86]. It would be possible to get to know what the maximum transmission power should be exactly in each secondary transmitter. In literature can be found some ways for trying to find the location of the primary receivers, see Section 3.6 for further details. However, this problem can be transformed into detecting primary transmitters problem, by limiting the level of interference at the edge of the coverage of the primary transmitter, as it has been explained in Section 5.1. Nevertheless, the FCC commission abandoned this approach as unworkable in 2007 [61,87], at the same time encouraging the researchers to find ways to solve this problem.

Figure 5.5: Received power of the licensed transmitter as a function of the distance to illustrate the interference temperature model. In the picture are shown several important regions in the model [10].

There are two approaches in the interference temperature management, one of them is when the parameters of the primary system are known (ideal model), and the second one is when these parameters are unknown (generalized model). As can be seen in Figure 5.6a, for the ideal model it is possible to have different interference temperature limits. In this case, the technology used by the primary system is known, which could be a cognitive radio system deployed over DTV bands or cellular bands. Therefore, the problem of distinguishing between primary and secondary transmissions becomes simpler, and the primary signals are not considered as an interference. When the secondary user is transmitting a wideband data which overlaps more than one primary channel, the lower interference temperature limit will set the constraint. In the generalized model case, as can be seen in Figure 5.6b, the primary parameters are considered unknown. Hence, all the sensed signals are considered as interference. Furthermore, the added interference temperature by the secondary users is computed at the centre frequency and with the bandwidth used by the secondary
user transmission. Further details about the ideal and generalized approaches are explained in the next sections.

Figure 5.6: Interference temperature calculation in ideal (A) and generalized (B) model. In the ideal model the centre frequency $f_c$ and the bandwidth $B$ of the signal are known. In the generalized model case, all the frequency range is considered as noise and neither $B$ nor $f_c$ are known [11].

### 5.4.1 Ideal model of interference temperature method

The goal of the ideal model is to attempt to limit the interference temperature in the licensed bands caused by unlicensed transmitters. If a secondary transmitter has a power $p_{t2}$, centre frequency $f_c$ and bandwidth $B$ in Hertz, the occupied spectrum in this case is the frequency range $[f_c - B/2, f_c + B/2]$. Let us assume that the frequency range occupied by the secondary transmissions overlaps $n$ licensed transmissions with centre frequencies and bandwidths of $f_i$ and $B_i$, respectively. The interference temperature model must guarantee that, in all the overlapped frequencies, the maximum interference temperature is less than the established interference temperature limit for a given frequency band in a particular location. Thereby, the expression which defines these previous requirements is [11,27]:

$$T_I(f_i, B_i) + \frac{M_{hi}p_{t2}}{kB_i} \leq T_L(f_i) \quad \forall \ 1 \leq i \leq n, \tag{5.15}$$

where the parameters $M_{hi}$ describes the effect of the fading and path loss between the second transmitter and the primary receiver, $T_I$ is the interference temperature and $T_L$ is the interference temperature limit in Kelvins. The first term of Equation (5.15) defines the
current interference temperature already existing in the primary receiver $T_I(f_i, B_i)$, while the second term defines the aggregated interference due to the secondary transmission.

Each overlapped unlicensed signal adds a new power constraint. When the unlicensed signal does not overlap with any licensed signal, the transmitted power is unconstrained but limited by the system regulator. In this approach it is assumed that the secondary node knows the technology used by the primary system and, therefore, the detector is able to distinguish between primary user waveform and interference. One problem is to measure the presence of the interference temperature when the primary signal is present but, since the assumption is that the secondary network knows what the used technology is, it is possible to measure the interference temperature easily. If the secondary nodes know just the centre frequency and the bandwidth, the interference temperature can be approximated by [11, 27]:

$$T_I(f_c, B) \approx \frac{p(f_c - B/2 - f_r) + p(f_c + B/2 + f_r)}{2kB},$$

(5.16)

where the parameter $f_r$ defines a security margin because of spectrum lateral lobes. The expression above approximates the interference temperature calculating its mean over the frequency band.

### 5.4.2 Generalized model of interference temperature method

In this approach the properties of the primary signal are not known. Hence, it is not possible to distinguish between the primary and the secondary signals. Since the RF features of the primary signal are not known, the limit interference temperature is computed over the whole frequency band, using the unlicensed signal parameters. In order to calculate the interference temperature in a specific frequency band, and check if the total temperature is higher than the limiting temperature, it is necessary to know what the current interference temperature at the centre frequency is, the bandwidth used by the secondary user, and the temperature added by the new secondary transmission. In this case, the aggregated interference at some primary receiver is given by the inequation:

$$T_I(f_c, B) + \frac{M_hp_{t2}}{kB} \leq T_L(f_c),$$

(5.17)

where $p_{t2}$ is the transmitted power by the secondary users in linear units and $M_h$ is the channel attenuation. If the inequations (5.17) and (5.15) are solved for $p_{t2}$, the power value for both ideal and generalized cases are obtained. As a result we get:

$$p_{t2}^{id} = \frac{k}{M_h B_i} \left( T_L(f_c) - T_I^{id}(f_i, B_i) \right)$$

(5.18)

$$p_{t2}^{gen} = \frac{k}{M_h B} \left( T_L(f_c) - T_I^{gen}(f_c, B) \right),$$

(5.19)
where $p_{i2}^{id}$ and $p_{i2}^{gen}$ are the calculated powers for the ideal and the generalized models respectively. Taking into account that in the generalized model there is less information, more interference could be experienced at the secondary receivers in this case. Thus, it would be interesting to evaluate the inequation $p_{i2}^{gen} \leq p_{i2}^{id}$ to restrict this produced interference. Considering the primary power of all the nodes as $p_i$, and the interference floor as Gaussian noise $T_N$, we get the following [11]:

$$kBT_L (f_c) (B - B_i) + kBT_N \sum_{j=1}^{n} B_j \leq \sum_{j=1}^{n} B_j p_j \quad \forall \ 1 \leq i \leq n. \quad (5.20)$$

Equation (5.20) sets the constraints to generate equal or less interference with the generalized approach compared to the ideal approach. Otherwise, this leads to higher probability of harmful interference, lower QoS and overlooks the spectrum opportunities because of the lack of information.

In the generalized model can be found two basic cases. The first one is when the bandwidth $B$ of the secondary user is known, so that the goal would be to compute the transmit allowed power $p_{i2}$. The second, given a power value $p_{i2}$, the goal is to find a valid value for $B$. In the first approach, using the ideal model, since the bandwidth $B$ is set to some value for the secondary users, the signal can overlap some primary channels $n > 1$. In that case, the established interference temperature limit must be the lowest temperature limit of the $B_i$ signal. The power $p$ as a function of the bandwidth $B_i$ is given by [11,27]:

$$p \leq \min_{i \in [1..n]} \left( \frac{B_i}{M_h} \left( T_L (f_i) - T_I (f_i, B_i) \right) \right) \quad \forall \ 1 \leq i \leq n, \quad (5.21)$$

where $i$ defines the different channels which the system is trying to find the minimum interference temperature limit. When the unlicensed signal does not overlap with any licensed channel, the maximum transmission power for the secondary user could be its maximum power [11].

In the generalized case, it will be necessary to calculate all the interference temperature in the established bandwidth, since the system is not able to distinguish primary and secondary signals in this model. By taking $S (f)$ as the power spectral density, the interference temperature is defined by the integral over the established bandwidth as shown in Figure 5.7 and in the following inequation:

$$p \leq \frac{Bk}{M_h} T_L (f_c) - \frac{1}{BM_h} \int_{f_c - \frac{B}{2}}^{f_c + \frac{B}{2}} S (f) df, \quad (5.22)$$

where $M_h$ describes the effect of the fading and path loss between the secondary transmitter and the primary receiver and $T_L$ is the interference temperature limit. In the second approach, where the transmission power is known, the bandwidth has to be calculated to satisfy the regulatory constraints [11]. To explain this approach three important parameters
will be defined. The first one is the parameter $m$, which indicates the channels which may overlap at a centre frequency $f_c$ with a maximum bandwidth $B_{\text{max}}$. Taking into account the maximum allowed power $p_{\text{max}}^k$ in each channel given in Equation (5.19), if the secondary signal is overlapped at $m$ channels and the transmission power is lower than the maximum allowed power, there will not be harmful interference if the transmission bandwidth is lower than the maximum one as well. Therefore, in order to find the available bandwidth given the transmission power $p_{\text{max}}^i$, it is necessary to know the closest channel around the centre frequency of the secondary transmission that does not support the established power. Let us define the parameter $\varrho$ as the channel where the transmitted power will cause harmful interference. Then, the maximum bandwidth can be calculated as shown below:

$$B_{\text{max}} \leq 2 \left( |f_c - f_\varrho| - \frac{B_\varrho}{2} \right), \quad (5.23)$$

where $B_\varrho$ and $f_\varrho$ are the bandwidth and the centre frequency of the channel $\varrho$ respectively.

Finally, in Figure 5.8 is shown the coexistence between some licensed and unlicensed system respecting the interference constraints. In this figure, regarding the primary system, the parameter $r_{SR}$ defines the protection radius for the secondary receivers, $r_{pcov}$ is the coverage radius for the system and $r_{psens}$ is the radius in which the licensed signal can be detected. In regard to the unlicensed system, $r_{scov}$ is the coverage radius of the system and $r_{PR}$ defines the protection radius for the primary receivers. Notice the radii between the licensed and unlicensed users, which allow the good performance of the interference
5.4 Interference temperature method

5.4.3 Estimation method for interference temperature

If the cognitive radio device is receiver-centric, it means that the primary receiver should be able to communicate its interference temperature estimates to the secondary users. So that, they can control the level of produced interference. In order to realize the estimation, the cognitive users should do what is presented in [1]. Firstly, they should try to estimate the interference temperature by using the Multitaper Method (MTM) [88]. Secondly, multiple individual spectrum sensors should be used, wherever it is possible, to sense properly the interference in the surroundings. If the total number of deployed sensors is $M$, let $Y_k^{(m)}(f)$ be the $k$th eigenspectrum computed by the $m$th sensor [1]. Taking into account all these parameters, a $M$-by-$K$ matrix can be defined [1], which is shown in (5.24). The columns in the matrix $A(f)$ define the sensed interference at different locations or gridpoints, the rows are different multitaper spectrum estimates per sensor and the parameter $\omega_m \ (m = 1 \ldots M)$ defines the weights for different sensor locations [89].

$$A(f) = \begin{bmatrix} \omega_1 Y_1^{(1)}(f) & \omega_1 Y_2^{(1)}(f) & \cdots & \omega_1 Y_K^{(1)}(f) \\ \omega_2 Y_1^{(2)}(f) & \omega_2 Y_2^{(2)}(f) & \cdots & \omega_2 Y_K^{(2)}(f) \\ \vdots & \vdots & \ddots & \vdots \\ \omega_M Y_1^{(M)}(f) & \omega_M Y_2^{(M)}(f) & \cdots & \omega_M Y_K^{(M)}(f) \end{bmatrix}.$$  \hspace{1cm} (5.24)

Therefore, the $A$ matrix 5.24 is generated by the interference at the sensors and the primary signal strength. Thus, it is necessary to extract the information of the primary signal from the sensor observations. The matrix (5.24) can be decomposed into a product.
of other simpler matrices by using the singular value decomposition (SVD) given as follows [88, 90]:

\[
A(f) = K^{-1} \sum_{k=0}^{K-1} \sigma_k(f) \mathbf{u}_k(f) \mathbf{v}_k^\dagger(f), \tag{5.25}
\]

where \( \sigma_k(f) \) is the \( k \)th singular value of the matrix, \( \mathbf{u}_k \) and \( \mathbf{v}_k \) are the associated left and right singular vectors respectively. By computing a new matrix product \( \Pi = A^\dagger \cdot A \), the main diagonal of this product is found to be the eigenspectrum of each Slepian taper [88], spatially averaged over the \( M \) sensors. Three main conclusions can be drawn from the singular value decomposition and the matrix \( \Pi \). First, the largest eigenvalue of any sensor \( m \), gives an estimate of the interference temperature plus some constant, that can be eliminated by using a linear combination among this largest eigenvalue and the two next largest eigenvalues. Second, the left singular vectors \( \mathbf{u}_k \) provides the spatial distribution of interferers. And finally, the right singular vectors \( \mathbf{v}_k \) represent the multitaper spectral coefficients for the waveform of the interferers. For more details about this interference temperature estimation method see [1, 88]. In [91] an improvement of this estimation technique can be found. The authors propose a method based on MTM called Adaptative Weighting MTM (AWMTM), which solves the problem that appears when the number of Slepian sequences is high since it would cause damage to the bias properties [91].

### 5.4.4 Interference Temperature Multiple Access (ITMA)

In reality, to apply the interference temperature method, some protocol should be used to make sure that the regulations and limitations established by the regulatory bodies are fulfilled. It is important to ensure as well that the secondary users can share properly the resources. Therefore some multiple access technique is needed in order to ensure that: (1) cognitive radios are using the bandwidth and the proper frequency range; (2) some way so that the cognitive radios can find one another; (3) there is some way to handle the management of lost connections and; (4) some way to realize proper performance in the cognitive radio users while all the regulatory requirements are satisfied. A multiple access technique called interference temperature multiple access (ITMA) is proposed in [13, 92]. ITMA uses interference temperature and CDMA to unify the concepts of dynamic spectrum allocation, medium access control (MAC) and power control. Hence, it uses code division techniques helped by spectrum sensing algorithms.

First of all, a channelization scheme should be defined between some \( f_{\min} \) and \( f_{\max} \) frequencies, considering equidistant central frequencies \( f_\Delta \). Thereby, a set of centre frequencies \( \mathbb{F} \) are obtained defined by \( f_i = f_{\min} + i f_\Delta \), where \( i \) are integer numbers. Once considered this scheme reads the relationship between the power and the bandwidth requirements. Therefore, given some sensed interference temperature level \( T_I \), the interference tempera-
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ture limit $T_L$ and some capacity for some specific QoS, the calculation of the power and bandwidth required through the Shannon-Hartley theorem [13, 92] is given by:

$$C = B \log_2 \left( 1 + \frac{l p_t}{kBT_I} \right) [b/s],$$  \hspace{1cm} (5.26)

where $l$ defines the signal attenuation between the transmitter and receiver, $p_t$ is the transmitted power in linear units, $B$ is the bandwidth, $T_I$ is the interference temperature, $k$ is the Boltzmann constant and $C$ is the capacity in bits per second. In order to compute the needed transmission power for some cognitive transmitter, taking into account the current limit and interference temperature, the following expression can be used:

$$M p_t = p_t - p_l,$$

$$p_t = \frac{kB}{M} (T_L - T_I),$$  \hspace{1cm} (5.27)

where the parameter $M$ is the signal attenuation between the cognitive transmitter and the primary receiver, $T_L$ is the temperature limit, $p_t$ is the power limit and $p_l$ is the interference power in linear units. Once the required power is calculated, by using Equation (5.26), the bandwidth expression in terms of the received power $p_t$ can be calculated as:

$$B = \frac{C}{\log_2 \left( 1 + \frac{l (T_L - T_I)}{kBT_I} \right)}. \hspace{1cm} (5.28)$$

Consequently, when the transmitter power $p_t$ is increased, the bandwidth is decreased and, on the other hand, when $p_t$ is decreased, the bandwidth is increased a specific QoS in the cognitive system. All the features described above must be accomplished for some protocol so that inside the ITMA protocol can be described the ITMA PHY (Physical layer), ITMA MAC (Medium Control Access layer) and higher MAC functions, where each one of them has a different operation properties.

The ITMA PHY layer manages the radio frequency properties of the cognitive link, and it configures parameters such as power and bandwidth, the equations of which have been already expressed before. The modulation DSSS (Direct-Sequence Spread Spectrum) may be used to achieve this aim. Before each packet transmission, the cognitive users should compute the required capacity $C$ and path loss $l$, and then compute the bandwidth $B$ by adjusting the chip rate of the DSSS modulation. Each transmitted packets starts with a PHY header containing a PN (Pseudo Noise) sequence which has a specific chip rate and a PN generator seed. The transmitter computes a new PN sequence each time a new packet is transmitted, maintaining the chip rate. Indeed, the transmission of packets with different PN sequences should be ensured, otherwise, the transmission of packets in different cognitive radios at the same time, may produce interference and collisions among the cognitive radios. The system would be similar to a system using CDMA technology.
Regarding the ITMA MAC layer, Figure 5.9 shows its operation. If some cognitive radio user desires to transmit a packet, the first step to take is to measure the interference temperature level $T_I$. Afterwards, with the help of the other parameters as $C$ and $l$, the aim is to compute the needed bandwidth $B$ and the chip rate in that case, as shown before. If the computed $B$ is smaller than some specific maximum bandwidth $B_{\text{max}}$, the transmission can be realized. Otherwise, when $B$ is higher than $B_{\text{max}}$, it is possible to proceed in several ways, as shown below and in Figure 5.9:

- The cognitive user can wait for some change in the level of interference temperature and then, the transmission could be possible.
- Decrease the capacity $C$.
- Increase the range $l$.
- At some point, if some timeout period has expired while the value of $C$ is smaller than $C_{\text{min}}$ and the value $l$ is higher than $l_{\text{max}}$, the system should change the centre frequency.

Finally, the higher MAC layer functions include the selection of a proper centre frequency, the reliable measure of $T_I$ and $l$, as well as the solution of the hidden terminal
problem. In order to choose the most proper centre frequency of the system, to minimize the bandwidth, the cognitive radio should follow the expression:

$$f_c = \arg \max_{f \in F} \left(T_L[f] - T_I[f]\right). \quad (5.29)$$

In order to compute the values of $T_I$ and $l$ with the maximum optimality, the cognitive transmitter will send its current value of $T_I$ and the value of the received power from the last packet sent in the inverse path. Thereby, the cognitive user will be able to compute some new value of $l$ by calculating the received temperature and comparing it with $T_I$, so that, if the received power at cognitive receiver is high enough, the $l$ parameter in that case could be increased. For further information about the ITMA protocol see [13].

### 5.4.5 Approaches for interference temperature technique

In this section some examples of different cognitive radio scenarios will be shown, in order to manage the interference produced at the primary receivers. These different schemes have been found in current literature [14–16,81].

**Scenario 1**

In [14] is a proposed deployment of an interference temperature limit approach, under a cellular network with pre-defined interference temperature levels (ITLs). In this scenario the secondary system works in both uplink and downlink in different ways. When the cognitive users are working in the uplink frequencies of the cellular system, the interference temperature limit can be established only at the cellular base station (CBS), instead of at all the cellular users. The secondary user can measure the path loss from the CBS in the downlink channel, and then use this information to compute the allowable maximum transmit power level (AMTPL) for the secondary user. This is necessary in order to ensure that the level of received power will be below the interference limit at the CBS. When the secondary users are using the cellular downlink channel, they could produce interference to all the surrounding primary users. In that case, the cognitive users should know what are the locations and the radio spectrum utilization of all the primary users around them. Notice that, as explained before, in the case of the uplink the cognitive radio users must take care only of the level of interference produced at the CBS.

The interference at the CBS will depend on the location and maximum transmission power of the cognitive user. If the cognitive user is located inside the coverage radius of the CBS, this cognitive user will produce interference to the CBS during the transmissions. Otherwise, when the secondary user is outside the coverage radius of the CBS, this user will not produce harmful interference with the CBS while the interference limitations are preserved. For the proper operation of these approaches, several assumptions should be taken:
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- The cellular download channel has pilot signals (with known transmit power) which the cognitive radios can hear.
- In the download frequency band of the cellular system FDD and TDD are used.
- The transmission in the uplink can be realized in a TDD or FDD scheme.

For further information about this cellular environment scenario see [14].

Figure 5.10: Communication environment in uplink and downlink when cognitive radio is working in a mobile communication environment [14].

Scenario 2

A different way to exploit the spectrum holes by using the white/gray spaces 2.2 in high traffic packet networks is proposed in [81]. A modified interference temperature approach will be used in this case. The proposed method is based on the detection of the statistic of the traffic of the primary system, by detecting the difference between its CDF taking into account several secondary users. In order to employ this method, a packet based network (PBN) will be considered in both the primary and the secondary system. Otherwise, when the physical layer of the cognitive system is working with DSA, the cognitive users need to know clearly the white spaces. Nevertheless, by using a PBN grey spaces can be used.

So that, the protocol presented below can work at the same time with other PBNs, regardless of the used protocol and the level of channel utilization in the primary system. The primary receiver needs a minimum SNR to ensure some minimum level of QoS. Thus, if the actual SNR is higher than this minimum, the primary receiver can support additional power insertion as interference without any significant change in its QoS. This presented method uses a new concept called Transmit Margin (TM), which can be defined as the allowable maximum secondary transmission power which does not degrade the primary network QoS.
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Beyond a small tolerable predeclared limit [81]. It is well-known that the problem with the interference temperature method is to be aware of the real interference that the secondary transmission is generating at the primary receivers. The cognitive users are only able to know the level of interference temperature that exists in its own location, and afterwards, they may estimate the level in the hypothetical location of some primary receivers. The TM method changes the problem by applying TM from the PHY cognitive radio layer to the MAC cognitive radio layer measured in QoS. The secondary users increases gradually its transmitted power and then it studies the generated effect on the QoS of the primary system. The basic principle is based on finding the transmission power of the secondary users, which permits the cognitive user the operation without causing a harmful effect on the QoS of the licensed system. The operation is described in two different steps: the transmission opportunity detection and the transmission power control loop. In the first step, transmit opportunity detection, the cognitive users keep on observing the activity of the primary system and then it constructs a statistic of the packet size distribution. This statistic will be called the prechange density. In the second step, transmit power control loop, the cognitive user increases its transmitter power step by step using a quantized increasing scale $p_k = k\Delta p$, where $k$ defines the quantified level given by $k = \frac{p_{\text{max}}}{\Delta p}$ where $p_{\text{max}}$ and $\Delta p$ are the maximum allowed power and the power increment respectively. The secondary users start to increase the transmitted power step by step and, in each one of them, a new study of the packet statistic is realized by constructing a CDF empirical function. This second function is called postchange density. When both prechange and postchange density are computed, by using the parallelized goodness-of-fit test [81], which will be explained below, the cognitive system can detect changes in the traffic level of the primary system. If the change in the probability functions is higher than some threshold, the cognitive user will transmit in the previous quantified level of transmitted power. Afterwards the process is repeated.

In regard to packets size distribution, when the communication channel is good, the packet distribution will be concentrated on big packet sizes for efficiency reasons. Otherwise, when the channel is degraded and with bad features, the packet size distribution will be more uniform [81].

Thus, the goodness-of-fit test will be able to detect the changes in the probability distributions of the packet size distribution. The test is based on the two hypothesis:

$$H_0 : F ( x ) = F_0 ( x ) \quad \forall x_n \in X$$
$$H_1 : F ( x ) \neq F_0 ( x ) \quad \forall x_n \in X,$$

(5.30)

where $F ( x )$ is the prechange density, $F_0 ( x )$ is the postchange density, $X$ is the set of $n$ independent and identical distributed observations sorted in ascending order, $H_1$ and $H_0$ are the hypothesis associated with the change in the probability function or not respectively.

The goodness-of-fit test is run with the methods Cramer von-Mises [93], Anderson-Darling [94] and two Rodriguez-Violaz variants [81] simultaneously. These methods are
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criteria used to judge the goodness-of-fit of a probability distribution compared to another distribution. The Cramer von-Mises method is able to detect changes in the central region of the distribution, the Anderson-Darling is able to detect changes in the lower and upper tails of the distribution, and the variants of Rodriguez-Viollaz’s methods, can work either in the lower or in the upper tail of the distribution. After the calculations, these several parallelized results are combined by ORing techniques making the final decision. For further information about this DSA method and about the goodness-of-fit functions and its tests, see [81].

Scenario 3

A scenario to take advantage of the spectrum holes, including the coexistence among the cognitive radios is proposed in [15]. The scenario is shown in Figure 5.11. The scenario has been proposed for the operation in TV bands and under the overlay approach. The primary transmitter will have two different radius. The first one is the protected radius, where all the primary receivers within it are ensured some QoS. The second radius is the security distance, which is needed to ensure that inside the protected radius all the primary users maintain under any circumstance the determined QoS. Hence, all the secondary users being inside the detectable radius of the primary transmitter can detected the presence of the primary user signal. In order to allow the sharing medium among secondary transmitters, they will be distributed as shown in Figure 5.11. Depending on the level of transmitted power of the secondary transmitters, the area outside the coverage radius of licensed users will be recovered in different percentages. Indeed, depending on the transmitted power of the secondary users as well as on its density, the security area will be different to ensure some specific QoS inside the protected radius.

Scenario 4

A different way to determine the interference constraints in frequency re-use in the secondary networks is proposed in [16]. It is assumed that all the users have some dedicated interference channel called Common Signalling Control Channel (CSCC), in order to manage the required parameters in the spectrum access by sending signalling and control messages. The power inserted by the secondary system at the primary one as harmful interference can be controlled at the cognitive transmitter by adjusting the transmitted power, the out-of-band power emissions and knowing the location of the individual transmitters. In order to manage the interference produced over the licensed system two strategies can be used. These strategies can be applied in two different ways: transmitter and receiver-centric ways. The constraints in the transmitter-centric way define a reuse frequency distance between any pair of cognitive transmitters, within this distance the reused of any used frequency is not allowed.
5.4 Interference temperature method

Interference in cognitive radio systems

Figure 5.11: Distribution of cognitive radio base stations, taking into account the coexistence among cognitive systems while the licensed user constraints are achieved [15].

Figure 5.12: Transmitter-centric interference constraints for the frequency reuse among secondary users (A) and factor graph colouring for this frequency reuse (B) [16].

The detection range \( d_s(t_i, c) \) is defined by the detection range of the transmitter \( t_i \), in the channel \( c \). Thereby, taking two cognitive transmitters \( t_i \) and \( t_j \), the reuse distance can be written as \( d_s(t_i, c) + d_s(t_j, c) \). So that, taking \( D(t_i, t_j) \) as the distance between the two transmitters, the users can use the same frequency in order to do reuse it if \( D(t_i, t_j) > d_s(t_i, c) + d_s(t_j, c) \). As an example, Figure 5.12a shows where two secondary transmitters are using two different frequencies with different transmission powers.
According to the expression given before, the transmitters cannot use the channel $C_1$ simultaneously, since the presented constraint is not held. Otherwise, both transmitters will be able to reuse the channel $C_2$ because the constraint is satisfied. In the Figure 5.12b is shown the graph colouring (GC) of the problem, where the nodes represent the different cognitive transmitters and the channel on the edge defines the frequency which can be used between those transmitters. The receiver-centric constraints are other approaches to control the inserted interference, which involve the interference temperature. So that, in this case, the method about limiting the interference produced at the primary receiver will be used. The quality of the transmission has been defined as the carrier-to-interference ratio $\frac{PC - PI}{PI}$ (in decibels expressed by $PC - PI_{c,i}$) for this scenario, where $i$ is the receiver and $c$ defines the used channel. The communication between a transmitter-receiver pair will be successful when $PC - PI_{i,c} > PC - PI_{th,i,c}$, where $PI_{th}$ represents the threshold interference. It is possible to define this equation defining straightly which the maximum inserted interference power can be as $PI_{c} < PI_{i} - PC - PI_{th,i,c} - Pn$, where $Pn$ is the noise power in decibels.

The receiver-centric constraints can be realized in two different ways: in a binary receiver and a non-binary receiver centric way. The binary receiver centric way attempts to ensure that the interference level at the primary receiver is lower or equal to the interference temperature threshold taking into account one interferer. Thus, the constraint for this way is defined by $PI_{j,i} < P_{i} - PC - PI_{th,i,c} - Pn$ where $PI_{j,i}$ is the received interference power at receiver $r_i$ from transmitter $t_j$. It is also suggested a representation of this constraint in terms of an exclusion distance defined as $D(t_j,r_i) > f(P_{i} - PC - PI_{th,i,c} - Pn)$, where $f(\cdot)$ is a decreasing function depending on the tolerable interference by the receiver. Notice that this approach works only with one interferer. The existence of more than one interferer may produce harmful interference at the receiver. The non-binary receiver-centric way solves this problem by taking into account all the possible interferers at the receiver. Let us assume that some receiver has three interferers and each one of them is using a determined transmission power. Taking these allocated powers, the new generated constraint will be a set of tuples with several possibilities of transmission for the interferers, as shown in the Table 5.2 [16]. In that case, the potential interferers are defined as co-channel (separation of 0 channels) or non-interfering (separation of at least 1 channel).
5.4 Interference temperature method

Table 5.2: Example of constraints in a non-binary transmitter centric way, based on three *tuples* for a safe transmission between transmitter $t_1$ and receiver $r_1$ ($t_1 \rightarrow r_1$). This example considers a set of four symmetric transmitters with the receiver $r_1$ in the middle. The table shows the minimum separation among the used channel by the communication ($t_1 \rightarrow r_1$) and other transmitters, in order to avoid the harmful interference at the receiver $r_1$. As in this example the scenario is symmetric. The three rows in the table can represent different combinations [16].

<table>
<thead>
<tr>
<th></th>
<th>$t_2$</th>
<th>$t_3$</th>
<th>$t_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td></td>
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<tr>
<td>0</td>
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<tr>
<td>1</td>
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</tbody>
</table>

Therefore Table 5.2 shows, when there is a communication between transmitter $t_1$ and receiver $r_1$, different *tuples* which allow the operation of the remaining transmitters without causing harmful interference. As an example in the first row of the Table 5.2, the $t_2$ and $t_3$ transmitters can operate in adjacent channels (minimum separation in frequency among $t_2$ and $t_3$ with $t_1$ is $\geq 0$) while the conditions of the transmitter $t_4$ are fulfilled (minimum separation in frequency channels between $t_4$ and $t_1$ is $\geq 1$).
Chapter 6

Power control in cognitive radio

Power control is an important topic in cognitive radio systems which allows managing the interference at primary receivers depending on the distances between primary and secondary transmitters, the density of secondary users, the receivers sensibility, etc. Until now, in order to manage the interference produced by the transmissions of the secondary system, the non-talk radius $r_n$ had been presented (Section 2.2). The $r_n$ radius represents some loss of possible recovered area for the secondary system. Nevertheless, this criteria is required to limit the quantity of interference that the unlicensed users produce when they are using some specific transmission power. The power control allows the reduction or removal of the $r_n$ radius, by decreasing the transmitted power of the secondary users which are closer to the protected or coverage radius. All this tries to find the optimal point of performance. These techniques will probably require some kind of cooperation with the primary system or other techniques, to be aware of the level of the real interference that the secondary transmitters are producing. These techniques will work by using some variant of the Waterfilling algorithm, to find the optimal point of operation. Beamforming may be used as well to control the amount of energy directed into certain direction. Hence it facilitates controlling the interference levels experienced in certain direction [95, 96]. However, this topic is not studied in this chapter. In Section 6.1 of the current chapter, is explained the power control based on spectrum overlay [71,73,97]. In Section 6.2 is explained the power control based on spectrum underlay and several iterative waterfilling solutions [98–105].

6.1 Optimization in spectrum overlay

The spectrum overlay method, as it was explained in Chapter 2, is based on taking advantage of the temporal slots which are not used by the licensed user during some specific time. In this approach, the unlicensed users will need to sense the primary signal in order to avoid causing interference in the primary system. Therefore, spectrum sensing techniques will be an important issue to try to avoid the interference in the licensed system, depending on its
sensing accuracy. Currently, there are many techniques for spectrum sensing such as energy detection, matched filter detection, cyclostationary feature detection, covariance-based detection, wavelet-based detection, etc. (Chapter 4). Assuming that the spectrum sensing techniques are totally reliable, they have still a problem which is the delay between the spectrum sensing and the data transmission, in other words, the sensing time. Depending on the sensing algorithm the sensing time could be different. If the duration of the temporal slot of the primary system is the same as the sensing time, when the unlicensed users decide to transmit, the primary system may use that subchannel again and it will interfere with the primary signal. To avoid this problem and manage the interference, many methods have been implemented for predicting the channel behaviour. This approach can work jointly with sensing algorithms in order to predict what will be the status of the channel in the future taking into account the previous one. To predict the status of the channel, it is possible to use traffic estimation models which already exist in the literature of traffic estimation or communication networks [106]. In cognitive radio systems, there are already some works using the Hidden Markov Model (HMM) to predict the state of the channel. Algorithms using the HMM based on pattern recognition are presented in [71, 97]. In [73] the authors consider that all the sensing algorithms have some sensing time, so that the algorithm predicts the future state of the channel taking into account the previous state, as well as the latency time needed for the hardware to detect the presence of the primary signal. In [73] is also proposed a Higher-Order HMM algorithm, which uses multiple previous states, as a generalization of first-order HMM which only takes the previous status. The Spectrum Sensing Slots (SSS) are defined in [73], being the time where the secondary user can transmit if any channel at any time is free. As explained above, when the SSS time is of the same order as the latency of the hardware, the delay becomes an important fact. Therefore, the optimal power control algorithms in the spectrum overlay approach, are important and still thoroughly studied.

6.2 Optimization in spectrum underlay

When the cognitive radio system is working with the underlay approach the secondary system is allowed to work at the same time as the primary system, indeed, without causing any harmful interference. It is important as well to avoid the interference among secondary users. In Section 5.1.1 it is possible to find at least two different approaches to avoid this happening. The first approach is to allocate different and unique subcarriers to the secondary users, so that the secondary users will not be able to produce interference to each other. The second approach is based on using a TDMA access system between the secondary users. In this way, the secondary user can use all the available carriers of the primary system to transmit its data at some specific time. All this process must be realized taking into account that the maximum interference allowed on the primary receivers cannot
be higher than the interference temperature limit.

In this approach, the primary receivers must send to the secondary transmitters what level of interference they have, so that, the primary network cannot be passive. Another approach can be used, which considers a passive primary network which is not able to send anything to the secondary network. Therefore, it should use some deployed sensors in the whole area and the same secondary users to sense the interference temperature around the environment. Considering secondary users and taking into account that they can be anywhere, the secondary transmitters may just as well be considered to sense the interference temperature environment. Assuming that the problem of sensing the interference temperature at the primary receiver has been solved, the solution to the power control is to find the optimum allocation of resources in the secondary users by searching the Nash equilibrium (NE) point [98] and assuming some constraints. This equilibrium point is achieved by using the Lagrange multipliers, Lagrange duality theory and some methods to solve the problem iteratively as ellipsoid and sub-gradient methods [99–102]. Game theory is used as well to achieve the optimal equilibrium point using so cooperative as non-cooperative games [107, 108].

Iterative waterfilling algorithms (IWFAs) are used to solve the problem [105]. This algorithm can also be applied when assuming MIMO technology in cognitive radio [103]. In [104, 109] can be found further details about IWFAs and a proof of its convergence leading to the unique NE. These kinds of algorithms update the allocated power in each secondary user over the available space of primary sub-carriers, considering the transmitted power of the rest of the secondary transmitters as interference. In that sense, for instance, an optimal algorithm using waterfilling techniques to maximize the performance of the unlicensed users is proposed in [79]. This algorithm computes the optimal transmission power for the secondary transmitters and the transmission time allocated to each one of them, in order to share the spectrum resources among unlicensed users. In [110] is proposed a price-based iterative waterfilling algorithm, using a distributed pricing strategy to improve the performance of the unlicensed system, modelled as a non-cooperative game. Another tax-based power control algorithm is proposed in [111], which uses a distributed method and guarantees the convergence to globally optimal power allocations.

Currently, the three most common waterfilling algorithms which can be found in cognitive radio systems are: (1) sequential iterative waterfilling [104, 105]; (2) simultaneous iterative waterfilling [104, 105] and; (3) asynchronous iterative waterfilling [104, 105]. In [104] another kind of iterative algorithm is also presented called smoothed asynchronous waterfilling, which is a variant of the asynchronous iterative algorithm. The algorithms to implement these different methods are shown below in the next section jointly with some other solutions. Figure 6.1 illustrate the waterfilling technique.
6.2 Optimization in spectrum underlay

6.2.1 Iterative Waterfilling solutions

The single waterfilling solution for a single user can be defined as [104]:

\[ \text{WF}_q^k \triangleq [\mu_q - \text{insr}_q(k)]p^k_{\text{max}}, \quad k = 0, ..., N - 1 \] (6.1)

\[ \text{insr}_q(k) \triangleq \frac{\sigma_{\omega_q}(k) + \sum_{r \neq q} |h_{rq}(k)|^2 p_r(k)}{|h_{qq}(k)|^2}, \] (6.2)

where in Equation (6.1) the parameter WF\textsubscript{\textit{q}}\textsubscript{\textit{k}} is the optimal allocated power (Waterfilling solution) over the \textit{k}\textsuperscript{th} subcarriers for the \textit{q}\textsuperscript{th} link, \textit{N} is the total number of carriers and \textit{\mu}_q is the level of water which will be chosen to satisfy the power constraint \((1/N) \sum_{k=0}^{N-1} p(k) = 1\). In Equation (6.2), the parameter \text{insr} is the inverse of the SNR, where \text{\sigma}_{\omega_q} defines the noise power at the carrier \textit{q}, \(H_{xy}(k)\) is the transfer function between the transmitter of the link \textit{x} to the receiver of the link \textit{y}, and \textit{p}_k is the transmission power.

In a general problem, the constraints that the secondary system must satisfy are:

\[
\begin{aligned}
\sum_{k=1}^{n} p^i_k &\leq p^i_{\text{max}} \\
p^i_k + I^k &\leq p^k_{\text{max}}, \quad \forall k \notin PS \\
p_k = 0, \quad \forall k \in PS \\
p^i_k &\geq 0,
\end{aligned}
\] (6.3)

where \(I^k = \sigma^k_{i} + \sum_{j \neq i} \alpha^{ij}_k p^j_k\) defines the interference at the primary receiver generated by the noise and the power transmitted by the secondary transmitters, \textit{p}^i_k are the transmission power of the secondary transmitter \textit{i} and \textit{\alpha}^{ij}_k denotes the different attenuation constants between the secondary transmitter \textit{i} and the primary receiver \textit{j} at the subcarrier \textit{k}. The
remaining parameters in (6.3) are $PS$, which defines the subset of used subcarriers by the licensed users and cannot be used by the unlicensed one, $p_{k_{\text{max}}}$ defining the level of maximum power allowed in the subcarrier $k$, $I_i^k$ and $I_i^k$ defining the power and the inserted interference of the user $i$ at the subcarrier $k$. Since the secondary users can join or leave the network randomly, the constraints shown above in (6.3), as the last and the second one are time varying. This follows from the appearance and disappearance of spectrum holes which depend on the activity of primary users and, furthermore, it will change the third constraint. The behaviour of the primary users as well as the availability and the duration of the spectrum holes, can be predicted using a predictive model. During a short time, assuming that the activity of the primary users does not change, two approaches can be also considered due to the joining and leaving of other secondary users as well as their mobility: stochastic optimization and robust optimization.

The stochastic optimization approach is based on the knowledge of the probability distribution of the unlicensed users. Let us assume that the noise-interference term is $I_i^k = T_i^k + \Delta I_i^k$, where $T_i^k$ is the vector of terms of noise-interference in each secondary user $i$ and $k$ the used subcarrier. The term $\Delta I_i^k$ defines the probability distribution uncertainty. By knowing this uncertainty and the allocated power at the secondary users $p_i^k$, it is possible to compute the maximal rate $R$ by using the following expression [105]:

\[
R = \max_{p_i^k} \left[ E_{\Delta I} \sum_{k=1}^n \log \left( 1 + \frac{p_i^k}{T_i^k + \Delta I_i^k} \right) \right], \tag{6.4}
\]

where $\Delta I = [\Delta I_1^i, \cdots, \Delta I_n^i]_T$. This calculation is useful when it is possible to know the probability function and its parameters. It computes the level of performance of the secondary system on average.

The robust optimization approach guarantees a good performance under the worst case conditions. When the parameters of the probability distribution uncertainty are unknown, this kind of optimization is better because the technique does not take it into account. Thus, this new optimization problem may be stated as follows:

\[
\max_{p_i^k} \left[ \min_{\|\Delta I\| \leq \varepsilon} \sum_{k=1}^n \log \left( 1 + \frac{p_i^k}{T_i^k + \Delta I_i^k} \right) \right], \tag{6.5}
\]

\[
s.t. \left\{ \begin{array}{l}
\sum_{k=1}^n p_i^k \leq p_{i_{\text{max}}}
\max_{\|\Delta I\| \leq \varepsilon} \left( p_i^k + T_i^k \Delta I_i^k \right) \leq p_{i_{\text{max}}}, \forall k \notin PS
p_k = 0, \forall k \in PS
p_i^k \geq 0.
\end{array} \right. \tag{6.6}
\]

Equation (6.5) defines the maximization of the rate and, Equation (6.6) defines the set of constraints.
Next, the most common iterative waterfilling algorithms (IWFA) will be described, which solve the problem of allocating the power iteratively. Due to the interference that the secondary users produce at the licensed receivers, the power allocation will change in each iteration until achieving an equilibrium point. A sequential iterative waterfilling algorithm is defined by [104,105]:

\[
\text{Set } p_q^{(0)} = \text{any feasible power allocation; for } n = 0 : \text{Number of iterations}, \quad p_q^{(n+1)} = \begin{cases} \text{WF}_q \left( p_{-q}^{(n)} \right), & \text{if } (n+1) \cdot (\text{mod } Q) = q, \forall q \in \Omega \\ p_q^{(n)}, & \text{otherwise,} \end{cases} \quad (6.7)
\]

where \( p_q^n \) is the power allocated to the link \( q \)th in the iteration \( n \), \( Q \) is the number of total users and \( \Omega \triangleq \{1, 2, ..., Q\} \) defines the set of active links. This algorithm updates the transmitted power by the secondary transmitters with a pre-selected order. Another common IWFA, where the power of all the secondary transmitters is updated at the same time in all the secondary users, is the simultaneous iterative algorithm, which is given by [104,105]:

\[
\text{Set } p_q^{(0)} = \text{any feasible power allocation; for } n = 0 : \text{Number of iterations}, \quad p_q^{(n+1)} = \text{WF}_q \left( p_{-q}^{(n)} \right), \quad \forall q \in \Omega \quad (6.8)
\]

Finally, the totally asynchronous iterative algorithm is described. In this case, all the secondary users are updated randomly and the algorithm is given as [104,105]:

\[
\text{Set } p_q^{(0)} = \text{any feasible power allocation; for } n = 0 : \text{Number of iterations}, \quad p_q^{(n+1)} = \begin{cases} \text{WF}_q \left( p_{-q}^{(\tau_q^{q}(n))} \right), & \text{if } n \in T_q, \forall q \in \Omega \\ p_q^{(n)}, & \text{otherwise,} \end{cases} \quad (6.9)
\]

where the parameter \( \tau_q^{q}(n) \) defines the most recent time at which the interference from some user is perceived by the link \( q \)th at the \( n \)th iteration.

Once the commonest iterative algorithms have been presented, their performance will be studied. The convergence of the power allocated to the unlicensed users on average, for different iterative waterfilling algorithms, is shown in Figure 6.2.a. Figure 6.2.b presents the variance, since depending on the location of the unlicensed users, the convergence of the optimal power will change. These plots are made using one fixed secondary user as
a probe, which is outside the protected radius of the primary system. Other changing secondary users around this probe user are as well used. The normalized allocated mean power shows that the optimum power is achieved faster when the simultaneous algorithm is used. The sequential algorithm is the second faster and the asynchronous or random algorithm is found to be the slowest one. Furthermore, all the considered algorithms are found to have slightly different points of convergence, as well as different values of variance $\sigma^2$ depending on the several unlicensed user locations evaluated. So that, the asynchronous algorithm is the one with more dependency on the location of secondary users, followed by the simultaneous and the sequential one. Therefore, the sequential iterative waterfilling algorithm has been found to be the most robust among the algorithms considered in front of the secondary users locations, as is shown in Figure 6.2.b.

Figure 6.2: Plot A shows the normalized mean power as a function of the number of iterations of the iterative waterfilling algorithms, considering different topologies of unlicensed users. In plot B is shown the variance of the normalized power. The results are shown for different iterative waterfilling algorithms, as the asynchronous (or random), simultaneous and sequential algorithms.

The performance of the unlicensed user is illustrated in Figure 6.3 showing the spectral efficiency of the unlicensed users and their performance as a function of the density of secondary users. In this case, the asynchronous and simultaneous methods achieve the best performance for the unlicensed users. However, the sequential algorithm has the worst performance. This result can be observed as well in Figure 6.2, since the sequential algorithm is the one with the lowest optimum power point and the one with less variance, so that, the lowest allocated powers for this algorithm are more often. This result can be seen as well in Figure 6.3.b, where the variance of the spectral efficiency is observed to be
the lowest for all the range of density $\rho_{ST}$ values. Nevertheless, the sequential algorithm is one of the fastest algorithms to converge with less variations (Figure 6.2).

The effect of the density of the unlicensed users in the asynchronous algorithm is important since the variance of the spectral efficiency increases significantly when the number of unlicensed users increases. However, the variance for the simultaneous algorithm tends to a constant value. Consequently, the use of the asynchronous algorithm will be similar to the use of the simultaneous one when the density of the unlicensed users is lower than some given threshold, in this case approximately 12, as Figure 6.3.b shows. Therefore, under this scenario the presence of a centralized node to achieve the optimality faster with the simultaneous algorithm is not required, since the asynchronous algorithm can be used with similar features for a low density value. Nevertheless, as studied in Figure 6.2, the velocity of convergence for the asynchronous method is slower.

Figure 6.3: The curves represented in A define the mean spectral efficiency as a function of the density of unlicensed users. The plot B shows the variance of the spectral efficiency. The plots are represented for different iterative waterfiling algorithms.

In order to see how a power control algorithm works, a 3D map with the power allocation in the secondary users by using the simultaneous algorithm is shown in Figure 6.4. In this case, the interference temperature is sensed directly at the secondary users. As it can be seen, the unlicensed users that are closer to the protected radius $r_{prot}$ have lower power allocations; as explained before, it is useful to decrease or remove the non-talk radius $r_n$.

In the asynchronous algorithm, which has been considered as the one of the most workable algorithms, is assumed that the users are sharing either the available licensed spectrum resources or any specific licensed channel. On the other hand, another approach is when the secondary users are working with some allocated subcarriers and they do not share them with other secondary users. Thus, the new maximization problem is based on searching for
6.2 Optimization in spectrum underlay

Optimization in spectrum underlay

Power control in cognitive radio

Figure 6.4: The map shows the allocated power to the unlicensed users by using the simultaneous iterative waterfilling algorithm. In this case, the interference temperature has been sensed by the secondary users considering that the secondary system is cooperative and it cannot know the real interference at the licensed users. The primary transmitter is located at the coordinates (0, 0).

The best subcarrier allocation for each secondary user, in order to maximize their utility function. In this approach, the maximum transmitted power of the secondary users and its power interference limit is chosen according to the expression given by [78]:

\[ p^i_k \leq B^i_k, \text{ where } B^i_k = \min_{m \in M} \frac{b^m_k}{h^i_{km}}, \]  

(6.10)

where \( p^i_k \) is the power transmitted by the user \( i \) at the subcarrier \( k \), \( b^m_k \) is the threshold power which can be inserted at the primary receiver \( m \) and, \( h^i_{km} \), is the channel gain of the channel between the secondary user \( i \) and the primary receiver \( m \). Finally, the parameter \( B^i_k \) defines the maximum transmitted power allowed for the user \( i \) at the subcarrier \( k \), taking into account the minimum power interference limit in order to avoid producing interference at any primary receiver. The maximization problem (6.11) and the new constraints (6.12) are given as follows [78]:

\[
\max \sum_{i \in M} \sum_{k \in N} U_i \left( \gamma^i_k \right), 
\]  

(6.11)
In the expression (6.11), $\gamma_k^i$ defines the SNR at the user $i$ in the subcarrier $k$, $M$ defines the maximum number of users and $N$ is the maximum number of subcarriers. The utility function $U_i$ to maximize the problem, in Equation (6.11), depends on the kind of application. It could be for applications like e-mail, web browsing, etc. or for delay sensitive services as video or voice. The specific utility functions can be found in [78].

The set of constraints shown in Equations (6.12), define the constraints which the maximization problem must consider to solve the given problem in Equation (6.11). The first constraint defines the SNR $\gamma_k^i$ which the secondary user $i$ is experiencing in the subcarrier $k$, where $p_k^i$ and $G_k^i$ are the transmitted power and the gain of the channel respectively. The second one establishes the range of allowed powers for the secondary user $i$ at the $k$th subcarrier. The third constraint establishes that the power transmitted by any secondary user through the used subcarriers is equal or less than its maximum transmission power $p_{i \text{max}}^i$. The parameter $D_i$, in the forth constraint, defines the set of subcarriers assigned to the user $i$, where $M$ defines the whole set of secondary users. So that, the forth constraint defines that the set $D_i$ must be constrained in the set of all the subcarriers and, the last constraint, establishes that the subcarriers allocated to the secondary users are unique and they cannot be shared among the secondary users.

When the cognitive system is in a fading channel scenario, the performance criteria of the average of transmit-power constraint (ATPC) and the peak interference-temperature constraint (PITC) are considered (Section 5.3). These quantities are used in [80] to compute the power control optimization taking into account the channel uncertainty. The goal of this algorithm is to maximize the sum-rate shown in (6.13). This new algorithm has been developed using a geometrical approach which can be found in [80]. Thus, the maximization problem and the constraints in this case, are given by:

$$
\max R = E \left[ \frac{1}{2} \log \left( 1 + \frac{\sum_{i=1}^{N} p_i h_i}{p_n} \right) \right]
$$

$$
\text{s.t.} \quad \left\{ \begin{array}{l}
E[p_i] \leq p_{i \text{max}}^i \quad i = 1, 2, \ldots, N \\
\sum_{i=1}^{N} p_i h_i \leq b_n
\end{array} \right.
$$

In Equations (6.13) and (6.14), the parameter $b_n$ is the maximum tolerable received power at the primary receiver, $p_{i \text{max}}^i$ is the average transmission power limit, $p_i$ is the power transmitted by the secondary user $i$, $h_i$ is the gain of the channel for the user $i$ and $R$ is the mean performance of the unlicensed users, which is maximized. The first constraint
in (6.14) is used to control the ATPC and, the second one, is used to control the PITC. According to the results shown by the authors in [80], at most two unlicensed users are found to be able to transmit simultaneously for optimality. Considering the ATPC and the PITC constraints, in [112] is also proposed an interference power outage constraint, which is maintained within a target level. The outage is defined as the probability where the PITC and ATPC at some primary receiver is larger than some threshold. This new constraint introduces a new performance criterion to use while the power control algorithm is working.
Chapter 7

Evaluation of the performance

Some performance criteria and quantitative performance results are presented in this chapter. At this point, it would be interesting to know the relation between them. Finding the behaviour of some performance criteria as a function of other performance or quantitative criteria parameters or physical parameters, will allow searching nearly the optimal operation point by selecting the correct performance criterion and unlicensed user parameters, as the power transmitted by the secondary users. Therefore, by using this criteria, the behaviour of several quantitative and performance criteria as a function of physical parameters as distances, density of secondary users, etc. will be studied.

Although the definitions of performance criteria and quantitative criteria have already been presented in Chapter 5, it will be helpful to define briefly again these terminologies. A quantitative criterion is a reference point or quantity, for instance it could be the interference or the bit error rate (BER) at the primary receivers, with which other parameters can be evaluated. This criteria will be used, for instance, to study the behaviour of some other parameters holding the level of interference at the primary receiver at some value. At this point, it is possible to define the quantitative criterion measure, which defines the value of any quantitative criterion, as the interference power at some primary receiver, the length of the non-talk radius $r_n$, etc. On the other hand, a performance criterion is any reference point, for instance the probability of miss detection (PMD), the weighted probability of area recovered (WPAR) or any criterion presented in Chapter 5.3, in order to evaluate the behaviour of other parameters. A performance criterion quantity, therefore, can be defined as the value of any performance criterion. After reminding some key terminologies, it is interesting to present as well the concept of optimal criteria, which can be defined as the best criteria that allow the unlicensed system to have the best behaviour in terms of harmful interference at the primary system, while respecting the constraints established by the licensed regulators. At the same time the unlicensed users will have as high as possible SNR value.

Therefore, after some brief reminder about terminology, in this chapter will be presented
some design curves which will allow to know what are the most important factors in the deployment of an unlicensed system. In Section 7.1 then, the effect of the density of unlicensed users will be studied in order to see what the influence is on the quantitative criteria, for instance, the effect on the SNR at the non-talk radius $r_n$. The relation among different quantitative criteria will be studied as well in this section. In Section 7.2 are studied several interference maps in terms of signal-to-noise ratio, according to different propagation models as ideal and fast fading. Therefore, the results will show the effect on the mean SNR over multiple secondary user and primary receiver locations, depending on the used propagation model. Finally, in Section 7.3 are shown some maps of performance criteria quantities, using both fast fading and shadowing propagation models, in order to see graphically what is the effect of these different channel models on these performance quantities. Additionally, in this section are studied some issues about the distribution probability function of these different propagation models and the relation between some quantities as the weighted probability of area recovered (WPAR). All the experiments in this section are made using the scenario presented in Figure 5.3 of Section 5.2.

7.1 Quantitative criteria - Design curves

The relation between the quantitative criteria measurement must be studied to discover the relation between them by using the architecture of the scenario shown in Figure 5.3 and the ideal propagation channel. As explained before, for the experiments will be used the quantitative criteria presented in Section 5.2. In the simulated scenario it is assumed that the secondary users are already located outside the non-talk radius $r_n$ and they are located following an uniform distribution. In the experiment shown in Figure 7.1, the secondary system computes the SNR level of the primary users increasing the distance from the primary transmitter until it finds the location where the SNR level indicates the presence of the edge of $r_n$. The $r_n$ location is calculated by considering that the SNR at the edge of the protected radius $r_{prot}$ must be the minimum SNR allowed by the primary receivers in order to decode the signal free error. When the SNR of the primary system is calculated, the transmitted power of the secondary users distributed uniformly is considered as interference. Thus, the distance where the calculated SNR indicates the presence of the edge of $r_n$ is found in the experiments. The parameters used in the simulations are shown in Table B1.

As it is shown in the distribution function of Figure 7.1, it is important to notice that the different locations of the secondary system will have an important impact on how much interference is generated at the primary receivers.

The different possible locations due to the uniform distributed secondary users, will add a statistical dependence to the scenario, since in each realization of the experiment different secondary users are deployed. Therefore, most of the experiments in this section
will be done taking into account the mean and variance of multiple locations of secondary users. In Figures 7.1.a and 7.1.b the probability density function of $r_n$ is shown depending on the effect of different locations of the surrounding secondary users. In the experiments, the protected radius is $r_{prot} = 3.8$ km and the coverage radius is $r_{pcov} = 4.5$ km. On the other hand, in Figure 7.1.b the protected radius is $r_{prot} = 2.3$ km and the coverage radius is $r_{pcov} = 2.5$ km. It can be seen that, by comparing both Figures 7.1.a and 7.1.b, the probability function of $r_n$ radius changes depending on the protected radius length.

For $r_{prot}=3.8$ km the mean of $r_n$ is found to be $E[X] = 4.8$ km with a variance of $\sigma^2 = 0.45$. In the case where the protection radius for the primary receiver is $r_{prot} = 2.3$ km, the mean of $r_n$ is $E[X] = 3$ km and the variance $\sigma^2 = 0.78$. Therefore, when the protected radius is long, the different locations of the secondary users does not produce as much effect on the $r_n$ as when the protected radius is shorter, since the variance value for $r_{prot}=3.8$ km is found to be lower.

Figure 7.1: A shows the probability density function of the non-talk radius depending on multiple unlicensed user locations, for a $r_{prot} = 3.8$ km and $r_{pcov} = 4.5$ km. B shows as well the probability density function in this case but using a $r_{prot} = 2.3$ km and $r_{pcov} = 2.5$ km.

Figure 7.2.a shows the influence of the density of secondary users $\rho_{SU}$ on the SNR at $r_n$ radius for $\omega = 1$ dB and $\omega = 3$ dB, where $\omega$ is the difference between the SNR at $r_{prot}$ and $r_{pcov}$ radii, which has been described previously in Section 5.2. When the density of secondary users increases, the $r_n$ radius also increases (or the SNR decreases), because the interference due to the larger number of secondary users becomes higher. Notice that, as Figure 7.2.b shows, the value of the variance tends to zero if the density of secondary users
increases, because the possibilities of different locations of the secondary transmitters are reduced on average.

Figure 7.2: The curve A shows the dependence of the SNR at the non-talk radius on the density of secondary users. B shows the variance of this SNR as a function of the density. Both plots are shown with different values of the parameter $\omega$, which denotes the difference in decibels between the protected radius $r_{prot}$ and the coverage radius $r_{pcov}$, as the scenario of Figure 5.3 shows.

Once the effect of the location and density of the unlicensed users has been studied, different results showing the relation among some quantitative criteria are presented. The curves shown in Figure 7.3 could be used to design and set the value of the quantitative criterion $\omega$, starting with the already set configuration of the primary system (i.e. the transmitted power). The best configuration can be found by trying to find the best parameters for the secondary system, maximizing the SNR in the secondary receivers and preserving the interference constraints in the primary system. When the regulatory bodies or the primary system regulator are trying to find the parameter $\omega$, which will permit the operation of the secondary users, they should be able to lose some effective coverage in the licensed system. In other words, by inserting the parameter $\omega$, the licensed system will sacrifice part of the service area to permit the secondary operation. Therefore, taking into account that the primary receivers can be calculated by units of area (i.e. users/km$^2$), some of the primary receivers located at the edge of the coverage area will lose the reception of
7.1 Quantitative criteria - Design curves

Evaluation of the performance of the signal. Thus, given a transmission power of the primary transmitter, the primary system should consider what the “percentage of lost area ($\chi$)” is. This proposed performance criterion implies the loss of some primary receivers depending on its density and it can be given by:

$$\chi = \frac{\pi r_{pcov}^2 - \pi r_{prot}^2}{\pi r_{pcov}^2} = 1 - \frac{r_{prot}^2}{r_{pcov}^2},$$  \hfill (7.1)

where $r_{pcov}$ and $r_{prot}$ are the coverage radius and the protection radius respectively.

Expressing this problem in terms of SNR, one gets:

$$\gamma_{pcov} = P_t - L_{pcov} - P_n \quad \gamma_{prot} = \gamma_{pcov} + \omega,$$  \hfill (7.2)

where $\gamma_{pcov}$ and $\gamma_{prot}$ are the SNR at the coverage and protection radius respectively, $P_t$ is the power transmitted by the primary user, $L_{pcov}$ is the attenuation for the coverage radius and $P_n$ is the power of the noise in decibels. Next, the equations shown in the previous expressions can be written as:

$$\gamma_{prot} - \omega = P_t + L_{cov} - P_n - 10\alpha \log_{10} r_{prot} + 10\alpha \log_{10} r_{pcov} = \omega$$

$$\frac{A_{pcov}}{A_{prot}} = 10^{\frac{\omega}{10}},$$  \hfill (7.3)

where $A_{pcov}$ and $A_{prot}$ denote the coverage and protected areas, respectively and $\alpha$ is the attenuation coefficient. Therefore, the equation of the percentage of lost area can be expressed as:

$$\chi = 1 - 10^{\frac{\omega}{10}}.$$  \hfill (7.4)

In (7.4) the used propagation model will be one of the most important factors to take into account at the moment of determining the parameters for the secondary system. In this case, the ideal propagation model is taken considering different attenuation constants. Figure 7.3 shows some representation of the expression (7.4) for three different values of $\alpha$.

Depending on the parameter $\alpha$ of the channel (it could mean different propagation environments: indoor, outdoor, urban, etc.), the $\omega$ parameter must be changed according to the $\chi$ value that the licensed user wants to preserve. Consequently, the primary system must decide this margin to choose where the interference of the secondary transmitters must be limited. For the experiment shown in Figure 7.4, the used parameters of the licensed and unlicensed users are set according to Table B1, preserving the value of percentage of lost area for the primary system to $\chi = 0.1$.

Thus, Figure 7.4.a shows the mean SNR at the $r_n$ radius as a function of the power transmitted by the secondary transmitters. Several curves for $\omega = 1$ dB and $\omega = 3$ dB are shown as well. Indeed, when the transmitted power of the secondary users increases,
7.1 Quantitative criteria - Design curves

Evaluation of the performance

Figure 7.3: The percentage of area ($\chi$) that the licensed users are losing due to the parameter $\omega$. Several plots are shown for different attenuation constants $\alpha$. The expression which defines these curves is given by Equation (7.4).

the distance of the $r_n$ radius becomes larger. In other words, when the transmitted power increases, the SNR at the $r_n$ radius decreases. As can be seen in Figure 7.4.a, for different values of $\omega$ the decreasing velocity is different. When the parameter $\omega$ is higher, it means that the protected radius is larger, the distance of $r_n$ can be decreased slightly due to the transfer function of the propagation model. Figure 7.4.b shows the variance of the SNR at $r_n$ of the experiments produced by different uniformly distributed locations of the secondary users. When $\omega = 3$ dB, the curve increases up to achieving a maximum of 29 dB. In the case of $\omega = 1$ dB, the variance increases taking the maximum value of 29, and then it decreases again as a function of the transmitted power by the unlicensed users. Therefore, as it can be observed on the curves in Figure 7.4.a, when the licensed system chooses a higher value of $\omega$, the unlicensed users are able to reduce less the $r_n$ radius preserving the percentage of lost area $\chi$. Nevertheless, by transmitting with a higher power, the length of the $r_n$ radius will have more dependence on the location of the secondary user, as it is shown in the variance curve of Figure 7.4.b. When $\omega = 1$ dB is used, the $r_n$ must be higher. However, the variance of the SNR at $r_n$ becomes lower for higher transmitted powers. Therefore, for $\omega = 1$ dB, the secondary users can transmit at higher power reducing the dependence on the location of these users.

However, when the secondary users are working with low transmission power, it is better to use the value $\omega = 3$ dB (smaller protection radius $r_{prot}$), since in this case the non-talk radius is preserved with a low value and the dependence on the different location of the secondary users is found to be practically null.

With the help of these curves, it is possible to know as well what transmitted power
Figure 7.4: A shows the mean SNR at the non-talk radius in decibels, as a function of the power transmitted by the unlicensed users for different $\omega$ values. Curve B shows the value of the variance due to the effect produced by the different uniformly distributed locations of the secondary users in each experiment realization. Therefore, in these plots can be seen the relation between the unlicensed transmitted power and the SNR of the licensed transmitter, calculated at the non-talk radius by the unlicensed users.

by the secondary transmitter should be, given some desired SNR at $r_n$, preserving the remaining parameters indicated in Table B1.

If the primary user decides to modify the transmitted power once all the parameters of the secondary system have been chosen, it would be interesting to know the effect on the SNR needed at the non-talk radius or its radius. Figure 7.5.a shows the SNR as a function of the power transmitted by the primary user for $\omega = 1$ dB and $\omega = 3$ dB. As can be seen in Figure 7.5.a, the mean SNR at the $r_n$ radius has an increasing linear behaviour. Therefore, if the licensed user decides to increase or decrease its transmission power, the SNR at the non-talk radius is modified linearly in decibels, while the remaining parameters are retained. The variance due to different uniform distributed locations of the secondary users is constant over the values of transmitted power, with an approximated value of 0.1, as can be seen in Figure 7.5.b. Therefore, the dependence of the density and of the multiple possible locations of the secondary users on the SNR at $r_n$, in this case, is practically negligible.

The behaviour of the SNR at the $r_n$ radius, in the case where the licensed system decides to increase the parameter $\omega$ preserving the remaining parameters, is shown in Figure 7.6.a.
7.1 Quantitative criteria - Design curves

Figure 7.5: A shows the relation between the SNR received at the non-talk radius and the power transmitted by the primary users. In plot B the variance generated by multiple different locations of secondary users is shown. The plots show different values of the parameter $\omega$.

When the values of $\omega$ are low, the SNR must increase faster. When the primary user decides to modify the parameter $\omega$, the secondary transmitter must increase the distance to preserve the no interference constraint at the protection radius $r_{prot}$. On the other hand, when the value of $\omega$ is higher, the unlicensed transmitters can preserve the no interference constraint by increasing the $r_n$ radius more slowly. When the value is higher than 8 dB in those conditions, the SNR value tends to a value of approximately 25 dB, which is the minimum SNR value with which the primary receivers can decode the signal error free. This means that when the $\omega$ parameter is high, the $r_n$ radius tends to be equal to the coverage radius $r_{pcov}$ of the primary transmitter on average, depending on the different locations of the secondary users. Indeed, it is due to the propagation model, since increasing the SNR at long distances means higher distances than increase it at closer distances to the transmitting source. Therefore, for high values of the parameter $\omega$, the $r_n$ radius becomes the same as the coverage radius.

Figure 7.6.b shows the variance of the SNR as a function of the $\omega$ parameter, which has a maximum when the parameter $\omega = 3$ dB. From $\omega = 1$ dB to $\omega = 3$ dB, the increasing behaviour is because, when the parameter $\omega$ starts to be higher, the received power coming from the secondary transmitters has more influence on the variation of the received power at the primary receivers. From $\omega = 3$ dB to $\omega = 10$ dB, the value of the variance tends to
Figure 7.6: Plot A shows the SNR at the non-talk radius as a function of the parameter $\omega$, which establishes the protection radius $r_{prot}$ for the licensed users. Plot B shows the variance of this SNR due to the multiple locations of the secondary users. All the values are expressed in decibels.

0. Indeed, this means that when the secondary users are located at longer distances, the effect of their transmitted power at the $r_n$ radius becomes lower. Therefore, for high values of $\omega$ the different locations and density of the secondary users produce no variation in the SNR at $r_n$.

### 7.2 Signal-to-Noise ratio maps

In this section, the effect of the coexistence of the primary and secondary systems by using temperature maps with SNR quantities will be shown. These experiments are made with five primary transmitters in order to see clearly what the effect can be in a more realistic scenarios. In order to know the location of the primary transmitters and the values of the remaining parameters see Table B2, which shows all the used parameters in the experiments of this section.

Figure 7.7.a shows the mean SNR map at the primary receivers, with the influence of secondary transmitters. Taking into account that the sensibility (minimum SNR) is in this case 25 dB, the coverage radius can be identified graphically for all the transmitters. Figure
7.2 Signal-to-Noise ratio maps

Figure 7.7: Map A shows the mean SNR for the licensed receivers, and B the variance $\sigma^2$ of the SNR at these receivers. On the other hand, map C shows the mean SNR at secondary receivers and, map C also shows the variance $\sigma^2$ at these receivers. The propagation channel used in this case is path loss with $\alpha = 4$.

7.7.b shows the variance of the SNR map of the primary system. In this case, the darkest dots represent the area where the secondary users have been more frequently in the different realizations of the experiments.

Figure 7.7.c shows the mean SNR map of the secondary users considering the interference produced by the primary transmitters. Taking into account that the sensibility for these users is 20 dB, it is possible to see the area which can be used for secondary users with successful transmissions. Figure 7.7.d shows the variance of the SNR map of the secondary users. In this figure it can be seen that when the secondary users are further from the primary transmitters, the dependence of the SNR on the different locations of secondary users is higher. All the interference maps containing Figure 7.7 are produced by an ideal propagation channel.

In Figure 7.8 a fast fading channel is used. Observing the SNR of the primary system it is possible to see, preserving the same parameters as in Figure 7.7 (shown in Table B2), a smaller coverage radius. Therefore, when the very demanding fading channels are used, it is necessary to add the SNR margin given in Equation (5.2) to achieve the desired level.
7.3 Maps and plots of performance criteria quantities

In this section quantitative results of performance criteria are provided in the case of fast fading (NLOS) and shadowing channels. For the experiments, the unlicensed users use the energy detection as spectrum sensing technique. The experiments are done with one licensed transmitter located at (0, 0) Km coordinates. To know the remaining parameters used in the experiments see Table B3.

Figure 7.9.a shows the curves of $P_{\text{PFA}}/P_{\text{NFH}}$, $\text{PMD}/P_{fr}$ and the probability of fear of harmful interference $F_{HI}$ (Section 5.3) for a fast fading channel. Figure 7.9.b shows the...
Figure 7.9: Plot B shows the probability of not finding a spectrum hole $P_{nFH}$, the fear of harmful interference $F_{HI}$ and the probability of interference $P_{fr}$, distinguishing between the area outside the non-talk radius $r_n$ and the area within $r_n$. Plot A is a 2D view from the further area to the origin of coordinates of the 3D plot B. The same occurs with plot C which shows the probability of finding a spectrum hole $P_{FH}$, the probability of non-interference $P_{nfr}$ and the safety of harmful interference $S_{HI}$. Plot D illustrates the same using 3D graphics. These curves are made using a fast fading propagation channel.

By comparing the experiments of both propagation models, it is possible to see that the fast fading channel produces larger probabilities of interference within the $r_n$ radius and larger probabilities of loss of spectrum opportunities outside of it. The $F_{HI}$ for fast fading channels, in those conditions, is approximately equal to 0.61. Nevertheless, in the case of shadowing, the same quantity has been found to be approximately 0.45, as Figure 7.10.a shows. Therefore, the fast fading introduces higher $F_{HI}$ and, in general, it deteriorates all the quantities since the fast fading NLOS has very demanding propagation conditions. From the unlicensed user point of view, the probability of not finding a spectrum hole $P_{nFH}$ outside the $r_n$ radius achieves lower values when a shadowing channel is used.

Figures 7.9.c and 7.10.c show the PMD/$P_{FH}$, PFA/$P_{nfr}$ and the safety of non-harmful interference $S_{HI}$ (Section 5.3). Figures 7.9.d and 7.10.d show these quantities but, in this
7.3 Maps and plots of performance criteria quantities

Figure 7.10: Plot B shows the probability of not finding a spectrum hole \( P_{nFH} \), the fear of harmful interference \( F_{HI} \) and the probability of interference \( P_{fr} \), distinguishing between the area outside of the non-talk radius \( r_n \) and the area within inside \( r_n \). Plot A is a 2D view from the further area to the origin of coordinates of the 3D plot B. The same occurs with plot C which shows the probability of finding a spectrum hole \( P_{FH} \), the probability of non-interference \( P_{nfr} \) and the safety of harmful interference \( S_{HI} \). Plot D illustrates the same using 3D graphics. These plots are made using a shadowing propagation channel.

In these experiments, the quantities achieve better values when a shadowing channel is used. Thus, the probability of finding a spectrum hole \( P_{FH} \), for any unlicensed user, increases faster when they are further from the \( r_n \) radius when a shadowing channel is used. As it can be seen, the \( F_{HI} \) is given by the largest probability of interference \( P_{fr} \) in the primary system.

Figure 7.11.d shows \( F_{HI} \) as a function of the parameter \( \Lambda \), which defines the difference in dB between the SNR at the coverage radius \( r_{cov} \) and the SNR at \( r_n \) radius of the primary system. This probability is observed to be constant for all the values of the parameter \( \Lambda \) for a fading channel. Figures 7.11.a, 7.11.b and 7.11.c can be used to illustrate the scenario better. Figure 7.11.a shows the histogram of the SNR at \( r_n \). The distribution of the SNR at any point of \( r_n \) will have this histogram but with different mean and variance as can be
7.3 Maps and plots of performance criteria quantities

seen in Figures 7.11.b and 7.11.c as a function of parameter Λ. The mean value decreases linearly in decibels with the distance, with a slope depending on the attenuation constant. The variance decrease linearly in decibels as well.

![Figure 7.11](image)

Figure 7.11: Plot A shows the histogram of the SNR at the $r_n$ radius. The curves B and C show the mean and the variance of this SNR as a function of the parameter Λ, which defines the radius $r_n$. The last plot D, shows the fear of harmful interference $F_{HI}$ as a function of the parameter Λ. All these plots are made using a fast fading channel.

The dependence of the variance of the fading channel on the distance, can be easily demonstrated by using the mathematical expression of fast fading. Thus this kind of channels can be approximated by an exponential distribution:

$$ f(x; \lambda) = \begin{cases} \lambda e^{-\lambda x} & x \geq 0 \\ 0 & x < 0 \end{cases} $$

where $\lambda$ in this case is the parameter of the distribution, which can be also called the rate parameter. Therefore, by taking into account the mean and the variance expressions of this probability density function, we get:
7.3 Maps and plots of performance criteria quantities

\[
E[X] = \frac{1}{\lambda} = pt \alpha; \quad \lambda = \frac{1}{pt} d^\alpha \\
\sigma^2 [X] = \frac{1}{\lambda^2} = \left(\frac{1}{pt} d^\alpha\right)^2 \\
\sigma^2 [X] = pt d^{-2\alpha}; \sigma^2 [X] (\text{dB}) = -20\alpha \log_{10} d + 2P_t. \tag{7.6}
\]

Indeed, the expression shows that the variance decreases with the distance in decibels. The $F_{HI}$ is always achieved at the $r_n$ radius, so that at any $r_n$ distance for fast fading channels, the received SNR will have the histogram shown in Figure 7.11.a, with mean and variance depending on the parameter $\Lambda$ as Figures 7.11.b and 7.11.c show. The $F_{HI}$ will be the integral from $-\infty$ to the mean of the histogram, which will have the same value independently of the value of mean and variance that the SNR has at the $r_n$ radius. This is because of the unimodality of the probability density function, in this case a Rayleigh distribution.

![Figure 7.12](image)

Figure 7.12: Plot A shows the histogram of the SNR at the $r_n$ radius. The curves B and C show the mean and the variance of this SNR as a function of the parameter $\Lambda$, which defines the radius $r_n$. The last plot D, shows the fear of harmful interference $F_{HI}$ as a function of the parameter $\Lambda$. All these plots are made using a shadowing channel.

Figure 7.12 shows the $F_{HI}$ and the properties of the received SNR at $r_n$ for a shadowing channel. In this case, the $F_{HI}$ has the same behaviour as in the fading channel case. For
shadowing channels, the constant value of $F_{HI}$ is because of the symmetry and the unimodality of the probability density function, in this case a normal distribution. Therefore, by comparing $F_{HI}$ between fading and shadowing channels it can be observed that the probability is higher when a fading channel is used. Finally, by comparing the variance of the histogram in the case of the fast fading and shadowing channels, it is possible to see that the variance of the fast fading is approximately 10 dB larger than the variance of the shadowing channel. So that, the uncertainty for fast fading channels will be much larger.

Figure 7.13: These curves show the weighted probability of area recovered (WPAR), which defines how much area has been recovered by the unlicensed users by finding spectrum opportunities. This quantity is expressed as a function of parameter $\Lambda$. In the figure are shown the curves for both fast fading and shadowing propagation models.

The weighted probability of area recovered (WPAR), as a function of the $r_n$ radius, will show the relation between the distance from the primary transmitter and the probability of recovering some area due to finding spectrum holes in space. Figure 7.13 shows the WPAR as a function of the parameter $\Lambda$ for fast fading (NLOS) and slow fading channels. In the plot can be observed that when the value of the parameter $\Lambda$ increases, the WPAR curves tend to the same value. This is because the variance of the probability distribution of the received power decreases and, as a consequence, the WPAR of both fast fading and shadowing tends to the same value. In order to do this experiment, a discrete version of the equation of WPAR shown in (5.13) is used. The discrete version is given by the expression:

$$WPAR = \sum_{n=r_n}^{r_{max}} P_{FH}[n] w[n],$$

(7.7)

where $r_n$ is the non-talk radius, $r_{max}$ is the maximum distance used in the simulation (what will be a high value), $P_{FH}$ is the probability of finding a spectrum hole and the
function $w(n)$ is a weighting function which is $w[n] = A \exp(-\kappa n)$ with $\kappa = 2 \times 10^{-5} \text{m}^{-1}$ and $A = 1$.

After all the simulations, in order to conclude this chapter, some important findings are summarized below.

- The different possible locations due to the uniform distributed secondary users, will add a statistical dependence to the scenario.

- When the density of secondary users increases, the $r_n$ radius also increases (or the SNR decreases). The value of the variance tends to zero in this case.

- The primary system should consider the percentage of lost area $\chi$, since it implies the loss of some primary receivers.

- When the transmitted power of the secondary users increases, the distance of the $r_n$ radius becomes larger.

- When the licensed system chooses a higher value of $\omega$, the unlicensed users are able to reduce less the $r_n$ radius preserving the percentage of lost area $\chi$. By transmitting with a higher power, the length of the $r_n$ radius will have more dependence on the location of the secondary users.

- The mean SNR at $r_n$ as a function of the power transmitted by the primary user has an increasing linear behaviour. The variance in this case is constant over the values of transmitted power.

- When the $\omega$ parameter is high, the $r_n$ radius tends to be equal to the coverage radius $r_{pcov}$ of the primary transmitter on average, depending on the different locations of the secondary users. For high values of $\omega$ the different locations and density of the secondary users produce no variation in the SNR at $r_n$.

- When very demanding fading channels are used, it is necessary to add the SNR margin given in Equation (5.2) to achieve the desired level of performance. This SNR margin has a direct relation to the distribution function of the received power.

- Fast fading channel produces larger probabilities of interference within the $r_n$ radius and larger probabilities of loss of spectrum opportunities outside of it.

- Fast fading introduces higher $F_{HI}$ and, in general, it deteriorates all the quantities since the fast fading NLOS has very demanding propagation conditions.

- $F_{HI}$ as a function of the parameter $\Lambda$ is observed to be constant for all the values for fading channels.
• When the values of the parameter $\Lambda$ is observed to be constant for all the values for fading channels.

• When the value of the parameter $\Lambda$ increases, the WPAR curves tend to the same value for fast and slow fading.
Chapter 8

Conclusions

Cognitive radio can become an important enabling technology to take advantage of the free resources in the licensed spectrum. Likewise, the technology increases the spectrum efficiency by transmitting data when the licensed users leave some free channel. Therefore, the concept of spectrum hole and its different types will be significant in order to know when, where and at what resource it is possible to use the unlicensed spectrum. The used propagation channel will play an important role in that sense, since the quantitative as well as the performance criteria depend on the reliability of spectrum sensing techniques, which depends at the same time on the propagation models.

The quantitative and performance criteria are one of the most important strategies in interference management in a cognitive radio system. They offer a set of techniques and strategies to evaluate the performance of the coexistence between the licensed and the unlicensed systems, while respecting the regulatory policies and constraints. Regarding the interference temperature method, although it has been thoroughly studied, the problem of detecting the location of the primary receivers is a really limiting fact. Nevertheless, the approach is under research. The MAC protocols for the cognitive users are as well an issue to take into account in the design of any cognitive system, since the secondary users can as well interfere with each other. The optimum power control in the cognitive radios will play also a significant role. It allows adjusting the power transmitted by the unlicensed users depending on its location and on the location of the licensed receivers. An efficient and reliable power control permits decreasing or even removing the non-talk radius $r_n$, which will produce a larger recovered area and, therefore, a higher WPAR quantity.

As it has been shown in the experiments of Chapter 7, the location of the secondary users has an important impact on the quantitative criteria as, for example, on the non-talk radius $r_n$. At the same time, the density of secondary users will have an effect on the quantitative criteria, reducing or increasing the $r_n$ radius according to its value. In the same chapter, a new performance criteria was presented which is called the percentage of lost area $\chi$ for the licensed users. It depends on the difference of the coverage radius $r_{pcov}$.
and the protection radius $r_{prot}$. It has been found as well that for low transmission powers of the secondary system, it is better to choose a high value of $\omega$ (smaller $r_{prot}$) and, for high transmission power, it is better to choose a low value of $\omega$ (larger $r_{prot}$). In those cases, the dependence on the multiple possible locations of the secondary users is lower. Another conclusion is that when some more realistic propagation channel (i.e. fast fading), apart from the statistical variation that the multiple locations of the secondary users inserts in the problem, the channel inserts still more uncertainty. This effect could be seen, for instance, in the SNR maps of Chapter 7. Comparing more realistic propagation channels as fast fading and shadowing, it could be seen that the fast fading makes worse practically all the performance criteria quantities. The shadowing has a good behaviour on average, but without taking into account the hidden node problem. The probabilities of fear of harmful interference $F_{HI}$, are found to be constant for any value of the parameter $\Lambda$ by using fading and shadowing channels. This is because the unimodality and symmetry of the probability density function of the received power. Finally, the WPAR performance criterion was checked, which was found to be higher when the secondary user is further from the non-talk radius $r_n$, as it was expected.

As future work, first of all it will be interesting to study more deeply the relation between the quantitative criteria and the performance criteria. Secondly, more research and experiments about applying optimum power control in cognitive radio can be significant, since these methods can reduce considerably (or remove) the non-talk radius, which represents some loss of potential recoverable area.

To conclude, some important results are listed below.

- The technology increases the spectrum efficiency by transmitting data when the licensed users leave some free channel.

- The quantitative and performance criteria are one of the most important strategies in interference management in a cognitive radio system.

- The MAC protocols for the cognitive users are as well an issue to take into account in the design of any cognitive system, since the secondary users can as well interfere with each other.

- The optimum power control in the cognitive radios will play also a significant role.

- The location as well as the density of the secondary users has an important impact on the quantitative criteria.

- When some more realistic propagation channel is used (i.e. fast fading) the uncertainty increases.

- The probability of fear of harmful interference $F_{HI}$, is found to be constant for any value of the parameter $\Lambda$ by using fading and shadowing channels.
Appendix A

Parameters of COST 259-GSM

Table A1: Structure of COST 259-GSCM channel model. The different diagrams are not shown in the table, but they can be found in [22]. The meaning of the acronyms are given in Table A2.

<table>
<thead>
<tr>
<th>Macrocell</th>
<th>Microcell</th>
<th>Picocell</th>
</tr>
</thead>
<tbody>
<tr>
<td>GTU</td>
<td>GRA</td>
<td>GBU</td>
</tr>
<tr>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>Different parameters for each RE (LP’s)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table A2: Global parameters of COST 259-GSCM channel model shown in Table A1 [22]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Acronym</th>
<th>Symbol</th>
<th>Acronym</th>
</tr>
</thead>
<tbody>
<tr>
<td>GTU</td>
<td>General Typical Urban</td>
<td>GOP</td>
<td>General Open Place</td>
</tr>
<tr>
<td>GRA</td>
<td>General Rural Area</td>
<td>GOL</td>
<td>General Office LOS</td>
</tr>
<tr>
<td>GBU</td>
<td>General Bad Urban</td>
<td>GON</td>
<td>General Office NLOS</td>
</tr>
<tr>
<td>GHT</td>
<td>General Hilly Terrain</td>
<td>GCL</td>
<td>General Corridor LOS</td>
</tr>
<tr>
<td>GSN</td>
<td>General Street NLOS</td>
<td>GCN</td>
<td>General Corridor NLOS</td>
</tr>
<tr>
<td>GSC</td>
<td>General Street Canyon</td>
<td>GFH</td>
<td>General Factory or Hall</td>
</tr>
<tr>
<td>GSX</td>
<td>General Street Crossing</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix B

Parameters of the simulations

Table B1: The table shows the values of the used parameters in the experiments of Section 7.1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
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</thead>
<tbody>
<tr>
<td>Number of PT</td>
<td>1</td>
</tr>
<tr>
<td>Position PT (x,y)</td>
<td>(0, 0) km</td>
</tr>
<tr>
<td>$P_T$ PT</td>
<td>40 dBW</td>
</tr>
<tr>
<td>$P_T$ ST</td>
<td>10 dBW</td>
</tr>
<tr>
<td>Sensibility PR (SNR$_{min}$)</td>
<td>25 dB</td>
</tr>
<tr>
<td>Sensibility SR (SNR$_{min}$)</td>
<td>20 dB</td>
</tr>
<tr>
<td>Density SU</td>
<td>0.17 users/km$^2$</td>
</tr>
<tr>
<td>Attenuation constant</td>
<td>$\alpha = 4$</td>
</tr>
<tr>
<td>Simulation radius</td>
<td>30 Km</td>
</tr>
</tbody>
</table>
Table B2: The table shows the values of the used parameters in the experiments of Section 7.2.

<table>
<thead>
<tr>
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<th>Values</th>
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<tbody>
<tr>
<td>Number of PT</td>
<td>5</td>
</tr>
<tr>
<td>Position PT (x,y)</td>
<td>(0,0),(-10,-10),(-10,10),(10,-10),(10,10) km</td>
</tr>
<tr>
<td>( P_T ) PT</td>
<td>40 dBW</td>
</tr>
<tr>
<td>( P_T ) ST</td>
<td>10 dBW</td>
</tr>
<tr>
<td>Sensibility PR (( SNR_{min} ))</td>
<td>25 dB</td>
</tr>
<tr>
<td>Sensibility SR (( SNR_{min} ))</td>
<td>20 dB</td>
</tr>
<tr>
<td>Density SU</td>
<td>0.25 users/km^2</td>
</tr>
<tr>
<td>Attenuation constant</td>
<td>( \alpha = 4 )</td>
</tr>
<tr>
<td>Simulation radius</td>
<td>20 Km</td>
</tr>
</tbody>
</table>

Table B3: The table shows the values of the used parameters in the experiments of Section 7.3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of PT</td>
<td>1</td>
</tr>
<tr>
<td>Position PT (x,y)</td>
<td>(0,0) km</td>
</tr>
<tr>
<td>( P_T ) PT</td>
<td>30 dBW</td>
</tr>
<tr>
<td>( P_T ) ST</td>
<td>10 dBW</td>
</tr>
<tr>
<td>Sensibility PR (( SNR_{min} ))</td>
<td>25 dB</td>
</tr>
<tr>
<td>Sensibility SR (( SNR_{min} ))</td>
<td>20 dB</td>
</tr>
<tr>
<td>Density SU</td>
<td>0.10 users/km^2</td>
</tr>
<tr>
<td>Attenuation constant</td>
<td>( \alpha = 4 )</td>
</tr>
<tr>
<td>Simulation radius</td>
<td>50 Km</td>
</tr>
</tbody>
</table>
Bibliography


[40] “IEEE standards coordinating committee 41 (dynamic spectrum access networks),” http://grouper.ieee.org/groups/scc41/ (Date Accessed 13/12/2010).


